Response letter to Referee #3

We would like to thank the reviewer for the time they have taken to offer insightful and constructive comments to our manuscript. We have addressed the comments in our responses to the reviewer below. This has led to several improvements and clarifications to our study. In particular, the reviewer was concerned about the lack of representation of direct model output and the numerical and physical reliability of our results.

To improve the presentation regarding model outputs, we have further extended the supplementary information with figures depicting direct model output. These are aimed for the interested readers and to further support and clarify our findings. We have also added a new conceptual diagram in the main text to aid the discussion on saturation, thermal conductivity and heat capacity. The numerical accuracy of simulations is ensured by assigning stringent numerical convergence criteria, monitoring output, and checking results are numerically stable. Therefore we expect the model outcomes to be robust and valid solutions of the system of equations. The model applicability and consistency with real-world conditions is achieved by using realistic boundary conditions and careful model design, including choice of parameter values and hillslope inclinations consistent with observations. Further, the model output in terms of thaw depth and active layer thickness is compared against measurements in Adventdalen, thereby attaining model confirmation (Oreskes et al. 1994) against field measurements.

With these changes and clarifications we believe the manuscript has been significantly improved and is highly relevant for the readership of the Cryosphere.

Our responses are written in blue font. Figures shown in this response letter are referred to as Figure R#. Otherwise, figure references refer to the main text.

Line numbers in the **revised manuscript** that contain changes are given in red font.

General comments:

The manuscript reports a numerical modeling study aiming to better understand lateral groundwater flow influence on temperature and heat transport in active layers. The study is well motivated and the presentation is well organized. I have some concerns on how the modeling is done and consequently how meaningful the interpretation of the model results is. Below are the specifics.

1. The model domain has a relatively small lateral dimension (~ 50 m), “a very short slope” as the authors recognize but justify it by needing to provide a trade off between resolution and computer time (Line 165-166). My concern is that the trade off may sacrifice the appropriateness of the model representation. Given the focus of this study is on processes in the lateral direction, the small lateral dimension casts much doubt on the validity of the interpretation of model results.

Response: Although the simulated hillslopes are relatively short, they are valid hillslope representations, certainly for small catchments. The results we observe are based on numerical representation of physical processes, as simulated by the model, and therefore represent relevant findings of this complex flow system. As mentioned in the main text, due to the model complexity a high vertical mesh resolution is required in the uppermost parts of the domain, in particular where the active layer is located, which greatly increases the computational effort. Consideration of larger systems is certainly of interest and deserves investigation, but is beyond the scope of our current study.

Furthermore, even if these results are in a strict sense limited to the distance considered, we consider possible effects of larger slope systems/catchments in the outlook section (section 3.7). Also, we include a sensitivity analysis of two additional wetness scenarios, which simulate dryer and wetter conditions than the current hydro-climatic conditions (section 3.6). We adjusted the sentence mentioned in the comment slightly for clarification (previously L165-166).

Changes: L168-170: The domain size is chosen to represent a generic hillslope that provides a reasonable trade off between model resolution and computational effort.

2. For a small model domain like this, boundary conditions could strongly dictate model outcomes. Much of the model interpretation is based on two control volumes near the left and right boundaries where no-flow (heat and water) conditions are applied. While a no-flow condition across the right boundary may be justified on the ground of valley symmetry, the no-flow condition for the left boundary, a short distance from the valley floor cannot be easily justified. The boundary condition on model top is vague without specific details. A slight change in these boundary conditions would likely lead to different model outcome. Ultimately the modeling here is to solve a boundary value problem.

Response: The control volumes are intentionally placed to monitor flows on the extreme ends of the slope, and to encompass the part of the active layer for which the most significant heat- and water flow dynamics occur. The no-flow boundary condition on the left side represents a water divide. This is chosen to avoid arbitrary inward mass flux, which would indeed obfuscate results. The boundary condition on the surface of the domain is a surface energy balance using hydro-meteorological inputs. This is presented in the main text (Section 2; Data and method) and supplementary information Figure S1. The surface energy balance model is described in Atchley et al. 2015. As such, the model is driven by the hydro-meteorological input, which is derived from weather station measurements in Adventdalen, Svalbard. Therefore, the model is not driven by an arbitrary set of boundary conditions and the results are robust, and only sensitive to the imposed hydro-meteorological input, which again, comes for real-world observations. This is one of the powerful features of the approach undertaken by the ATS model.

Furthermore, as mentioned above in response to comment 1, we also investigate the sensitivity of the system with respect to the current hydro-climatic conditions by considering two additional hydro-meteorological scenarios derived from the original weather station input, one corresponding to dry conditions and another one to wetter conditions (S0R0 and S2R2, Section 3.6; Impact of changes in precipitation).

The “short distance from the valley floor” (we believe this is referring to the distance between the foot of the slope and the right boundary) was chosen to be 16m long (8 columns). We have investigated the effect of a shorter “valley bottom” of 4m and found no significant differences between those two scenarios and therefore conclude that 16m in the valley bottom is more than suitable to avoid any boundary effects on that edge. This information is not included in the manuscript but was previously provided in our response to Referee #1, where we state how we approached the valley bottom geometry.

No changes

3. On model initialization and spin-up (section 2.2.2), it is puzzling why the authors used 33 1D column and then map the result to the 2D model, instead of using the actual 2D domain to initialize the model. A common way to initialize models is to use time-averaged conditions to let the model spin up to a quasi-steady background state and use the quasi-steady state as the initial condition for transient runs. The unusual approach used in this study may pose additional problem for the no-flow conditions across the two lateral boundaries.

Response: The initialization procedure adopted is well-established and consistent with previous efforts for modeling Arctic/permafrost hydrogeological systems (e.g. Painter et al. 2016, Jafarov et al. 2018, Jan and Painter 2020). The procedure used, described in section 2.2.2, is necessary to obtain a physically consistent, periodically stable annual flow system undergoing freeze-thaw. Note the initialization procedure includes a spin-up also for the full 2D domain, after the mapping of the 1D column has been performed, which allows for stabilization of lateral processes (step 4 in section 2.2.2).

Our intention is to investigate an annually periodic system consistent with recent climate conditions and therefore longer term transient runs are intentionally not performed. The periodic steady-state is ensured by using the last (100th) year of the final stage spin-up. In our evaluations we have determined 100 years for the final stage spin-up to be more than sufficient to obtain annually stable/consistent conditions.

The lateral no-flow boundaries are intentionally assigned as such as they represent symmetry boundaries. They do not pose a problem for the flow field because the top surface of the domain allows for both recharge and discharge to occur and the water table during unfrozen conditions is a free-surface.

No changes

4. Model result presentation needs much improvement.

4.1 Presenting temperature difference (Figure 4) is difficult to make sense. Direct modeled temperature outputs for different scenarios need to be presented (even in supplement). The difference of two wrong sets of data may look reasonable. Please excuse my bluntness, I do not mean to say that the model results here were wrong, but just to say that the difference may not tell the whole story.

Response: We find temperature differences to be the most convenient and clear way to present and compare results. For the interested reader, the direct modeled temperature outputs are indeed available in the supplementary information (Figure S3) as mentioned in L215-116 in the old version of the manuscript (now L218-219).

No changes

4.2 The temperature time series or whatever condition is applied on the top boundary need to be added to the top of Figure 3 for readers to make better sense of the modeled temperature results at three depths. For example, I am puzzled by the wiggles in all of the modeled temperature time series. Is it because of the temperature variations in the boundary condition propagating down or because of potential numerical errors? It is also puzzling why temperatures at 0.5 m experienced the most dramatic changes while deeper and shallower temperatures are more subdued.

Response: A surface energy balance is used for the top surface of the model domain, which includes several input variables in addition to temperature. For completeness, these are presented in Figure S1 in the supplementary information. Due to the complexity of surficial processes, including the SEB and the fact that hydro-meteorological data with considerable daily variation is used as input, the surface signals propagate into the subsurface causing day-to-day changes in subsurface state variables. These are a result of system behavior and not numerical artifacts. We added a sentence to explain that the forcing dataset has not been smoothed before applying it as a boundary condition in the main text as well as in the figure caption of Figure 3)

We address the observation that temperature differences at 0.5m depth are the most considerable (L225-226 of the previous version of the manuscript, now L228-229) and it can also be seen in Figure 4, which presents temperature differences in the active layer and the upper permafrost. With Figure S7, we explain that heat capacity has a major influence on temperature differences as described in L320-321 (previous version of the manuscript, now L327-329)

Changes: L119-120:Apart from the redistribution of precipitation, the meteorological data has not been smoothed.

4.3 The unsmooth curve for the flat slope scenario (Figure 5) also is puzzling. If there are any numerical issues with this base case flat slope scenario , then the other two cases comparing with the base case may be problematic.

Response: The incremental changes in thaw depth in Figure 5 are a reflection of the mesh resolution of the model domain in the active layer (5cm depth, cf. Figure S2) and because we chose to present direct modeled results without smoothing or interpolation. We define thaw depth as the depth for which the entire mesh volume is at or above 0 degC, therefore the thaw depth propagation over time has an incremental nature. Note also that the thaw depth shown in Figure 5 is a spatial average over the entire transect length, which varies slightly for the inclined cases but not for the flat case. Therefore, the sloped cases appear to have a smoother propagation over time.

Changes: Figure 5 has been moved from the main text to the supplementary information following a suggestion by Referee #4

4.4 The discussion on saturation, thermal conductivity and heat capacity (section 3.3) is laborious and stressful to read. A conceptual illustration may aid the discussion. My bigger concern is that if the numerical model results were not proper, then discuss would be strenuous.

Response: We have made efforts to improve this part of the presentation, both text and by adding a new conceptual figure as suggested (Figure 6 of the revised manuscript and Figure R1 below), which we believe helps clarify the discussion and analysis of this section.

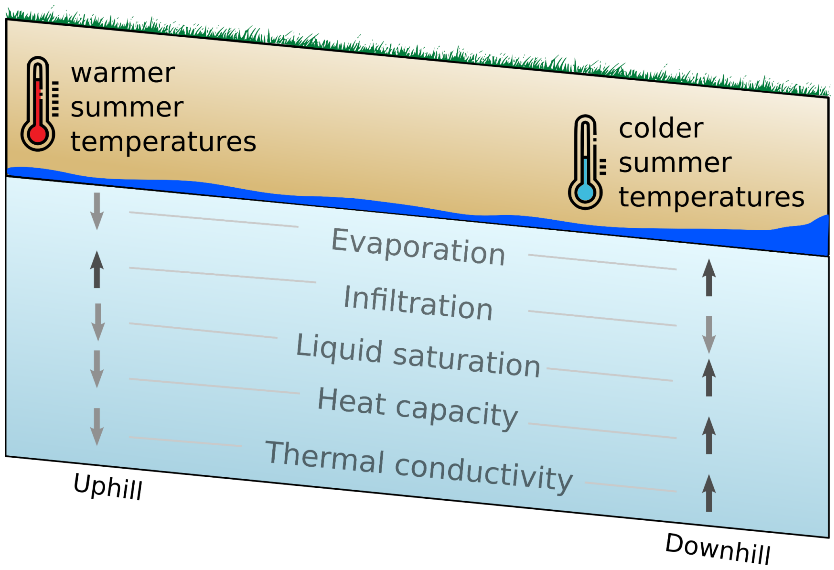

Figure R1: Conceptual diagram of the effects of saturation on ground temperatures in the active layer in summer time. The arrows indicate if the quantity is increased (up, dark) or decreased (down, light).

Changes: Section 3.3 and Figure 7.

5 The authors need to provide a big picture about what the groundwater flow field is like, lateral and vertical, given the intention of this paper is to look at the role of lateral groundwater flow. Direct model output in terms of groundwater head (or pore pressure) field and water flow velocity field in the main text or in supplement would go a long way to provide key model results necessary for readers to comprehend how the physical process of lateral flow influences heat transport in active layers. One piece of information may be the mass flux (Figure 9), but then why the dip in mass flux (meaning recharge?) in November in downhill locations?

Response: Our intention is to show condensed information of the model output, such as temperature differences in the main text to enable the analysis. However, direct model output can be of interest for highlighting technical details, and for this reason we have added a selection of plots in the supplementary information. Due to the vast number of possible depictions, including multiple simulations each with several output variables and with transient dynamics occurring over the year, it is not feasible to show a full set of plots consistent in both space and time. Therefore, we chose a selection of variables for specific points in time focusing on the upper part of the domain (upper 1.2m) analogous to Figure 4 in the main text. This direct model output includes temperature, liquid-, ice-, and gas saturation. This has been added to the supplementary information (Figure S5 and Figure R2 below).

We have omitted representations of the pressure field and darcy velocity field because they are not informative for this analysis; an example of the pressure field with a restricted pressure range can be seen below (Figure R3). Snapshots of darcy velocity vector fields are not informative in our case because of the transient nature of the simulations.

Figure 9 depicts lateral fluxes of heat and water flow. The negative values occurring in November in Fig 9b,d indicate fluxes leaving the downhill CV across its vertical face (at x=48 m). This is an effect of lateral cryosuction as well as two-sided freezing and pressure differences in the domain.We discuss and elaborate on this in Section 3.5

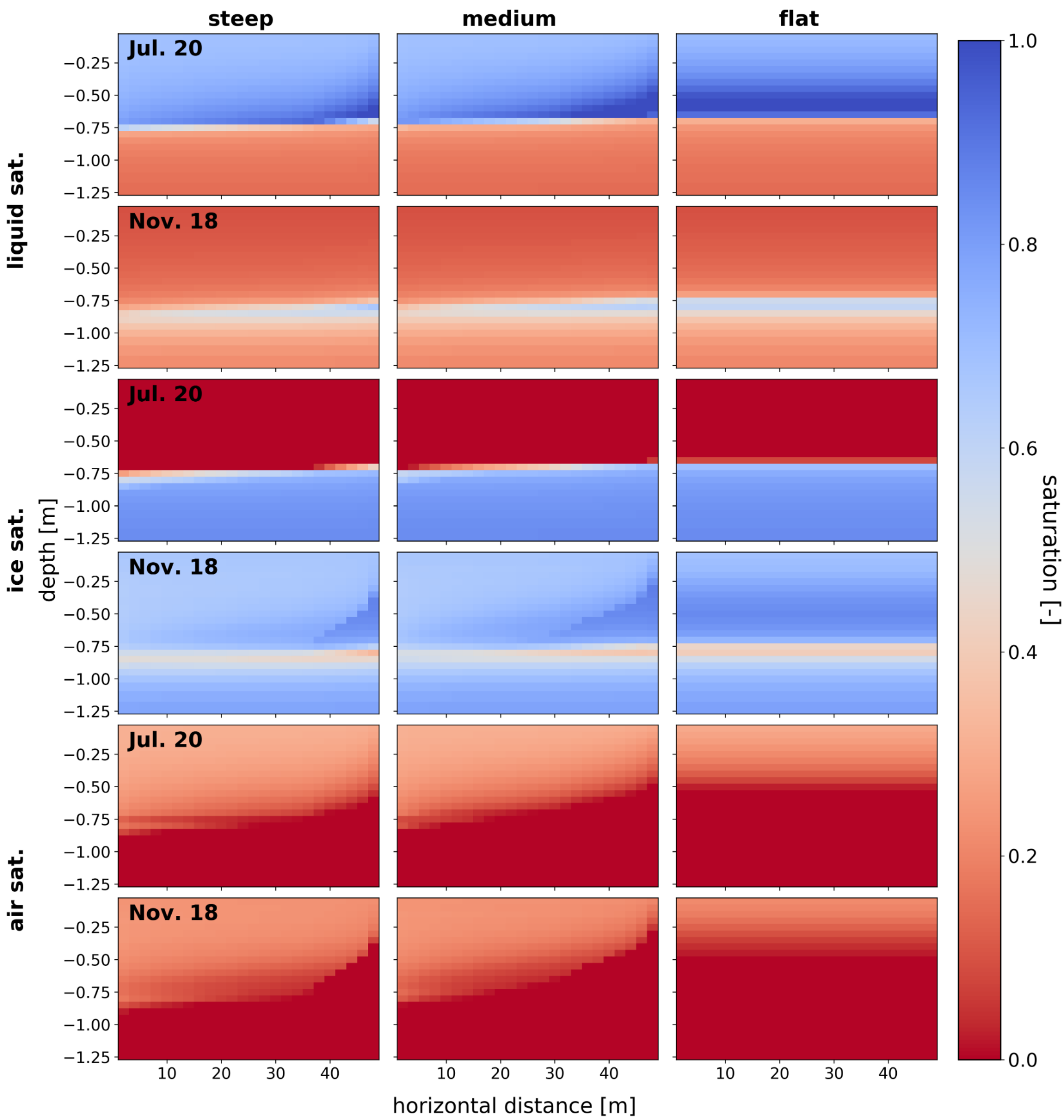

Figure R2: Representation of liquid- (rows 1 and 2), ice- (rows 3 and 4), and gas saturation (rows 5 and 6) on summer day (July 20) and a winter day (November 18) throughout the transect (representation of the upper 1.2m of the model domain across the 50m slope transect). Red colors represent low saturation, blue colors high saturation.

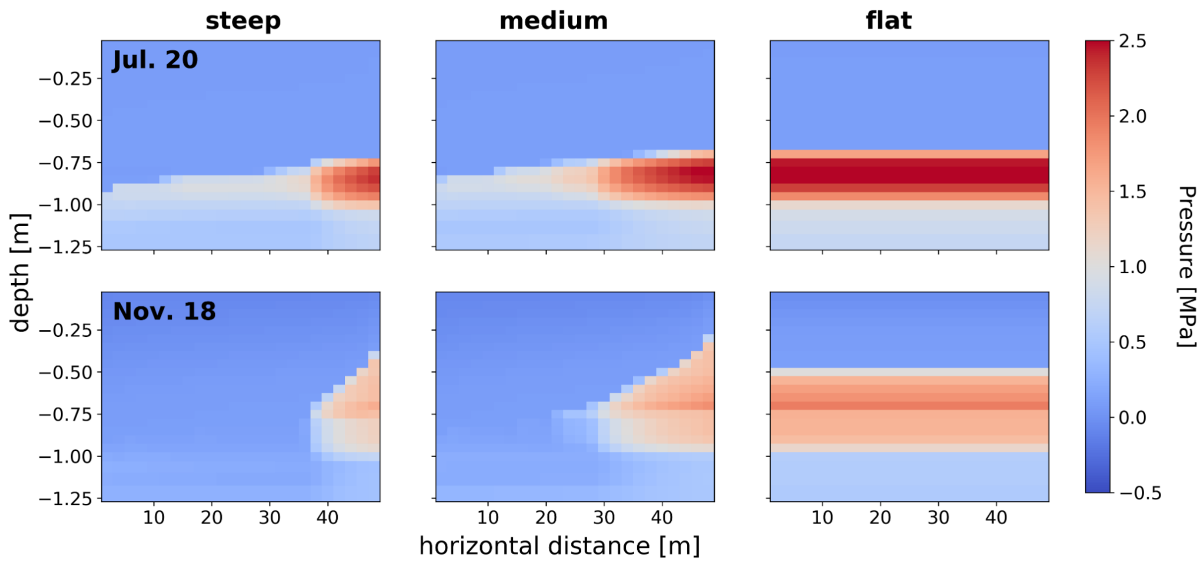

Figure R3: Representation of pressure on summer day (July 20) and a winter day (November 18) throughout the transect (representation of the upper 1.2m of the model domain across the 50m slope transect). Red colors represent high pressure, blue colors low pressure. The lower range of pressure has been restricted to 0.5 MPa for better visualization.

Changes: L404-410: Note also that during freeze-up (November) in the downhill CVs, there are negative values for mass flux (Fig. 9b,d), indicating moisture is leaving the CV in the uphill direction, which we attribute to two-sided freezing and lateral cryosuction. While the active layer starts freezing from above, it also freezes from below, causing high water pressure in the remaining space occupied by liquid water. Due to the temperature distribution in the slope and valley bottom, the only direction the water can be squeezed out towards is uphill. Even though this effect might be overemphasized in a 2D domain, it is a physical based effect unique to permafrost landscapes. Additionally, unfrozen water in the downhill side of the domain can migrate towards the freezing front approaching from the uphill side (lateral cryosuction).

6 The relative magnitude/significance of heat conduction versus heat advection by groundwater is unclear. After all, this study aimed to examine the effects of groundwater on temperature, basically advective heat transport. Conduction and advection were presented in separate figures 7 and 8 and the axis scales differ. It is not easy to compare them, for example, a basic question is what the relative percentages of energy transport by conduction versus advection are. An additional figure to show the system energy balance would be helpful.

Response: The advective and diffusive heat transport are intentionally depicted in separate figures for clarity of presentation. The ratio is also interesting and we have calculated the Péclet number for each of the faces of the CVs as well as the entire model domain and included this as a new figure in the supplementary information (Fig. S8 and Figure R4 below) to avoid excessive detail in the main text.

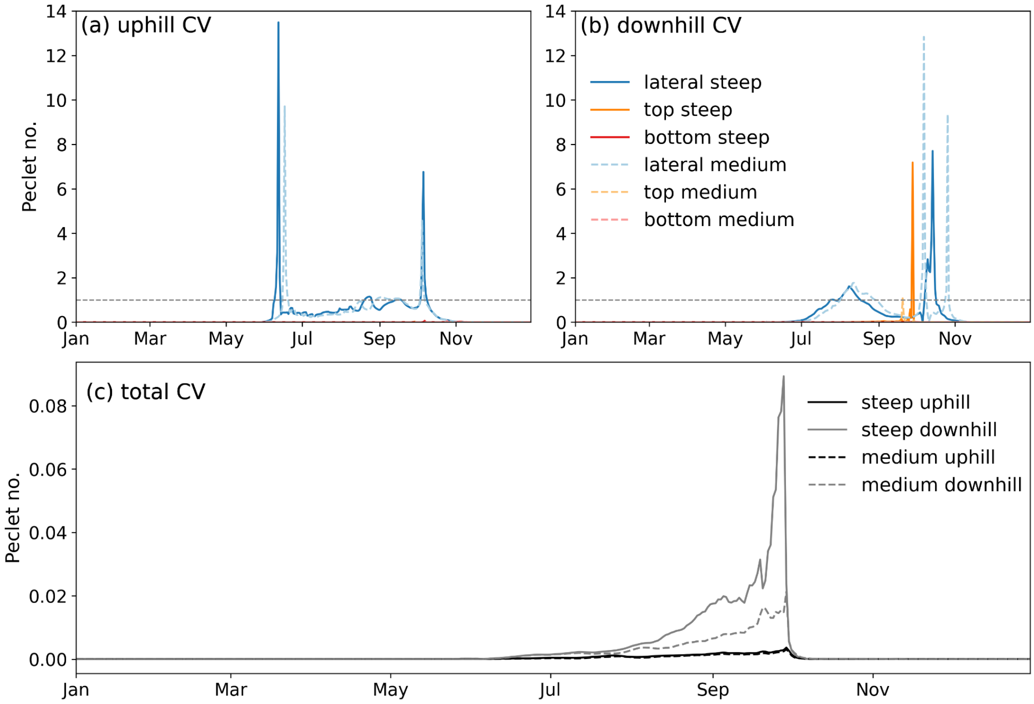

Figure R4: Daily ratio between advective and diffusive energy flux on each of the faces of the a uphill CV, b downhill CV and c the entire CV. Solid lines represent values for the steep case, dashed lines represent the medium case, while colors indicate the different faces of the CV. Dashed horizontal lines in a and b indicate the value of 1, where the advective energy flux becomes more pronounced than the diffusive energy flux. Note that there is no such line in c, as the Péclet number over the total CV is very small.

Changes: Figure S7

7 Model result interpretation may be questionable. No attempt is made to model calibration. At the very least, a first order check of the model results with any field observations would be necessary to convince readers that the model results make sense. For example, one model result is that warmer temperature in uphill and cooler temperature in downhill slopes (Section 3.1, Conclusion i). My intuition seems to be the opposite. The explanation provided (evaporative cooling) is quite strenuous and unconvincing. Any broad observational data may support such model results? Similarly, any broad observations that suggest “steep slope develops deeper thawing front” (Line 255)?

Response: The purpose of this study is to investigate effects of hillslope inclination using realistic conditions; a site-specific study with calibration, inverse modelling or parameter estimation is neither intended nor necessary. Note that the model is a physically-based model adopting conservation equations for energy, mass and momentum and in addition to using realistic physical parameters (Table 1) and hillslope inclinations (Table S1), site-specific hydro-meteorological data are derived and used as input for the surface energy balance and top surface boundary condition to ensure realistic weather variability conditions, thereby achieving relevant and realistic simulation scenarios as needed for this study.

Available field observations are used to attain confirmation (Oreskes et al. 1994) of the applicability of the model, which includes measured active layer thickness in Adventdalen, Svalbard (Strand et al. 2020, Schuh et al., 2017), where our simulated ALT are consistent with those measured ALT. This information is included in Section 2.1 “Field data”.

To clarify the model consistency with field measurements, we have added a sentence in Section 3.2, where we analyse the progressing thaw depth in each of the cases and explain that those simulated values are consistent with ALT measurements in Adventdalen, with citation to the studies mentioned above. This shows that the model is indeed capable of simulating the hydrothermal state of the active layer very well, in fact remarkably well considering it is a forward model.

Our results indicate a downhill cooling effect which may indeed be contrary to initial assumption or intuition, and we are very excited about this important discovery. In our study we carefully and meticulously analyse the phenomenon and provide physically-based, mechanistic explanations of the effect. As such, our study is robust and of great significance to the cryosphere community and warrants prompt distribution.

No changes

In conclusion, I like this study but feel quite uncomfortable about the modeling approach and consequently the results. More direct model results must be presented before readers can assess the interpretation of model results. More bluntly, without showing those direct model output, I am not confident that the results are good. (BTW, my research has involved numerical modeling on water and heat transport in porous media for decades.)

Response: We appreciate and greatly value the careful scrutiny and attention to detail. We are confident we have thoroughly addressed these and made all necessary clarifications and amendments to our presentation.

References in this letter

Atchley, A. L., Painter, S. L., Harp, D. R., Coon, E. T., Wilson, C. J., Liljedahl, A. K., and Romanovsky, V. E.: Using field observations to inform thermal hydrology models of permafrost dynamics with ATS (v0.83), Geoscientific Model Development, 8, 2701–2722, https://doi.org/10.5194/gmd-8-2701-2015, https://www.geosci-model-dev.net/8/2701/2015/, 2015.

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Schuh, C., Frampton, A., and Christiansen, H. H.: Soil moisture redistribution and its effect on inter-annual active layer temperature and thickness variations in a dry loess terrace in Adventdalen, Svalbard, The Cryosphere, 11, 635–651, https://doi.org/10.5194/tc-11-635- 2017, https://www.the-cryosphere.net/11/635/2017/, 2017.

Strand, S. M., Christiansen, H. H., Johansson, M., Åkerman, J., and Humlum, O.: Active layer thickening and controls on interannual variability in the Nordic Arctic compared to the circum-Arctic, Permafrost and Periglacial Processes, p. ppp.2088, https://doi.org/10.1002/ppp.2088, https://onlinelibrary.wiley.com/doi/10.1002/ppp.2088, 2020

Response letter to Referee #4

We would like to thank the reviewer for the time they have taken to offer insightful and constructive comments to our manuscript. We have addressed the comments in our responses to the reviewer below. This has led to several improvements and clarifications to our study. In particular, we improved the visualization of some figures and included a new conceptual figure to simplify the interpretation of our results. We further worked on text passages, which were unclear and improved readability.

With these changes we believe the manuscript has been further improved.

Our responses are written in blue font. Figures shown in this response letter are referred to as Figure R#. Otherwise, figure references refer to the main text.

Line numbers in the **revised manuscript** that contain changes are given in red font.

This manuscript addresses a novel topic using a robust simulator of surface and subsurface cryohydrological processes and will be an important contribution to the cryosphere literature. The authors thoroughly address reviewer comments and have greatly improved the manuscript. However, the results/discussion section is still difficult to digest despite text revisions. I suggest separating the results and discussion section to more clearly convey the results and more comprehensively discuss the findings. If keeping the results and discussion section merged, I suggest further revision of the text (some suggestions included below) as well as inclusion of a conceptual diagram that visually displays the results. One option is to reorganize the section to enhance clarity, perhaps based on mechanism or question addressed (L69-72).

Specific suggestions:

1. L32-35: revise sentence for clarity. Perhaps “Further, higher moisture abundance in the active layer regulates the decomposition of organic carbon, can affect infrastructure built on the fragile frozen ground, and can change the thermal properties of the permafrost.”

Response: Changed sentence according to the suggestion by the reviewer

Changes: L32-34 Further, higher moisture abundance in the active layer regulates the decomposition of organic carbon (e.g., McGuire et al., 2009; Koven et al., 2011), can affect infrastructure built on the fragile frozen ground (e.g., de Grandpré et al., 2012), and can change the thermal properties of the permafrost (e.g., Schuh et al., 2017).

2. L59: Change untangling to untangle.

Response: Changed

3. L142: Please extend the sentence to elaborate on why this is important for the choice of boundary conditions in the model domain. It is not clear from the sentence or paragraph as it is now.

Response: Extended the sentence and added examples for potential boundary conditions.

Changes: L143-146: This is important for the choice of boundary conditions in the model domain, which regulates the water flux out of the domain. Potential boundary conditions for this set-up could be either a closed boundary (no outflow) an open boundary (outflow through the surface and subsurface) or a constant head boundary, which would indicate a persistent river and allow for groundwater discharge into the river.

4. L153-154: Please add more detail with respect to the cell thickness. What is the maximum cell thickness?

Response: Added maximum cell thickness information in brackets (~1.5m)

Changes: L157-158: With increasing depth, cell thickness gradually increases (up to max. ~1.5m cell thickness).

5. L229: Remove comma after slopes.

Response: Removed

6. L231: Remove 'or'.

Response: Removed 'are' in L230 instead (old manuscript) and changed 'as' to 'to' ('or' is correct).

Changes: L233-234: Deeper layers have similar temperatures to the flat case or are even warmer.

7. L263: Perhaps the authors can add a few sentences discussing the patterns seen in the winter panels.

Response: We have added an explanation of the patterns in the December 7 snapshot seen in Figure 4. The new sentences are placed after L245 (of the previous version of the manuscript) to better fit in with the flow of the text.

Changes: L257-260: The patterns seen in both December 7 plots (red patches between -0.2 and -1.2m) are consequences of the timing of freezing in the slopes. While the flat cases freezes uniformly, the active layer slopes freezes faster uphill and slower downhill, causing those temperature differences.

8. L282: Remove "does" and replace "play" with "plays".

Response: Changed

9. Figure 4: Is it possible to add the O degree C isotherm for the flat case to each plot? This addition could also take the place of Figure 5. Given that you discuss differences in the thaw depth between the steep/medium and flat case in the text, it would be beneficial to see that

difference in the figure. Perhaps the flat isotherm could have a different color and line pattern.

Response: We appreciate the idea of including the flat 0°C isotherm into Figure 4 and changed Figure 4 accordingly (see Figure R1 below). We also agree that Figure 5 is partly redundant with this figure and moved it to the supplement.

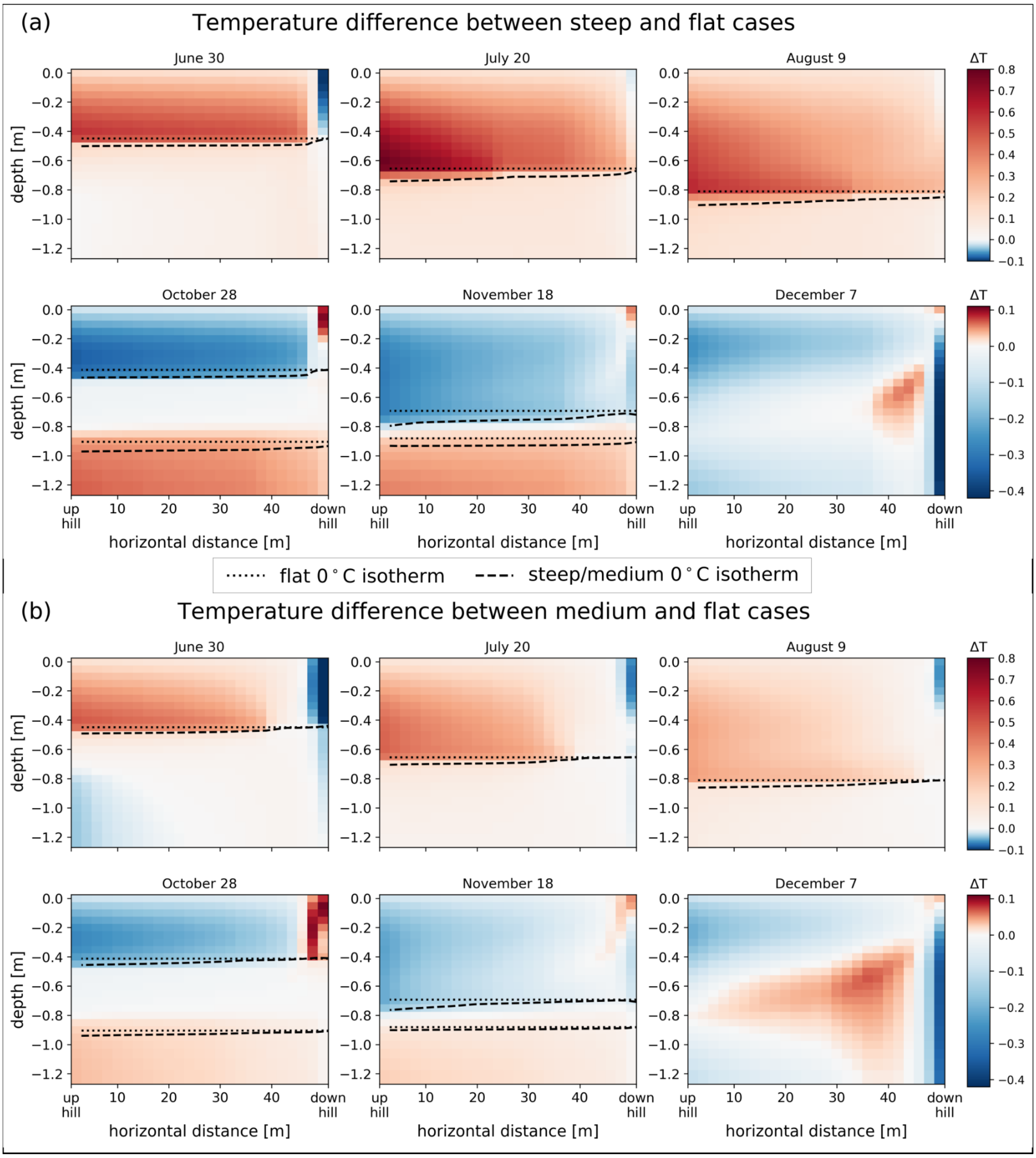

*Figure R1: Temperature difference between **a** the steep and the flat case and **b** the medium and flat case at six selected dates highlighting thaw, summer, freeze-up and winter. Red colors indicate warmer temperatures in the hillslope cases than in the flat case, blue colors indicate cooler temperatures (note the color scale differs between summer and winter comparisons). The black dashed lines indicate the 0°C isotherm(s) in the corresponding hillslope cases (steep and medium) at the respective dates. The 0°C isotherm lines of the flat case are represented by dotted lines. During* *freeze-up, it can be seen that two-sided freezing occurs. (For clarity, only the upper 1.2m of the simulation domain is shown.)*

Changes: Figure 4 in the main text and Figure S4 in the supplementary information

10. Figure 5: If keeping this figure in the manuscript, please consider including three line styles in addition to three colors to help see different in lines.

Response: Added line styles in addition to the colors and moved previous Figure 5 (now Figure S4 and Figure R2 below) to the supplementary information and the text has been adjusted accordingly.

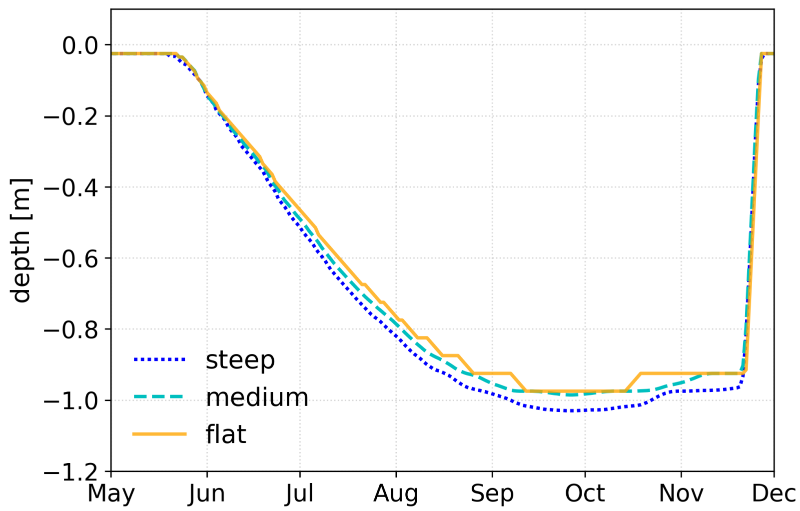

Figure R2: Representation of thaw depth compared between the steep (blue), medium (cyan) and flat case (yellow) as daily, spatially averaged thaw depth (averaged over a 5-day window) from May to December in the last year of the simulation. Note that thaw depth is defined as cells within the model domain that exceed 0°C.

Changes: Figure S4 and L270-273: The spatial mean active layer depth in the deep slope on the date of maximum active layer depth is 1.03 m (min.:1.03 m, max.: 1.03 m along the transect). The medium slope exhibits a smaller uphill warming than the steep slope resulting in a spatial mean active layer depth on the date of maximum active layer depth of 0.986 m (min.:0.975 m, max.:1.030 m along the transect), which is only slightly deeper than in the flat case (0.975 m).

11. L289: Please provide more detail to clarify your reasoning for a more saturated downhill side on the medium slope.

Response: The main reason for higher liquid saturation in summer in the downhill side of the slope is the geometry of our slopes. As can be seen in Figure R3 below, gravity driven water flow causes the fully saturated cells in the steep slope to be deeper (40cm depth) than in the medium slope (35cm depth). On the other hand, the first column in the valley bottom (which we do not discuss in the manuscript) is saturated up until 25cm below the ground surface in the steep case and only until 30cm below the ground surface in the medium case.

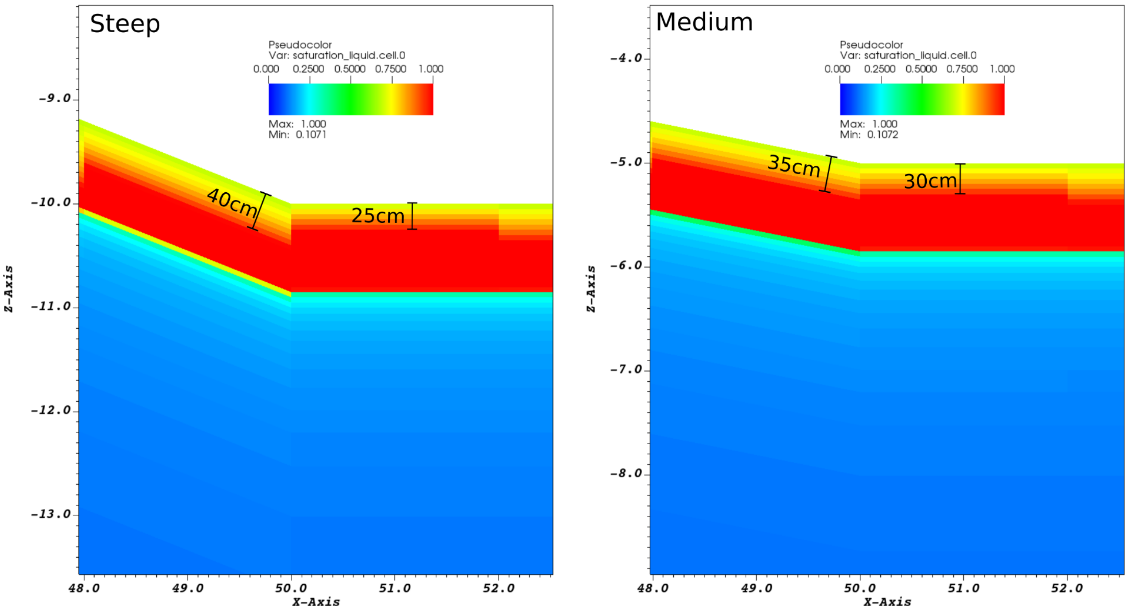

Figure R3: Subsurface water level (red colors) in the foothill of the steep (left) and medium (right) slope in summer. The depth below the ground surface at which the soil is fully saturated is given in cm.

We changed the text in the revised manuscript and removed this superfluous comment because it diverts from the main message of the section. As pointed out by the reviewers, this section (Section 3.3) is already very complex and therefore we hope to make it easier for the reader to follow our line of thought.

Changes: Removed L287-298 in the old manuscript

12. L289-292: I suggest removing the '/' and separate this sentence into two sentences for clarity.

Response: We restructured the sentence for clarity

Changes: L289-296: Due to gravitational flow of water during the warm period, moisture is drained from the uphill side and accumulates on the downhill side, reducing liquid saturation uphill and increasing it downhill when compared against the flat reference case which is not subject to lateral flow (Fig. 5, first column). This leads to differences in ice saturation during the frozen period (Fig. 5, second column), specifically reduced ice saturation uphill and increased downhill. Consequently, the uphill side of the sloped cases experience increased air saturation (Fig. 5, third column), which yields a considerably lower effective thermal conductivity during winter and slightly lower effective thermal conductivity during summer (Fig. 5, fourth column). Similarly, the downhill side has reduced air saturation (Fig. 5, third column), yielding greater effective thermal conductivity; considerably greater during winter and slightly greater during summer (Fig. 5, fourth column).

13. L300: I suggest rephrasing this topic sentence. Perhaps modify sentence 1 and merge with sentence two.

Response: This sentence has been improved by reorganizing the beginning of this paragraph.

Changes: L306-308: Recall the previous discussion on temperature differences between the sloped and flat cases (Section 3.2). The uphill sides of the sloped domains (Fig. 3c,e) are slightly drier at depths 0.2m, 0.5m and 1m, both for summer with less liquid saturation, and winter with less ice saturation (Fig. 6, first and second columns, respectively).

14. L313: I suggest rephrasing this topic sentence. More specific topic sentences will help clarify this section, as it is long and detailed and can be difficult to follow. Additionally, this is one place where a conceptual diagram to support the discussion would be useful.

Response: Parts of this section have been rephrased. A new conceptual figure added (Figure 6 in the manuscript and Figure R4 below).

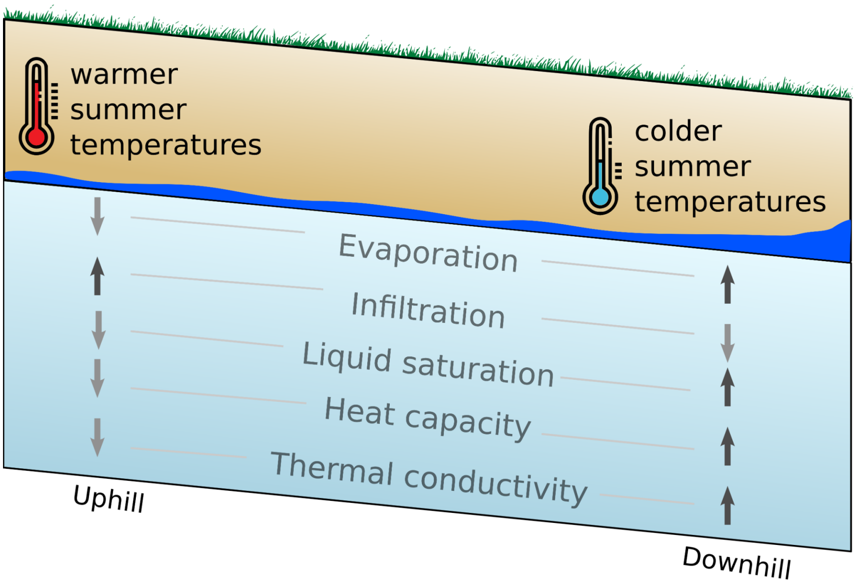

Figure R4: Conceptual diagram of the effects of saturation on ground temperatures in the active layer in summer time. The arrows indicate if the quantity is increased (up, dark) or decreased (down, light).

Changes: L333-336: In summary, moisture redistribution mainly causes differences in thermal conductivity and heat capacity between the uphill and downhill sections (Fig. 6). Thermal conductivity mainly affects energy transport by conduction, and heat capacity attenuates transport by storage. However, to fully understand the effects of energy transport on ground temperatures, a complete analysis of energy fluxes is needed, which is discussed in the next section.

15. L332: Add (CV) after control volume.

Response: Added

16. L349: Smaller than what? Please expand the sentence.

Response: Added missing information

Changes: L357-358: In the uphill CV (Fig. 7b, solid), the lateral heat diffusion is more than one order of magnitude smaller than in the downhill CV (-0.01–0.015 W m^{-2}) and heat is being lost in summer, but gained after freeze-up in winter.

17. L404: Perhaps the authors can include some numbers with this statement such as average temperature.

Response: We included a table (Table S4 in the revised supplementary information) with average upper domain (up to 1.2m depth) temperatures for the original scenario (equivalent to Table 2 in the main text) alongside active layer temperatures in the two precipitation scenarios. We also added numbers for the relative difference between the slopes and the flat case.

Changes: L417-421: Firstly, we find that both slopes and the flat case are notably warmer in the no-precipitation scenario (S0R0) and colder in the doubled precipitation (S2R2) scenario (Table S4 in the supplementary material). Relative temperature differences between the slopes and the flat case are generally in a similar range as in the original precipitation scenario. The steep slope in S2R2 is up to 0.7°C warmer than the flat case in summer and up to -0.6°C colder in winter. In S0R0, the steep slope is up to 0.3°C warmer than the flat case in summer and up to -0.2°C colder in winter.

18. Figure 10: Consider distinguishing lines with line style (dot, dash) as well as color.

Response: Added line styles in addition to the colors in Figure 10 in the main text.

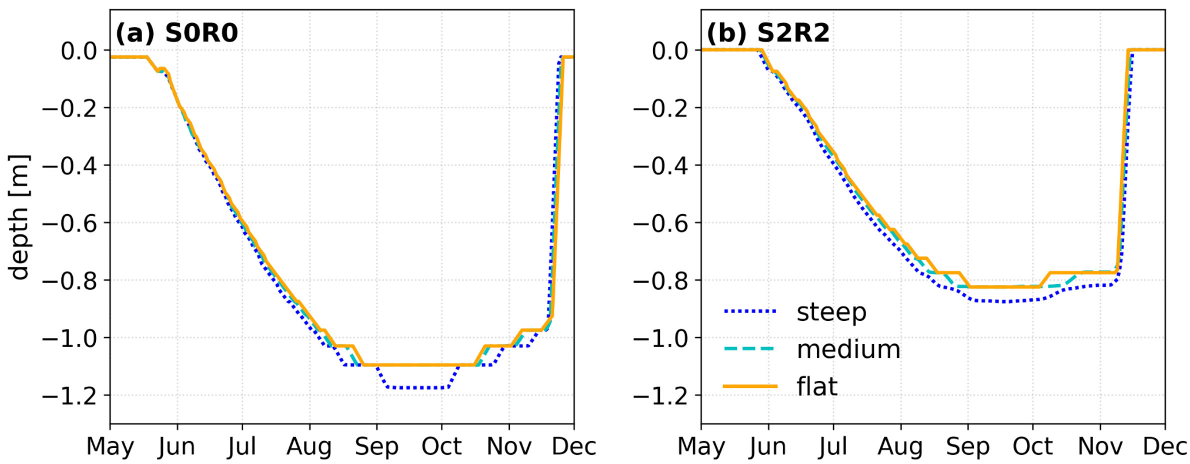

Figure R5: Representation of thaw depth compared between the steep (blue), medium (cyan) and flat case (yellow) as daily, spatially averaged thaw depth temporally averaged over a 5-day window from May to December in the last year of the simulation. Note that thaw depth is defined as cells within the model domain that exceed 0 °C. ***a*** *shows the results for the S0R0 (dry) scenario, while* ***b*** *shows daily thaw depths for the S2R2 (wet) scenario.*

Changes: Figure 10

19. L416: Remove ‘the’ before ‘both’. I suggest rephrasing the sentence for clarity.

Response: We have rephrased the sentence to make it more clear

L432-433: Overall, the scenarios show that a higher amount of recharge added through precipitation on the surface will decrease the ground temperatures in the slopes as well as in the flat case.

20. L440: Replace ‘where’ with ‘were’.

Response: Corrected

21. L479: Remove the comma after ‘both’ and after ‘conductivity’.

Response: Removed