We would like to thank the reviewers and the Editor Ylva Sjöberg for their attention on our study and kind comments that help us improve the quality of our manuscript. Following the comments from the Referee, we have further revised the manuscript and we believe the quality has been further improved. Below please find the point-by-point responses to the comments.

Texts in red are the reviewer's comments; **those in black** are the authors' explanations to the reviewer's comments; and **those in blue** are the revised texts in the revised manuscript.

Comments from Referee #2:

I basically satisfied with your revisions on the manuscript. Please address following minor issues before publication.

(1) Some of its details are not adequately rigorous in the introduction, such as the results of Zhang et al. (2021) (Impact process and mechanism of summertime rainfall on thermal–moisture regime of active layer in permafrost regions of central Qinghai–Tibet Plateau), which also focus on the convective heat transfer. Authors are suggested to add a comprehensive summary of the latest researches and point out what the strengths of your findings are.

We are very grateful to the reviewer for updating us on relevant researches that we have not been aware of before. We have reviewed more recent works related to this topic. In this revision, we have added some representative researches published recently to the Introduction:

"As a result, warming of soil temperature by liquid CHT due to summertime rainfall increases the thaw depth of frozen ground (Douglas et al., 2020; Guan et al., 2010; Karjalainen et al., 2019) and promotes the greenhouse gas emissions (Neumann et al., 2019). However, an opposite view also exists that infiltration of precipitation has a cooling effect on the temperature of the active layer (Wen et al., 2014; Yang et al., 2018), indicating a complex mechanism of the CHT impacts on the soil thermal regime. "

and:

"However, relatively few studies have examined liquid CHT processes in permafrost context. Kurylyk et al. (2016) developed a three-dimensional coupled soil heat and water model to investigate the effects of runoff on soil temperature. Recently, Zhang, M. et al. (2021)quantified the energy flux of infiltrative CHT during a summertime rainfall event and reported that the thermal impacts of CHT were not pronounced compared to other energy transfer pathways. While their studies improve our understanding on the role of CHT in altering permafrost thermal dynamics, they focused on specific permafrost conditions or single events, and the established methods were difficult to transfer to other regions with conditions dissimilar to those in these study regions."

and to Discussion 4.1:

"The same weak significance of CHT associated with summer rainfall is also reported by Zhang, M. et al. (2021), where the positive energy flux of rainfall convection into soil layers was low, in contrast to other negative energy fluxes due to increased soil evaporation and latent heat, and decreased soil conductivity due to growing soil moisture."

In our study, A control experiment with three scenarios with full, partial and no consideration of CHT was implemented by the SHAW model. This design enables us to distinguish the CHT from different sources, i.e., precipitation/snowmelt and ground ice melt, and precisely quantify the impacts of these CHT processes, which has never been accomplished in previous studies that focused on reginal specific conditions or single summer rainfall events.

We have strengthened the description on the advantages in the last paragraph of Introduction:
"Therefore, this study uses the SHAW model to quantify the impacts of liquid CHT on the soil temperature and moisture in the active layer through numerical modelling at a typical permafrost site, i.e., the Tanggula (TGL) site on the QTP, China. The SHAW model was modified to exclude the CHT processes, and then control experiments were implemented to simulate comparative scenarios with or without CHT included in the model. This enables precise and separate quantification of the thermal impacts of liquid CHT from different sources such as precipitation infiltration, snow melt and ground ice melt, which has never been accomplished in previous studies. The specific objectives are: (1) to illustrate the characteristics of CHT events in time and depth; (2) to quantify the sole impacts of liquid CHT on the thermal regime of the active layer; (3) to elucidate the interplay of heat and soil moisture during the freezing-thawing process in the active layer. "

(2) It is recommended to add the simulation results of QT08 to the context for comparative analysis.
It's really a hard decision. Initially we don't want to include it in the manuscript because the data for QT08 simulation is not ideal and the results are not accurate enough to show the CHT effects. To accomplish the purpose of this study, so far only the TGL site on the QTP can provide sufficient supports of data and parameters. But as Reviewer said, a simulation at another permafrost site with success in reproducing the same CHT effects can help eliminate the worry that the findings from TGL are special for the TGL. Therefore, we decided to include the QT08 simulation.
In order to avoid messing up the structure of the manuscript, we chose to include the results of QT08 in Appendix A. We also discussed this comparative analysis in Discussion 4.1.

"Appendix A: SHAW simulation at the Wudaoliang site (QT08)

Site QT08 was set up since 2009 to monitor water and heat dynamics in the active layer and is located at 35.22° N and 93.08° E near the town of Wudaoliang alongside the Qinghai-Tibet highway (Figure 1b). It is covered by alpine desert steppe. Permafrost is beneath 2.4 m. A nearby meteorological station in the Wudaoliang town can provide daily observations of atmospheric elements. The site provides daily observations of soil temperature and moisture content at 0.1, 0.4, 1.2, 2.0 and 2.4 m depth from January 1, 2012 to December 31, 2018 for this study. However, numerous zeros and missing values exist in the soil moisture data, preventing us from using it for validation. In general, this is not an ideal site for the SHAW model to precisely simulate the occurrence of convective heat transfer (CHT). CHT often occurs in a short interval, so the model must be fed hourly or higher resolution forcing data and observations that are not available at this site. The purpose of this simulation is to ensure our finding on the bidirectional thermal impacts of liquid CHT was not an exception at TGL and can be reproduced at other permafrost sites.

Based on the borehole information, the soil column was stratified into 9 layers (centered at 0.0, 0.02, 0.07, 0.13, 0.23, 0.39, 0.66, 1.11 and 1.84 m) with discrete soil texture types. The values for the vegetation and soil parameters were determined by the lookup table provided with the Noah land surface model as in our previous work (Wu et al., 2018). For the remaining parameters, the default values of the model were used. Since hourly meteorological data are not available for this site, we extracted the meteorological forcing at the corresponding point from the gridded China Meteorological Forcing Dataset (CMFD) with a resolution of 0.1°and 3 h (He et al., 2020). The CMFD has been widely used for regional permafrost modelling on the QTP (Wu et al., 2018; Yang et al., 2021; Zhang, G. et al., 2021) and has good accuracy, especially on the eastern QTP, because most of its data were collected on the eastern QTP. The lower boundary was set at 2.4m depth based on daily observations of soil temperature and moisture at this depth. The simulation period was from January 1, 2015 to December 31, 2018.

The Control and NoConv scenarios were simulated at QT08 using the original SHAW model and the modified model (with CHT removed), respectively. The occurrences of heating and cooling events of CHT were counted and analysed following Eq. 12.

The simulation results at QT08 clearly reflect the bidirectional thermal impacts of CHT, although the model was not carefully configured, for example, as it used coarse-resolution forcing data and uncalibrated parametric values for all soil layers. The role of CHT at QT08 was primarily to warm the ground during the spring thaw period, along with a small number of cooling effects (Figure A1). The magnitude of CHT-induced soil temperature deviations at QT08 (mean about 0.2 °C, range -4 to 4 °C) was not as pronounced as at TGL site (mean 0.9 °C, range -5 to 10 °C, Figure 4) because the longer modelling time step of 3 h attenuated the thermal influence of CHT, which is a rapid heat exchange process that normally occurs in an hourly or less interval. There was more active heat exchange and water migration in the deep layer (1.84 m, Table A1) at QT08 than in the deep layer (2.45 m, Table 2) at TGL, resulting in more frequent cooling events occurring in the deep layer at QT08. Both layers are near the bottom of the active layer, but the thickness of the active layer at QT08 is much less than that at TGL. Due to the coarse spatial resolution of the forcing data (a grid of 0.1°), model performance for QT08 (Figure A2) was not so good as for TGL, which was driven by in-situ meteorological observations. At QT08, soil temperatures at depth were generally overestimated. This experiment provides useful evidence that the bidirectional thermal effects of CHT may be common in alpine permafrost environments during thaw.

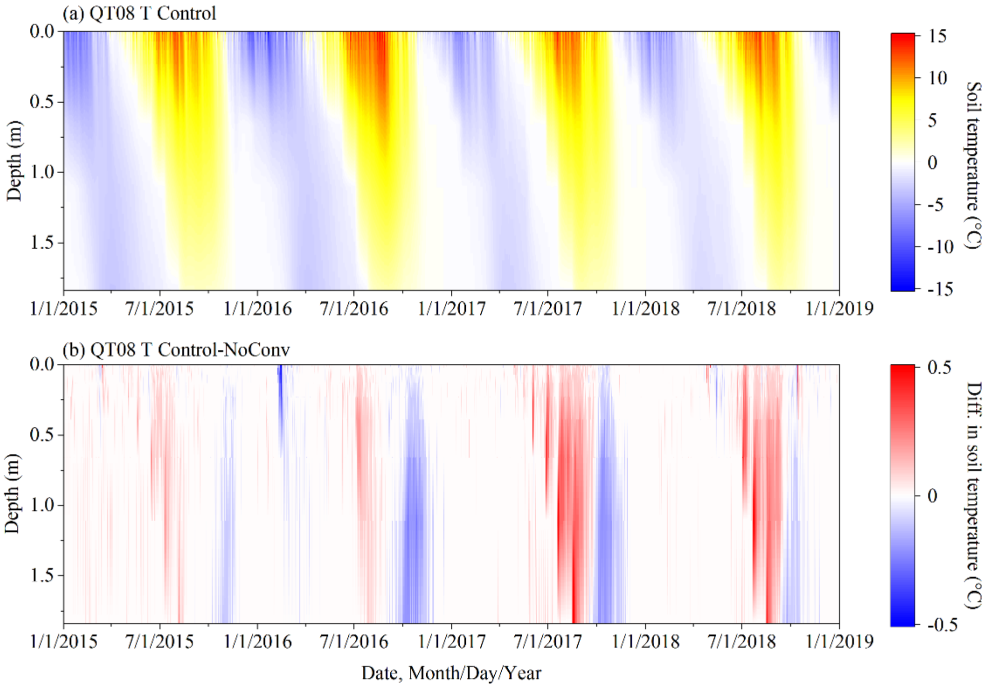

Figure A1 Simulated ground temperature profiles at QT08 under the Control scenario (a), and the differences in simulated soil temperature between the Control and NoConv scenarios (Control−NoConv) (b). Control and NoConv represent the scenarios with full and no consideration of convective heat transfer (CHT) in the SHAW model, respectively. Note, this figure has a different scale than Figure 4.

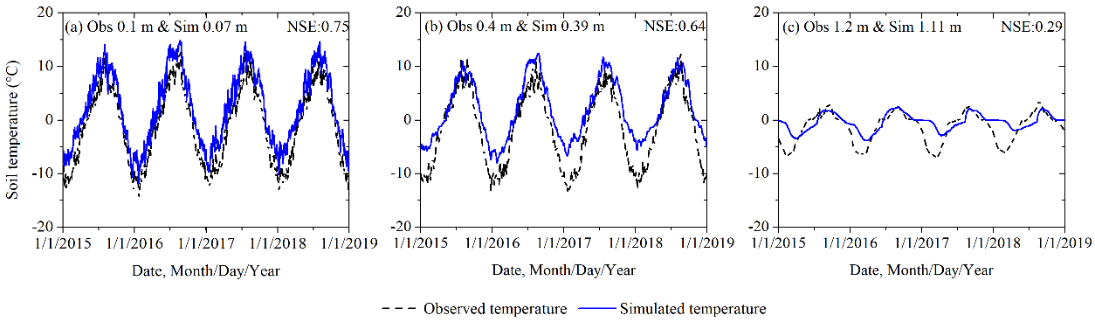

Figure A2 Validation of simulation results at different depths at QT08 against the observed daily soil temperatures during January 1, 2015 to December 31, 2018. (a) for simulation depth of 0.07m and observation depth of 0.1m; (b) 0.39m for simulation and 0.4 m for observations; and (c) 1.11 m for simulation and 1.2 m for observations.

Table A1 The numbers of occurrences of heating and cooling CHT events and the average temperature deviations caused by CHT at 0.07 m, 0.66 m and 1.84 m depths at the QT08 site. The deviations of 0.1 °C or less were excluded for statistics.

	Control−NoConv		
	0.07 m	0.66 m	1.84 m
Number of heating events	405	1250	241
Average increase (°C)	0.16	0.20	0.31

Number of cooling events	149	288	348
Average decrease (°C)	-0.27	-0.17	-0.20

”

in Section 4.1, we discussed this auxiliary experiment and clarify its purpose:
“To ensure that the experiment at TGL was not an exception, we performed a similar simulation (spanning 2015-2018) at another permafrost site (coded QT08) near the town of Wudaoliang alongside the Qinghai-Tibet highway to verify the bidirectional thermal impacts of CHT. Since hourly meteorological observations are not available for QT08, we extracted the atmospheric forcing at the corresponding point from a reanalysis dataset with a resolution of 0.1° and 3 h resolution (He et al., 2020). This dataset has been widely used for permafrost simulations on the QTP due to its high accuracy in this region (Wu et al., 2018; Yang et al., 2021; Zhang, G. et al., 2021). The bidirectional thermal impacts of CHT were well observed at QT08 although the model was not well informed owing to, for example, coarse-resolution forcing data and uncalibrated parametric values for all soil layers. The role of CHT at QT08 was primarily to warm the ground during the spring thaw, along with a small number of cooling effects (Figure A1 and Table A1). Compared to the TGL results, the magnitude of CHT-induced soil temperature fluctuations at QT08 was attenuated by a longer 3 h time step and was not as pronounced as at TGL (Figure A1 and Table A1) because CHT is the rapid heat exchange process that normally occurs in a hourly or less interval. Although the accuracy of the QT08 simulation was not as good as that of TGL (Figure A2), this experiment provides useful evidence that the bidirectional thermal effects of CHT can be common in alpine permafrost environments during the thaw period. Appendix A gives more details regarding the simulation at QT08.”

(3) In table1: I noticed great difference between these soil texture data and the soil texture data for this site in other articles (especially the publication of co-author Dr. Lin Zhao’s group), what is the reason for this?

The soil texture data at each soil depth applied in this study were based on the borehole information at TGL, which was published in a research article (in Chinese) in 2013 by Prof. Lin Zhao’s group (Liu et al., 2013), as shown in Figure S1 below. After that, they subdivided the soil column and made more strata to fit a numerical simulation purpose (Hu et al. 2015). During this process, they made some adjustments, resulting in some differences between the original data and the modified data as shown in Figure S2. For example, the sand percentages at 0.1-0.2 m and around 2.45 m in the 2015’s data are lower than in 2013’s, and oppositely, the percentages of slit become higher (Figure S1 and Figure S2). But basically, in both datasets the soil is mostly composed of sand (over 65% in both datasets) and the differences are not much.

We discussed this with Prof. Zhao and Dr. Hu, and we all agreed to use the original data from Liu et al. (2013) for this study. First, the 2015 data are not the original and have been purposely modified by some interpolation method. Second, we are modeling the period of 2008-2010, closer in time to Liu et al. (2013). In addition, we have applied an uncertainty analysis for the key soil hydraulic parameters and then obtained the most optimal parameter values, which can also mitigate the influences of the given soil texture data.

表 2 活动层土壤各层土壤状况

Table 2 Soil information within the active layer at different depths

层次 Number	深度/m Depth	土壤容重/(g·cm^{-3}) Bulk density	土壤质地% Soil texture		
			砂土 Sand	黏土 Clay	粉土 Silt
1	0.0	1.176	93	6	1
2	0.02	1.176	93	6	1
3	0.05	1.176	93	6	1
4	0.1	1.176	93	6	1
5	0.2	1.331	87	10	3
6	0.5	1.103	89	9	2
7	0.7	1.405	87	10	3
8	0.9	1.405	84	13	3
9	1.05	1.235	75	18	7
10	1.4	1.281	75	18	7
11	1.75	1.253	71	21	8
12	2.1	1.460	71	21	8
13	2.45	1.332	71	21	8
14	2.8	1.109	71	21	8
15	3.0	1.832	71	21	8

Figure S1 Soil texture at TGL site published in Liu et al., 2013

Table 2 Soil texture parameters used as inputs for COUPMODEL

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)
0–2	85	10	5	49–83	85	10	5
2–5	85	10	5	83–138	95	3	2
5–9	75	18	7	138–230	90	5	5
9–17	70	18	12	230–380	68	20	12
17–29	65	22	13	380–628	95	3	2
29–49	85	10	5	–	–	–	–

Figure S2 Soil texture at TGL site published in Hu et al., 2015

Reference:

Hu, G., Zhao, L., Wu, X., Li, R., Wu, T., Xie, C., Pang, Q., Xiao, Y., Li, W., Qiao, Y., Shi, J.: Modeling Permafrost Properties in the Qinghai-Xizang (Tibet) Plateau, Science China Earth Sciences, 58, 2309-2326, https://doi.org/10.1007/s11430-015-5197-0, 2015.

Liu, Y., Zhao, L., Li, R.: Simulation of the soil water-thermal features within the active layer in Tanggula Region, Tibetan Plateau, by using SHAW model, Journal of Glaciology and Geocryology, 35, 280-290, 2013. (In Chinese with English abstract)

(4) I wonder the reason of your division for the 0.05 m depth which is the shallow layer, 1.05 m depth which is at the middle of the active layer, and 2.45 m depth is deep soil depths. Is it based on soil thermal conditions? Or is it a random division? I suggest the author clarify that.

We stratified the soil layers into shallow, intermediate and deep depths, based on both the measurement depths in the active layer and the characteristics of the CHT impacts along the depth. On one hand, the soil column stratification scheme was designed according to the measurement depths of the active layer at TGL site. The near-surface soil was densely discretized with more depths (such as 0.00m, 0.02 m) to accommodate rapid hourly temperature and moisture dynamics near the ground surface. Because we don't have instruments installed at those depths, we used the first available depth (0.05m) to represent the shallow depths.

On the other hand, from Figure 4 in the revised manuscript and the supplementary Figure S3 shown below, we found that the CHT process have very non-uniform thermal effects between different soil depths, such as between 0.05 m, 1.05 m and 2.45 m. Therefore, it is necessary to explore how and why the CHT performs inconsistent at these different depths. We selected the 0.05 m depth, the closest depth to the ground surface and for which observations are available, for representing the shallow layers (above 0.2 m) which control by strong and rapid infiltrative CHT; and 1.05 m, which is at the middle depth of the entire active layer, for representing the intermediate layers (about 0.4 m to 1.3 m), where the infiltrative CHT has been weakened and CHT within the soil layers becomes more pronounced; and 2.45 m, adjacent to the bottom of the active layer, for representing the deep layers where no significant CHT process occurs.

We have added a new paragraph to justify the selection of those representative depths for our analyses at the beginning of Section 3.3:

"As shown in Figure 4a, CHT processes have very non-uniform thermal effects at different soil depths. Therefore, to illustrate the inconsistent impacts of CHT at depth and to identify the driving factors, three specific soil layers, i.e., the layer centered at 0.05 m depth closest to the ground surface and for which observations are available, the layer at 1.05 m depth, which is at the middle depth of the entire active layer, and the layer at 2.45 m adjacent to the bottom of the active layer, were selected to represent the shallow (0-0.2 m), intermediate (0.4-1.3 m) and deep depths (deeper than 1.75 m), respectively, where very different impacts of CHT were observed. "

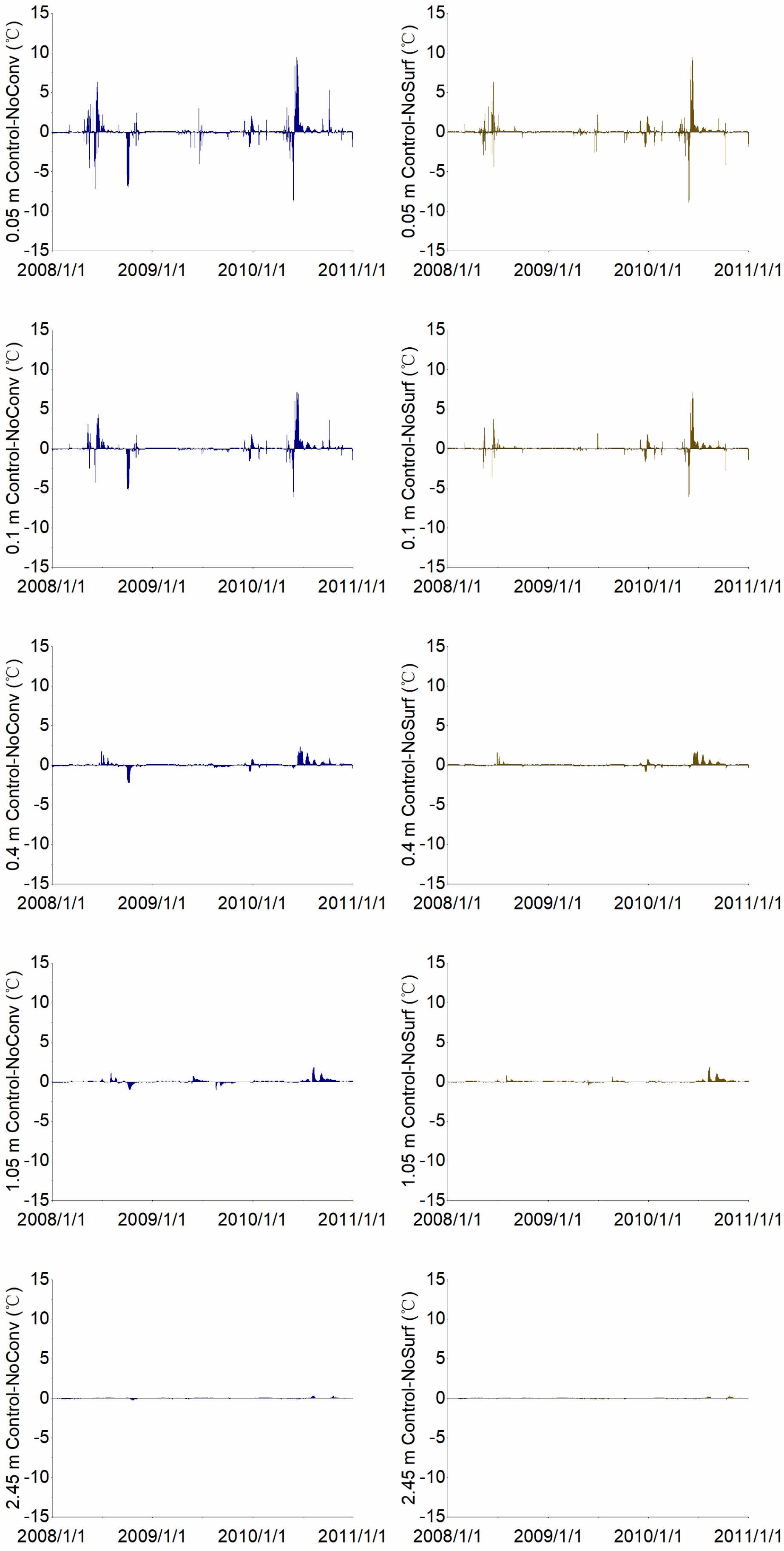
0.05 m Control-NoConv (℃)
0.05 m Control-NoSurf (℃)
0.1 m Control-NoConv (℃)
0.1 m Control-NoSurf (℃)
0.4 m Control-NoConv (℃)
0.4 m Control-NoSurf (℃)
1.05 m Control-NoConv (℃)
1.05 m Control-NoSurf (℃)
2.45 m Control-NoConv (℃)
2.45 m Control-NoSurf (℃)
15
10
5
0
-5
-10
-15
2008/1/1
2009/1/1
2010/1/1
2011/1/1

Figure S3 The differences in soil temperature between the scenarios: Control−NoSurf (right panels) and Control−NoConv (left panels) at 0.05 m, 0.1 m, 0.4 m, 1.05 m and 2.45 m. The temperature deviations present in this figure is the same as in Figure 4 b and c in the revised manuscript at the same depths.

(5) What does it mean ground ice melt water during spring? Could the author depict the process of ground ice thawing when the active layer is completely frozen in spring?

We did not mean to express the process of ground ice thawing when the active layer is completely frozen in spring. Sorry for the misunderstanding caused here. Here, we want show is a simple top down thawing process during thaw periods.

It is shown in the Figure 6 and Figure 7 that in addition to the infiltration from ground surface, the melt water of ground ice in the active layer is also one contributor to the liquid migration fluxes among soils in thaw periods. Water flux from soil ice melt must happen after the upper layer thaws. We can see that the deeper soil layers always thawed later than the upper layers in Figure 4, and the CHT impacts of deeper layers also happened later than the upper layers, because the upper infiltrative water cannot percolate to the lower layers when the lower layers were still frozen. Thus, our simulation results do follow the principle that active layer thaws from top to bottom and the melt water are not able to transfer to the soil depth which is still frozen. To avoid any confusion here, we explained this top down ground ice thawing process in Section 3.3.1:

"Nevertheless, as the ambient temperature rises, the underlying frozen ground begins to thaw to depth (Figure 4b), and ground ice melt also partially contributes to the liquid flux. It is difficult to distinguish which fraction of the flux comes from snowmelt and which from ground ice melt."

(6) The simulation errors for soil temperature and moisture in the article are still large, especially below 0.4 m in Figure 2. So the possible reasons are suggested to discuss in the context.

Error sources in this simulation mainly include: (1) model structure uncertainty; (2) model parameter uncertainty, and (3) input data biases. We have performed a parameter uncertainty analysis for the SHAW simulation at TGL site and optimized the parametric values, so that the errors associated with parameter uncertainty can be much reduced. We also have discussed the flaws of model physical processes in simulating vapor flux direction and unfrozen water migration in freeze periods in Section 4.4.

According to previous studies, the results of SHAW are very sensitive to the lower boundary conditions. We found that the observed soil moisture data contain some abnormal zero values at and below 0.4 m depth. It is possible that the lower boundary conditions at 2.8 m that we applied to drive the model also lead to some uncertainties in the simulation results.

We provided an explanation related to the inaccuracy of lower boundary in Section 4.4:

"Therefore, in the TGL application, the inaccurate lower boundary conditions for the

SHAW model, particularly soil moisture, which is subject to appreciable measurable errors, also adversely affected the accuracy of the simulation at depth."

In addition to the changes listed above, we provided a new Figure 1b in the revised manuscript for presenting the locations of TGL and QT08 along with the permafrost distribution on Qinghai-Tibet Plateau. We have also improved the DPI of the images to 600 to make them clearer for reading. The inappropriate formatting in the reference list has also been fixed.

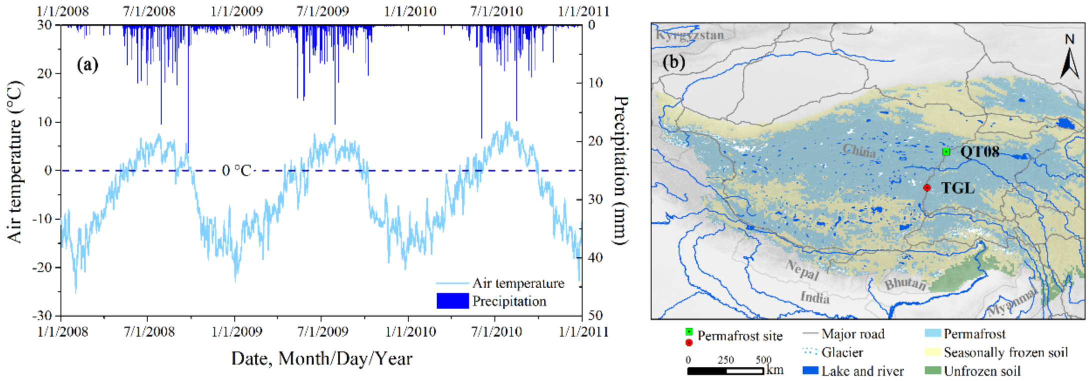

Figure 1 Air temperature and precipitation (a) at the Tanggula (TGL) site during 2008-2010 and the map (b) showing the locations of permafrost sites considered in this study. Times series of daily air temperature at 2 m height and precipitation at TGL aggregated from the hourly measurements. The base map of permafrost distribution on the Qinghai-Tibet plateau (QTP) is from (Zou et al., 2017).