Response letter to Referee #2

Our responses are written in blue

General comments

1. Based on what I read, the main message is because of variable saturation, hillslopes experience different thermal regimes with warmer upslope areas and cooler down slope areas. The paper seems to focus on how increased moisture in the down slope area causes increased evaporative cooling. However, the overall thermal state of the domain is slightly warmer. I'm left wondering why are sloped simulations overall warmer? Only at the end of the manuscript when the authors do an additional sensitivity study by adding more precipitation do we see a general cooling effect of the entire domain. This then suggests that it is a water balance mechanism caused by slope, i.e the system tips the evapotranspiration into an energy limited system rather than water limited and as more water is added. And that area of the domain with more evaporative cooling outweighs the domain that is water limited. However, the water balance verses degree slope, which appears to control the overall thermal state of the entire domain is not discussed.

Response: Thank you for the valuable comment. We realize that the downhill cooling effect received too much attention and that the overall warming of the slope as compared to the flat case has fallen short. We explain the uphill warming effect by increased infiltration (heat advection), less evaporative cooling and overall lower heat capacity as compared to the flat case. In the text, we briefly mention that vertical heat advection plays a major role in the differences between the up- and downhill section. While the uphill experiences less evaporation and more infiltration, the downhill experiences notably more evaporative cooling . We added a figure with a simple water balance (difference between precipitation and evaporation; P-ET) below (Fig. 1 in this letter and Fig. S6c and d in the supplementary material). It shows that overall evaporation is higher in the downhill side and lower in the uphill side (Fig. 1a,b in this letter), which in turn leads to positive values in the summer water balance (P-ET) in the uphill side (Fig. 1c in this letter), i.e. more rain than evaporation, and negative values in the summer water balance on the downhill side (Fig. 1d in this letter), i.e. more evaporation than rain.

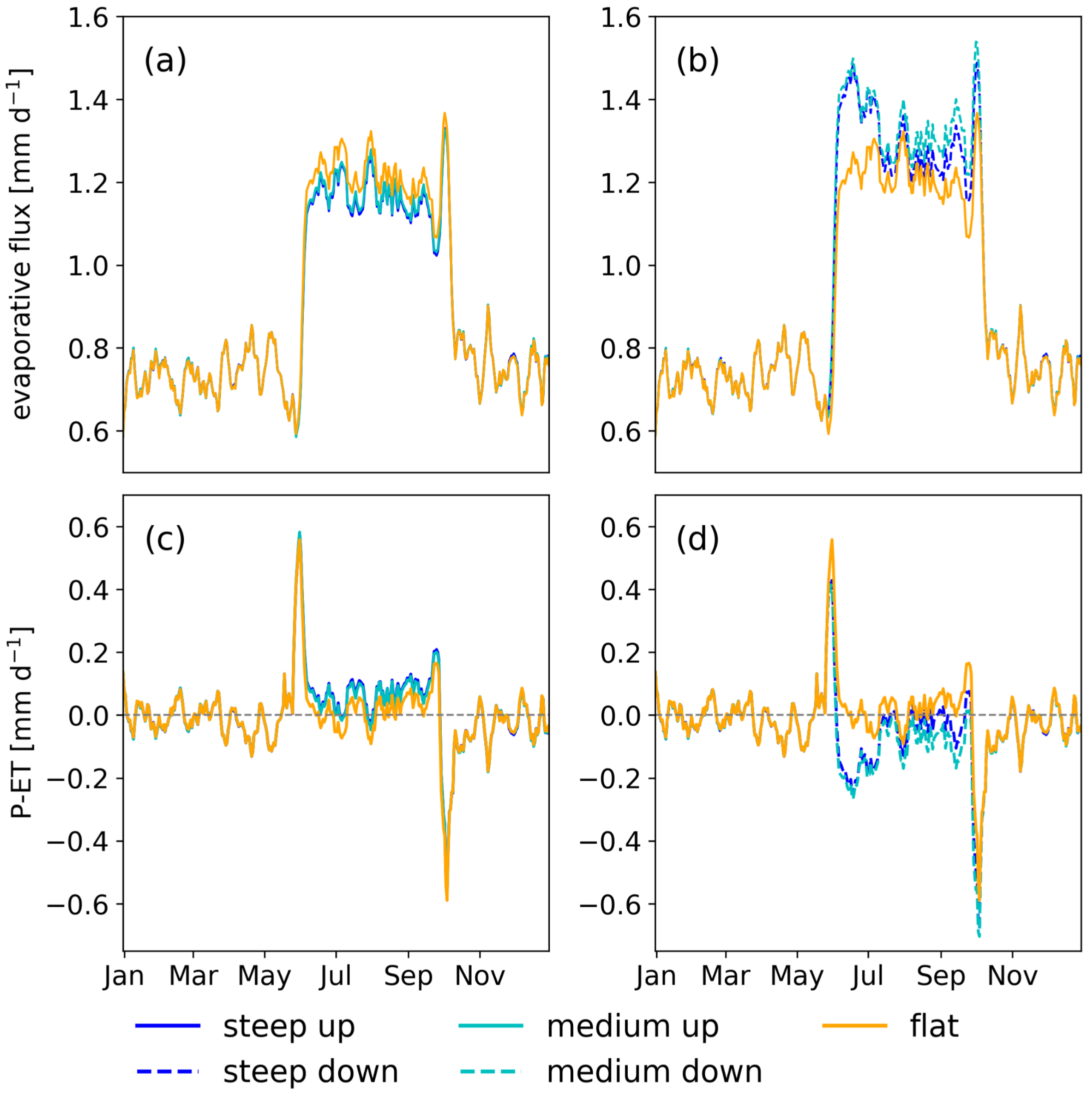

*Figure 1: Evaporative flux (**a** and **b**) and net infiltration (precipitation-evaporation; **c**, **d**) at the surface on the uphill (solid lines; **a** and **c**) location and the downhill (dashed lines; **b** and **d**) location. Daily values are averaged over a 7-day window. Blue, cyan and yellow represent the steep, medium and flat case, respectively.*

2. Similarly – and at a much smaller scale, Abolt et al., (2020) found (using the same ATS model) that rims in polygonal ground warm more in the summer due to drier conditions and associated weakened evaporative cooling, which then provides energy laterally to the cooler saturated troughs in the summer (see section 5.2 of Abolt et al., 2020). However, what determines if a saturated area is cooler or not also depends on the mass of water present. If enough water is present, especially on the surface, then a Talik will begin to form, as demonstrated in a 1D column by Atchley et al., (2016-section 4.2) and by Abolt et al., (2020) for wide troughs. This is because the timing of phase change during freeze up when snow is building can cause wet areas to stay warm throughout the winter, especially as the amount of water increases because it then requires a lot more energy loss to cross the freeze curtain. The difference with the study presented here is: 1) vary little surface inundation occurs due the surface runoff boundary condition and the assumed energy equilibrium at the downhill domain boundary condition. This assumption may not capture the thermal influence of the saturated

condition beyond the boundary of the domain. And 2) very little snow accumulation occurs, which would otherwise insulate the more saturated areas during freeze up. Given that the simulations with added precipitation showed an overall decrease in ALT, this work might suggest that increased evaporative cooling affect may outweigh the increased energy loss necessary to cross the freeze curtain. However, given the larger thermal hydrology work in literature, it would be beneficial discuss these tradeoffs as well as discuss how influential an appreciable snowpack may change the results. i.e there could be a combined warming in the dry areas (little evaporative cooling) and persistent warm winter conditions in wet areas from insulative snowpacks.

Abolt, C.J., Young, M.H., Atchley, A.L., Harp, D.R. and Coon, E.T., 2020. Feedbacks between surface deformation and permafrost degradation in ice wedge polygons, Arctic Coastal Plain, Alaska. Journal of Geophysical Research: Earth Surface, 125(3), p.e2019JF005349.

Atchley, A.L., Coon, E.T., Painter, S.L., Harp, D.R. and Wilson, C.J., 2016. Influences and interactions of inundation, peat, and snow on active layer thickness. Geophysical Research Letters, 43(10), pp.5116-5123.

Response: Thank you for this comment. As you mention, the formation of a potential talik is not so relevant for this study site since water does not start pooling above ground, even in the cases with twice the amount of precipitation, and snow cover is overall very shallow, due to the very dry climate in Adventdalen (the hydro-meteorological forcing conditions are taken from site data). However, in general ponding could occur, and surface water formation would in turn likely trigger talik formation. We have attempted to discuss various effects mentioned in your comment in the Outlook section (section 3.7) of the revised manuscript (previously "Further implications"), where we have adjusted the text and incorporated citations to Abolt et al. 2020 and Atchley et al. 2016 in this part.

Minor comments:

1. L58-59: In this case the benefit of numerical modeling probably has less to do with the remoteness of the study area, and more to do with a characterized sensitivity study as well as being able to dissect the energy fluxes across the full domain, something that would take tons of sensors to do in the field.

Response: Thank you for this comment. Indeed, we agree and have adjusted the text accordingly.

2. L72: Change 'Tho' to 'To'

Response: Corrected.

3. L89: (Painter, 2011) is outside of either sentence, I think it goes with the previous one.

Response: Corrected.

4. L118: Omit one of the 'a steep case'.

Response: Corrected.

5. L147-148: Why would you want to maintain a constant (same) snow accumulation across the hillslope domain, and is that realistic? This is likely to have a strong effect of simulations results.

Response: In this study we wish to investigate the effects of slope inclination on the hydrothermal conditions of the active layer. To enable clear and consistent comparisons we keep the boundary conditions and the hydrothermal forcing identical between the different cases, and enabling snow redistribution would potentially obfuscate comparisons. Also, since the site conditions are dry with very little snow precipitation, the effect of snow insulation and melt are minimal. However, adding snow redistribution would certainly be interesting for sites with more snowfall, as the lower end of the slope could then represent a snow pit/trap, and under those conditions much of the snow could end up on the lowermost part, and would then likely influence subsurface conditions locally. We provide additional clarification and justification of our model design in section. 2.2 “Simulation configurations”.

6. L153-161: Note that these CV locations are right at the domain boundary, and therefore subject to any edge effects of the model domain. The assumptions and implications of being on these domain boundaries needs to be discussed in more detail. This might be especially problematic with the downhill CV, given that the no flow (energy) boundary condition assumes equilibrium with a larger body of water or saturated area.

Response: Thank you for the comment. We address this question in more detail in our response to Reviewer 1 (please see General comment 1 of Reviewer 1). This has led to a slightly modified model domain, which more clearly represents the valley base and allows for energy and water fluxes out of the slope. The location of the CVs on the outermost boundaries of the domain was intentionally chosen to capture the most extreme values (drying on uphill side, and accumulation on downhill side). Now with the revised model domain, the downhill side CV is not on the right-most boundary anymore. Aslo, potential boundary effects are evaluated (see response to General Comment 1 of Reviewer 1). The intention of the placement of the CVs has been clarified in the main text, in the Section 2.2.

7. L207-208: This sentence needs to be more specific. What do you mean by inversion of temperature differences? Differences between uphill and downhill observations? Or differences between sloped and flat? Also, what are the different processes responsible here?

Response: We restructured the text and removed the paragraph that contains this unclear formulation.

8. Figure 3 needs more explanation in the caption. Hard to interpret it at a glance.

Response: We have made attempts to clarify this figure and caption text; we extended the caption text with an explanation indicating what positive and negative values mean in each of the panels. Further, we added the original time series from which the differences are derived, and placed this in the supplementary information (Fig. S3).

9. L215: “The upper three panels in each figure…”. I assume you are talking about Figure 4 here, but it is not clear. I suggest phrasing this as, “The upper three plots in each panel…” as ‘figure’ refers to figure 1 through 9 in the paper, ‘panel can refer to a and b, and plot is the sub plot of each panel.

Response: Thank you for the suggestion. We adjusted text according to the comment.

10. Figure 7: I like this figure, or at least what it is attempting to convey. However, I think it could be improved, or perhaps simplified. Is the story in the time series of the flux? Is it necessary to show the whole time series? If not, I would suggest just showing the cumulative flux, or maybe the difference of the fluxes between the cases. That may help with the scale issue. Additionally, the location of the representative volumes in relation to the fluxes going in and out is confusing, i.e, the lateral energy flux going in the downhill volume (positioned right in the domain) is found left in the figure. This means the reader (me) has to mentally flip the image.

Response: Thank you for the comment on this admittedly complex figure. We tried to simplify the figure according to your very useful feedback. Below you can find the figure with the cumulative sum (Fig. 2 in this letter), however this unfortunately leads to a significant loss of information in terms of direction of fluxes (specially for the vertical fluxes). The new final figure includes adjustments to the moving average (90 day window) and placing of the uphill and downhill panels as well as an adjustment to the titles (Fig. 3 in this letter and Figs. 7 and 8 in the main text). We aimed for the best compromise between correctness and simplicity. This should improve readability.

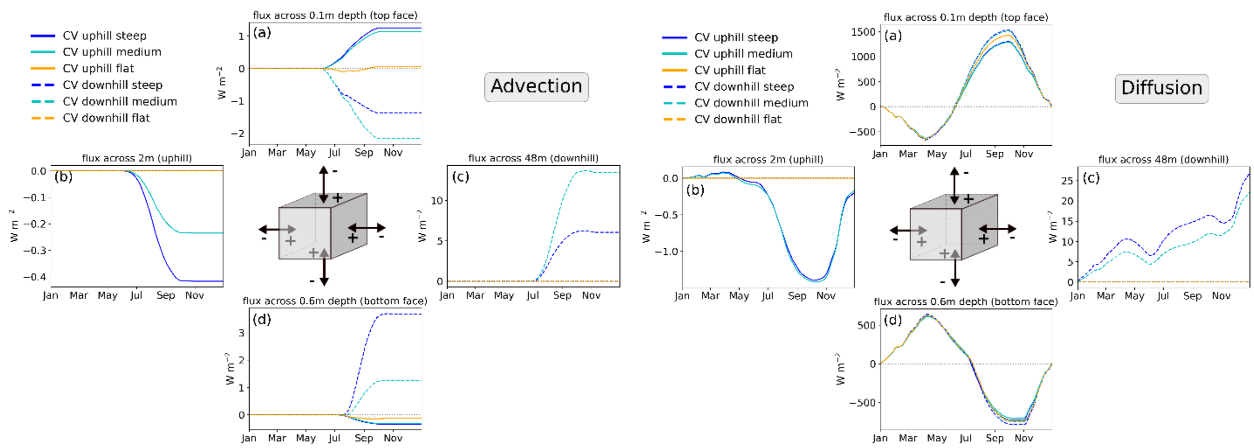

Figure 2: Advection and diffusion of heat through the control volumes (cumulative sum) (not used)

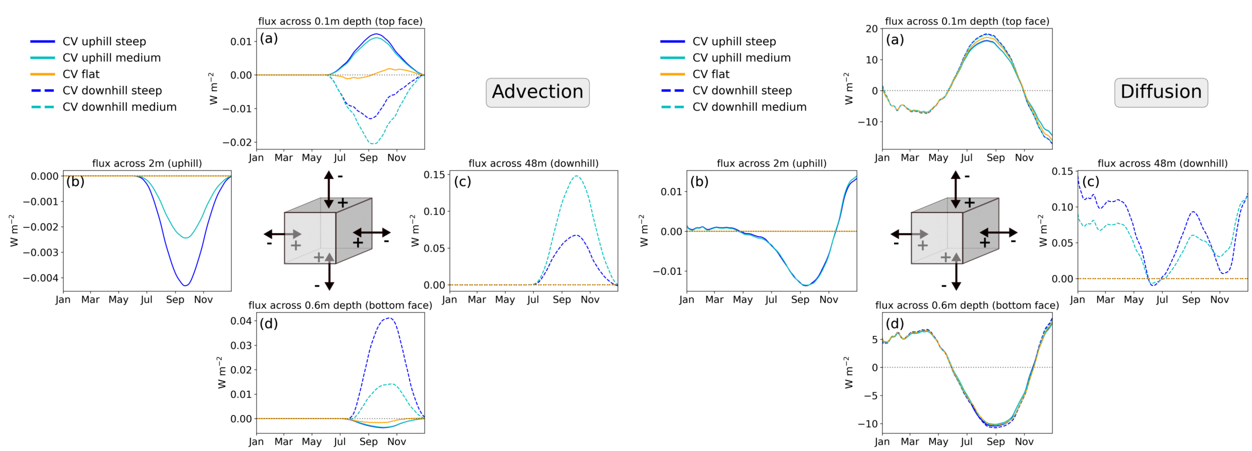

Figure 3: Advection and diffusion of heat through the control volumes (90 day moving average) (used in revised manuscript as Figures 7 and 8)

11. Figure 8: These are pretty small fluxes. Is this figure necessary? I think this paper as a whole makes a decent argument that groundwater dynamics are important in determining the thermal state of the hillslope, even if advective fluxes only play a small role. In other words, the influence of groundwater dynamics happens in other processes. I would suggest focusing as much as possible on those processes rather than advection.

Response: Thank you for this remark. Even though the values are fairly small, especially vertical advection plays a big role in the differences between up- and downhill (namely evaporation and infiltration). As described in the text, the uphill section is mostly dominated by infiltration rather than evaporation, which on the other hand dominates in the downhill section.

12. L462: "as compared to the flat case (0.75cm)." is confusing. Does the flat case change in the simulations? I thought the flat case provided a reference datum and therefore should be 0.

Response: Thank you for catching this typo. This sentence was supposed to refer to the active layer depth of the flat case in absolute values and should say 0.75m instead of cm. So the baseline active layer depth was 75cm and was increased in the steep case by 5cm (as stated in the sentence) to 80cm. Note that the active layer depth has changed to max. 1.03m in our new simulations, mainly because we have corrected the thermal conductivity values (please see our response to Comment 10 by Reviewer 1). Thus, the values have been updated in the revised text. For completeness, we have added the maximum active layer depth for the medium case as well, so all three cases have their respective absolute maximum active layer depth.

13. Figure 9: "The sign convention adopted is positive values represent heat entering the CV and negative values leaving the CV." This would mean that I should see the evaporative cooling affect? Correct? Heat and mass leaving the downslope CV during summer?

Response: Your assumption is correct. However, we are only showing the lateral mass flux here to explain the relationship between advective heat transfer and mass flux. To see mass fluxes in vertical direction, please refer to Figure S7 (in the supplementary information), which includes mass fluxes in vertical direction and shows the influence of evaporation and infiltration.

14. Section 3.6: This section tests the effect of overall precipitation and demonstrates the overall effect of increased evaporative cooling – at least I think that is the purpose. However, as written it seems to play only a minor role in the manuscript (the text devoted to this seems like an after thought), and there is no figure associated with this text that actually illustrates the point other than those in the supplementary information. It would be better to have a figure in this text.

Response: Thank you for these suggestions. We revisited the section and added a thaw-depth-plot with both scenarios (S0R0 and S2R2) analogous to Figure 5a in the main text (panel b of Fig. 5 in the main text has been removed). The new plot (see Fig. 4 in this letter) is now part of the main text (Fig. 10 in the main text) and is removed from the supplementary material. We have also improved and simplified the text around the sensitivity study.

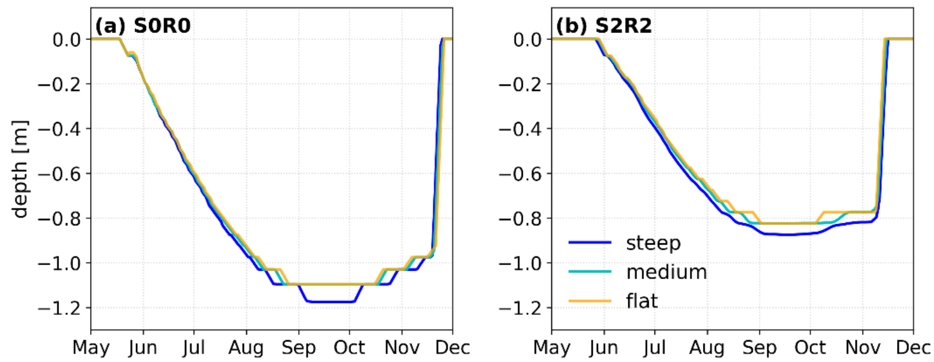

Figure 4: Spatial mean active layer depth for scenarios S0R0 (a) and S2R2 (b). The thaw depth indicates the transect-average thaw depth of each case (steep, medium, flat)

15. L424-L432: This paragraph provides a good summery of what was found. It seems like it would fit better in the conclusion section.

Response: Thank you for the suggestion. We agree and have moved this part of the discussion to the conclusions section.

16. L458-46: "This downhill cooling effect is up to about 1.2 C for steep (22°) and 0.6 C for medium (11°) inclinations across a lateral distance of 50m representative for valleys in Adventdalen, Svalbard." Seems to me that the bigger story here is not the increased downhill cooling caused by the evaporative flux, but the increased uphill warming presumably caused by the lack of an evaporative flux because overall the entire domain is warmer than the flat case.

Response: We agree that the focus of the study was too much shifted towards the downslope cooling effect while the uphill warming has fallen a bit too short. We revised the manuscript accordingly to put the uphill warming more into the focus and highlight that the warming actually causes the active layer to be deeper. Furthermore, the downhill cooling effect is moderated with the revised model domain.

17. The conclusion section is not very impactful. The paragraph in L424-432 seems to be a much better conclusion paragraph. Also, after reading the paper several times, I am confused as to why the entire sloped domains are over all warmer than flat domains? The focus appears to be more on the evaporative cooling effect, yet the domains are overall warmer unless precipitation is increased.

Response: Thank you for the tip. As mentioned above, we have merged the paragraph from L424-432 to the conclusions section. Indeed, the summer warming of the sloped cases compared to the flat case is mainly attributed to additional heat through infiltration and overall lower moisture content causing a lower heat capacity and reduced evaporation. We now also address heat capacity and more clearly emphasize the overall warming effect on the uphill section of the domain (see general comment 1 above).