

Author Comments to REFEREE #2

We thank the Referee for the constructive comments. Typing errors, grammatical mistakes and technical corrections were corrected in the text without further comments.

MAJOR COMMENTS

RC: An additional effort should be done to improve the structure and organization of the paper and to clarify some sections (especially site description and methods) and to increase the overall readability of the paper. Moreover figure order is difficult to follow and confusing: figure references in the text continuously jump back and forward.

This paper is admittedly quite long and addresses a wide range of topics and associated problems. The paper has undergone also a series of reviews, partly with opposing advice when it comes to structure. The present structure is a sort of compromise of earlier suggestions, but we followed the principle to distinguish between methods, results and discussion and reflect this distinction in the structure. The position of the "validation" section is discussed below under one of the more detailed points.

Concerning the figure references in the text, we found that Fig. 6 was not referred to, which now is done. Figures are numbered in chronological order as they are referred to in the text. However, during the discussion refer three times to earlier figures to support certain statements.

RC: Referring to various specific comments related to the number of boreholes used in this study:

Why 13 boreholes, while less boreholes are shown in the tables and modelling plots?

A total number of 13 boreholes (12 from the Cryolink project + PACE borehole) were available. The entirety of these boreholes was used to calculate altitudinal lapse rates and do correlations to weather stations for the long time series air temperatures and climate change scenarios. Therefore all of these boreholes are illustrated in the overview figures and used in the introduction. Not all of the boreholes, however, could be used for the calibration and validation of the 1D modelling (data gaps or pronounced 3D effects). We therefore chose to present only the boreholes that were actually used in the modelling study in the tables

This is now explained in the first paragraph of Chapter 2:

“Data from all boreholes were used in this chapter to give an introduction to climate setting and altitudinal variations at the study sites. However, only a selection of nine boreholes (Table 1) was used for the modelling study.”

SPECIFIC COMMENTS

P342 L7 RC: you mention 13 boreholes and in the paper (tab1 and tab3) you show data from 9 boreholes.

See reply above

P344 L3-L8: RC: move this paragraph before P343 L19. You are generally describing your approach/method which is should be presented before the major aims of the manuscript.

The introduction has been restructured (also in accordance to REFEREE 1).

P344 L5/P344 L13: RC: 13 boreholes or the 9 presented in tab1 and tab3? Why Juv-BH5 which is presented at P360 is not in the tables? If you add Juv-BH5 to the boreholes in tab1 and tab3 you get 10 boreholes. Which are the other 3?

See reply above

P345L1: RC: you cite six boreholes + PACE (which are shown in Fig1) but in the following lines you present only BH1, BH3, BH4, BH6 (the same listed in tab1 and tab3).

See reply above

P345L5: RC: you cite 3 boreholes (which are shown in Fig1) but in tab1 and tab3 you only have BH1 and BH3

See reply above

P345 L10: RC: you cite two boreholes but Fig1 shows 3 boreholes.

See reply above

P345 L10: RC: you are presenting the sites in the order Juv/Jetta/Tron. It's rather easy to get lost in boreholes acronym throughout the paper so, in order to help the reader, try to respect this order in all section, figures and tables.

Wherever needed and possible the order was adjusted to Juv/Jetta/Tron

P345 L22: RC: The "entire period". Which period? There are many time intervals considered in the manuscript, so be more precise. Maybe you should say "the period used for model calibration was divided..."

This refers to the entire period where ground temperatures were recorded. The sentence therefore was changed and clarified:

"The entire observation period from September 2008 to July 2011 was divided into..."

P346 L20: RC: lower boreholes (Tro-BH2). Indicate also the acronym in order to help the reader become familiar with your boreholes.

Done

P346 L27: RC: Jet-BH2 is not in Tab1!!

Reference removed. See Reply above

P346L27: RC: the uppermost borehole: add also the acronym (?Jet-BH1?) in order to help the reader to become familiar with your boreholes.

Synonym "Jet-BH1" added to the text

P347L8. *RC: Figure order. In the previous section you present information that are in figure 3. Here you present data that are plotted in figure 2. Consider the idea to change the order of figure 3 and figure 2. Figures order should follow the order with which they are introduced in the manuscript.*

Figure order changed as proposed

P347L11. *RC: Why 1640 m asl ?*

The elevation of one of the sites was chosen as a basis, and the others projected to that same elevation using the ALRT in order to compare temperatures. In that case the elevation of Tro-BH1 was chosen, however, there is no particular other reason.

P348L21: *RC: you should start this section with a sentence that explains your objectives: which data do you want to reconstruct for the past and which mains steps you follow. Then go into the details of each methods.*

We added a sentence, that we need SAT time series to force the model.

“Surface air temperature series are needed for forcing the heat flow model for historic or future time periods. For the historic period dating back to 1860, we used data series provided by the Norwegian Meteorological Institute (met.no)....”

P348L21-P349L6: *RC: this part is unclear.*

This issue has been addressed during previous reviews. We have now tried to further clarify this point by modifying our description the paragraph with the goal of clarification. However, the reconstruction of the regional and historic air temperatures was not done as part of this study, but by Hanssen-Bauer (2005) and Hanssen-Bauer and Nordli (1998). We therefore consider that the full discussion of this method is beyond the scope of this manuscript and we need to refer to the above mentioned references for detailed reading. This method is widely applied by the Norwegian Meteorological Institute.

P349L7: *RC: MDAT ? I guess it's mean daily air temperature but you should define this acronym*

Done

P349L15: *RC: does the RMSE has a seasonality?*

Probably, thinking about winter inversions etc. RMS-values during winter normally are worse than during summer, as also mentioned in the paragraph.

P350L1: *RC: lapse rate do not change in time? As you are using lapse rates observed in the period 2008-2011 to reconstruct data back to 1870, try to find some references that address this topic and authorise you to assume that lapse rate over more than a century does not change.*

We are aware that lapse rates might be undergoing changes just as air temperatures. Relatively long air temperature series are available from weather stations in the valleys, however, no weather stations at higher elevations exist that date back long enough.

As it is shown in Chapter 3.5, the model accurately reproduces the today's permafrost conditions quite well using the air temperature series based on the lapse rate. We therefore feel that the assumption of a constant lapse rate is sufficient within this context.

- P350L17: RC: the reference to fig8 a) is not necessary and not so clear.*
Reference to Fig 8 removed
- P351L3: RC: you used reconstructed and future air temperature data together with n factors to derive GST values. Explain how you computed daily/monthly GST data from n factors. Inverting eq5 and eq6 you only get FFDs or TDDs. How you get daily/monthly GST values form annual sums of thawing/freezing degree days?*
Nf and Nt factors are here used as scaling factors between T_{AIR} and GST.
- P353L25 RC: This section should be shifted in the results.*
Well, this section was a bit back and forth during the various revisions of this paper, following different review comments. Technically, the section could be divided into two smaller paragraphs, the validation procedure in “Methods” and the validation outcome in “Results”. We choose to give this important paragraph as a whole and place as last paragraph into “Methods”, as a sort of transition into the “Result” chapter. However, this is of course always discussable.
- P353 RC: GT modelling and figure 7. You present ME values as means at all depths. Which is ME variability with depth?*
The ME varies between 0.60 at a depth of 10m and 0.8 to >0.90 in the upper meter. We added a sentence to the paragraph 3.5.
- P353 RC: Does ME have a seasonality?*
Probably, and depending on water content. Deviations are surely higher during periods with water movement and melting/refreezing, as obvious in fig. 6. We think this might not add any new information to the uncertainty of our study results, so we have not further investigated seasonal variations of fit estimates.
- P355L25: RC: what happen at Jetta?*
The warming at Jetta is in the same range as on Juvvasshøe due to proximity. A sentence was added to the text.
- P356L11: RC: you present Juv-BH6 results which are not in figure 9.*
Figure 9 now contains Juv-BH6
- P356L13: RC: define what “permafrost degradation” is and how you define it’s relation to ALT increase as you are showing and discussing ALT increase data.*
Permafrost degradation in literature is not clearly defined, but normally we mean with the term that taliks develop and persist in the ground. With further warming this would lead to that permafrost not being present at a particular site, based on the thermal definition of permafrost. In the referred case, permafrost thicknesses are modelled to exceed 10 m and do not refreeze. We therefore use the term “permafrost degradation” for this process.
- P356L26: RC: until 1990. why 1990? you said that your analysis periods were 1860-1999 and 2000-2010.*
We re-worked the paragraph. To avoid confusion with the time periods we now use the time periods 1860/1854 to 1986/1990 and 1986/1990 to 2009 for the estimations of trends of active layer thickness for all boreholes.

P357L7 *RC: you should explain why Fig 3c indicates the possible beginning of a talik development and how this concept is related to the definition of permafrost degradation.*

See comment above. The thermal regime of the borehole illustrated in Fig. 3c shows an ALT of >10m, trends of increasing ALT and increasingly longer time periods with $GT > 0$ °C. This indicates a probable reduction of the refreezing towards the winter and, the possible development of a talik. This is also described in Farbrot et al. (2011).

P357L13 *RC: Why are you only presenting results for Juv-BH1 and Juv-BH4? Consider the idea to select 2 boreholes for each area and add a plot that show GT data presented in section 4.2.2 and in section 4.3.1*

These two boreholes were chosen because of several reasons:

- At Juvvasshøe permafrost is best investigated, and represent longest series of all three study sites.
- These two boreholes show different ground characteristics, typical for many sites in the Norwegian high mountains: : a coarse blocky surficial material with relatively high water content at BH1, and bare rock at Juv-BH4
- They are located relatively close to each other and thus climate conditions are similar.

We therefore think that the numbers for these two boreholes representing typical situations and are sufficient to underline our statements.

P359L21. *RC: Discuss the effect of this interesting sensitivity analysis also on ME.*

The Nash-Sutcliffe values were calculated between the “warmest” and “coldest” model run. Between these extreme value model runs the depth-averaged ME varies by less than 0.15. This was added to the paragraph.

P360L18. *RC: BH5 results are never mentioned or shown before in the manuscript (at least after a quick search – BH5 is only cited in P360 and in the Acknowledgements). You just introduce this Juv-BH5 in the discussion. As you are generally discussing the effect of constant SWC and 3-D effect, I do not think that it's necessary to cite Juv-BH5 whose data and results are not presented in the manuscript.*

The reference to Juv-BH5 was removed.

P361L19 *RC: do you show somewhere the results of this important test? If not insert here in the text summary statistics (ME, RMSE).*

As described in the text, model results are the same and no difference in the statistics in the terms of ME and RMSE error were found between the model runs using monthly values and daily values.

P362L16 *RC: inter-annual change of ALT is computed as the mean of the yearly anomalies respect period (1860-2010) mean? Do you get similar results if you compute inter-annual change of ALT over the two periods you used in section 4.2.3?*

The inter-annual change of ALT is calculated as the difference in maximum thaw depth between two consecutive years. With this approach an overall estimation of the variability of the maximum thaw depth is given on a longer time scale, therefore the period 1860 – 2009. The variability during the two observed seasons is comparatively high, reflecting the highly seasonal patterns during the observation period.

P364L21 RC: which 13 boreholes? See my previous comments P344L5

See reply above

P365L6 RC: move this paragraph after P366L2

Paragraph moved.

P365L19 RC: move this paragraph after P366L2 (this should be the last one)

Paragraph moved.

P373 table 1: RC: change line position below Juvasshoe

changed

P377 figure 2: RC: panel a and b should have the same x-axis

Fig. 1a was adjusted in order to have the same x-axis (see also answer to REFEREE #1)

P381 figure 6: RC: show also a Tron plot

As it used to be before, validation plots for Tron BH1 and Tron BH2 are now again included in Figure 6. Also we changed the shaded areas and hope that they are now shaded enough.

