Response to Reviewer#1 TC-2022-123

Review of "Simulation of the current and future dynamics of permafrost near the northern limit of permafrost on the Qinghai–Tibet Plateau" By Zhao et al.

This study simulates the thermal state and its dynamics of permafrost over a small region near the northern limit on the Qinghai-Tibet Plateau (QTP) where the permafrost is a fragile state. The simulation relies on a model developed from numerically solving the one-dimensional transient Fourier's law heat conduction equation. The model has taken several important biogeophysical processes, such as the phase change of soil water, into consideration for a better reproduction of the soil temperature field. The model is carefully validated and calibrated over the study area using meteorology and borehole data. As the result, the validated and calibrated model successfully improve the simulation of the spatial-temporal distribution/variation of permafrost thermal state over the study area, The model is then forced by CMIP5/CMIP6 projection data under the scenario of RCPs and SSPs. The warming rate of permafrost is slightly higher in the SSP scenario than in the RCP scenario. This study highlights the slow delaying process of the mountain permafrost in response to the warming climate. In general, this model-based study is well-shaped with model development, model evaluation/calibration, and model application/projection. The newly-developed model provides a new tool in estimating the response of mountain permafrost in the QTP to the warming climate, supporting new studies to the observational results. Overall, I recommend an acceptance after addressing some minor revisions.

Response:

Thanks a lot for all the comments, revisions and suggestions, especially for your positive comment on our work. We provide our responses one by one to the comments. The original reviewer comments are in normal black font while our answers appear in bule font. The corresponding edit in the manuscript are included in red font.

Major issues:

The resolution of this modeling study is relatively high (1km), and the model configuration is totally one-dimensional. So, in my opinion, the model biases resulted from ignoring the horizontal fluxes of heat and water should not be ignored any more under such a fine grid spacing. Considering the complex topography in the study area, authors should do more in estimating the model uncertainty because of the ignorance of horizontal heat and water fluxes.

Response:

It is a real issue to pay more attention for ignoring the horizontal heat and water fluxes during simulation, and it would be more important for simulate the water cycles in such regions than the heat dynamics. Our answer is:

Firstly, our model reasonably reproduces the vertical ground temperature profile, and active layer thickness is in good agreement with the observation for the last 10 years. The good model performance might be compensated by the calibration parameters. We also believe that the one-dimensional heat flow model can realistically capture the dominating processes of vertical heat transfer processes because the lateral conductive heat into and out of every simulated pixel (1 km) must be much low, and even to nearly balanced, which is due to the much smaller lateral temperature gradient. These facts are strongly corroborating the effect of lateral heat fluxes by Etzelmüller et al. (2011), Jsfarov et al. (2012), Hipp et al. (2012), and Westermann et al. (2013).

Secondly, Xidatan region is in a faulted valley with relatively gentle topography (slopes of ~90% of areas are lower than 5°). The heat transfer caused by lateral groundwater fluxes in and out the simulated pixel would be nearly balanced in most parts of this area, and the effect of this kind of lateral heat fluxes caused by water fluxes thus is considered minor and does not have a significant role in these regions. But small areas of flood land in the valley, where high spatial heterogeneity of surface condition, includes fine particle soil with relatively high soil hydraulic conductivity. In these regions, the transfer process of lateral water fluxes may exist in the active layer and play a crucial role in the ground thermal regime (Bense et al., 2012; Sjöberg et al., 2016; Kurylyk et al., 2016). The impact of this local hydrological process on permafrost thermal regimes is unknown at the current model configuration, but investigations into hydrogeological processes will form the basis of future work.

In the revised manuscript, we have made a supplement to the description of the current uncertainties of model and future improvements in the discussion section. The text there reads as: "*Note that the limitation of the current model is one-dimensional, which assumes each grid cell to be uniform without lateral exchange. Our simulations, therefore, are considered as conservatively changes in the ground temperature in areas with lateral water fluxes, such as flood land in the valley. The representation of the horizontal fluxes exchange of heat and water deserves increased attention in future modeling approaches, and coupling the current model with this physical process of heat transfer could be an important step toward better simulation results of high-resolution in the next generation of permafrost models*."

In any way, we will try to do more work on the issues raised by the reviewers.

Reference:

Etzelmüller, B., Schuler, T., Isaksen, K., Christiansen, H., Farbrot, H., and Benestad, R.: Modeling the temperature evolution of Svalbard permafrost during the 20th and 21st century, The Cryosphere, 5, 67-21, https://doi.org/10.5194/tc-5-67-2011, 2011.

Jafarov, E., Marchenko, S., and Romanovsky, V.: Numerical modeling of permafrost dynamics in Alaska using a high spatial resolution dataset, The Cryosphere, 6, 613-624, https://doi.org/10.5194/tc-6-613-2012, 2012

Hipp. T., Etzelmüller, B, Farbrot, H., Schuler, T., and Westermann, S.: Modelling borehole temperatures in Southern Norway–insights into permafrost dynamics during the 20th and 21st century, The Cryosphere, 6, 533-571, https://doi.org/10.5194/tc-6-553-2012, 2012.

Westermann, S., Schuler, T., Gisnȧs, K., and Etzelmüller, B.: Transient thermal modeling of permafrost conditions in Southern Norway, The Cryosphere 7, 719-739, https://doi.org/10.5194/tc-7-719-2013, 2013

Wu, T., Li, S., Cheng, G., and Nan, Z.: Using ground-penetrating radar to detect permafrost degradation in the northern limit of permafrost on the Tibetan plateau, Cold Reg. Sci. Technol., 41,211-219, https://doi.org/10.1016/j.coldregions.2004.10.006, 2005.

Luo, J., Niu, F., Lin, Z., Liu, M., and Yin, G.: Variations in the northern permafrost boundary over the last four decades in the Xidatan region, Qinghai–Tibet Plateau. J. Mt. Sci., 15, 765–778, https://doi.org/10.1007/s11629-017-4731-2, 2018.

Bense, V., Kooi, H., Ferguson, G., Read, T.: Permafrost degradation as a control on hydrogeological regime shifts in a warming climate, J Geophys Res Earth Surf 117. https://doi.org/10.1029/2011JF002143, 2012.

Sjöberg, Y., Coon, E., Sannel, A., Pannetier, R., Harp, D., Frampton, A., Painter, S., Lyon SW.: Thermal effects of groundwater flow through subarctic fens: a case study based on field observations and numerical modeling, Water Resour Res 52:1591–1606.https://doi.org/10.1002/2015WR017571, 2016.

Kurylyk, BL., MacQuarrie, K., Voss, C.: Climate change impacts on the temperature and magnitude of groundwater discharge from shallow, unconfined aquifers, Water Resour Res, 50:3253–3274 ,2014b.

Minor comment:

Section 2.3.1 What is the vertical resolution of your soil model?

Response:

In our simulations, each grid cell on the map uses a one-dimensional multilayer soil profile down to the depth of 100 m. The vertical grid has fine resolution between nearby point at the near ground layer (0.05m) and become coarse towards the bottom boundary (0.5m). More detailed description, readers are kindly referred to previously published literature in PPP and GRL by Sun et al. (2019 and 2022).

We have added relevant description in section 2.3.1 in the revised manuscript. The text there read as: "*With comprehensive consideration of the modeling precision and computation cost, we choose the calculate time step to be one day, and set a total of 282 vertical levels for each soil column, with the vertical resolution configurations of 0.05m (the upper 4 m) and 0.5m (remaining soil layer to 100 m).*"

Reference

Sun, Z., Zhao, L., Hu, G., Qiao, Y., Du, E., Zou, D., and Xie, C.: Modeling permafrost changes on the Qinghai-Tibetan plateau from 1966 to 2100: a case study from two boreholes along the Qinghai-Tibet engineering corridor. Permafrost and Periglac. Process., 32:156-171, https://doi.org/10.1002/ppp.2022, 2019.

Sun, Z., Zhao, L., Hu, G., Zhou, H., Liu, S., Qiao, Y., Du, E., Zou, D., and Xie, C.: Numerical simulation of thaw settlement and permafrost changes at three sites along the Qinghai-Tibet Engineering Corridor in a warming climate, Geophysical Research Letters, 49, e2021GL097334, https://doi.org/10.1029/2021GL097334, 2022.

Line 320: I suppose the warming rate of SSP245 should be 0.032 instead for 0.32.

Response:

We have changed in the revised manuscript. The text there reads as: "*0.032℃ a^{-1}(SSP2-4.5, moderate mitigation)*".

Line 348: The single quotation mark in "model's performance evaluation" is not correct.

Response:

We have changed in the revised manuscript. The text there reads as: "*model's performance evaluation*".

Fig. 2-5. I have several questions concerns about the results shown by these figures on model evaluation.

- How do you explain the better permafrost of model in reproducing the soil temperature in the shallow layers than that in the deep layers (8m and 15m) for some sties?

Response:

This is just a special case in some areas, where complex surface conditions. The deviation between measured and simulated soil temperature in this special case might be caused by micro-scale heterogeneity in terms of surface cover, topography, and soil stratigraphy at the sub-grid scale. For example, XD2-6 has relatively poor performance compared with other sites. It may be attributed to being located at the edge of the island permafrost of river erosion area with high spatial heterogeneity of surface conditions (Luo et al., 2018; Yin et al., 2021). However, the deviation between the modelled results and measured values for this site within 0.38℃ at the deep layer (15 m), superior to other models, such as LSMs. Furthermore, island permafrost was simulated to disappear in the mid-late 2010s, which was reasonable and in compliance with direct observation facts (Yin et al., 2021). We can conclude that various depths of ground temperature simulated by our model are still satisfactory for this site. On the other hand, the coordinate range of the graph is not adjusted well so that some sites seem to have a larger error in the deep layer. We have modified Fig. 2-5 in the revised manuscript.

We have made a supplement in the "3.1 model's performance evaluation" section in our revised manuscript, the text there reads as "*Site XD2–6 has relatively poor performance compared with other sites, it might be caused by micro-scale heterogeneity in terms of surface cover, topography, and soil stratigraphy at the sub-grid scale, leading to more difficulty in accurate modeling.*"

Reference

Yin, G., Luo, J., Niu, F., Lin, Z., and Liu, M.: Thermal regime and variations in the island permafrost near the northern permafrost boundary in Xidatan, Qinghai–Tibet Plateau, Front. Earth Sci., 560, https://doi.org/10.3389/feart.2021.708630, 2021.

Luo, J., Niu, F., Lin, Z., Liu, M., and Yin, G.: Variations in the northern permafrost boundary over the last four decades in the Xidatan region, Qinghai–Tibet Plateau. J. Mt. Sci., 15, 765–778, https://doi.org/10.1007/s11629-017-4731-2, 2018.

- Why in Fig.3 and 5, there are discontinuity of time series for modelled temperature while no discontinuity in observed results, which is against common sense.

Response:

We reversed the legend of simulation and observation, sorry for the mistake, and we have corrected the mistake in new figures.

- I recommend to use dotted line rather than dashed line for modeled time series since the dashed lines cannot clearly show the annual peak temperature.

Response:

Fig. 2-5 have been modified to make the contrast clearer.

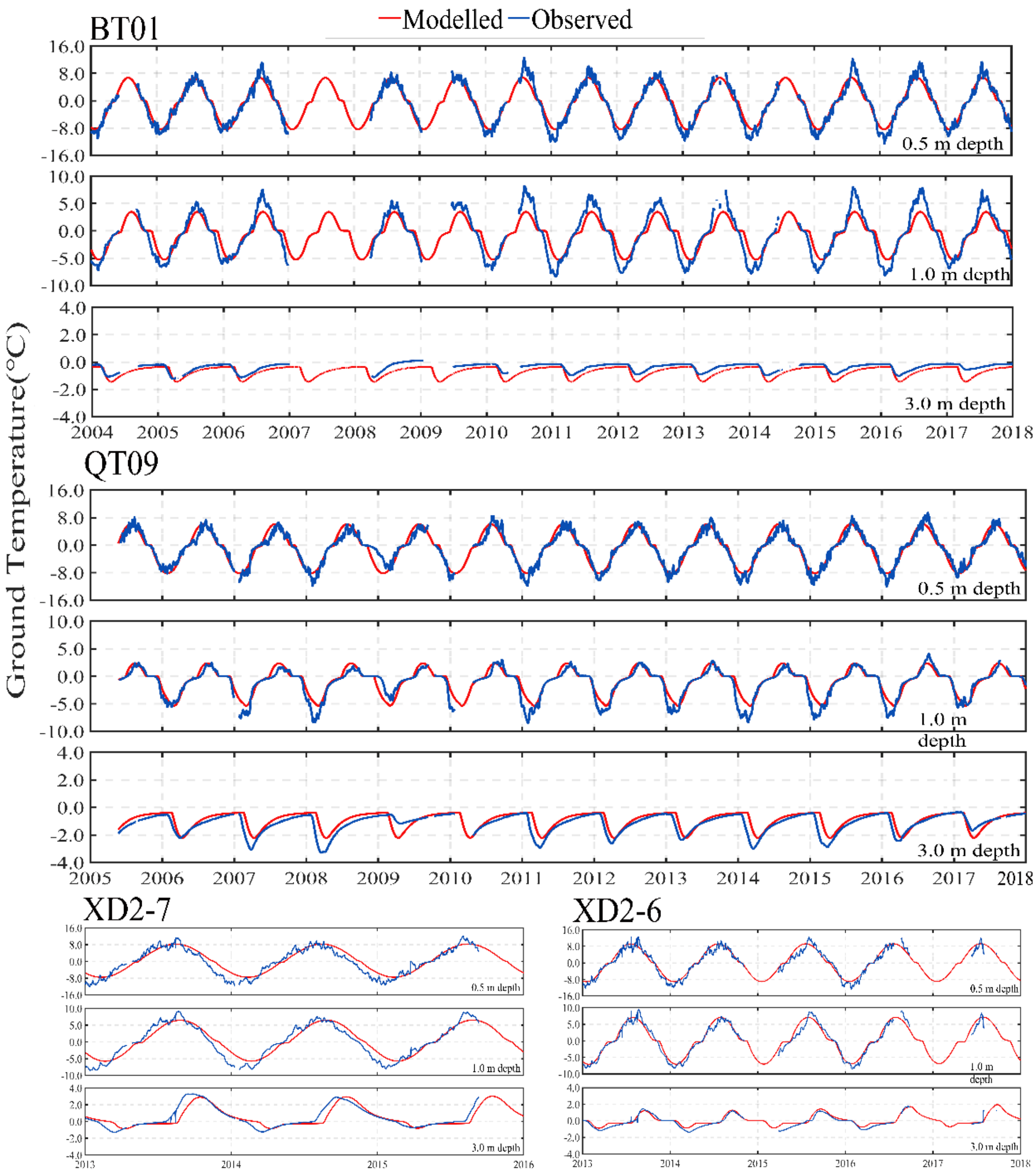

Figure 2. Comparison of the modelled (red lines) to observed (blue lines) daily mean ground temperature at 0.5 m, 1.0 m, 3.0 m depth in four calibration boreholes (BT01, XD2-7, QT09, and XD2-6) during the observation period (There were some data gaps due to temperature probe failure in some years, at the BT01, the data gaps in the record mainly occurred at 0.5-15 m in 2007-2008, and at 15-30 m during the 2005-2007 and 2011-2018, at the QT09, observations at 15-30 m of 2006-2008, 2011-2013, and 2015-2018 are not available, at the XD2-6, the data gap in the record in 2016-2017).

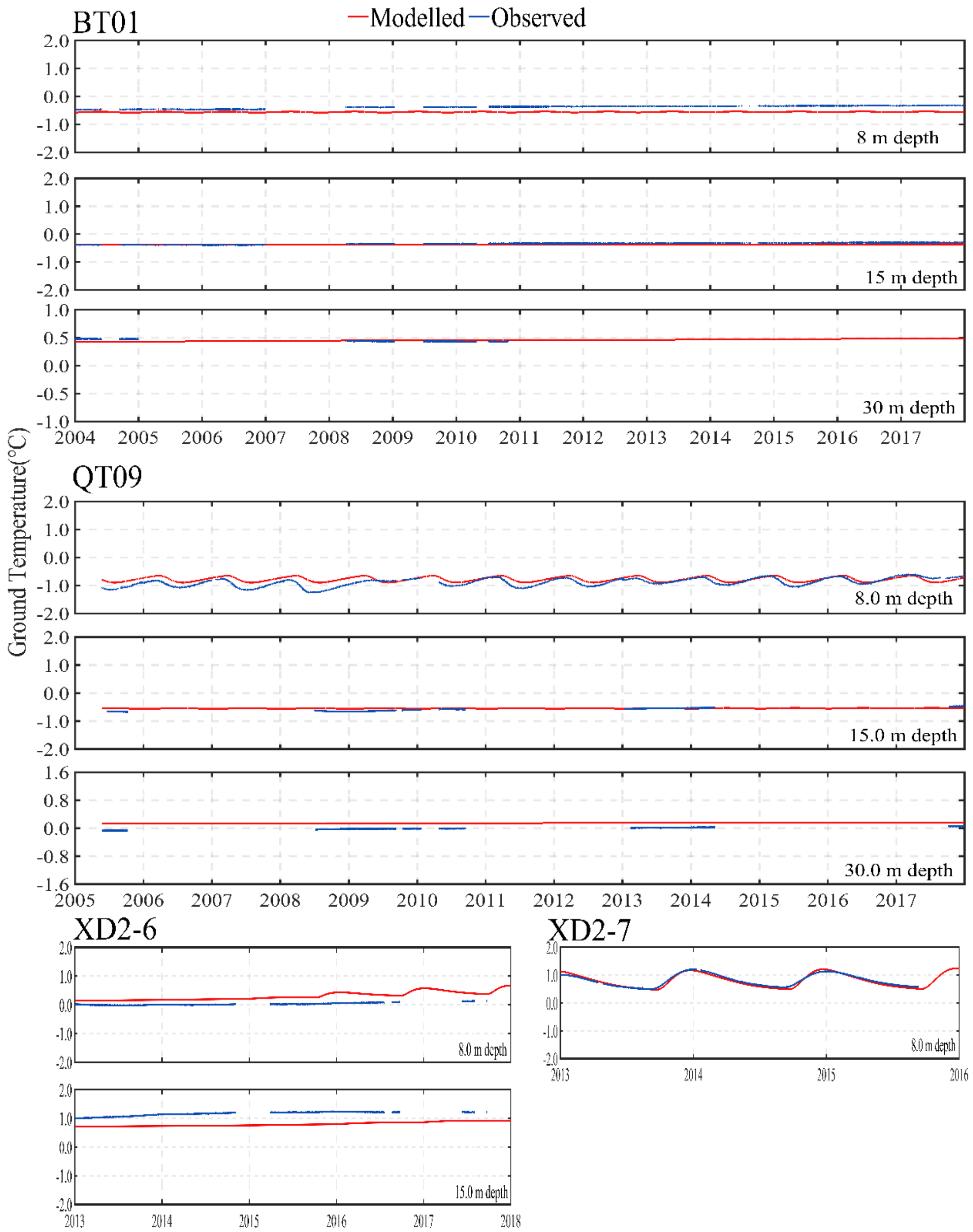

Figure 3. Same as Figure 2. but for daily mean ground temperature at 8 m, 15 m, and 30 m.

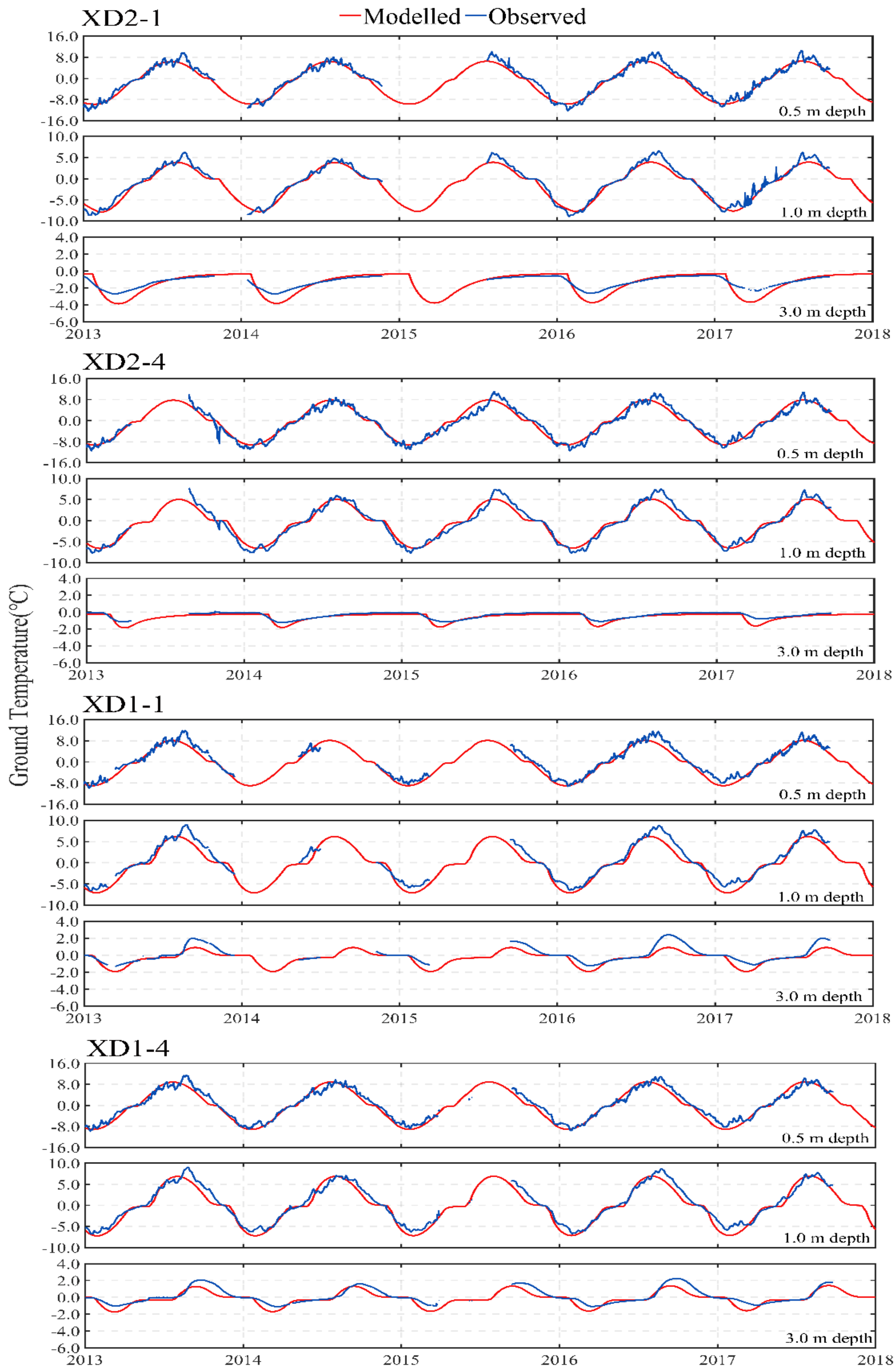

Figure 4. Comparison of the simulated (red lines) to observed (blue lines) daily mean ground temperature at 0.5 m, 1.0 m, and 3.0 m depth in four validation boreholes (XD2-1, XD2-4, XD1-1, and XD1-4) during the observation period from 2013 to 2018 (There were some data gaps due to temperature probe failure in some years, at the XD2-1, the data gaps in the record mainly occurred at 0.5-3.0 m in the first half of 2015. At the XD1-1, the data gap in the record at 0.5-3.0 in 2014-2015, at 8-15 m during the 2013-2015. At the XD1-4, the data gap in the record in the first half of 2015).

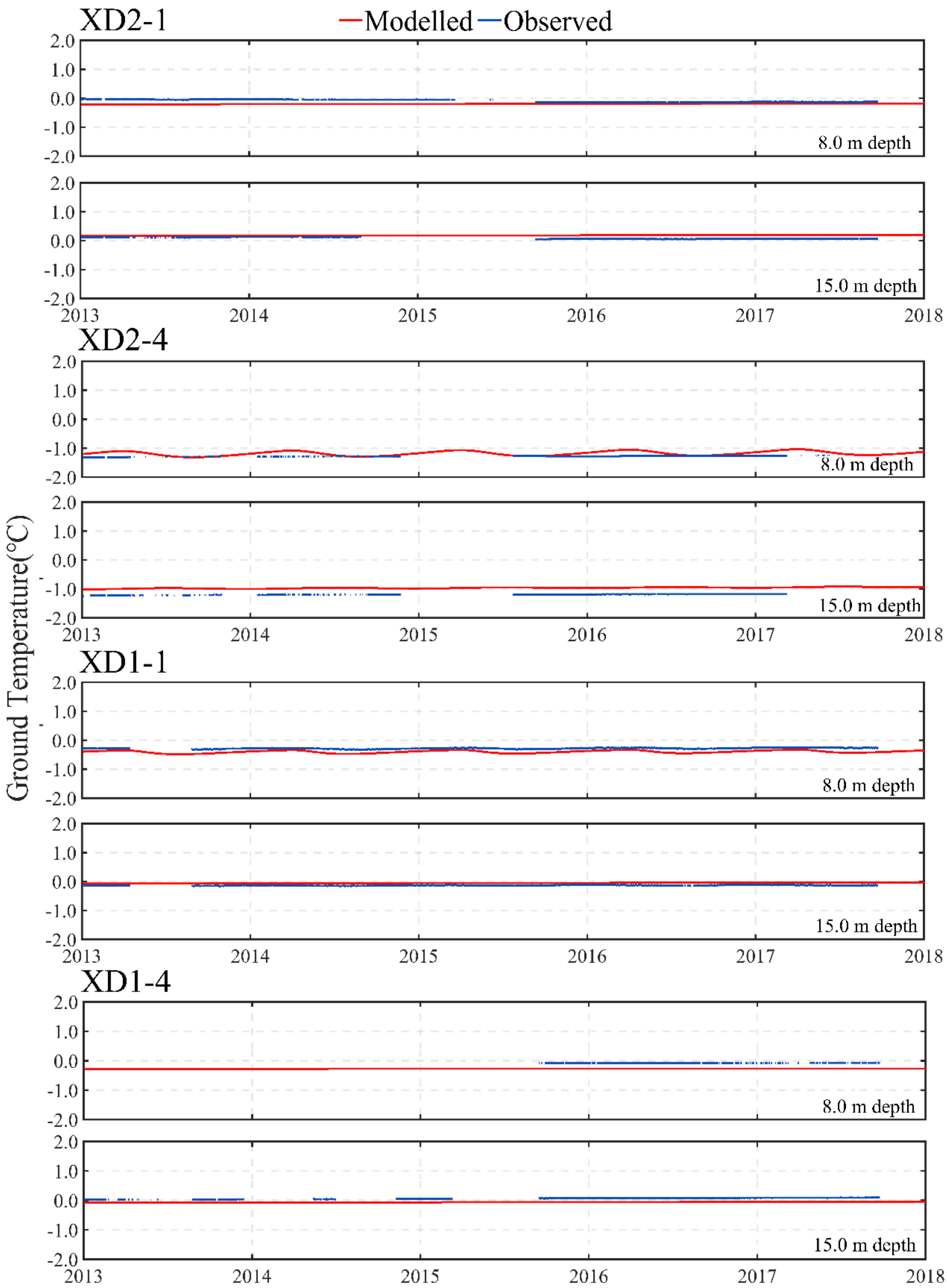

Figure 5. Same as Figure 4. But for daily mean ground temperature at 8 m, and 15 m.

Fig.6, 8, 9, and 10. For these spatial patterns, some of them has while line for topography, while some do not. I recommend to add topography in all figures.

Response:

We have added topography in all figures in the revised manuscript. The details are as follows:

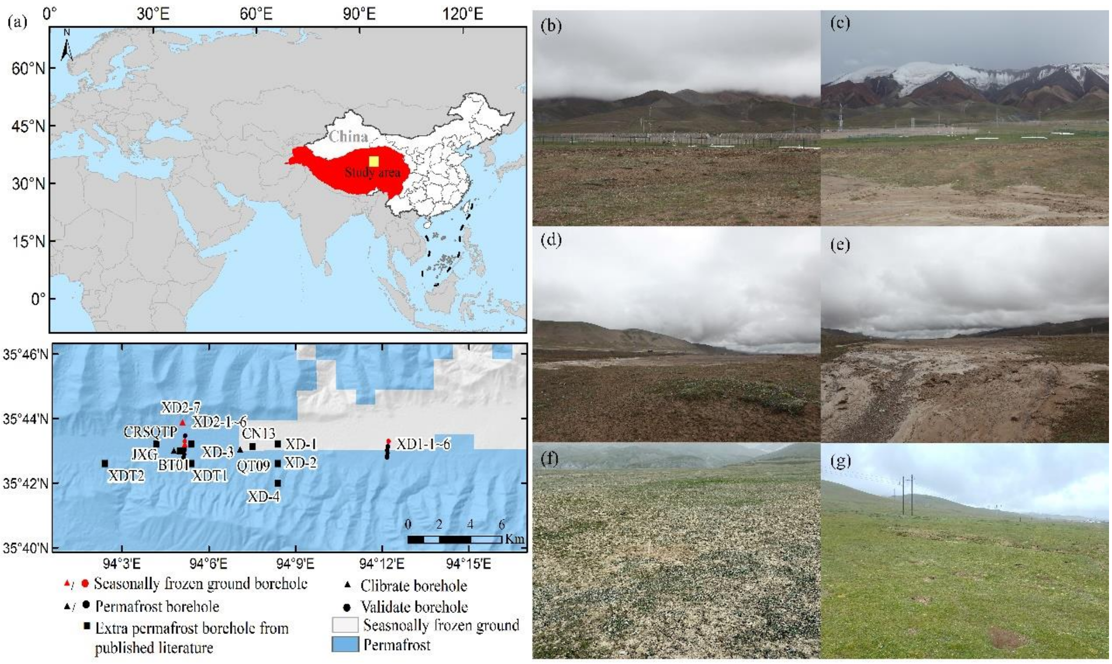

Figure 1. Geographical location of the Xidatan on the QTP, and its topography as well as the location of 24 borehole sites (a). Surface condition at monitoring borehole sites in the study area (b–g): view over the Xidatan comprehensive observation site (b), QT09, view towards the southern (c), QT09, view towards the northeast (d), view from the vicinity of QT09 towards the east (e), XD2–1~2–7, view towards the south (f), XD1–1~1–6, view towards the east (g) (the spatial distribution of permafrost is derived from Zou et al. (2017); topography was generated by the Digital Elevation Model constructed (DEM) from the Shuttle Radar Topography Missions (SRTM) with a 1-arcsecond (~30 m) (Jarvis et al., 2008), all photographs were taken during the field investigation from 23 Jul. 2021 to 2 Aug. 2021).

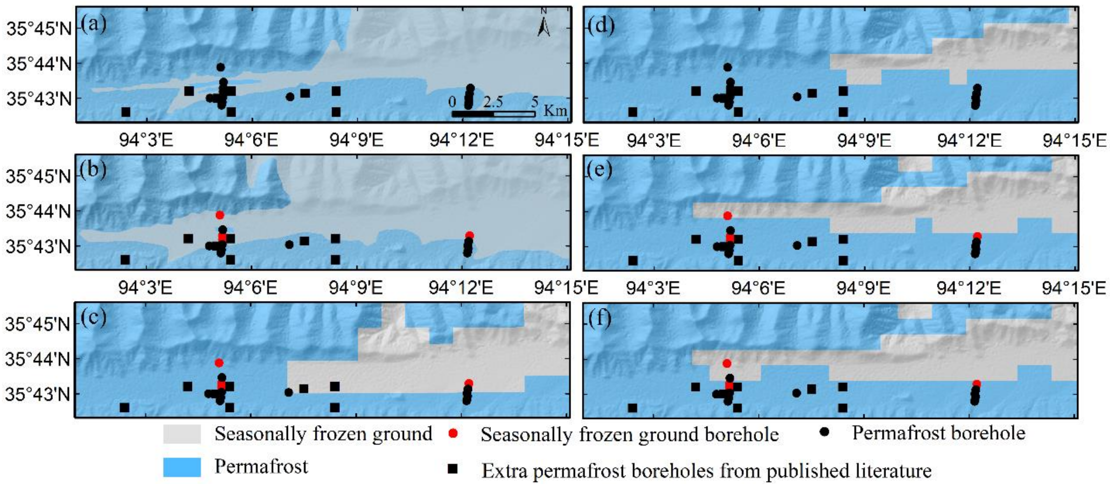

Figure 6. Geographic distribution of permafrost and seasonally frozen ground across the Xidatan for three permafrost maps accomplished in 1975, 2012, and 2016 (left panels 1975 (a), 2012 (b),

2016 (c), published in Nan et al. (2003), Luo et al. (2018) and Zou et al. (2017)) compared to corresponding modeled outputs (right panels, 1975 (d), 2012 (e), 2016 (f)).

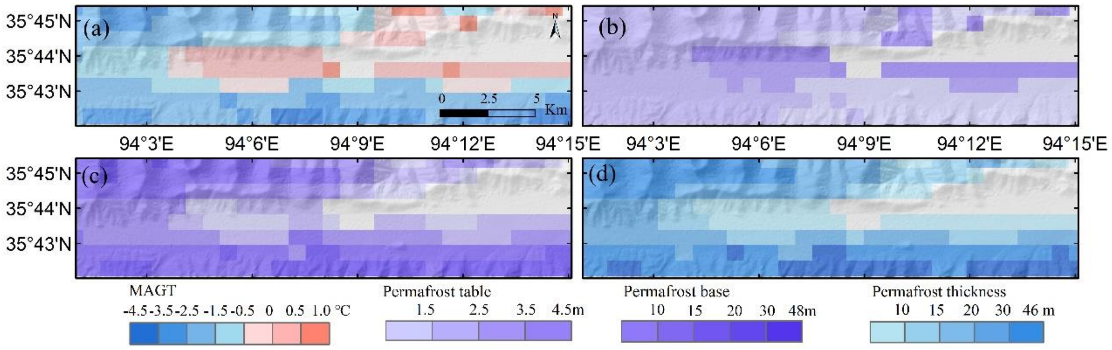

Figure 8. Spatial distributive features of MAGT (a), permafrost table (b), permafrost base (c), and permafrost thickness (d) for the initial simulation of the 1970s over the Xidatan (grey areas with the seasonally frozen ground were excluded).

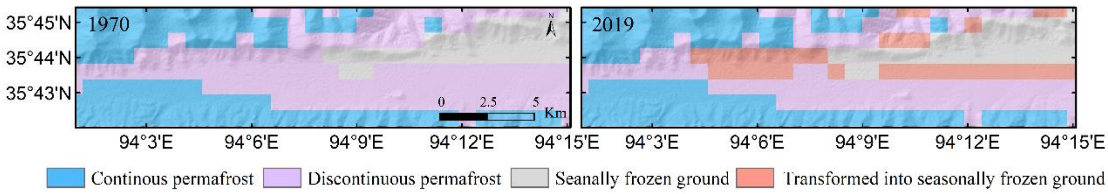

Figure 9. Spatial distributive changes of continuous and discontinuous permafrost, and seasonally frozen ground zone over the Xidatan from 1970 to 2019 (grey areas with the seasonally frozen ground were excluded).

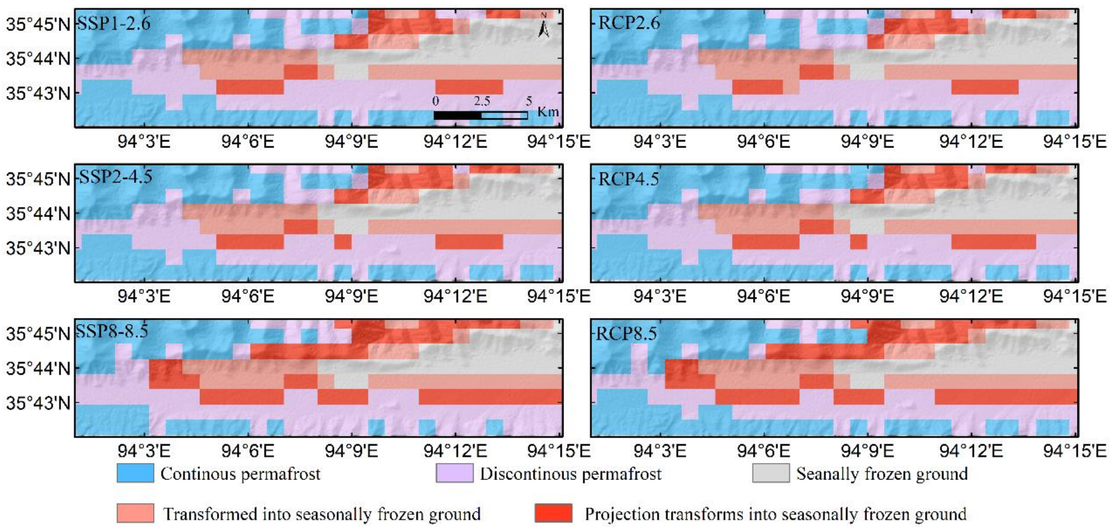

Figure 10. Projected spatial distributive changes of continuous, discontinuous, and seasonally frozen ground over the Xidatan in the future period by 2100 under RCPs and SSPs scenarios (left column, from top to bottom, each row shows under SSP1–2.6, SSP2–4.5, and SSP5–8.5 scenarios, right column, from top to bottom, each row shows under RCP2.6, RCP4.5, and RCP8.5 scenarios).