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Post Little Ice Age rock wall permafrost evolution in Norway

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General response to referees

We would like to thank the two referees for their reviews. We modified the manuscript according to the comments made by the referees.

Response to individual referees

Referee comments are in bold
Author replies are in normal text (*Italic is for the manuscript text*)

Anonymous Referee #1

<u>**General Comments**</u>

Czekirda et al. have submitted a revised manuscript in response to reviewer comments. A detailed response addressing the major comments has been provided. This is much appreciated. The authors appear to have addressed the main concerns that I raised, and the manuscript is much improved. In particular, the authors have included a more detailed comparison between the simulated ground thermal regime and observational data (ground temperatures and geophysical surveys) available for the region. Although deeper temperature data and geophysical surveys in the region are limited (particularly in close proximity to the study transects), the authors have made good use of available data to support validation of simulated results. This strengthens the paper and increases confidence in the conclusions regarding the evolution of rock wall permafrost in Norway. The clarifications and additional information provided in the revised MS are also appreciated and these will make the paper easier to read especially for people that are less familiar with permafrost conditions in Norway including mountainous regions.

I have no major concerns with the revised MS. However, I do have some minor comments, many of which are editorial and are meant to improve language. As mentioned in my previous review, this is an interesting study and with some additional minor revisions it should be acceptable for publication.

We want to thank Anonymous Referee #1 for the additional suggestions how to improve the language and correct our language pitfalls.

<u>**Additional Comments**</u>
L13, L14, L16, L17-18, L19, L20, L21, L22, L26, L30-32, L42, L46, L53, L82, L83-84, L85-86, L92, L92-93, L96, L97-98, L98-99, L111, L112, L120-121, L125, L131-132, L133, L138, L163, L262, L269, L270, L277, L278, L280, L286-287, L288, L295, L301, L302-304, L332, L340, L364, L388 (typo? We corrected L358), L390, L405, L511, L548, L563, L592-595, L623-627, L677 (typo? We corrected L657), L678 (typo? We corrected L658), L669, L694, L702-703, L706, L714-715, L718, L719, L720, L764, Figure 4, 6, 7, 8

Done as suggested.

L72-73 – In the earlier review, I mentioned that the type of sensor and its accuracy and precision are usually provided in the methodology section. I realize that you have included it here but normally this level of detail isn't provided in the Introduction (i.e. we would just say that "field observations of rock wall temperatures were acquired at selected sites in previous studies") and the details on instrumentation utilized would be provided in the methodology section.

We removed this information from Introduction, and moved it to each subsection in Section 2 Study areas and field installations:

> 2.1 Western Norway: "*During 2015–2017 nine Geoprecision, M-Log 5W Rock loggers with at least 0.1 °C at 0 °C accuracy were installed at selected rock walls to measure surface temperature in Western Norway (Magnin et al., 2019).*"

2.2 The Jotunheimen Mountains: "*Furthermore, Geoprecision, M-Log 5W Rock loggers (at least 0.1 °C at 0 °C accuracy) were installed at selected sites in Jotunheimen (Hipp et al., 2014).*"

2.3 Northern Norway: "*All sites are instrumented with Geoprecision, M-Log 5W Rock loggers with at least 0.1 °C at 0 °C accuracy.*"

L75-76 – Do you mean that the data acquired from these earlier studies helped to calibrate the model?

Yes, we modified it: "*From 2015 through 2017 other sites across Southern and Northern Norway were also logged (Magnin et al., 2019), allowing for the improvement of earlier approaches by Hipp et al. (2014) and Steiger et al. (2016). The acquired data helped to calibrate a near-surface thermal regime model for rock wall permafrost in Norway, by using mean annual air temperature (MAAT) as an explanatory variable instead of elevation.*"

L158 – specify whether the resolution given is vertical or horizontal

We skip this information since we believe it is generally accepted that resolution of a 2.5-dimensional DEM represents a horizontal grid cell, and vertical resolution would be probably better described as e.g. its vertical accuracy, which we do not mention at all.

L191-192 – unclear – do you mean bedrock is at the ground surface?

No, we mean that we use bedrock class to assign volumetric contents of the soil constituents from the interface between glaciers/perennial snow and ground below all the way down to the lower model boundary. We rewrote "*Bedrock stratigraphy is assumed to be below glaciers and perennial snow*." To "*Bedrock class (Class "a" in Supplementary Table S1) is assumed below glaciers and perennial snow*".

L250-253 – The issue is probably that nT and nF together consider surface offset.

nT and nF-factors mostly influence GST in the months when surface air temperature has largest magnitudes. During spring months, surface air temperature usually has small magnitudes regardless of sign and neither nF nor nT can account for the large surface offsets in rock walls during spring months.

L312 and L316 – Sporadic permafrost is also discontinuous. "sporadic to extensive discontinuous permafrost" or "sporadic to widespread permafrost" is probably what you mean

It depends on the definition of permafrost zones. We are aware of the mentioned definitions; however, permafrost zones are usually as follows: continuous (90-100 % area), discontinuous (50-90 %), sporadic (10-50 %), and isolated (0-10 %). For instance, the most recent global permafrost map uses this definition (Obu et al, 2019; doi: 10.1016/j.earscirev.2019.04.023). So, to be specific, we added in the first sentence on L312: "*indicate that sporadic (10-50 % area) to discontinuous (50-90 % area) permafrost*".

L319 – are you referring to GT or GST here?

We refer to GT field, although note that it also includes GST at the surface. Hence, we do not really see the need to specify whether we mean GT or GST for the two-dimensional case in our study.

L574-573 – I assume in this section you are referring more to spatial variation rather than temporal variation (i.e more a comparison between sites with more or less snow cover). In your last sentence, you could consider saying that your measurements don't indicate a negative SO.

We suggest to keep this part as it is since we mentioned in the previous sentence that "*the overall annual cooling of the ground surface due to snow cover is not observed in Norway*".

L604 – Reduces convective cooling?

We keep this part, because this is how the authors describe the process in the cited paper.

L730-733 – This bit about "hot spots" is unclear.

We removed "hot spots" from the sentence and modified it: "*Thus, especially the constant change of ground thermal regime associated with rock walls and their vicinity facilitates material production and further geomorphological transport processes.*"

Figure 2 – Be clear about what that red and green sections are.

We added in the caption: "*Different colours near the surface show various stratigraphic layers (See Supplement Table S1 for details)*".

Figure S24 – Are you considering temperatures measured from 5 – 100m depth. You refer to 100m borehole but not clear if you are comparing temperatures to this depth.

Yes, we do compare to temperatures measured at depths between 5 to 100 m. We modified the caption: "*Supplementary Figure S24. Comparison of annual modelled ground temperature at depths between 5 and 100 m along the Galdhøe profile to ground temperatures measured in PACE borehole in the Jotunheimen Mountains. RMSE-root mean square error, MAE-mean absolute error, ME-mean error. Refer to Figure 1 in the main text for the borehole location.*"

Anonymous Referee #3

In their manuscript, Czekirda et al. model the evolution of rock wall permafrost for selected profiles in Norway since the Little Ice Age using the CryoGrid2D model. They use nine transects for their study that cross steep rock walls at high elevation, where rock wall temperatures have been monitored, and assess temperature changes over the past 120

years. Their results indicate rising ground temperatures, especially following the 1980s. Moreover, they find that within individual rock walls there is a trend in warming rate with elevation. Though the model is rather simplistic (2D case, only conductive heat transfer), the authors gain interesting insights into e.g. the role of snow cover and the steepness of rock walls, and discuss these parameters in great detail. The paper is potentially of interest for a large readership, especially those working on slope (in-)stability and permafrost distribution in mountain areas. This is obviously a revised version of the original submission that was commented on in great detail by two anonymous reviewers. After thoroughly addressing all concerns raised, rephrasing large parts of their manuscript and adding a new section on the geomorphological implications of the study, the paper significantly improved in quality. It is now very well written and merits publication in TC. I recommend to accept the manuscript after addressing a few technical corrections mentioned below.

We thank Anonymous Referee #3 for his/her comments, and we try to address the specific comments in the following.

Specific comments

L46, L85, L425-426, L657

Done as suggested.

- L230: I suggest to quickly explain the idea and values of the "freezing n-factors" here in a brief sentence

We modified and added sentences about the nF-factors: "*In equilibrium permafrost models such as the TTOP-model (Smith and Riseborough, 2002), insulating snow effects are usually accounted for by using semi-empirical transfer functions, so-called freezing n-factors (nF). The nF-factors link SATs and GSTs by relating the freezing degree days at the surface to the air. In Norway, the freezing n-factors vary between 0.1 for the attenuation effects of deep snow cover to 1.0 for very thin or absent snow cover (Gisnås et al., 2013).*"

Gisnås, K., Etzelmüller, B., Farbrot, H., Schuler, T. V., and Westermann, S.: CryoGRID 1.0: Permafrost Distribution in Norway estimated by a Spatial Numerical Model, Permafrost Periglac, 24, 2-19, https://doi.org/10.1002/ppp.1765, 2013.

- L228-239: Is there some factor included for snow redistribution towards the lower portions of steeply inclined bedrock walls?

No, avalanche patterns are highly variable in space and time, so accounting for this in the model is not possible at this stage. We added a short sentence: "*Note that snow redistribution towards the lower portion of the slope is not considered.*"

- L503: may occur? I would think that 3D heat transfer is the default…

We removed "may". It is now: "*heat transfer processes in complex terrain occur three-dimensionally*".