

# ***Interactive comment on “Change in Frozen Soils and Its Effect on Regional Hydrology in the Upper Heihe Basin, on the Northeastern Qinghai-Tibetan Plateau” by Bing Gao et al.***

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First we want to thank Anonymous Referee #2 for his constructive comment and his good suggestions. We are answering his comments in the following, for clarity we repeat the original comment (C) and answer (A) afterwards.

General comments:

C: This paper reports a modelling study about the impacts of climate warming on frozen ground and hydrological processes for a large mountainous area containing permafrost and non-permafrost areas. The model reasonably captured the thermal and hydrologi-

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cal processes, especially the seasonal and long-term variations of river discharge and runoff. The results show changes in permafrost extent and thawing/freezing deaths, and associated changes in hydrological processes in this large area. The spatially distributed modelling approach is novel and efficient for such a large and cold region as well. This work is valuable to demonstrate the progress in high-resolution thermal-hydrological integrated spatial modelling for large cold regions and to understand the impacts of climate change on frozen ground and associated hydrological processes. Although I agree with some of the concerns indicated by the previous reviewer (see details below), I feel it is worthy to be published after a revision.

A: Thanks for this positive comment.

Specific comments:

C:I agree with the concern of the previous reviewer that the almost exact simulation of ground temperatures at deep layers at the test sites (Figure 3, and Figure S1) probably is the results of calibration, i.e., setting the initial values. The paper should indicate that and probably needs to revise the phase “generally accurate” to a looser term. In addition, if there is no geothermal heat flux at the bottom, ground temperature profile in lower ground should not vary much with depth under equilibrium conditions (unless the 10-year climate force used to spin-up varied significantly from year to year). Most simulated and observed soil temperature increased with depth, indicating the existence of a geothermal gradient. The assumption of zero geothermal heat flux at the lower boundary (Line 279) seems not right.

A: We have deleted “accurate”, and changed the expression as “The model generally captured the vertical distribution of the soil temperature at T1, T2, T3 and T4 in the permafrost area. Good agreement between the simulated and observed soil temperature profiles below the depth of 20 m is probably due to fitting of initial values.” We also recognized the fact of soil temperature increased with depth, indicating the existence of a geothermal gradient, which may cause uncertainty in our simulation. We will estimate

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the geothermal heat flux at the lower boundary and run the model by considering the heat flux at the lower boundary and compare the results.

C: The causal relationship between changes in frozen ground and runoff is an important issue and the paper tried to answer it. The high correlation between liquid soil moisture and runoff in freezing season is not enough to establish that causal relationship (Line 471-474). The modelling exercise of without frozen soil and Figure S2 are a direct way to show the effects of frozen ground and its thaw. More detailed explanation of the modelling exercise needs to be provided (e.g., how the model was modified to do that? is this a run for a grid or for the entire basin?). Figure 15 is interesting but not so clear for me. An analysis from typical grids (permafrost and non-permafrost grids) and seasonal patters (e.g., Figure S2) might be helpful to understand it.

A: For Figure S2, the result is obtained by a run for entire basin. We have modified the figure caption to indicate this. We have added explanations about how the model is modified to run without frozen soil in section 3.4. Figure S4 has been added in supplement files to show runoff changes in typical regions where the permafrost changed into seasonally frozen ground. We have added discussions on the runoff changes in section 5.1 as “Runoff changes of typical grids in areas (with elevation between 3500-3700 m) covered by permafrost in the period of 1971 to 1980 and by seasonally frozen ground in the period of 2001 to 2010 are shown in Figure S4. It illustrates that thaw of permafrost increased the runoff in the freezing season and slowed recession processes in autumn. The increase in freezing season runoff and shift in the seasonal flow pattern are also illustrated by the model simulation without frozen soil scheme as shown in Figure S2.” We will also show seasonal pattern of the runoff in the permafrost areas and the seasonally frozen ground areas in Figure 15.

Minor comments:

C: Line 30: “active layer depth”. Using “active layer thickness” for consistency in the paper

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## Interactive comment

A: We have revised as suggested.

C: Line 34: “large changes in runoff”, can you specify “change” as “increase”?

A: Yes, we have use “increase” instead of “change”.

C: Line 38-39: “due to the degradation of permafrost in the study area”. Increase in precipitation probably also contributed to that change”.

A: Increase in precipitation may also contribute to this change, but degradation of permafrost is the major reason. We modified this sentence as “mainly due to the degradation of permafrost in the study area”

C: Line 47: revise “regime” to “regimes”

A: We have revised as suggested.

C: Line 51: delete “the”.

A: We have revised as suggested.

C: Line 59: “...the frozen soil, and the long-term...”, separate it into two sentences.

A: We have revised as suggested.

C: Line 71: “...processes especially ...”, add a comma after “processes”.

A: We have modified this sentence as “but they represent the flow routing at the catchment scale by simplified ways” according to the comment of reviewer 1.

C: Lines 85-86. Unpack it into two sentences. “The Qinhai-Tibetan Plateau is characterized by.... Cryospheric processes have great impacts on its hydrological processes”.

A: We have revised as suggested.

C: Line 88: “permafrost thickness”, delete “thickness”

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## Interactive comment

A: We have revised as suggested.

C: Line 91: delete “the”

A: We have revised as suggested.

C: Line 103-110: Agree with the previous reviewer, delete it.

A: We have delete the sentences about the Heihe Research plan as suggested.

C: Section 2: probably no needs for the sub-titles. Just describe the study area, field observations and spatial data. Try to focus on data description rather than how they are used (leave that in the next section).

A: We have revised as suggested.

C: Line 135-136: moving “provided by ..(CMA)” to the end of the sentence.

A: We have revised as suggested.

C: Line 141: revise “build” to “run”

A: We have revised as suggested.

C: Line 173-175: “in an integrated . . . 2016)” delete it.

A: We have revised as suggested.

C: Line 176: The approach of the model is very interesting. It is not a fully distributed model with lateral interactions but efficient in computation and handling water flows. I feel that is a important progress of spatial modelling. You may add some sentences about the feature of the model (not branding the project or funding) before “As. . .”.

A: We have added some sentences as “GBEHM is a spatial distributed model for large-scale river basin. It employs the geomorphologic properties to reduce the lateral two-dimensions into one-dimension for flow routing calculation within a sub-catchment, which greatly improves the computation efficiency while retaining the spatial hetero-

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genety in water flow paths at basin scale."

C: Line 188 revise "used in" to "of"

A: We have revised as suggested.

C: Line281-285: You used thinner layers around 0.8m and from 1.7-3m, probably to capture the details of maximum thawing/freezing depths. You mad add some explanations about that.

A: We have added a sentence as "As shown in Figure 2, thinner layers are used at the depth from 1.7 to 3 m for better capturing the maximum frozen depth according to the field observations."

C: Section 3.3: you may begin the section by "to initialize the model, we first estimated the soil temperature profiles based on the assumption that ....". You may delete the sentence "For spin up run, the initial ... this relationship".

A: We have revised as suggested.

C: Line 318-319: the good agreement probably is due to calibration of initial values. A 500 year spin up run should change to a near constant ground temperature with depth. You need to check the model or whether the climate data from 1961-1970 vary significantly from year to year that prevent the establishment of equilibrium conditions.

A: We have checked the climate data, air temperature rising started from 1980s. We have changed this sentence as "Good agreement between the simulated and observed soil temperature profiles below the depth of 20 m is probably due to fitting of initial values".

C: Line 338-339. The value of RMSE and variation with depth is comparable with the study of Ou et al. (2016).

A: We have added a sentence as "This result is similar with the findings by Ou et al. (2016) using the Northern Ecosystem Soil Temperature (NEST) model."

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C: Line 353: revise “station” to “stations”

A: We have revised as suggested.

C: Line 366: “without the frozen soil scheme”. How the model was modified? and is the Figure S2 for the entire basin or just a grid? This is an important part of directly show the effects frozen ground on runoff. More description is needed, probably in the method section.

A: We added some explanations about the model modification in section 3.4. Figure S2 is for entire basin.

C: Section 4.2: It would be useful include the trends of air temperature (annual, thawing and freezing seasons) in the analysis.

A: We have added a table in supplement file (Table S2) and discussions in the manuscript as “Table S2 shows that annual mean air temperature increased by approximately  $1.2^{\circ}\text{C}$  in the period of 2001 to 2010 comparing with the period of 1971 to 1980. And air temperature in the freezing season shows larger increase (approximately  $1.4^{\circ}\text{C}$ ) than in the thawing season ( $1.1^{\circ}\text{C}$ ) between the two periods.”

C: Line 407: “In contrast”. Not a real contrast. It is expected. Delete it.

A: We have revised as suggested.

C: Line 434 “accurately reproduced” may be replace by “well reproduced”

A: We have revised as suggested.

C: Line 453: is increasing in precipitation a factor?

A: Increasing precipitation may be a factor, but it is not the major factor.

C: Line 455-469. It is easy to understand that the volume of soil liquid water increases with the increase in the volume of unfrozen soils. The sentences in these lines are long and complicated. You may simplify them.

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A: We have simplified this part as suggested.

C: Lines 471-474: You need more evidence to support the causal relations. The correlation is only one evidence. See the specific comments.

A: We have added new figures and analysis to support the causal relations as mentioned above.

C: Line 482: From Table 2, the increase probably is mainly due to increase in snow run off in thaw season.

A: We have revised this sentence as “The increased runoff mainly came from increased precipitation and snowmelt in the thawing season.”

C: Line 484-485: revise “during the different seasons” to “between the two seasons”.

A: We have revised as suggested.

C: Line 499, 506, 512: “change in frozen soil”. You may specify it as “thaw of frozen soil”

A: We have revised as suggested.

C: Line 508: “was controlled by” the word probably is too strong. You may use “strongly affected by”

A: We have revised as suggested.

C: Line 512 revise “soil moisture” to “soil liquid moisture”

A: We have revised as suggested.

C: Line 540-522: “Different methods produce large differences in their estimates”. The following citations do not support such a statement since they are mainly for different areas. Actually, some of the estimates in Qinghai-Tibetan Plateau is comparable with your estimate, which is a support of your estimate.

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A: We have deleted the citations (Jorgenson et al., 2006 and Chasmer et al., 2010) for other areas and only compared our results with estimates in the Qinghai-Tibetan Plateau. A new citation of Guo et al. (2013) for the change of permafrost area in the Qinghai-Tibetan Plateau is added. We have deleted the sentence “Different methods produce large differences in their estimates”

C: Line 568: “especially in spring”, not clear for me.

A: Here this means high groundwater flow rate events such as spring freshet. To make it more clear. We modified this as “especially when high groundwater flow rate events occur”

C: The sediment thickness (depth from surface to bedrock), top organic layer thickness, and fraction of rock in soil are important to ground temperature and permafrost. You may add some sentences about them in sections of data, discussion or uncertainty. Active layer is thinner in valleys than in high slopes and on top of mountains due to differences in organic layer and vegetation conditions (Zhang et al., 2013). Temperature inversion and shading by surroundings may also keep the valley cooler than top of the mountains (O’Neil et al., 2015). You may comments on this in the discussions.

A: We have added some discussions about this in section 5.3 as “Sub-grid topography may also affect the frozen soil simulation. For example, active layer thickness is different in the low valleys and high slopes due to different vegetation conditions, soil organic layers and shading by surroundings. These factors are not well considered in this study.”

C: Figures: The font of words or numbers are too small in most figures.

A: We will change the font of words or numbers in the figures to make it clear.

C: Figure 3, S1: It is better to use a line with dots to represent the observations (so readers know the depths of observations). If you have annual averages, it is better to use annual averages rather than a specific date or month.

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A: We have modified the figure as suggested. We do not have annual averages.

C: Figure 10b: revise “thaw depth” to “active layer thickness”

A: We have modified the figure as suggested.

C: Figure 11d,e, Red curves are not necessary. For easy understanding, you may put elevation as Y axis, and percentage of permafrost to x axis.

A: We have modified the figure as suggested.

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