

# 1. Comments from Referees

## Comment by Anonymous Referee #1

### General comments

The paper is improved. I have only minor specific comments other than the general comment below.

In general, in this paper I would like the authors to address if there is a horizontal talik above the permafrost or not. Surely there would be somewhere in the catchment especially where the permafrost is discontinuous. Horizontal taliks exist where the maximum frost depth does not extend as deep as the maximum seasonal thaw depth. So there is a perennially unfrozen zone above the permafrost but below the active layer. Could this be significant like the conversion from permafrost to seasonally frozen ground? Would the model account for this?

### Minor comments

1. L51, delete 'the'.
2. L56, delete 'the'
3. L57,58, the authors should be careful with the phrase 'field experiments' here. If they are talking about looking at field data, some of the studies (e.g., Jacques and Sauchyn 2009) have been done on large spatial scales. If they are talking about intensively monitoring a catchment, that is different and likely only accomplished on fine scales.
4. L62, delete 'the'.
5. L31 and many other places in the manuscript. If I were the authors I would define runoff up front. They use it in the normal hydrological way, but many hydrogeologists or civil engineers could be interested in this paper, and runoff often means different things to different people. Given that The Cryosphere is a bit of a general cold regions journal, I'd suggest a clear precise definition early on in the paper for runoff.
6. L70, delete 'the' before 'vertical'.
7. L72, 'overly simple ways' is vague. Explain or remove?
- [8. L83, delete 'the' before 'downstream'
9. L88, 'thickness' can be removed (besides it makes no sense to say that the thickness is thin and the thickness is warm).
10. L91, delete 'the' after 'air'.
11. L103-107 and 172-175. This seems to be almost branding for the research grant and, in my mind, is only suitable for the acknowledgements not the main body of a research paper.
12. L122, 'mean' should be before 'annual'.
13. I'm surprised by the high RMSE in the soil temperature results, especially after calibration'
14. Section 5.3, the uncertainty 'analysis' is highly qualitative.

15. Figure 1, The authors could show the plateau on the map of China. OR be clearer what the grey zone refers to in the inset.?
16. Figure 7, the caption should be clearer why there are groups of 2 figure panels for each location.

## **Comment by Anonymous Referee #2**

### **General comments**

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 hydrological 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.

### **Specific comments**

1. 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 phrase “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.
2. 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 patterns (e.g., Figure S2) might be helpful to understand it.

## Minor comments

1. Line 30: “active layer depth”. Using “active layer thickness” for consistency in the paper
2. Line 34: “large changes in runoff”, can you specify “change” as “increase”?
3. Line 38-39: “due to the degradation of permafrost in the study area”. Increase in precipitation probably also contributed to that change”.
4. Line 47: revise “regime” to “regimes”
5. Line 51: delete “the”.
6. Line 59: “...the frozen soil, and the long-term...”, separate it into two sentences.
7. Line 71: “...processes especially ...”, add a comma after “processes”.
8. Lines 85-86. Unpack it into two sentences. “The Qinghai-Tibetan Plateau is characterized by... . Cryospheric processes have great impacts on its hydrological processes”.
9. Line 88: “permafrost thickness”, delete “thickness”
10. Line 91: delete “the”
11. Line 103-110: Agree with the previous reviewer, delete it.
12. Section 2: probably no need 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).
13. Line 135-136: moving “provided by ..(CMA)” to the end of the sentence.
14. Line 141: revise “build” to “run”
15. Line 173-175: “in an integrated ... 2016)” delete it.
16. 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 an important progress of spatial modelling. You may add some sentences about the feature of the model (not branding the project or funding) before “As...”.
17. Line 188 revise “used in” to “of”
18. Line 281-285: You used thinner layers around 0.8m and from 1.7-3m, probably to capture the details of maximum thawing/freezing depths. You may add some explanations about that.
19. 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”.
20. 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.
21. Line 338-339. The value of RMSE and variation with depth is comparable with the

study of Ou et al. (2016).

**22.** Line 353: revise “station” to “stations”

**23.** 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.

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

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

**26.** Line 434 “accurately reproduced” may be replace by “well reproduced”

**27.** Line 453: is increasing in precipitation a factor?

**28.** 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.

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

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

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

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

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

**34.** Line 512 revise “soil moisture” to “soil liquid moisture”

**35.** 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.

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

**37.** 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.

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

**39.** 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.

**40.** Figure 10b: revise “thaw depth” to “active layer thickness”

**41.** 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.

## 2. Author's response

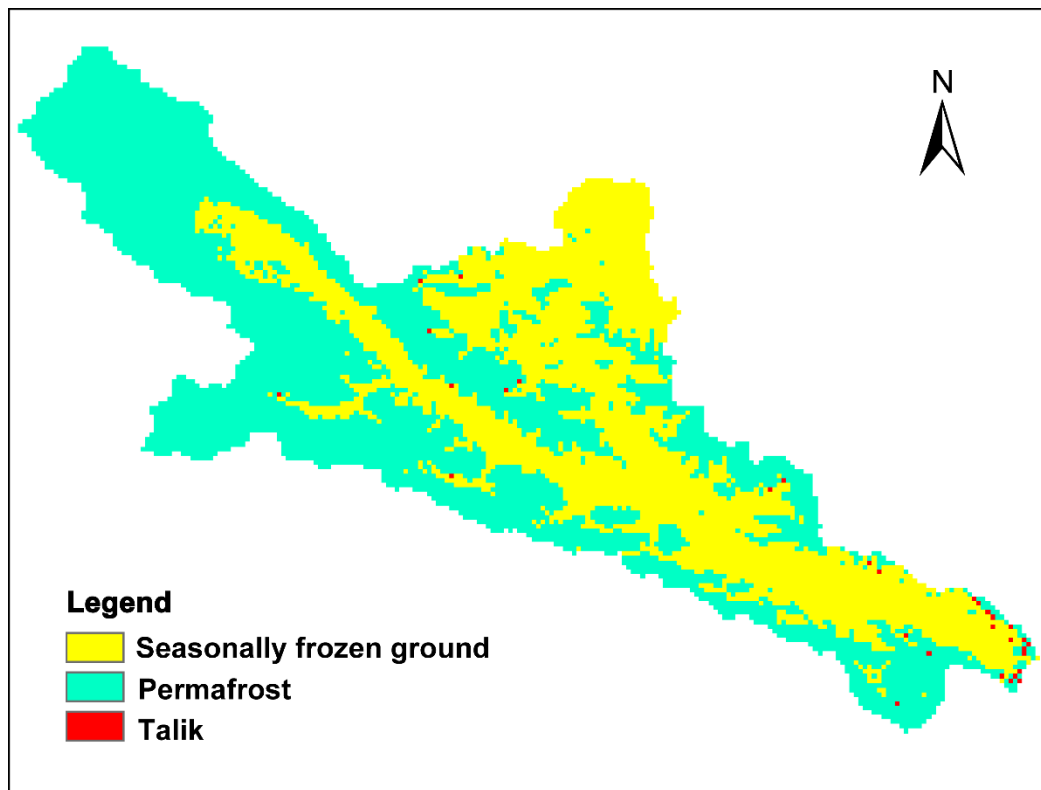
### Reply to the Referee Comment by Anonymous Referee #1

#### General comments:

The paper is improved. I have only minor specific comments other than the general comment below.

In general, in this paper I would like the authors to address if there is a horizontal talik above the permafrost or not. Surely there would be somewhere in the catchment especially where the permafrost is discontinuous. Horizontal taliks exist where the maximum frost depth does not extend as deep as the maximum seasonal thaw depth. So there is a perennially unfrozen zone above the permafrost but below the active layer. Could this be significant like the conversion from permafrost to seasonally frozen ground? Would the model account for this?

**Reply:** Thanks for this comment. We have checked the results of soil temperature of each layer for all grids. We have found some taliks in permafrost region. But the horizontal taliks are not significant as shown in the following figure.



#### Minor comments:

Q[1]: L51, delete 'the'.

**Reply:** We have revised as suggested (Please see line 51 in the revised clean version

manuscript ).

**Q[2]:** L56, delete ‘the’

**Reply:** We have revised as suggested (Please see line 56 in the revised clean version manuscript).

**Q[3]:** L57,58, the authors should be careful with the phrase ‘field experiments’ here. If they are talking about looking at field data, some of the studies (e.g., Jacques and Sauchyn 2009) have been done on large spatial scales. If they are talking about intensively monitoring a catchment, that is different and likely only accomplished on fine scales.

**Reply:** We have modified “field experiments” as “intensive field observations” (Please see line 58-59 in the revised clean version manuscript).

**Q[4]:** L62, delete ‘the’.

**Reply:** We have revised as suggested (Please see line 63 in the revised clean version manuscript).

**Q[5]:** L31 and many other places in the manuscript. If I were the authors I would define runoff up front. They use it in the normal hydrological way, but many hydrogeologists or civil engineers could be interested in this paper, and runoff often means different things to different people. Given that The Cryosphere is a bit of a general cold regions journal, I’d suggest a clear precise definition early on in the paper for runoff.

**Reply:** Thank you for this suggestion, we added the runoff definition when it first appeared in this paper. The related sentence has been revised as “A few studies reported that permafrost thawing might reduce river runoff (This paper defines the runoff as all liquid water flowing out of the study area.)”. Please see line 57 in the revised clean version manuscript.

**Q[6]:** L70, delete ‘the’ before ‘vertical’.

**Reply:** We have revised as suggested (Please see line 71 in the revised clean version manuscript).

**Q[7]:** L72, ‘overly simple ways’ is vague. Explain or remove?

**Reply:** We modified “in overly simple ways” as “by simplified ways” (Please see line 72 in the revised clean version manuscript).

**Q[8]:** L83, delete ‘the’ before ‘downstream’

**Reply:** We have revised as suggested (Please see line 83 in the revised clean version manuscript).

**Q[9]:** L88, ‘thickness’ can be removed (besides it makes no sense to say that the thickness is thin and the thickness is warm).

**Reply:** We have revised as suggested (Please see line 88 in the revised clean version manuscript).

manuscript).

**Q[10]:** L91, delete 'the' after 'air'.

**Reply:** We have revised as suggested (Please see line 90 in the revised clean version manuscript).

**Q[11]:** L103-107 and 172-175. This seems to be almost branding for the research grant and, in my mind, is only suitable for the acknowledgements not the main body of a research paper.

**Reply:** we have delete the sentences about the Heihe Research plan in the main body (Please see line 103-106 and line 161-164 in the revised clean version manuscript).

**Q[12]:** L122, 'mean' should be before 'annual'.

**Reply:** We have revised (Please see line 119 in the revised clean version manuscript).

**Q[13]:** I'm surprised by the high RMSE in the soil temperature results, especially after calibration'

**Reply:** We calibrated the soil reflectance according to vegetation type, and we do not calibrate the soil heat capacity and soil thermal conductivity. The soil heat capacity and soil thermal conductivity are estimated using the method developed by Farouki (1981). This may lead uncertainties in simulation of the soil temperature.

**Q[14]:** Section 5.3, the uncertainty 'analysis' is highly qualitative.

**Reply:** We have quantified the uncertainties of soil temperature simulation induced by geothermal flux (Please see line 576-580 in the revised clean version manuscript). However, due to the complexity of the distributed model and large number of model parameters, it is challenge to quantify overall simulation uncertainty. This work will be done in the future study.

**Q[15]:** Figure 1, The authors could show the plateau on the map of China. OR be clearer what the grey zone refers to in the inset.?

**Reply:** We have modified Figure 1 to show the plateau on the map of China (Please see Figure 1 in the revised clean version manuscript).

**Q[16]:** Figure 7, the caption should be clearer why there are groups of 2 figure panels for each location.

**Reply:** We have changed the caption of Figure 7 as "Comparison of the simulated and the observed daily river discharge at: (a) the Yingluoxia Gauge, (b) the Qilian Gauge, and (c) the Zhamashike Gauge (The upper panel is the calibration period, and the bottom panel is the validation period for each gauge)". Please see Figure 7 in the revised clean version manuscript.



## **Reply to the Referee Comment by Anonymous Referee #2**

### **General comments:**

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 hydrological processes, especially the seasonal and long-term variations of river discharge and runoff. The results show changes in permafrost extent and thawing/freezing depths, 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.

**Reply:** Thanks for this positive comment. We have revised the manuscript according to your suggestions.

### **Specific comments:**

**Q[1]:** 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 phrase “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.

**Reply:** 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.” (Please see line 316-320 in the revised clean version manuscript).

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 have estimated the geothermal heat flux at the lower boundary and run the model using a heat flux of  $0.2 \text{ W/m}^2$  at the lower boundary and compared the results with simulation



with zero heat flux. The geothermal heat flux of  $0.2 \text{ W/m}^2$  is estimated by geothermal gradient of T4 shown in Figure 3. And the geothermal gradient of T4 is larger than the other boreholes. The results are shown in Figure S5 in the supplement file. It can be seen from Figure S5 that geothermal heat flux only causes slightly increase in soil temperature below 30 m. We have added discussions about the uncertainties due to geothermal heat flux in section 5.3 as “Figure S5 in the supplement material compares the results of simulation with zero thermal flux at the lower boundary and the results of simulation with thermal flux of  $0.2 \text{ W/m}^2$  (Estimated by geothermal gradient at T4 in Figure 3). It can be seen that the geothermal heat flux at the lower boundary causes slight increase in soil temperature below the depth of 30 m.” (Please see line 576-580 in the revised clean version manuscript).

**Q[2]:** 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 patterns (e.g., Figure S2) might be helpful to understand it.

**Reply:** 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 (Please see line 302-306 in the revised clean version manuscript). 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 also checked seasonal pattern of the runoff in the permafrost areas and the seasonally frozen soils, see Figure 15(c).

We discussed the runoff changes in section 5.1 as “Figure 15(c) shows the seasonal pattern of runoff in the permafrost area and seasonally frozen soils. From April to October (the thawing season), runoff in the permafrost area is much larger than in the seasonally frozen soils, but in the freezing season runoff in the permafrost area is lower than in the seasonally frozen soils. Figure S4 in the supplement material shows runoff changes from typical area (with elevation between 3500-3700 m) where covered by the permafrost in the period of 1971 to 1980 and changed into the seasonally frozen ground in the period of 2001 to 2010. This 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.” (Please see line 481-491 in the revised clean version manuscript)

## Minor comments:

**Q[1]:** Line 30: “active layer depth”. Using “active layer thickness” for consistency in the paper

**Reply:** We have revised as suggested (Please see line 30 in the revised clean version manuscript).

**Q[2]:** Line 34: “large changes in runoff”, can you specify “change” as “increase”?

**Reply:** Yes, we have use “increase” instead of “change” (Please see line 34 in the revised clean version manuscript).

**Q[3]:** Line 38-39: “due to the degradation of permafrost in the study area”. Increase in precipitation probably also contributed to that change”.

**Reply:** 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” (Please see line 38-39 in the revised clean version manuscript).

**Q[4]:** Line 47: revise “regime” to “regimes”

**Reply:** We have revised as suggested (Please see line 48 in the revised clean version manuscript).

**Q[5]:** Line 51: delete “the”.

**Reply:** We have revised as suggested (Please see line 51 in the revised clean version manuscript ).

**Q[6]:** Line 59: “...the frozen soil, and the long-term...”, separate it into two sentences.

**Reply:** We have revised as suggested (Please see line 60 in the revised clean version manuscript).

**Q[7]:** Line 71: “...processes especially ...”, add a comma after “processes”.

**Reply:** 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 (Please see line 72 in the revised clean version manuscript).

**Q[8]:** Lines 85-86. Unpack it into two sentences. “The Qinhai-Tibetan Plateau is characterized by... . Cryospheric processes have great impacts on its hydrological processes”.

**Reply:** We have revised as suggested (Please see line 85-87 in the revised clean version manuscript).

**Q[9]:** Line 88: “permafrost thickness”, delete “thickness”

**Reply:** We have revised as suggested (Please see line 88 in the revised clean version manuscript).

**Q[10]:** Line 91: delete “the”

**Reply:** We have revised as suggested (Please see line 90 in the revised clean version manuscript).

**Q[11]:** Line 103-110: Agree with the previous reviewer, delete it.

**Reply:** We have delete the sentences about the Heihe Research plan as suggested (Please see line 103-106 in the revised clean version manuscript).

**Q[12]:** 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).

**Reply:** We have revised as suggested (Please see line 114, line 127-130, line 148-149 in the revised clean version manuscript).

**Q[13]:** Line 135-136: moving “provided by ..(CMA)” to the end of the sentence.

**Reply:** We have revised as suggested (Please see line 132-133 in the revised clean version manuscript).

**Q[14]:** Line 141: revise “build” to “run”

**Reply:** We have revised as suggested (Please see line 138 in the revised clean version manuscript).

**Q[15]:** Line 173-175: “in an integrated ... 2016)” delete it.

**Reply:** We have revised as suggested (Please see line 161-163 in the revised clean version manuscript).

**Q[16]:** 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...”.

**Reply:** 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 heterogeneity in water flow paths at basin scale.” (Please see line 164-168 in the revised clean version manuscript)

**Q[17]:** Line 188 revise “used in” to “of”

**Reply:** We have revised as suggested (Please see line 179 in the revised clean version manuscript).

**Q[18]:** 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.

**Reply:** 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.” (Please see line 274-275 in the revised clean version manuscript).

**Q[19]:** 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”.

**Reply:** We have revised as suggested (Please see line 285-289 in the revised clean version manuscript).

**Q[20]:** 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.

**Reply:** 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” (Please see line 318-320 in the revised clean version manuscript).

**Q[21]:** Line 338-339. The value of RMSE and variation with depth is comparable with the study of Ou et al. (2016).

**Reply:** 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.” (Please see line 342-343 in the revised clean version manuscript).

**Q[22]:** Line 353: revise “station” to “stations”

**Reply:** We have revised as suggested (Please see line 356 in the revised clean version manuscript).

**Q[23]:** 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.

**Reply:** We added some explanations about the model modification in section 3.4. Figure S2 is for entire basin (Please see line 302-306 in the revised clean version manuscript).

**Q[24]:** Section 4.2: It would be useful include the trends of air temperature (annual, thawing and freezing seasons) in the analysis.

**Reply:** We have added a table in supplement file (Table S2) and discussions in the manuscript as “Table S2 in the supplement material shows that annual mean air temperature increased by approximately 1.2°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°C) than in the thawing season (1.1°C) between the two periods.” (Please see line 384-387 in the revised clean version manuscript).

**Q[25]:** Line 407: “In contrast”. Not a real contrast. It is expected. Delete it.

**Reply:** We have revised as suggested (Please see line 414 in the revised clean version manuscript).

**Q[26]:** Line 434 “accurately reproduced” may be replace by “well reproduced”

**Reply:** We have revised as suggested (Please see line 441 in the revised clean version manuscript).

**Q[27]:** Line 453: is increasing in precipitation a factor?

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

**Q[28]:** 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.

**Reply:** We have simplified this part as suggested (Please see line 462-472 in the revised clean version manuscript).

**Q[29]:** Lines 471-474: You need more evidence to support the causal relations. The correlation is only one evidence. See the specific comments.

**Reply:** We have added new figures and analysis to support the causal relations as mentioned above (Please see line 481-491 in the revised clean version manuscript).

**Q[30]:** Line 482: From Table 2, the increase probably is mainly due to increase in snow run off in thaw season.

**Reply:** We have revised this sentence as “The increased runoff mainly came from increased precipitation and snowmelt in the thawing season.” (Please see line 495-496 in the revised clean version manuscript)

**Q[31]:** Line 484-485: revise “during the different seasons” to “between the two seasons”.

**Reply:** We have revised as suggested (Please see line 498-499 in the revised clean version manuscript).

**Q[32]:** Line 499, 506, 512: “change in frozen soil”. You may specify it as “thaw of

frozen soil”

**Reply:** We have revised as suggested (Please see line 513, 519, 526 in the revised clean version manuscript).

**Q[33]:** Line 508: “was controlled by” the word probably is too strong. You may use “strongly affected by”

**Reply:** We have revised as suggested (Please see line 522 in the revised clean version manuscript).

**Q[34]:** Line 512 revise “soil moisture” to “soil liquid moisture”

**Reply:** We have revised as suggested (Please see line 526 in the revised clean version manuscript).

**Q[35]:** 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.

**Reply:** 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” (Please see line 555-561 in the revised clean version manuscript).

**Q[36]:** Line 568: “especially in spring”, not clear for me.

**Reply:** 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” (Please see line 589 in the revised clean version manuscript).

**Q[37]:** 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.

**Reply:** We have added some discussions about this in section 5.3 as “The uncertainty in simulation of soil heat-water transfer processes might result from the soil water and heat parameters and the bottom boundary condition of heat flux. For example, soil depth and fraction of rock in soil may greatly affect soil temperature simulation.” and “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 (Zhang et al., 2013; O’Neill

et al., 2015). These factors are not well considered in this study.” (Please see line 571-574 and line 582-585 in the revised clean version manuscript).

**Q[38]:** Figures: The font of words or numbers are too small in most figures.

**Reply:** We will change the font of words or numbers in the figures to make it clear (Please see Figure 5, Figure 6, Figure 7, Figure 8, Figure 10, Figure 11, Figure 12 and Figure 13 in the revised clean version manuscript).

**Q[39]:** 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.

**Reply:** We have modified the figure as suggested. We do not have annual averages. Please see Figure 3 and Figure S1 in the revised clean version manuscript.

**Q[40]:** Figure 10b: revise “thaw depth” to “active layer thickness”

**Reply:** We have modified the figure as suggested. Please see Figure 10 in the revised clean version manuscript.

**Q[41]:** 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.

**Reply:** We have modified the figure as suggested. Please see Figure 11 in the revised clean version manuscript.



### **3. Author's changes in manuscript**

1. Add figure S4 in the supplement file to show the runoff changes in typical regions.
2. Add Table S2 in the supplement file to show the changes in air temperature.
3. Add Figure S5 to show the effect of geothermal flux at the lower boundary.
4. Modified Figure 3 and Figure S1 to use a line with dots to represent the observations.
5. Modified Figure 5, Figure 6, Figure 7, Figure 8 and Figure 10, Figure 12, Figure 13 to use larger fonts.
6. Add Seasonal patterns of runoff in permafrost area and seasonally frozen ground in Figure 15.
7. Add introductions about the model without frozen soil scheme in section 3.4.
8. Add analysis about the runoff changes in typical regions and seasonal pattern changes in section 5.1.
9. Add discussions about uncertainty caused by geothermal flux at the lower boundary in section 5.3.
10. Delete sub-titles in Section 2 and focus on data description.
11. Modified Figure 1 to show the Plateau on the map
12. Modified Figure 11d,e and put elevation as Y axis, and percentage of permafrost to x axis
13. Add some discussions in section 5.3 about the factors which influences the soil temperature simulation.
14. Some other changes according to the minor comments of two reviewers

**Change in Frozen Soils and Its Effect on Regional Hydrology in the  
Upper Heihe Basin, on the Northeastern Qinghai-Tibetan Plateau**

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**ABSTRACT:**

Frozen ground has an important role in regional hydrological cycles and ecosystems, especially on the Qinghai-Tibetan Plateau, which is characterized by high elevation and a dry climate. This study modified a distributed physically based hydrological model and applied it to simulate the long-term (from 1971 to 2013) change of frozen ground and its effect on hydrology in the upper Heihe basin located in the northeastern Qinghai-Tibetan Plateau. The model was validated carefully against data obtained from multiple ground-based observations. Based on the model simulations, we analyzed the changes of frozen soils and their effects on the hydrology. The results showed that the permafrost area shrank by 9.5% (approximately 600 km<sup>2</sup>), especially in areas with elevation between 3500 m and 3900 m. The maximum frozen depth of seasonally frozen ground decreased at a rate of approximately 5.2 cm/10yr, and the active layer ~~thickness~~depth over the permafrost increased by about 3.5 cm/10yr. Runoff increased significantly during cold seasons (November-March) due to the increase in liquid soil moisture caused by rising soil temperature. Areas where permafrost changed into seasonally frozen ground at high elevation showed especially large ~~changes~~increase in runoff. Annual runoff increased due to increased precipitation, the base flow increased due to permafrost degradation, and the actual evapotranspiration increased significantly due to increased precipitation and soil warming. The groundwater storage showed an increasing trend, which indicated that the groundwater recharge was enhanced mainly due to the degradation of permafrost in the study area.

**KEYWORDS:** permafrost; seasonally frozen ground; soil moisture; soil temperature;

41 runoff

## 1. Introduction

Global warming has led to significant changes in frozen soils, including both permafrost and seasonally frozen ground at high latitudes and high altitudes (Hinzman et al., 2013; Cheng and Wu, 2007). Changes in frozen soils can greatly affect the land-atmosphere interaction and the energy and water balances of the land surface (Subin et al., 2013; Schuur et al., 2015), altering soil moisture, water flow pathways and stream flow regimes (Walvoord and Kurylyk, 2016). Understanding the changes in frozen soils and their impact on regional hydrology is important for water resources management and ecosystem protection in cold regions.

Previous studies based on either ~~the~~ experimental observations or long-term meteorological or hydrological observations have examined changes in frozen soils and their impacts on hydrology. Several studies reported that permafrost thawing might enhance base flow in the Arctic and the Subarctic (Walvoord and Striegl, 2007; Jacques and Sauchyn, 2009; Ye et al., 2009) and in northeast China (Liu et al., 2003; Duan et al., 2017). A few studies reported that permafrost thawing might reduce ~~the~~ river runoff (This paper defines the rIn this paper, runoff as all means total amount of liquid water flowing out of leaving the study area. region), especially in the Qinghai-Tibetan Plateau (e.g. Qiu, 2012; Jin et al., 2009). Intensive fField ~~experiments~~ observations were usually carried out at small spatial scales over short periods, which lacked the regional pattern and long-term trends of the frozen soils, ~~-, and~~ And the long-term meteorological and hydrological observations did not provide detailed data on soil freezing and thawing processes (McClelland et al., 2004; Liu et al., 2003; Niu et al., 2011). Therefore, ~~the~~

previous observation-based studies have not provided a sufficient understanding of the long-term changes in frozen soils and their impact on regional hydrology (Woo et al., 2008).

Hydrological models have been coupled with soil freezing-thawing schemes to simulate impacts of the changes in frozen soils on catchment hydrology. Several hydrological models (Rawlins et al., 2003; Chen et al., 2008) used simple freezing-thawing schemes, which could not simulate the vertical soil temperature profiles. The SiB2 model (Sellers et al., 1996), the modified VIC model (Cherkauer and Lettenmaier, 1999) and the CLM model (Oleson et al., 2010) simulate ~~the~~ vertical soil freezing-thawing processes, but they represent ~~the hydrological processes especially~~ the flow routing at the catchment scale ~~by, in simplified overly simple~~ ways. Subin et al. (2013) and Lawrence et al. (2015) used the CLM model to simulate the global change of permafrost. Cuo et al. (2015) used the VIC to simulate frozen soil degradation and its hydrological impacts at the plot scale in the headwater of the Yellow River. The GEOTop model (Endrizzi et al., 2014) simulates three-dimensional water flux and vertical heat transfer in soil, but it is difficult to apply to regional scales. Wang et al. (2010) and Zhang et al. (2013) incorporated frozen soil schemes in a distributed hydrological model and showed improved performance in a small mountainous catchment. More regional studies are necessary for better understanding of the frozen soil changes and their impacts on the regional hydrology and water resources.

The Qinghai-Tibetan Plateau is known as Asia's water tower, and runoff changes on the plateau have significant impacts on water security in ~~the~~ downstream regions

(Walter et al., 2010), which have received an increasing amount of attention in recent years (Cuo et al., 2014). ~~Hydrological processes on the~~ The Qinghai-Tibetan Plateau, ~~which~~ is characterized by high elevation and cold climate. Cryospheric processes have great impacts on its hydrological processes ~~are greatly influenced by cryospheric processes~~ (Cheng and Jin, 2013; Cuo et al., 2014). In contrast with the Arctic and Subarctic, the permafrost ~~thickness~~ on the Qinghai-Tibetan Plateau is relatively thin and warm, and the frozen depth of the seasonally frozen soils is also relatively shallow. As a result, the frozen soils on the Qinghai-Tibetan Plateau are more sensitive to air ~~the~~ temperature rising (Yang et al., 2010), and the changes of frozen soils may have more significant impacts on regional hydrology.

An evident increase in the annual and seasonal air temperature has been observed in the Qinghai-Tibetan Plateau (Li et al., 2005; Liu and Chen, 2000; Zhao et al., 2004). Several studies have shown the changes of frozen soils based on long-term observations. For example, Cheng and Wu (2007) analyzed the borehole observations of soil temperature profiles on the Qinghai-Tibetan Plateau and found that the active layer thickness of frozen soils increased by 0.15-0.50 m during the period of 1996-2001. Zhao et al. (2004) found a decreasing trend of freezing depth in the seasonally frozen soils using observations at 50 stations. Several studies have analyzed the relationship between the change of frozen soils and river discharge using the observed data (Zhang et al., 2003; Jin et al., 2009; Niu et al., 2011). However, the spatio-temporal characteristics of the long-term change in frozen soils are not sufficiently clear. Based on comprehensive field experiments (Cheng et al., 2014), ~~Having comprehensive~~



~~experiments carried out by a major research plan, titled “Integrated research on the~~  
~~ecohydrological processes of the Heihe basin” funded by the National Natural Science~~  
~~Foundation of China (NSFC) (Cheng et al., 2014),~~ a hydrological model coupling  
cryospheric processes and hydrological processes has been developed (Gao et al., 2016).  
This provides a solid basis upon which to analyze the spatio-temporal changes in frozen  
soils and their impacts on the regional hydrology in the upper Heihe basin located on  
the northeastern Qinghai-Tibetan Plateau.

On the basis of the previous studies, this study aims to: (1) explore the spatial and  
temporal changes of frozen soils using a distributed hydrological model with  
comprehensive validation and (2) analyze the hydrological responses to the change of  
frozen soils during the past 40 years in the upper Heihe basin.

## **2. Study Area and Data**

### ~~**2.1 The Heihe River and the upper Heihe basin**~~

The Heihe River is one of the major inland basins in northwestern China. As shown in  
Figure 1, the upper reaches of the Heihe River are located on the northeastern Qinghai-  
Tibetan Plateau at an elevation of 2200 to 5000 m with a drainage area of 10,009 km<sup>2</sup>.  
The upper reaches provide the majority of the water supplied to the middle and lower  
reaches (Cheng et al., 2014). The annual precipitation in the upper Heihe basin ranges  
from 200 to 700 mm, and the mean annual ~~mean~~-air temperature ranges from -9 to 5 °C.  
Permafrost dominates the high elevation region above 3700 m (Wang et al., 2013), and  
seasonal frozen ground covers other parts of the study area. Glaciers are found at an  
elevation above 4000 m, covering approximately 0.8% of the upper Heihe basin. There

are two tributaries (East and West Tributaries) in the upper Heihe basin, on which two hydrological stations are located, namely, Qilian (on the east tributary) and Zhamashike (on the west tributary). The outlet of the upper Heihe basin has a hydrological station, namely, Yingluoxia (see Figure 1).

## **~~2.2 Data used in the study~~**

### **~~(1) Forcing data of the hydrological model~~**

The spatial data used in this study includes the atmospheric forcing data, the land surface data and the actual evapotranspiration data based on remote sensing. The atmospheric forcing data ~~used to drive the hydrological model~~ include a 1-km gridded dataset of daily precipitation, air temperature, sunshine hours, wind speed and relative humidity. The gridded daily precipitation was interpolated from observations at meteorological stations (see Figure 1) ~~provided by the China Meteorological Administration (CMA)~~ using the method developed by Wang et al. (2017). provided by the China Meteorological Administration (CMA). The other atmospheric forcing data were interpolated by observations at meteorological stations using the inverse distance weighted method. The interpolation of air temperature considers the temperature gradient with elevation which was provided by the HiWATER experiment (Li et al., 2013).

The land surface\_data used to ~~build-run~~ the model include land use, topography, leaf area index, and soil parameters. The topography data were obtained from the SRTM dataset (Jarvis et al., 2008) with a spatial resolution of 90 m. The land use/cover data were provided by the Institute of Botany, Chinese Academy of Sciences (Zhou and

Zheng, 2014). The leaf area index (LAI) data with 1-km resolution were developed by Fan (2014). The soil parameters were developed by Song et al. (2016); they include the saturated hydraulic conductivity, residual soil moisture content, saturated soil moisture content, soil sand matter content, soil clay matter content and soil organic matter content. Monthly actual evapotranspiration data with 1-km resolution during the period of 2002-2012 estimated based on remote sensing data (Wu et al., 2012; Wu, 2013) were used to evaluate the model simulated evapotranspiration.

## **~~(2) Data used for model calibration and validation~~**

~~This study uses the observed daily river discharge data from the Yingluoxia, Qilian and Zhamashike stations, the daily soil temperature of different depths from the Qilian station and the daily frozen depths from the Qilian and Yeniugou stations for model calibration and validation. Field observation data used in this study includes river discharge, soil temperature, frozen depth, soil moisture and borehole observation.~~ Daily

river discharge data were obtained from the Hydrology and Water Resources Bureau of Gansu Province. Daily soil temperature data collected at the Qilian station from January 1, 2004 to December 31, 2013, and daily frozen depth data collected at the Qilian and Yeniugou stations from January 1, 2002 to December 31, 2013 were provided by CMA.

~~To investigate the spatial distribution of permafrost, boreholes were drilled during the NSFC major research plan.~~ Temperature observations from six boreholes, whose location are shown in Figure 1, were provided by Wang et al. (2013). The borehole depths are 100 m for T1, 69 m for T2, 50 m for T3, 90 m for T4, and 20 m for T5 and T7. Monthly actual evapotranspiration data with 1-km resolution during the period of

~~2002–2012 estimated based on remote sensing data (Wu et al., 2012; Wu, 2013) were used to evaluate the model simulated evapotranspiration. We also used field observations of the hourly liquid soil moisture to validate the model simulation of soil moisture profiles.~~ The HiWATER experiment (Li et al., 2013; Liu et al., 2011) provided the soil moisture data from January 1 to December 31, 2014 at the A'rou Sunny Slope station (100.52 E, 38.09 N).

### 3. Methodology

#### 3.1 Brief introduction of the hydrological model

This study used a distributed eco-hydrological model GBEHM (geomorphology-based ecohydrological model), which was developed ~~in an integrated research project under the major research plan “Integrated research on the ecohydrological process of the Heihe River Basin” (by Yang et al., (2015) and Gao et al., (2016))~~ based on the geomorphology-based hydrological model (Yang et al., 1998 and 2002; Cong et al., 2009). GBEHM is a spatial distributed model for catchment large-scale river basin. It employs the geomorphologic area function and width function properties to reduce the lateral two-dimensions into one-dimension for flow routing within a sub-catchment, which greatly improves the computation efficiency while retaining the spatial heterogeneity in water flow paths at basin scale description. As shown in Figure 2, the GBEHM used a 1-km grid system to discretize the study catchment, and the study catchment was divided into 251 sub-catchments. A sub-catchment was further divided into flow-intervals along its main stream. To capture the sub-grid topography, each 1-km grid was represented by a number of hillslopes with an average length and gradient,

but different aspect, which were estimated from the 90-m DEM. The terrain properties of a hillslope include the slope length and gradient, slope aspect, soil type and vegetation type (Yang et al., 2015).

The hillslope is the basic unit for the hydrological simulation, upon which the water and heat transfers (both conduction and convection) in the vegetation canopy, snow/glacier, and soil layers are simulated. The canopy interception, radiation transfer in the canopy and the energy balance of the land surface are described using the methods ~~used in~~ SIB2 (Sellers et al., 1985, 1996). The surface runoff on the hillslope is solved using the kinematic wave equation. The groundwater aquifer is considered as individual storage units corresponding to each grid. Exchange between the groundwater and the river water is calculated using Darcy's law (Yang et al., 1998, 2002).

The model runs with a time step of 1 hour. Runoff generated from the grid is the lateral inflow into the river at the same flow interval in the corresponding sub-catchment. Flow routing in the river network is calculated using the kinematic wave equation following the sequence determined by the Horton-Strahler scheme (Strahler, 1957). The model is driven by the atmosphere forcing data and land surface data which are introduced in section 2.

### **3.2 Simulation of cryospheric processes**

The simulation of cryospheric processes in GBEHM includes glacier ablation, snow melt, and soil freezing and thawing.

#### **(1) Glacier ablation**

Glacier ablation is simulated using an energy balance model (Oerlemans, 2001) as:

$$Q_M = SW(1-\alpha) + LW_{in} - LW_{out} - Q_H - Q_L - Q_G + Q_R \quad (1)$$

where  $Q_M$  is the net energy absorbed by the surface of the glacier ( $\text{W/m}^2$ );  $SW$  is the incoming shortwave radiation ( $\text{W/m}^2$ );  $\alpha$  is the surface albedo;  $LW_{in}$  is the incoming longwave radiation ( $\text{W/m}^2$ );  $LW_{out}$  is the outgoing longwave radiation ( $\text{W/m}^2$ );  $Q_H$  is the sensible heat flux ( $\text{W/m}^2$ );  $Q_L$  is the latent heat flux ( $\text{W/m}^2$ );  $Q_R$  is the energy from rainfall ( $\text{W/m}^2$ ); and  $Q_G$  is the penetrating shortwave radiation ( $\text{W/m}^2$ ). The surface albedo is calculated as (Oerlemans and Knap, 1998):

$$\alpha = \alpha_{snow} + (\alpha_{ice} - \alpha_{snow})e^{-h/d^*} \quad (2)$$

where  $\alpha_{snow}$  is the albedo of snow on the glacier surface;  $\alpha_{ice}$  is the albedo of the ice surface;  $h$  is the snow depth on the glacier surface (m);  $d^*$  is a parameter of the snow depth effect on the albedo (m).

The amount of melt water is calculated as (Oerlemans, 2001):

$$M = \frac{Q_M}{L_f} dt \quad (3)$$

where  $dt$  is the time step used in the model (s) and  $L_f$  is the latent heat of fusion ( $\text{J/kg}$ ).

## (2) Snow melt

A multi-layer snow cover model is used to describe the mass and energy balance of snow cover. The parametrization of snow is based on Jordan (1991), and each snow layer is described by two constituents, namely, ice and liquid water. For each snow layer, temperature is solved using an energy balance approach (Bartelt and Lehner, 2002):

$$C_s \frac{\partial T_s}{\partial t} - L_f \frac{\partial \rho_i \theta_i}{\partial t} = \frac{\partial}{\partial z} (K_s \frac{\partial T}{\partial z}) + \frac{\partial I_R}{\partial z} + Q_R \quad (4)$$

where  $C_s$  is the heat capacity of snow ( $\text{J} \cdot \text{m}^{-3} \cdot \text{K}^{-1}$ );  $T_s$  is the temperature of the snow layer (K);  $\rho_i$  is the density of the ice ( $\text{kg/m}^3$ );  $\theta_i$  is the volumetric ice content;

240  $K_s$  is the thermal conductivity of snow ( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ );  $L_f$  is the latent heat of ice fusion  
 241 ( $\text{J/kg}$ );  $I_R$  is the radiation transferred into the snow layer ( $\text{W/m}^2$ ) and  $Q_R$  is the energy  
 242 brought by rainfall ( $\text{W/m}^2$ ) which is only considered for the top snow layer. The solar  
 243 radiation transfer in the snow layers and the snow albedo are simulated using the  
 244 SNICAR model which is solved using the method developed by Toon et al. (1989). Eq.  
 245 (4) is solved using an implicit centered finite difference method, and a Crank-Nicholson  
 246 scheme is employed.

247 The mass balance of the snow layer is described as (Bartelt and Lehman, 2002):

$$248 \quad \frac{\partial \rho_i \theta_i}{\partial t} + M_{iv} + M_{il} = 0 \quad (5)$$

$$249 \quad \frac{\partial \rho_l \theta_l}{\partial t} + \frac{\partial U_l}{\partial z} + M_{lv} - M_{il} = 0 \quad (6)$$

250 where  $\rho_l$  is the density of the liquid water ( $\text{kg/m}^3$ );  $\theta_l$  is the volumetric liquid water  
 251 content;  $U_l$  is the liquid water flux ( $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ );  $M_{iv}$  is the mass of ice that is changed  
 252 into vapour within a time step ( $\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$ );  $M_{il}$  is the mass of ice that is changed into  
 253 liquid water within a time step ( $\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$ ); and  $M_{lv}$  is the mass of liquid water that is  
 254 changed into vapour within a time step ( $\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$ ). The liquid water flux of the snow  
 255 layer is calculated as (Jordan, 1991):

$$256 \quad U_l = -\frac{k}{\mu_l} \rho_l^2 g \quad (7)$$

257 where  $k$  is the hydraulic permeability ( $\text{m}^2$ ),  $\mu_l$  is dynamic viscosity of water at  $0^\circ\text{C}$   
 258 ( $1.787 \times 10^{-3} \text{ N s/m}^2$ ),  $\rho_l$  is the density of liquid water ( $\text{kg/m}^3$ ) and  $g$  is gravitational  
 259 acceleration ( $\text{m/s}^2$ ). The water flux of the bottom snow layer is considered snowmelt  
 260 runoff.

261 (3) Soil freezing and thawing



The energy balance of the soil layer is solved as (Flerchinger and Saxton, 1989):

$$C_s \frac{\partial T}{\partial t} - \rho_i L_f \frac{\partial \theta_i}{\partial t} - \frac{\partial}{\partial z} (\lambda_s \frac{\partial T}{\partial z}) + \rho_l c_l \frac{\partial q_l T}{\partial z} = 0 \quad (8)$$

where  $C_s$  is the volumetric soil heat capacity ( $\text{J} \cdot \text{m}^{-3} \cdot \text{K}^{-1}$ );  $T$  is the temperature (K) of the soil layers;  $z$  is the vertical depth of the soil (m);  $\theta_i$  is the volumetric ice content;  $\rho_i$  is the density the ice ( $\text{kg}/\text{m}^3$ );  $\lambda_s$  is the thermal conductivity ( $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ );  $\rho_l$  is the density of liquid water ( $\text{kg}/\text{m}^3$ ); and  $c_l$  is the specific heat of liquid water ( $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ ). In addition,  $q_l$  is the water flux between different soil layers (m/s) and is solved using the 1-D vertical Richards equation. The unsaturated soil hydraulic conductivity is calculated using the modified van Genuchten's equation (Wang et al., 2010) as:

$$K = f_{ice} K_{sat} \left( \frac{\theta_l - \theta_r}{\theta_s - \theta_r} \right)^{1/2} \left[ 1 - \left( 1 - \left( \frac{\theta_l - \theta_r}{\theta_s - \theta_r} \right)^{-1/m} \right)^m \right]^2 \quad (9)$$

where  $K$  is the unsaturated soil hydraulic conductivity (m/s);  $K_{sat}$  is the saturated soil hydraulic conductivity (m/s);  $\theta_l$  is the volumetric liquid water content;  $\theta_s$  is the saturated water content;  $\theta_r$  is the residual water content;  $m$  is an empirical parameter in van Genuchten's equation and  $f_{ice}$  is an empirical hydraulic conductivity reduction factor which is calculated using soil temperature as (Wang et al., 2010):

$$f_{ice} = \exp[-10(T_f - T_{soil})], \quad 0.05 \leq f_{ice} \leq 1 \quad (10)$$

where  $T_f$  is 273.15 K and  $T_{soil}$  is the soil temperature.

Eq. (8) solves the soil temperature with the upper boundary condition as the heat flux into the top surface soil layer. When the ground is not covered by snow, the heat flux from the atmosphere into the top soil layer is expressed as (Oleson et al., 2010):

$$h = S_g + L_g - H_g - \lambda E_g + Q_R \quad (11)$$

where  $h$  is the upper boundary heat flux into the soil layer ( $\text{W m}^{-2}$ );  $S_g$  is the solar radiation absorbed by the top soil layer ( $\text{W m}^{-2}$ );  $L_g$  is the net long wave radiation absorbed by the ground ( $\text{W m}^{-2}$ ),  $H_g$  is the sensible heat flux from the ground ( $\text{W m}^{-2}$ );  $\lambda E_g$  is the latent heat flux from the ground ( $\text{W m}^{-2}$ ); and  $Q_R$  is the energy brought by rainfall ( $\text{W/m}^2$ ). When the ground is covered by snow, the heat flux into the top soil layer is calculated as:

$$h = I_p + G \quad (12)$$

where  $I_p$  is the radiation that penetrates the snow cover, and  $G$  is the heat conduction from the bottom snow layer to the top soil layer. Eq (8) is solved using a finite difference scheme with an hourly time step which is similar with the solutions of Eq (4).

To simulate the permafrost we consider an underground depth of 50 m. ~~We~~ and assume the bottom boundary condition as zero heat flux exchange due to the data limitation. This assumption may not be true because the observed soil temperature increased with depth in the deep layer. The vertical soil column is divided into 39 layers in the model (see Figure 2). As shown in Figure 2, thinner layers are used at the depth from 1.7 to 3 m for to better capturing the maximum frozen depth according to the field observations. The topsoil of 1.7 m is subdivided into 9 layers. The first layer is 5 cm, and the soil layer thickness increases with depth linearly from 5 cm to 30 cm up to the depths of 0.8 m and later decreases linearly with depth to 10 cm up to the depths of 1.7 m. ~~There~~ are 12 soil layers from 1.7 m to 3.0 m with a constant thickness of 10 cm. From the depth of 3 m to 50 m, there are 18 layers with thickness increasing exponentially from 10 cm to 12 m. The liquid soil moisture, ice content, and soil

temperature of each layer is calculated at each time step. The soil heat capacity and soil thermal conductivity are estimated using the method developed by Farouki (1981).

### 3.3 Model calibration

~~We~~ To initialize the model, we first estimated the soil temperature profiles based on the assumption ~~assume~~ that there is a linear relationship between soil temperature and elevation at the same depth below surface. The relationship between soil temperature at a specific depth and elevation is estimated from the observed soil temperature at 6 boreholes (see Figure 1). ~~For spin-up run, the initial soil temperatures at different depths for all grids of the whole study area were interpolated from the borehole observations using this relationship.~~ Next, the model had a 500 year spin up run to specify the initial values of the hydrological variables (e.g., soil moisture, soil temperature, soil ice content, and groundwater table) by repeating the atmospheric forcing data from 1961 to 1970.

The period of 2002 to 2006 was used for model calibration and the period of 2008 to 2012 was for model validation. The daily soil temperature at the Qilian station and the frozen depths at the Qilian and Yeniugou stations were used to calibrate the soil reflectance according to vegetation type. The other parameters such as groundwater hydraulic conductivity were calibrated according to the observed baseflow discharge in the winter season at the Qilian, Zhamashike and Yingluoxia stations. We calibrated the surface retention capacity and surface roughness to match the observed flood peaks, and calibrated the leaf reflectance, leaf transmittance and maximum Rubisco capacity of the top leaf based on the remote sensing evapotranspiration data. Table 1 shows the

major parameters used in the model.

### **3.4 Simulation Model case without the frozen soil scheme and scenario**

A One simulation case scenario without the frozen soil scheme is designed to investigate the impact of frozen soil on the hydrological processes. In this scenario case, the phase transition of soil water between the solid and the liquid is not considered a model without the frozen soil scheme is set up. The modified model is identical to the current version of GBEHM except that except that phase changes of water between liquid and solid states are not considered in soil, although soil temperatures is are still simulated. Other processes are simulated as the same as the normal run.

## **4. Results**

### **4.1 Validation of the hydrological model**

We carried out a comprehensive validation of the GBEHM model using the soil temperature profiles observed at six boreholes, long-term observations of the soil temperature and frozen depths at ~~two CMA~~ the Qilian and Zhamashike stations, soil moisture observations at the A'rou Sunny Slope ~~one HiWATER~~ station, long-term observations of streamflow at three hydrological stations shown in Figure 1 and monthly actual evapotranspiration estimated from remote sensing data.

Figure 3 shows the comparison of the model-simulated and observed soil temperature profiles at six boreholes. The model ~~was~~ generally accurate in capturing the vertical distribution of the soil temperature at T1, T2, T3 and T4 in the permafrost area, but overestimations were produced above 20 m depth for T1 and T3. Good agreement between the simulated and observed soil temperature profiles below the

depth of 20 m is probably due to fitting of initial values. This implies that the temperature in the deep soil is stable, which is confirmed by the comparison of temperature profiles in different years as shown in Figure S1 in the supplemental file. Figure S1 also illustrates that temperature above 20 m shows significant increasing trends in the past 40 years. The errors in simulating the vertical temperature profile near the surface might be caused by simplification of the 3-D topography. At T5 located in seasonally frozen ground, the simulated soil temperature profile did not agree well with that observed at depth of 4-20 m. This error might also be related to the heterogeneity of soil properties, especially the thermal conductivity and heat capacity since no such information is available. The model simulation agrees well with the borehole observation at T7, which is located at the transition zone from permafrost to seasonally frozen ground. This indicates that the model can identify the boundary of the permafrost and the seasonally frozen ground.

We also validated model simulation of the freezing/thawing cycles based on long-term observations of soil temperature and frozen depth. Figure 4 compares the simulated soil temperature with the observed temperature at the Qilian station, which is located in the seasonally frozen ground (observed daily soil temperature data are available from 2004 on). Generally, the model simulations accurately captured the seasonal changes in soil temperature profile. Validation of the soil temperature at different depths (5 cm, 10 cm, 20 cm, 40 cm, 80 cm, 160 cm, and 320 cm) showed that the root mean square error (RMSE) decreases with increasing depth. The RMSE were approximately 2.5°C for the top three depths (5 cm, 10 cm and 20 cm). The RMSE

for depths of 40 cm and 80 cm were 1.7°C and 1.5°C, respectively, and the RMSE was 0.9°C at a depth of 3.2 m. This result is similar with the findings by Ou et al. (2016) using the Northern Ecosystem Soil Temperature (NEST) model. We compared the model-simulated daily frozen depth with in situ observations at the Qilian and Yeniugou Stations from 2002 to 2014, as shown in Figure 5. The model reproduced well the daily variations in frozen depth although the depth was underestimated by approximately 50 cm at the Yeniugou station. In general, the validation of soil temperature and frozen depth indicates that the model captured well the freezing and thawing processes in the upper Heihe basin.

The observed hourly liquid soil moisture at the A'rou Sunny Slope station was used for an additional independent validation. Figure 6 shows the comparison between the simulated and observed liquid soil moisture at different depths from January 1 to December 31 in 2014. By comparing with the observed liquid soil moisture, we can see that the model simulation is reasonable.

Figure 7 compares the model simulated and the observed daily streamflow discharge at the Yingluoxia, Qilian and Zhamashike stations. The model simulation agreed well with the observations. The model simulation captured the flood peaks and the magnitude of base flow in both of the calibration and validation periods. In the calibration period, the Nash-Sutcliffe efficiency (NSE) coefficients were 0.64, 0.65 and 0.70 for the Yingluoxia, Qilian and Zhamashike stations, respectively; in the validation period, the NSE values were 0.65, 0.60, and 0.75, respectively. The relative error (RE) was within 10% for both the calibration and validation periods (see Figure 7). Figure 8

shows the comparison of the model-simulated monthly actual evaporation and remote sensing-based evaporation data for the entire calibration and validation periods. The GBEHM simulation showed similar temporal variations in actual evapotranspiration compared with the remote sensing based estimation, and the RMSE of the simulated monthly evapotranspiration was 8.0 mm in the calibration period and 6.3 mm in the validation period.

The model simulated river discharges with and without the frozen soil scheme were compared. Table S1 in the supplement material shows that model with the frozen soil scheme achieves better simulation of the daily hydrograph than the model without the frozen soil scheme. Figure S2 in the supplement material shows that the model without the frozen soil scheme overestimated the river discharge in the freezing season and underestimated flood peaks in the warming season.

## **4.2 Long-term changes in frozen soils**

In the upper Heihe basin, the ground surface starts freezing in November and thawing initiates in April (Wang et al., 2015a). From November to March, the ground surface temperature is below 0°C in both the permafrost and seasonally frozen ground regions, and precipitation mainly falls in the period from April to October. Therefore, a year is subdivided into two seasons, i.e., the freezing season (November to March) and the thawing season (April to October) to investigate the changes in frozen soils and their hydrological impact. Increasing precipitation and air temperature in the study area in both seasons in the past 50 years was reported in a previous study (Wang et al., 2015b).

Table S2 in the supplement material 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 these two periods.

Figure 9 shows the changes in the basin-averaged soil temperature in the freezing and thawing seasons. The soil temperature increased in all seasons, especially in the past 30 years. The increasing trend of soil temperature was larger in the freezing season than in the thawing season. In the freezing season (Figure 9(a)), the top layer soil temperature was lower than the deep layer soil temperature. The linear trend of the top layer (0-0.5 m) soil temperature was  $0.48^{\circ}\text{C}/10\text{yr}$  and the trend of the deep layer (2.5-3 m) soil temperature was  $0.34^{\circ}\text{C}/10\text{yr}$ . The soil temperature in the deep layer (2.5-3 m) changed from  $-1.1^{\circ}\text{C}$  in the 1970s to approximately  $0^{\circ}\text{C}$  in the most recent decade. In the thawing season (see Figure 9(b)), the increasing trend of the top layer (0-0.5 m) soil temperature ( $0.29^{\circ}\text{C}/10\text{yr}$ ) was greater than the trend of the deep layer (2.5-3 m) soil temperature ( $0.21^{\circ}\text{C}/10\text{yr}$ ). The warming trend is larger in shallow soils and this is because the surface heat flux is impeded by the thermal inertia as it penetrates to greater depths.

Permafrost is defined as ground with a temperature at or below  $0^{\circ}\text{C}$  for at least two consecutive years (Woo, 2012). This study differentiated permafrost from seasonally frozen ground based on the simulated vertical soil temperature profile in each grid. For each year in each grid, the frozen ground condition was determined by searching the soil temperature profile within a four-year window from the previous three years to the current year. Figure 10 shows the change in permafrost area during 1971-2013. As

shown in Figure 10(a), the permafrost areas decreased by approximately 9.5% (from 6445 km<sup>2</sup> in the 1970s to 5831 km<sup>2</sup> in the 2000s), indicating evident degradation of the permafrost in the upper Heihe basin in the past 40 years.

Figure 10 (b) shows the changes in the basin-averaged maximum frozen depth for the seasonally frozen ground areas and active layer thickness over the permafrost areas. The basin-averaged annual maximum frozen depth showed a significant decreasing trend (5.2 cm/10yr). In addition, the maximum frozen depth had a significantly negative correlation with the annual mean air temperature ( $r = -0.73$ ). In contrast, an increasing trend of active layer thickness in the permafrost regions was observed (3.5 cm/10yr), which had a significantly positive correlation with the annual mean air temperature.

Figure 11 shows the frozen soil distributions in the period of 1971 to 1980 and in the period of 2001 to 2010. Comparing the frozen soil distributions of the two periods, major changes in frozen soils were observed on the sunny slopes at elevations between 3500 and 3700 m, especially in the west tributary, where large areas of permafrost changed into seasonally frozen ground.

Figure 12 shows the monthly mean soil temperature over the areas with elevation between 3300 and 3500 m and over areas with elevation between 3500 and 3700 m in the upper Heihe basin. In the areas with elevation between 3300 and 3500 m located in the seasonally frozen ground region, as shown in Figure 12(a), the frozen depth decreased and the soil temperature in the deep layer (with depth greater than 2 m) increased. Figure 12(b) shows that the increase in soil temperature was larger in the area with higher elevation (3500-3700 m). This figure shows that the thickness of the

permafrost layer decreased as soil temperature increased, and the permafrost changed into seasonally frozen ground after 2000.

### 4.3 Changes in the water balance and runoff

Table 2 shows the decadal changes in the annual water balance from 1971 to 2010 based on the model simulation. The annual precipitation, annual runoff and annual runoff ratio had the same decadal variation; however the annual evapotranspiration maintained an increasing trend since the 1970s which was consistent with the rising air temperature and soil warming. Although the actual evapotranspiration increased, the runoff ratio remained stable during the 4 decades because of the increased precipitation.

The changes in runoff (both simulated and observed) in different seasons are shown in Figure 13 and Table 2. The model-simulated and observed runoff both showed a significant increasing trend in the freezing season and in the thawing season. This indicates that the model simulation ~~well accurately~~ reproduced the observed long-term changes. In the freezing season, since there was no glacier melt and snow melt (see Table 2), runoff was mainly the subsurface flow (groundwater flow and lateral flow from the unsaturated zone). In the thawing season, as shown in Table 2, snowmelt runoff contributed approximately 16% of the total runoff and glacier runoff contributed only a small fraction of total runoff (approximately 2.4%). Therefore, rainfall runoff was the major component of total runoff in the thawing season, and the runoff increase in the thawing season was mainly due to increased rainfall. As shown in Figure 13, the actual evapotranspiration increased significantly in both seasons due to increased precipitation and soil warming. The increasing trend of the actual evapotranspiration

was higher in the thawing season than in the freezing season.

Figure 14 shows the changes in the basin-averaged annual water storage in the top 0-3 m layer and the groundwater storage. The annual liquid water storage of the top 0-3 m showed a significant increasing trend especially in the most recent 3 decades. This long-term change in liquid water storage was similar to the runoff change in the freezing season, as shown in Figure 13 (a), with a correlation coefficient of 0.80. The annual ice water storage in the top 0-3 m soil showed significant decreasing trend due to frozen soils changes. Annual groundwater storage showed a significantly increasing trend especially in the most recent 3 decades, which indicates that the groundwater recharge increases with the frozen soil degradation.

## 5. Discussion

### 5.1 Impact of frozen soil changes on the soil moisture and runoff

~~Based on the model simulated daily soil moisture,~~ Long-term changes of the spatially averaged liquid soil moistures in the region with elevation between 3300 and 3500 m ~~(covered by the seasonally frozen ground)~~ and in the region with elevation between 3500 and 3700 m ~~(where the permafrost changed into seasonally frozen ground)~~ are shown in Figure S3 in the supplement material. In the seasonally frozen ground with elevation of 3300-3500 m, by comparing with the soil temperature shown in Figure 12 (a), we can see that the liquid soil moisture increase was mainly caused by the decrease in the frozen depth. The liquid soil moisture in the deep soil layer increased significantly since the 1990s in the area with elevation of 3500-3700 m where the permafrost changed to seasonally frozen ground which is shown. ~~Compared with the soil~~

~~temperature change shown~~ in Figure 12 (b), ~~the liquid soil moisture increases in this region were primarily caused by the change of permafrost to seasonally frozen ground,~~  
~~This indicating indicates~~ that the frozen soil degradation caused a significant increase in liquid soil moisture in both the freezing and thawing seasons.

In the freezing season, since the surface ground is frozen, runoff is mainly subsurface flow coming from the seasonally frozen ground. Runoff has the highest correlation ( $r=0.82$ ) with the liquid soil moisture in the freezing season, which indicates that the frozen soils change was the major cause of the increased liquid soil moisture, resulting in increased runoff in the freezing season. During the past 40 years, parts of the permafrost changed into seasonally frozen ground, and the thickness of the seasonally frozen ground decreased, which led to increased liquid soil moisture in the deep layers during the freezing season. The increase in liquid soil moisture also increased the hydraulic conductivity which enhanced the subsurface flow. Figure 15(c) shows the seasonal pattern of runoff in the permafrost area and seasonally frozen soils. From April to October (the thawing season), runoff in the permafrost area is much larger than in the seasonally frozen soils, but in the freezing season runoff in the permafrost area is lower than in the seasonally frozen soils. Figure S4 in the supplement material shows runoff changes from typical area (with elevation between 3500-3700 m) where covered by the permafrost in the period of 1971 to 1980 and changed into the seasonally frozen ground in the period of 2001 to 2010. This 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.

In the thawing season from April to October, the thickness of the seasonally frozen ground rapidly decreased to zero and the thaw depth of permafrost reached the maximum. Runoff in the thawing season was mainly rainfall runoff, as shown in Table 2. The increased runoff mainly came from increased precipitation and snowmelt in the thawing season.

Figure 15 shows the changes in areal mean runoff along the elevation for different seasons. There was a large difference in runoff variation with the elevation between the two during the different seasons. In the freezing season, the runoff change from the 1970s to the 2000s in the areas of seasonally frozen ground (mainly located below 3500 m, see Figure 11) was relatively small. The areas with elevations of 3500 to 3900 m showed larger changes in runoff. This is due to the shift from permafrost to seasonally frozen ground in some areas in the elevation range of 3500 to 3900 m, as simulated by the model, particularly for the sunny hillslopes (see Figure 11). This finding illustrates that a change from the permafrost to the seasonally frozen ground has a larger impact on the runoff than a change in frozen depth in the seasonally frozen ground. In the thawing season, runoff increased with elevation due to the increase in precipitation with increasing elevation, and the runoff increase was mainly determined by increased precipitation (Gao et al., 2016). Precipitation in the region with elevation below 3100 m was low, but air temperature was high. Runoff in this region decreased during 2001-2010 compared to 1971-1980 because of higher evapotranspiration.

## **5.2 Comparison with the previous similar studies**

In this study, the model simulation showed that ~~thaw of changes in~~ frozen soils led to increased ~~—~~ freezing season runoff and base flow in the upper Heihe basin. This result is consistent with previous findings based on the trend analysis of streamflow observations in high latitude regions (Walvoord and Striegl, 2007; Jacques and Sauchyn, 2009; Ye et al., 2009) and in northeast China (Liu et al., 2003). However, those studies did not consider spatial variability. This study found that the impact of the ~~thaw of change in~~ frozen soils on runoff had regional characteristics. In the upper Heihe basin (see Figure 15), ~~a thaw of change in~~ frozen soils led to increased runoff at higher elevations but led to decreased runoff at lower elevations during the freezing season. This implies that change of the freezing season runoff was ~~strongly affected controlled~~ by the permafrost degradation in the higher elevation region but by the evaporation increase in the lower elevation region due to the air temperature rising. However, runoff at the basin scale mainly came from the higher elevation regions.

This study also showed that the ~~thaw of change in~~ frozen soils increased the soil ~~liquid~~ moisture in the upper Heihe basin, which is consistent with the finding of Subin et al. (2013) using the CLM model simulation in northern latitude permafrost regions, and the findings of Cuo et al. (2015) using VIC model simulation at 13 sites on the Tibetan Plateau. However, Lawrence et al. (2015) found that permafrost thawing caused soil moisture drying based on CLM model simulations for the global permafrost region. This might be related to the uncertainties in the soil water parameters and the high spatial heterogeneity of soil properties, which are difficult to consider in a global-scale model. Subin et al. (2013) and Lawrence et al. (2015) modelled the soil moisture

changes in the active layer of permafrost in large areas with coarse spatial resolution. This study revealed the spatio-temporal variability of soil moisture with high spatial resolution and analyzed the correlations with the change in frozen soils.

Wu and Zhang (2010) focused on the changes in the active layer thickness at 10 sites in the permafrost region on the Tibetan Plateau and found a significant increasing trend during the period of 1995-2007, which is consistent with the result of this study. Jin et al. (2009) found decreased soil moisture and runoff due to the permafrost degradation based on observations at the plot scale in the source areas in the Yellow River basin. This result is different from the present study, possibly due to the difference of hydrogeological structure and the soil hydraulic parameters in the source area of the Yellow River from those in the upper Heihe basin. Wang et al. (2015a) focused on the change in the seasonally frozen ground in the Heihe River basin based on plot observations, and the increasing trend of the maximum frozen depth was estimated as 4.0 cm/10yr during 1972-2006, which is consistent with the GBEHM model simulation in this study. The increase in groundwater storage illustrated in this study is also consistent with the finding of Cao et al. (2012) based on the GRACE data which showed that groundwater storage increased during the period of 2003~2008 in the upper Heihe basin.

### 5.3 Uncertainty in simulation of the frozen soils

Estimation of the change in permafrost area is a great challenge due to such complex factors as climatology, vegetation, and geology. ~~Different methods produce large differences in their estimation results. Jorgenson et al. (2006) found a 4.4% decrease in~~



~~the area of permafrost in Arctic Alaska from 1982 to 2001 based on analyses of aerial photo.~~ Guo et al. (2013) reported permafrost area for the whole Qinghai-Tibetan Plateau decreased from about  $175.0 \times 10^4 \text{ km}^2$  in 1981 to  $151.5 \times 10^4 \text{ km}^2$  with a relative change of 13.4%. Wu et al. (2005) reported that the permafrost area decreased by 12% from 1975 to 2002 in the Xidatan basin, Qinghai-Tibetan Plateau based on a ground penetration radar survey. Jin et al. (2006) found an area reduction of 35.6% in island permafrost in Liangdaohe, which is located at the southern Qinghai-Tibet Highway, from 1975 to 1996. ~~Chasmer et al. (2010) found a 30% reduction of the discontinuous permafrost area in the Northwest Territories, Canada from 1947 to 2008 based on remote sensing.~~ Compared with the borehole observations by Wang et al. (2013) shown in Figure 2, this model slightly overestimated the soil temperature in permafrost areas, which might lead to overestimation of the rate of permafrost area reduction.

There were two major uncertainties in the frozen soils simulation which may lead to overestimation: uncertainty in the land surface energy balance simulation and uncertainty in the simulation of the soil heat-water transfer processes (Wu et al., 2016). Uncertainty in the land surface energy balance simulation might result from the estimations of radiation and surface albedo due to the complex topography, vegetation cover and soil moisture distribution, which may introduce uncertainties in the estimated ground temperature and thermal heat flux into the deep layers. The uncertainty in simulation of soil heat-water transfer processes might result from the soil water and heat parameters and the bottom boundary condition of heat flux. For example, soil depth and fraction of rock in soil may greatly affect soil temperature simulation. Permafrost

degradation is closely related to the thermal properties of rocks and soils, geothermal flow and initial soil temperature and soil ice conditions. Figure S5 in the supplement material compares the results of simulation with zero thermal flux at the lower boundary and the results of simulation with thermal flux of 0.2 W/m<sup>2</sup> (Estimated by geothermal gradient at T4 in Figure 3). It can be seen that the geothermal heat flux at the lower boundary causes slight increase in soil temperature below the depth of 30 m and it does not influence the soil temperature simulation in depth above 30 m. The lack of observed initial condition data could also cause uncertainty in the permafrost change estimation. Sub-grid topography effect 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 (Zhang et al., 2013; O'Neill et al., 2015). This is not well considered in this study. For discontinuous permafrost, lateral heat flux may increase the thawing rate (Kurylyk et al., 2016; Sjöberg et al., 2016) and this effect is not considered in the present study. This may lead to underestimation of thawing rates of discontinuous permafrost, especially when high groundwater flow rate events occur in spring. In addition, uncertainties from input data, particularly the solar radiation which is estimated using interpolated sunshine hour data from limited observational stations and precipitation which is also interpolated by observations at these stations, may also influence the results of the model simulation. Due to the complexity of the distributed model and large number of model parameters, it is challenge to quantify overall simulation uncertainty. This work will be done in the future study.

## 6. Conclusions

A distributed hydrological model coupled with cryospheric processes was carefully validated in the upper Heihe River basin using available observations of soil moisture, soil temperature, frozen depth, actual evaporation and streamflow discharge. Based on the model simulations from 1971 to 2013 in the upper Heihe River, the long-term changes in frozen soils were investigated, and the effect of the frozen soils change on hydrological processes were explored. Based on these analyses, the following conclusions can be drawn:

(1) The model simulation suggests that 9.5% of permafrost areas degraded into seasonally frozen grounds in the upper Heihe River basin during the period of 1971 to 2013, which predominantly occurred at the elevations between 3500 m and 3900 m. The decreasing trend of annual maximum frozen depth is estimated to be 5.2 cm/10yr for the seasonally frozen grounds, which is consistent with previous observation-based studies at plot scale. The increasing trend of active layer thickness is estimated to be 3.5 cm/10yr in the permafrost regions.

(2) Model simulated trends in runoff agree with the observed trends. In the freezing season (November-March), based on the model simulation, runoff was mainly sourced by subsurface flow which increased significantly in the higher elevation regions where significant frozen soil changes occurred. This finding implies that runoff increase in the freezing season is primarily caused by frozen soil changes (permafrost degradation and decrease of the seasonally frozen depth). In the thawing season (April-October), model simulation indicates that runoff mainly came from rainfall and showed an increasing

trend at the higher elevations, which can be explained by the increased precipitation. In both the freezing and thawing seasons, model simulated runoff decreased in the lower elevation region, which can be explained by increased evaporation due to the rising air temperature.

(3) Model simulated changes in soil moisture and soil temperature indicates that annual storage of the liquid water increased especially in the most recent three decades, due to the change in frozen soils. Annual ice water storage in the top 0-3 m of soil showed a significant decreasing trend due to soil warming. Model simulated annual groundwater storage had an increasing trend, which is consistent with the changes observed by the GRACE satellite. This indicated that groundwater recharge in the upper Heihe basin was enhanced in recent decades.

(4) Model simulation indicated that regions where the permafrost changed into the seasonally frozen ground had larger changes in runoff and soil moisture than the areas covered by seasonally frozen ground.

For a better understanding of changes in frozen soils and their impact on ecohydrology, the interactions among the soil freezing-thawing processes, vegetation dynamics and hydrological processes need to be investigated in future studies. There are uncertainties in simulations of the frozen soils and the hydrological processes that might be related to the soil properties, the high spatial heterogeneity, and the [assumption of zero geothermal heat flux at the lower boundary](#)~~parameterization of the lower soil boundary conditions~~, all of which warrant further investigation in the future.

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888 **Figure caption:**

889 Figure 1. The Study area, hydrological stations, borehole observation and flux tower stations

890 Figure 2. Model structure and vertical discretization of soil column

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893 Figure 4. Daily soil temperature at the Qilian station: (a) observation; (b) simulation; (c) Simulation-  
894 Observation

895 Figure 5. Comparison of the simulated and observed daily frozen depths during the period of 2002-  
896 2014 at: (a) the Qilian station, (b) the Yeniugou station

897 Figure 6. Comparison of the simulated and the observed hourly liquid soil moisture at the A'rou  
898 Sunny Slope station

899 Figure 7. Figure 7. Comparison of the simulated and the observed daily river discharge at: (a) the  
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Figure 11. Distribution of permafrost and seasonally frozen ground: (a) distribution in the period of 1971-1980; (b) distribution in the period of 2001-2010; (c) Areas where where permafrost changed into seasonally frozen ground (d) percentage of areas of permafrost on sunny slope; (e) percentage of areas of permafrost on shaded slope (the same legend as (d))~~Distribution of permafrost and seasonally frozen ground: (a) distribution in the period of 1971-1980; (b) distribution in the period of 2001-2010; (c) Areas where where permafrost changed into seasonally frozen ground (d) percentage of areas of permafrost and seasonally frozen ground on sunny slope; (e) percentage of areas of permafrost and seasonally frozen ground on shaded slope (the same legend as (d))~~

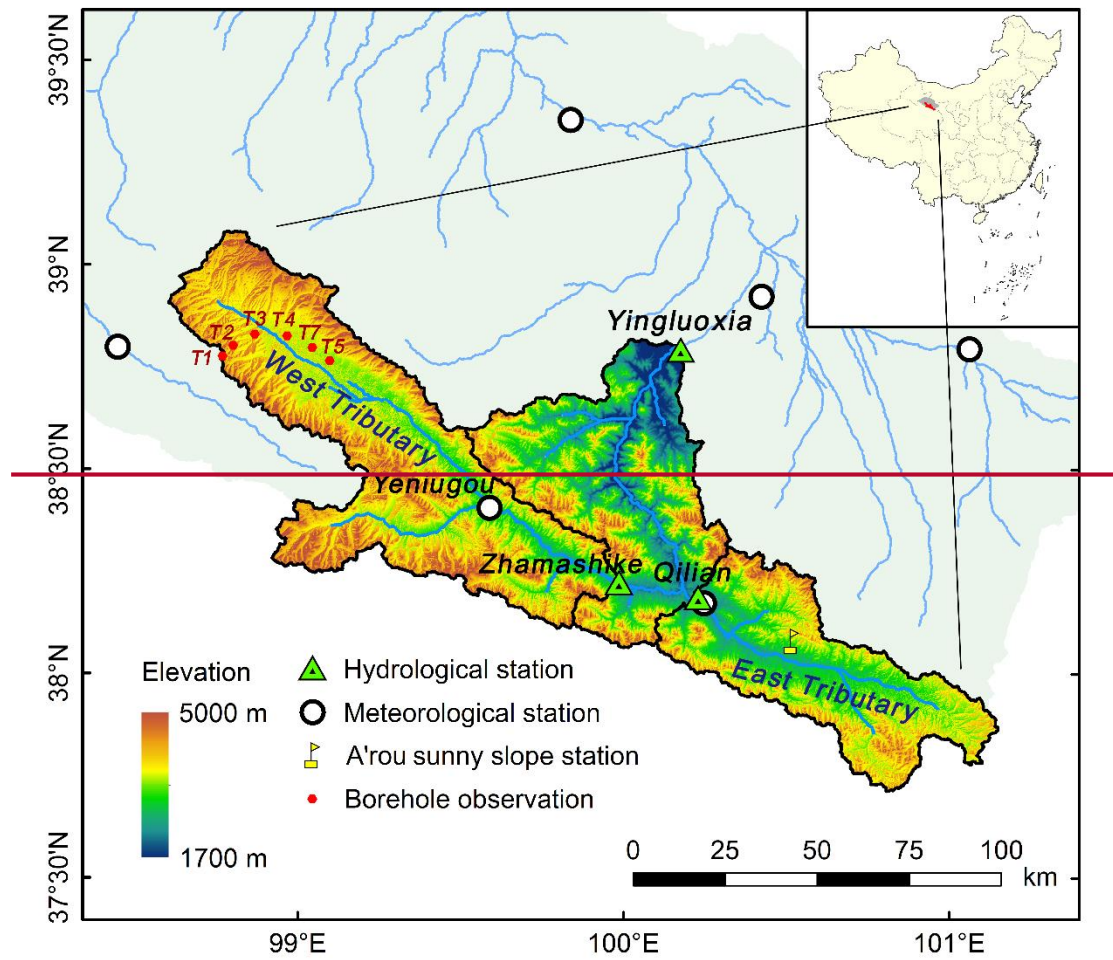
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Figure 13. Changes of the runoff and actual evapotranspiration: (a) in the freezing season; (b) in the thawing season

Figure 14. Changes of the annual water storage (equivalent water depth) during the period of 1971-2013: (a) the liquid soil water storage of the top 0-3 m layer; (b) the ice water storage of the top 0-3 m layer; (c) the groundwater storage

Figure 15. Model simulated runoff change with elevation: (a) in the freezing season, (b) in the thawing season, and (c) seasonal pattern of the runoff in the permafrost areas and in the seasonally frozen ground areas in the period of 2001-2010.~~Model simulated changes of runoff: (a) in the freezing season, (b) in the thawing season~~





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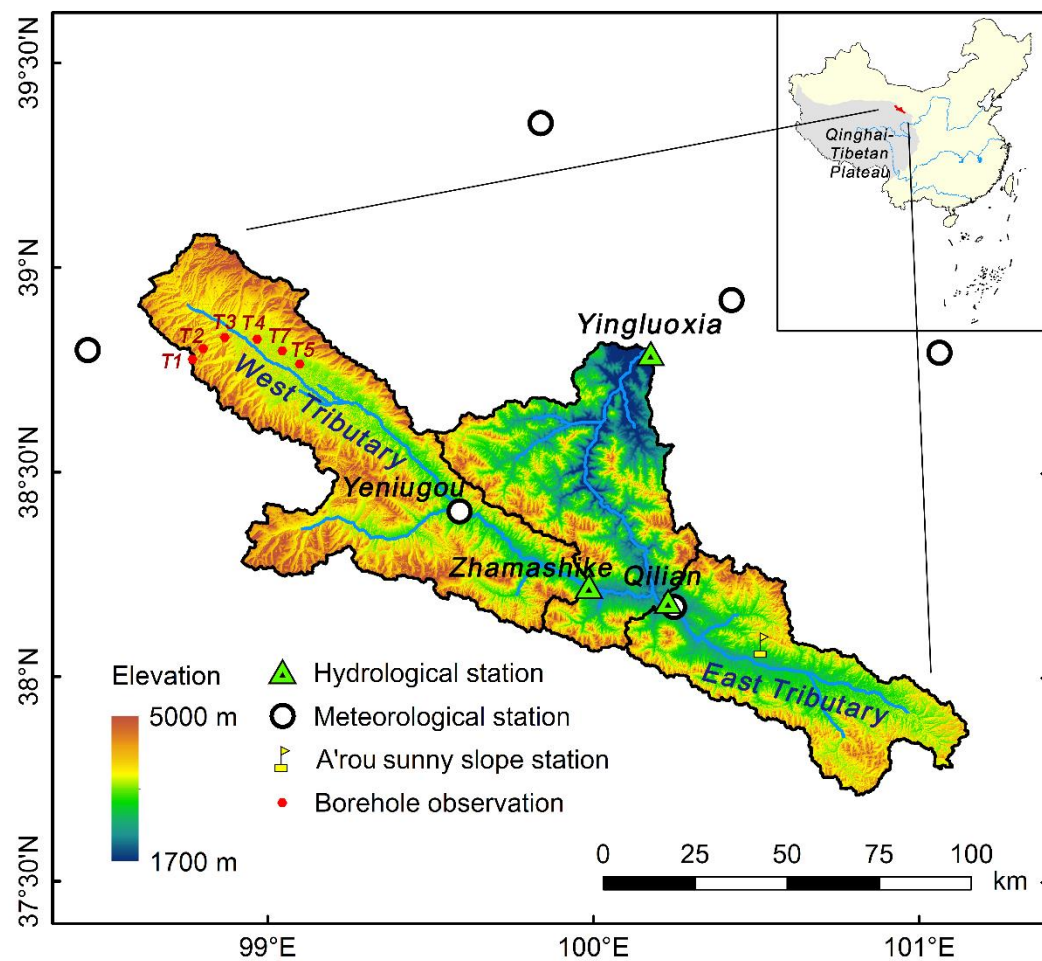


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(a) Model structure

(b) Vertical discretization

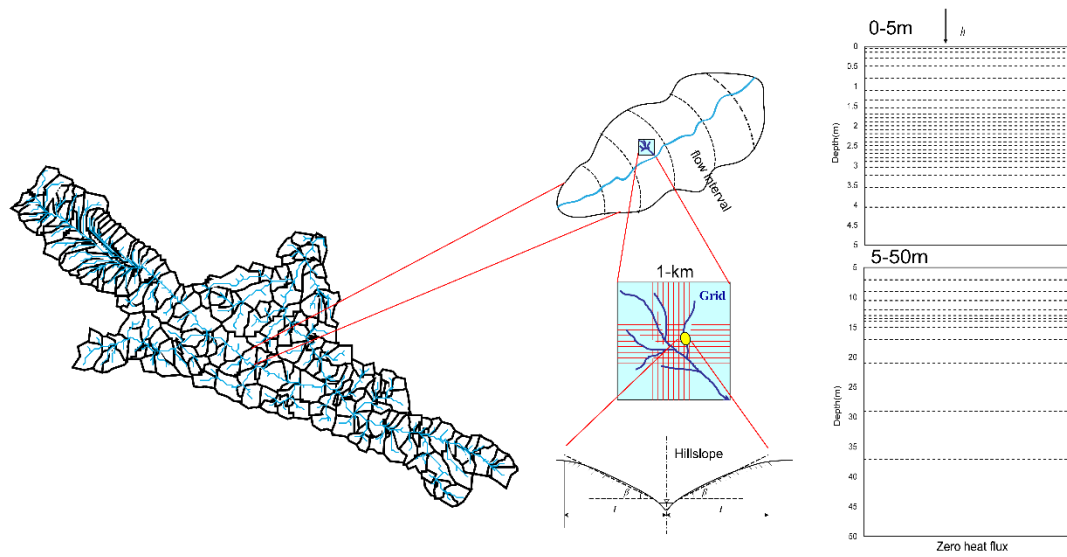
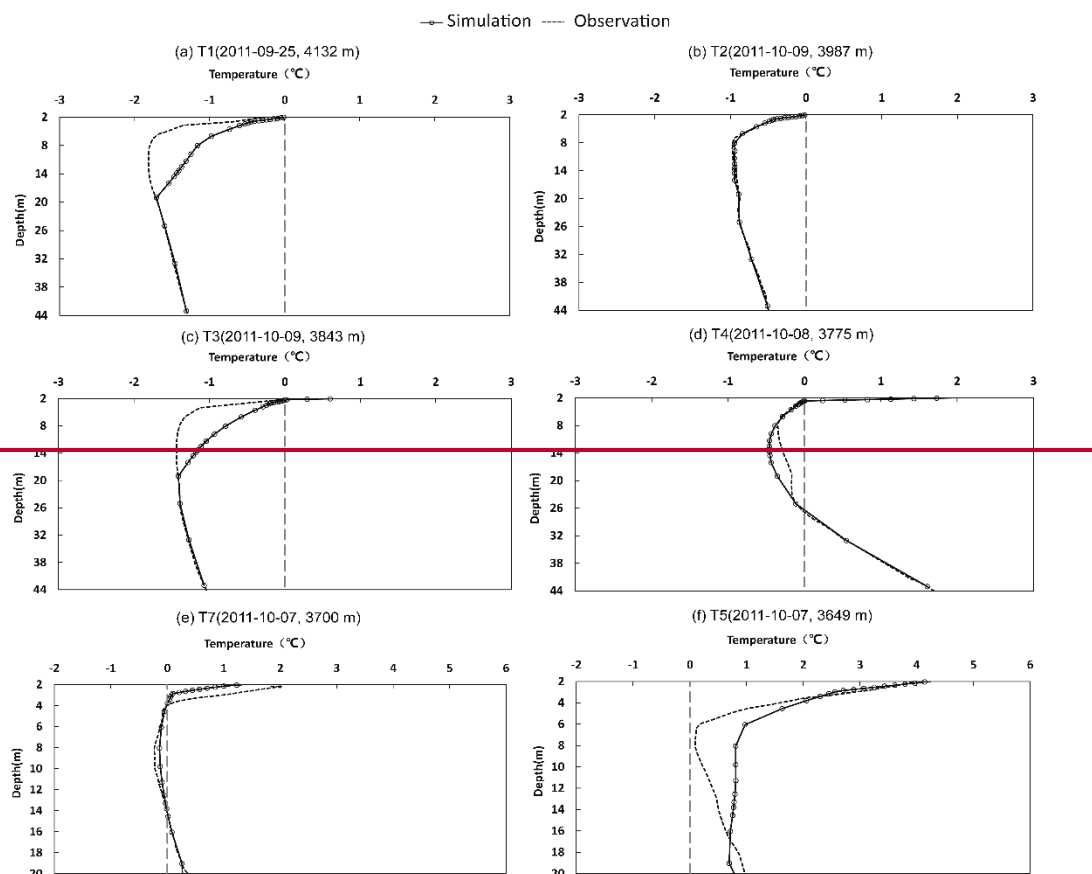


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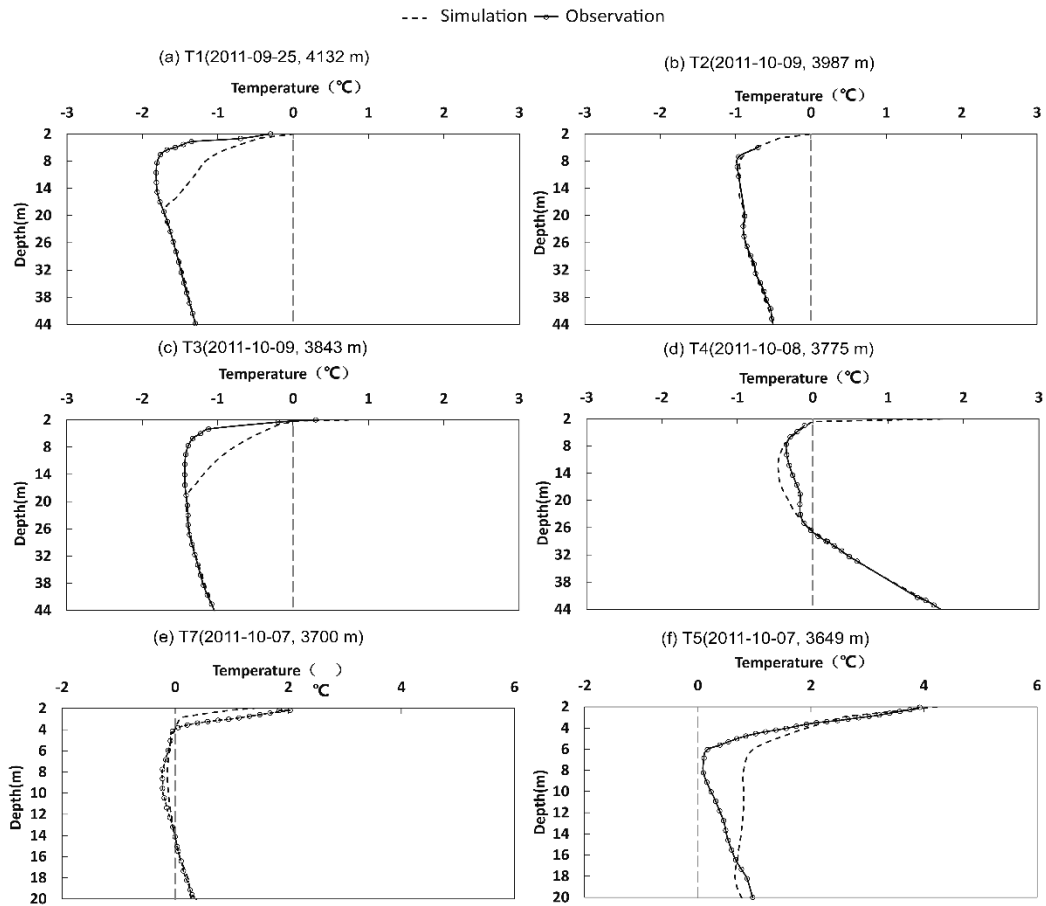


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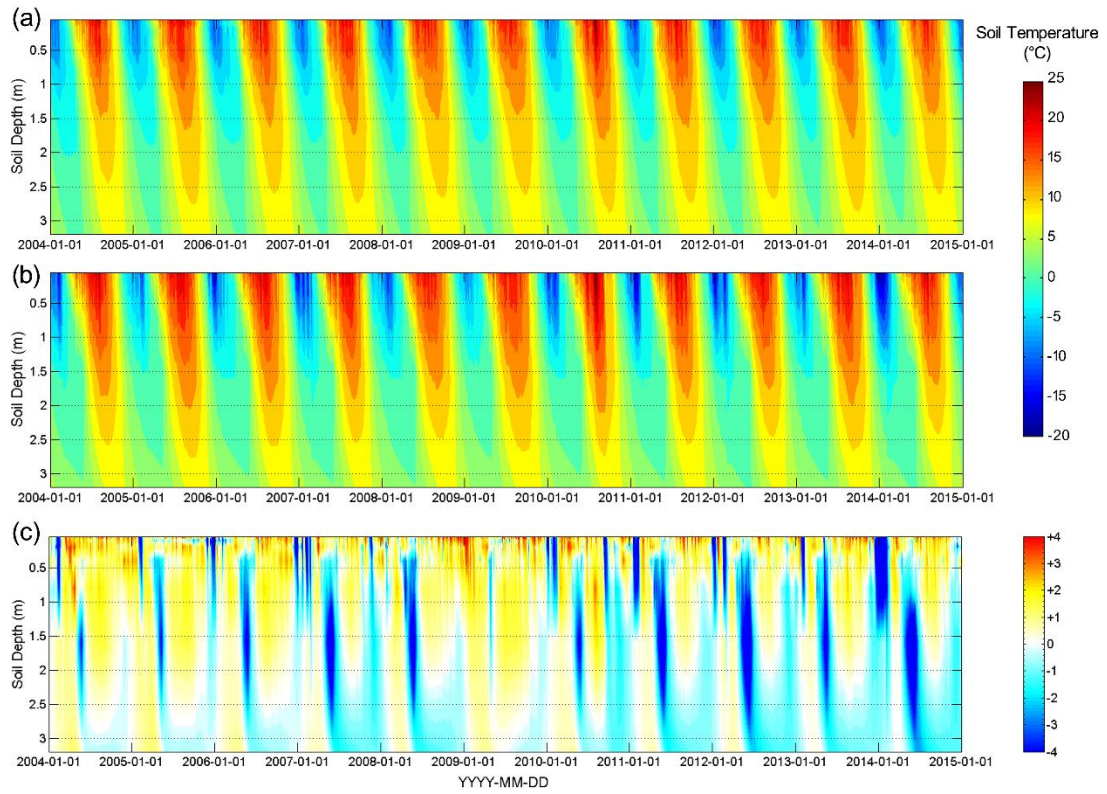


Figure 4 Daily soil temperature at the Qilian station: (a) observation; (b) simulation; (c) Simulation-Observation

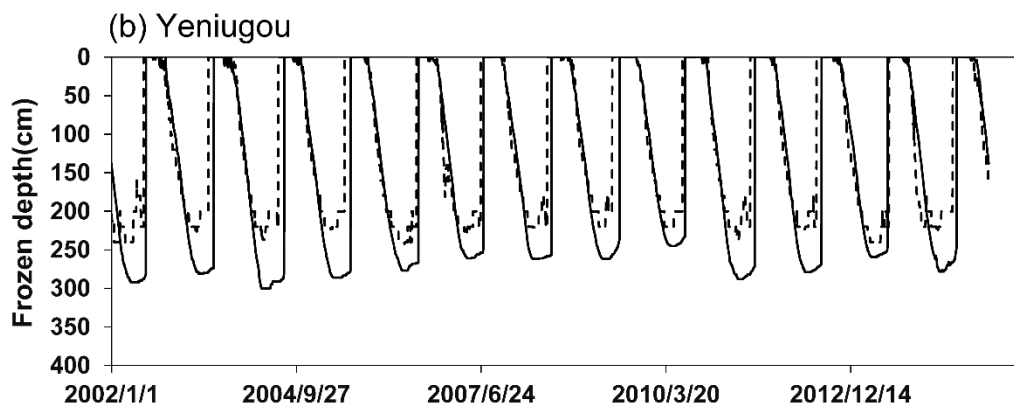
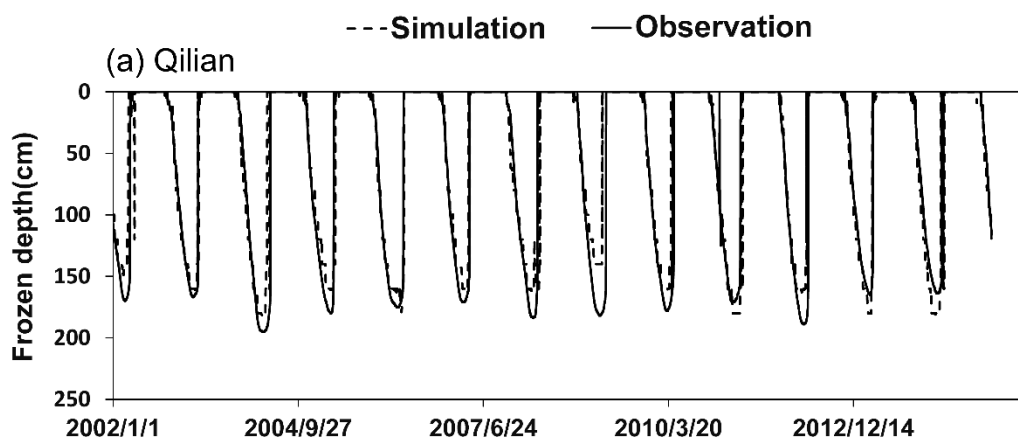
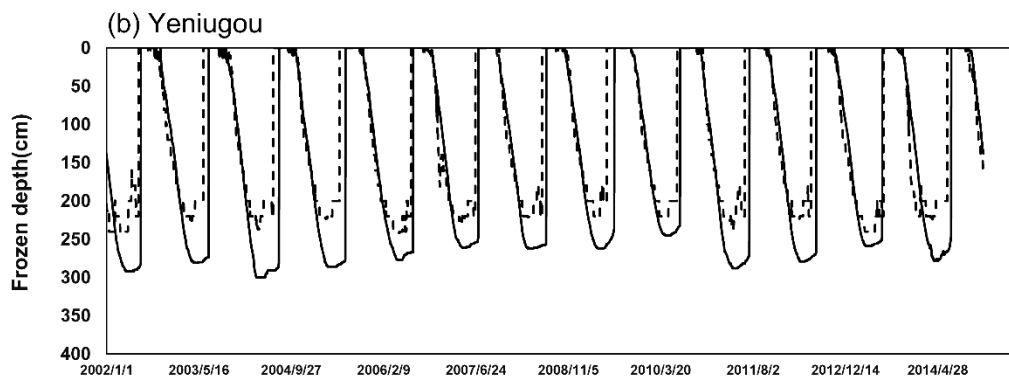
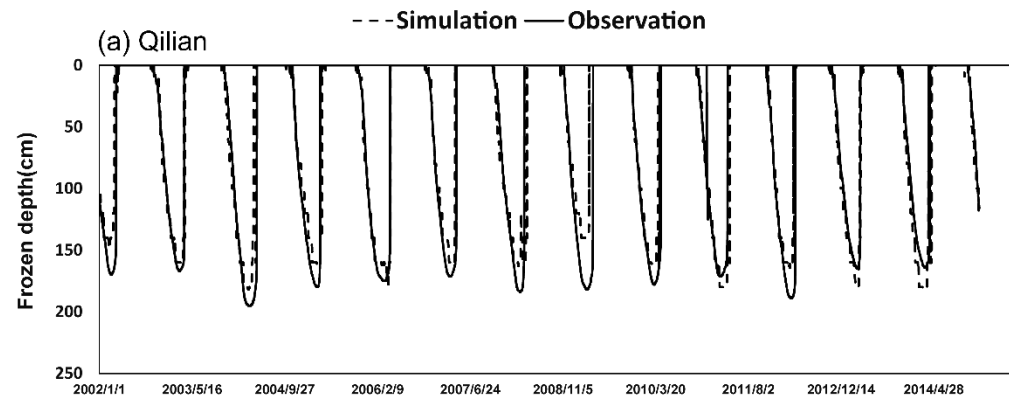
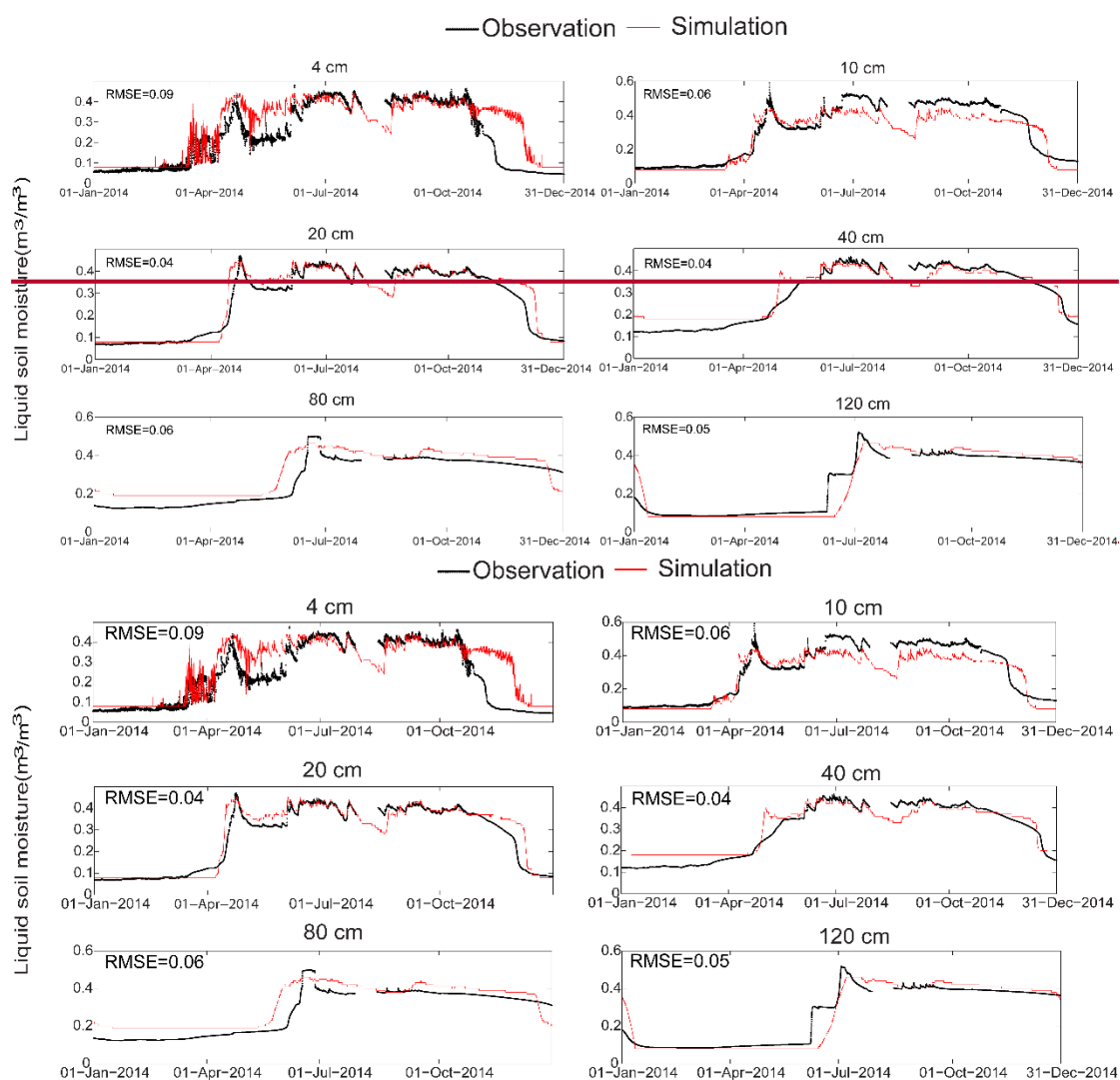


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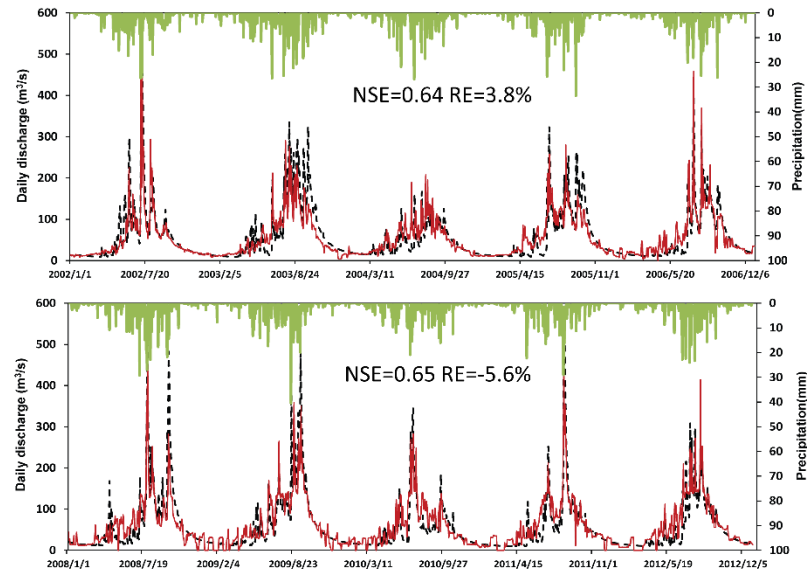
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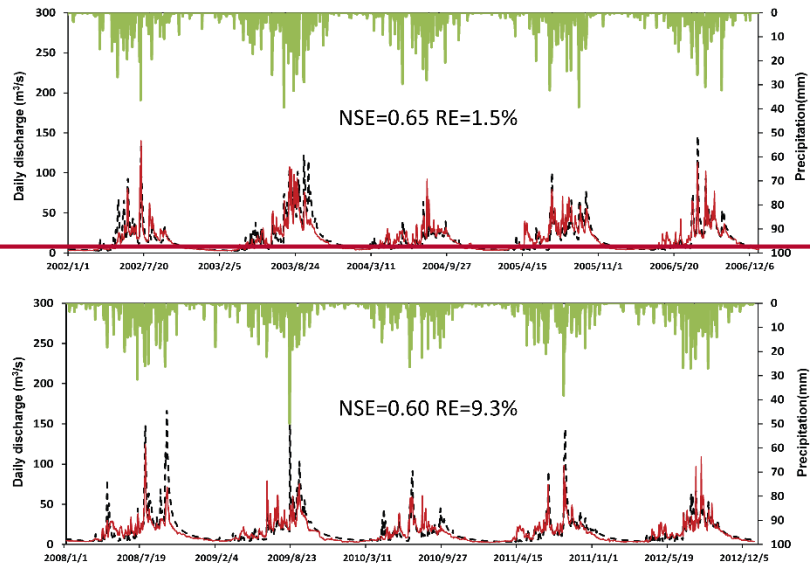


---Sim — Obs — Precipitation

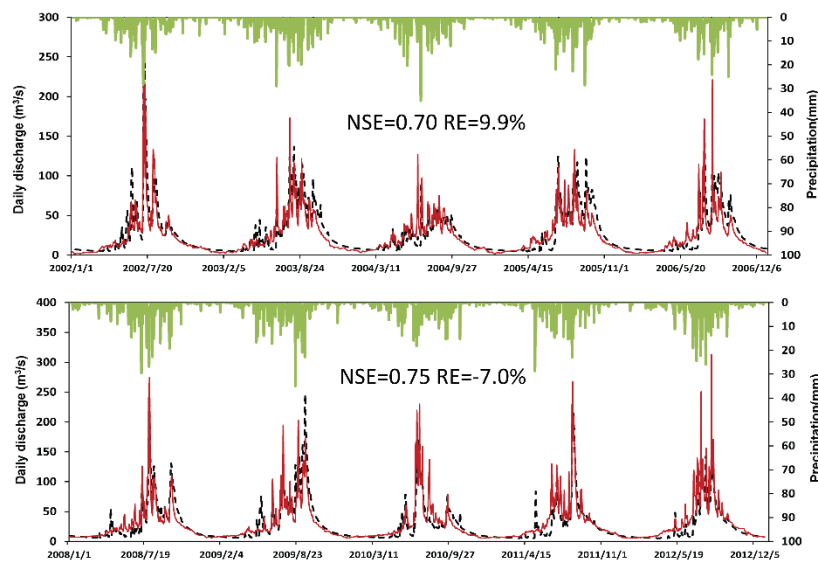
(a) Yingluoxia



(b) Qilian



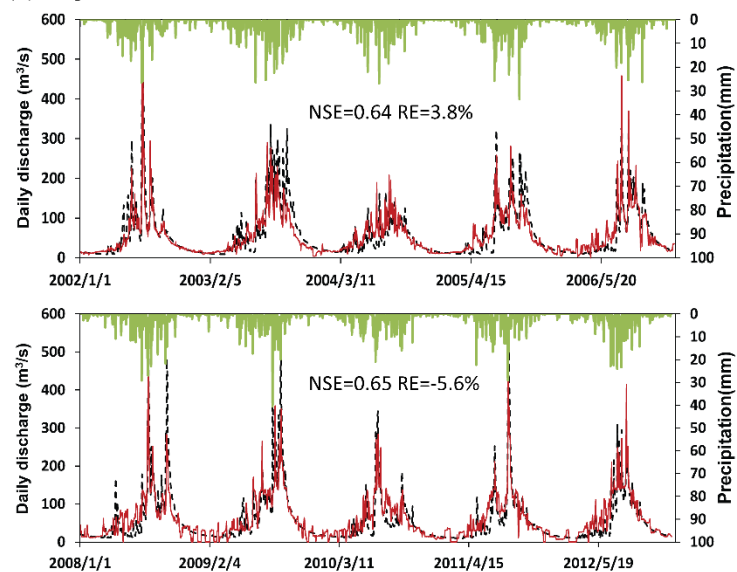
(c) Zhamashike



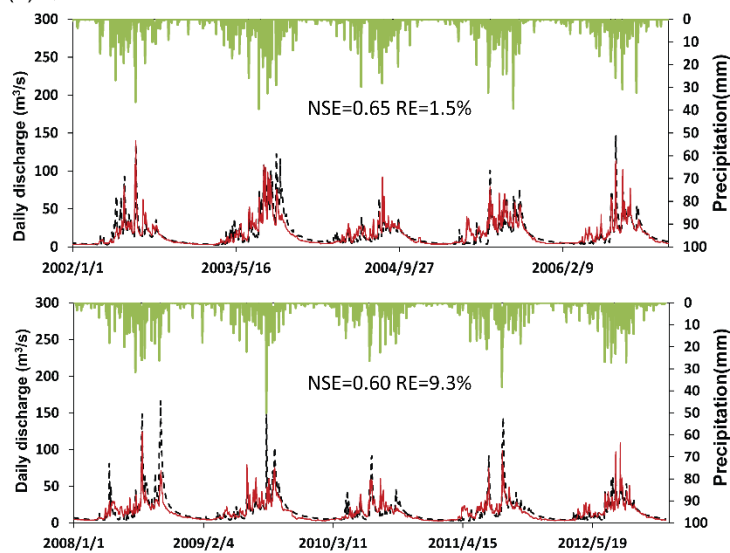


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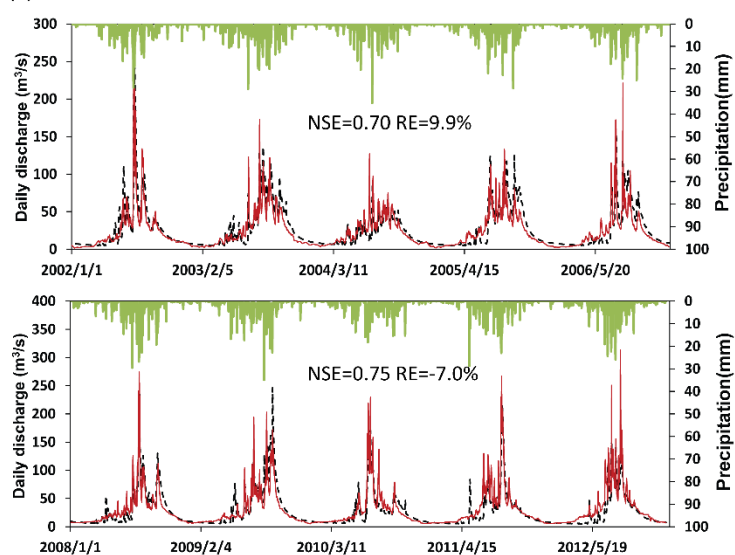


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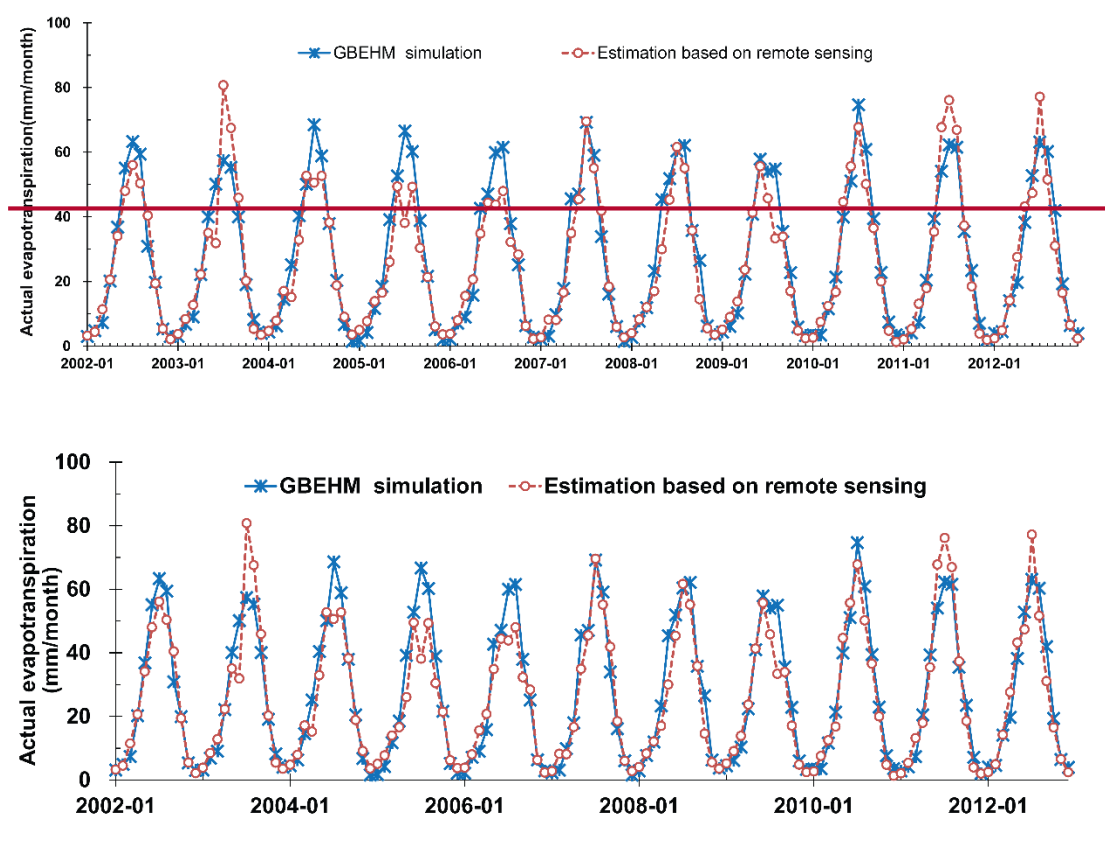


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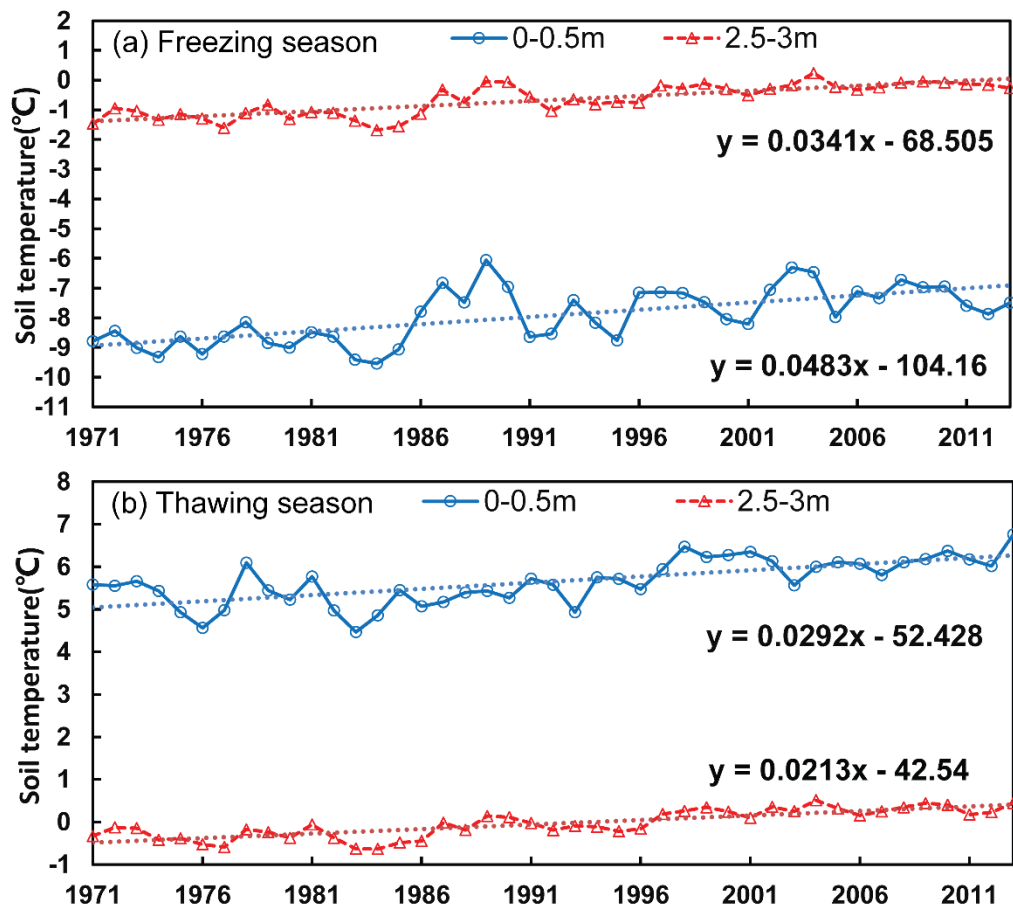
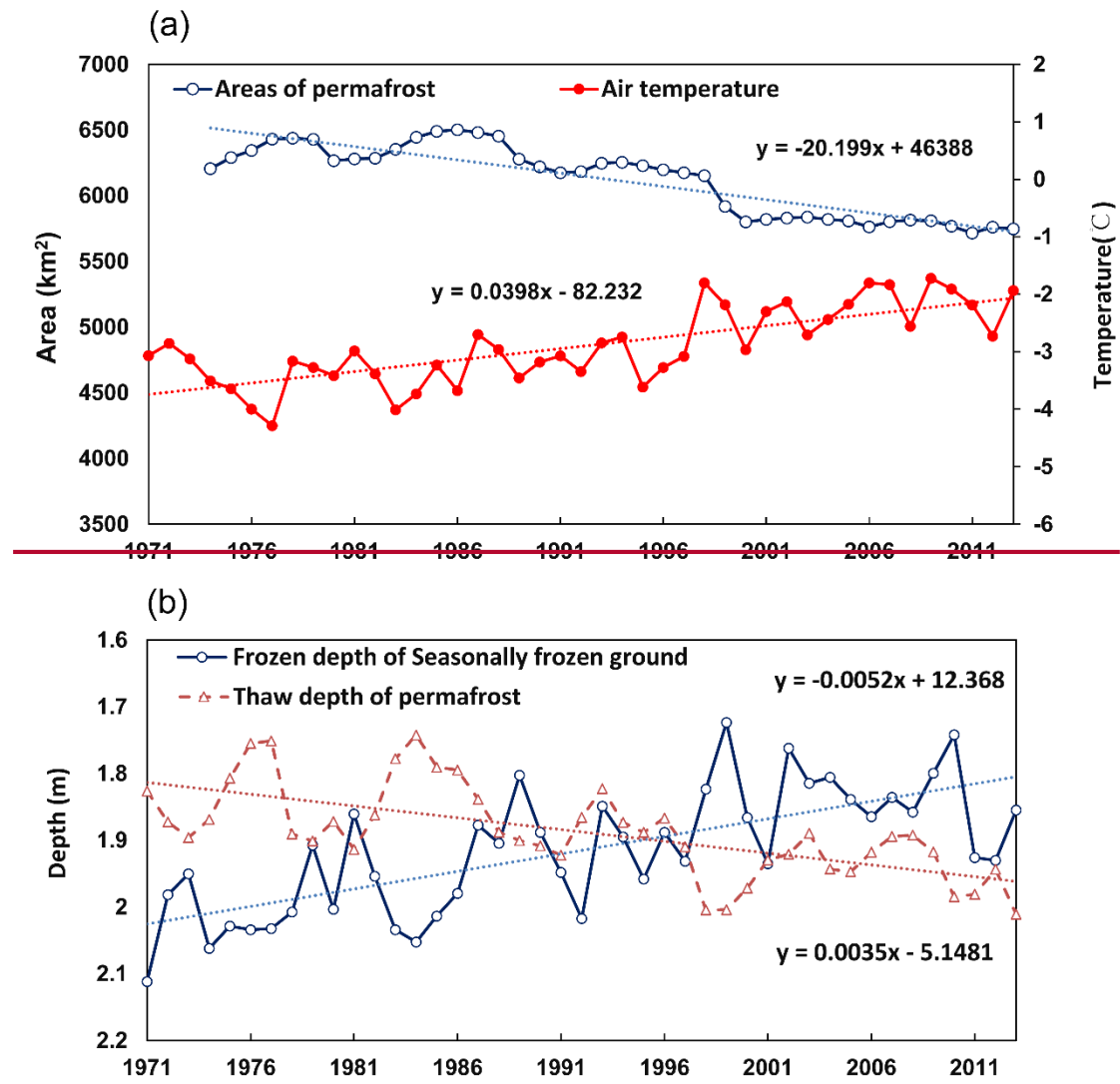


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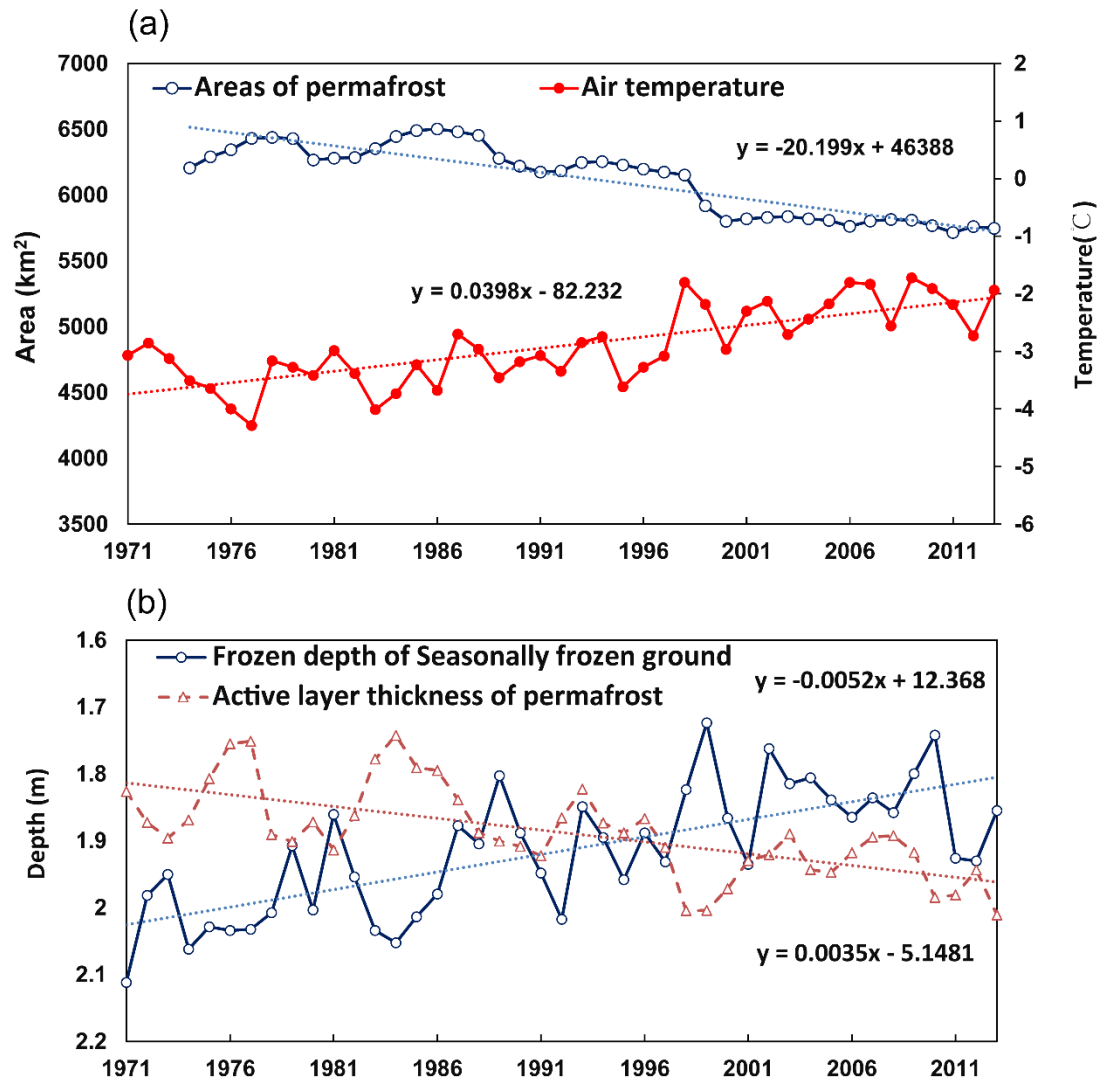


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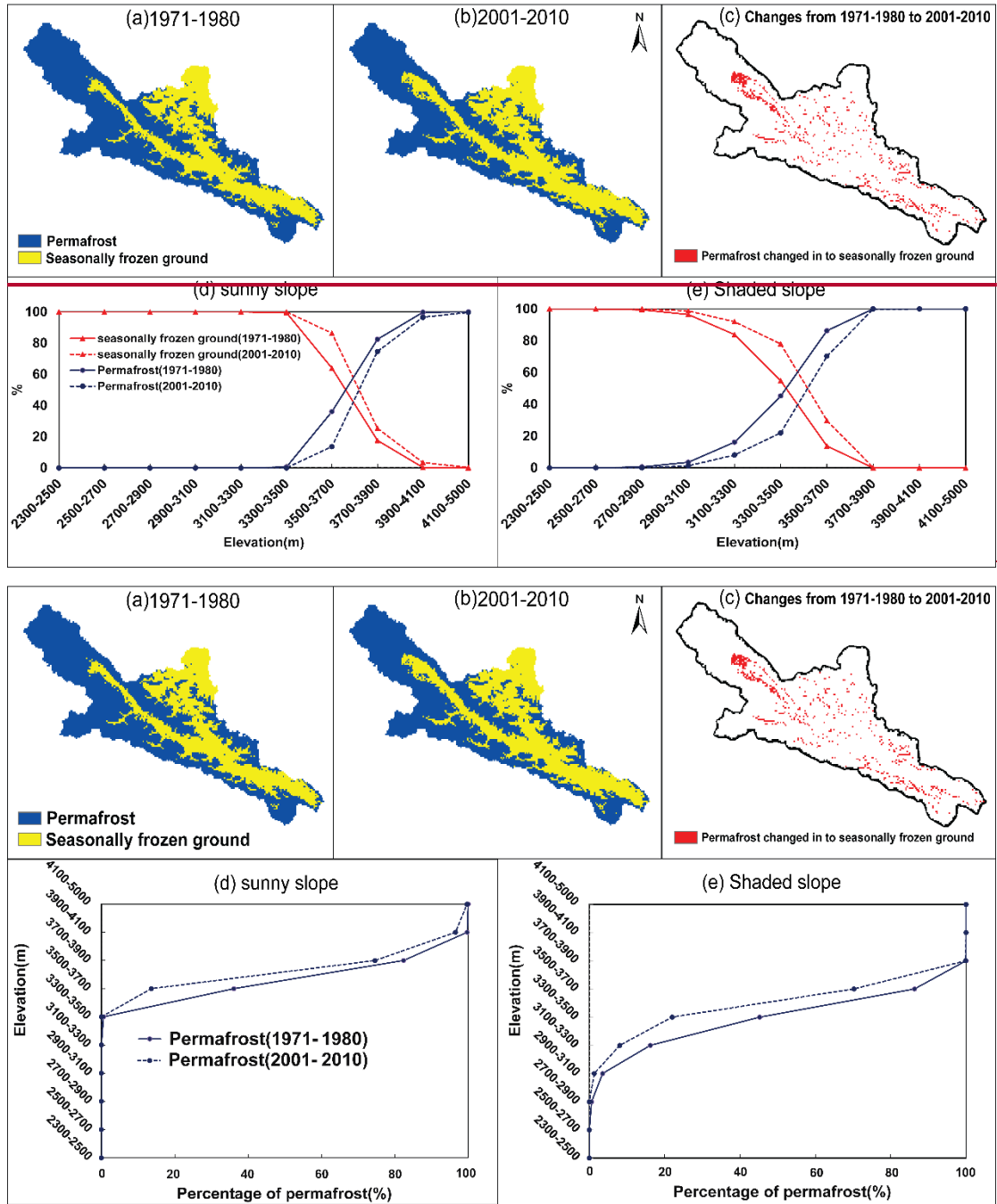


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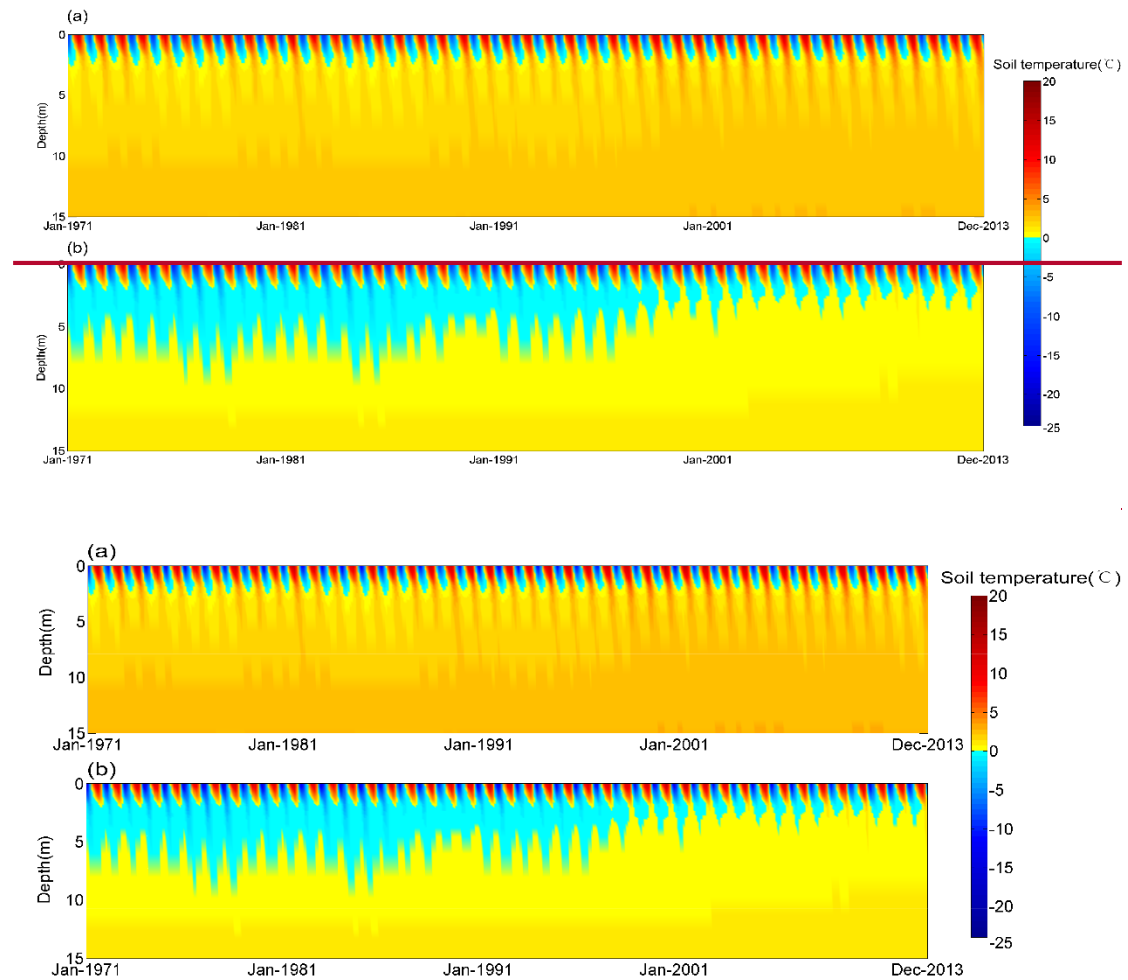


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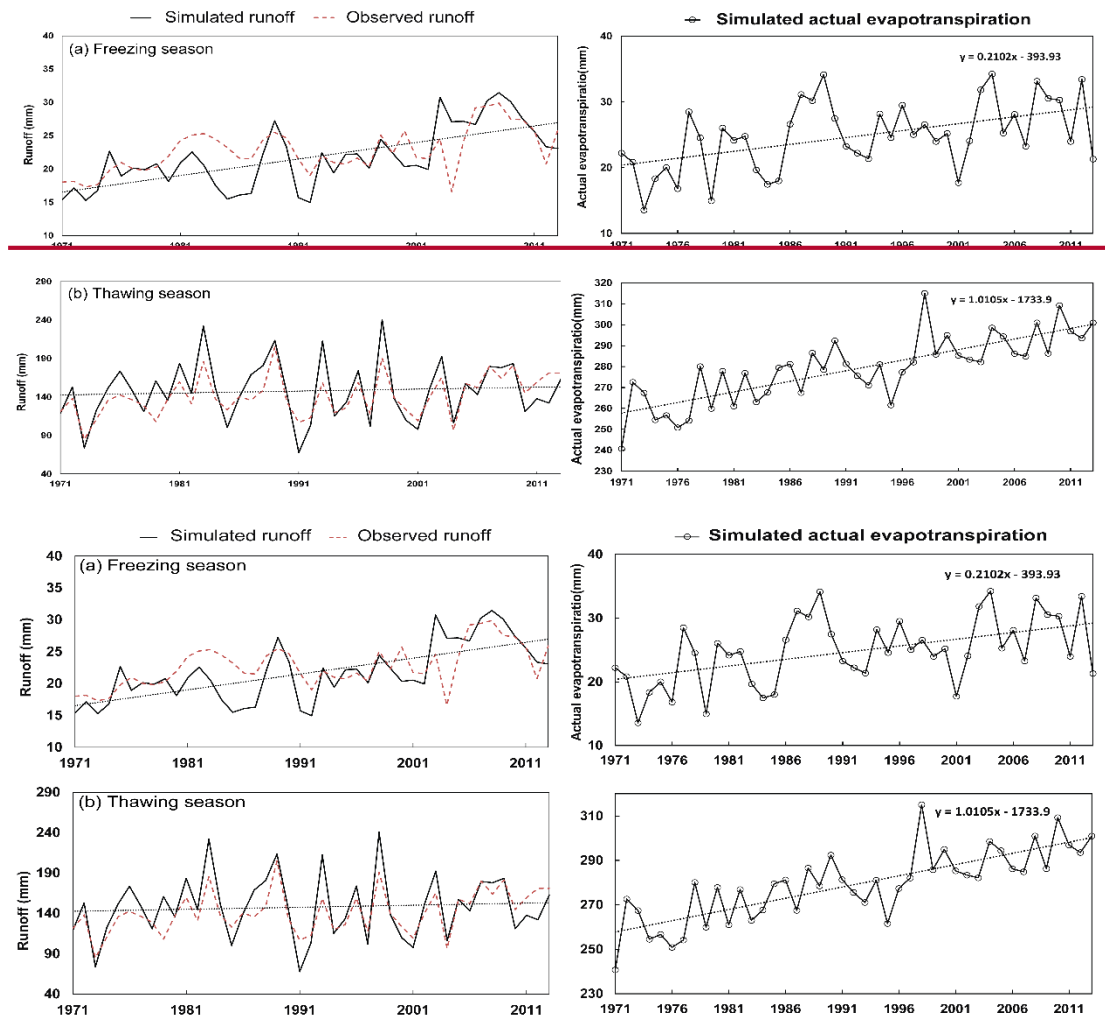


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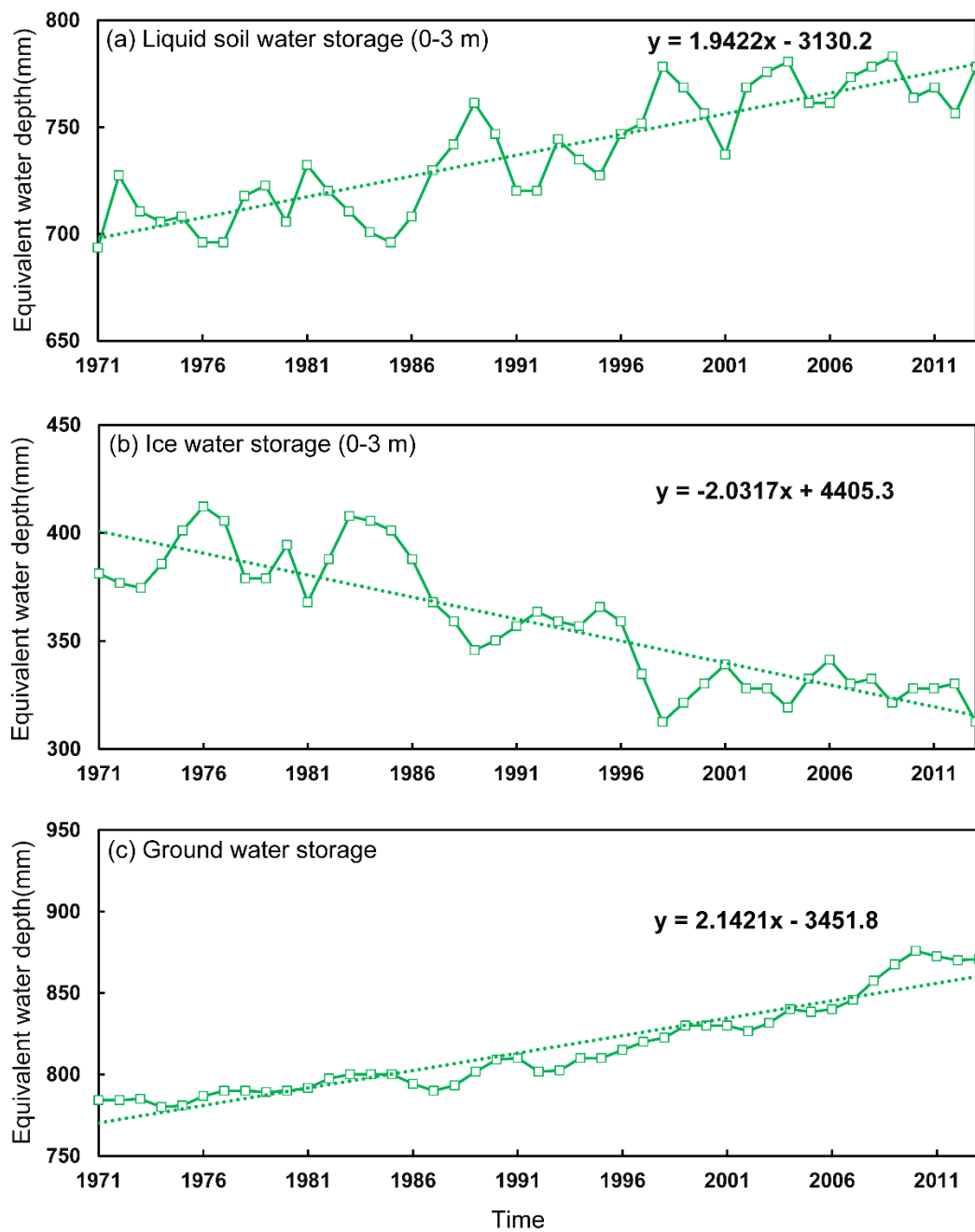
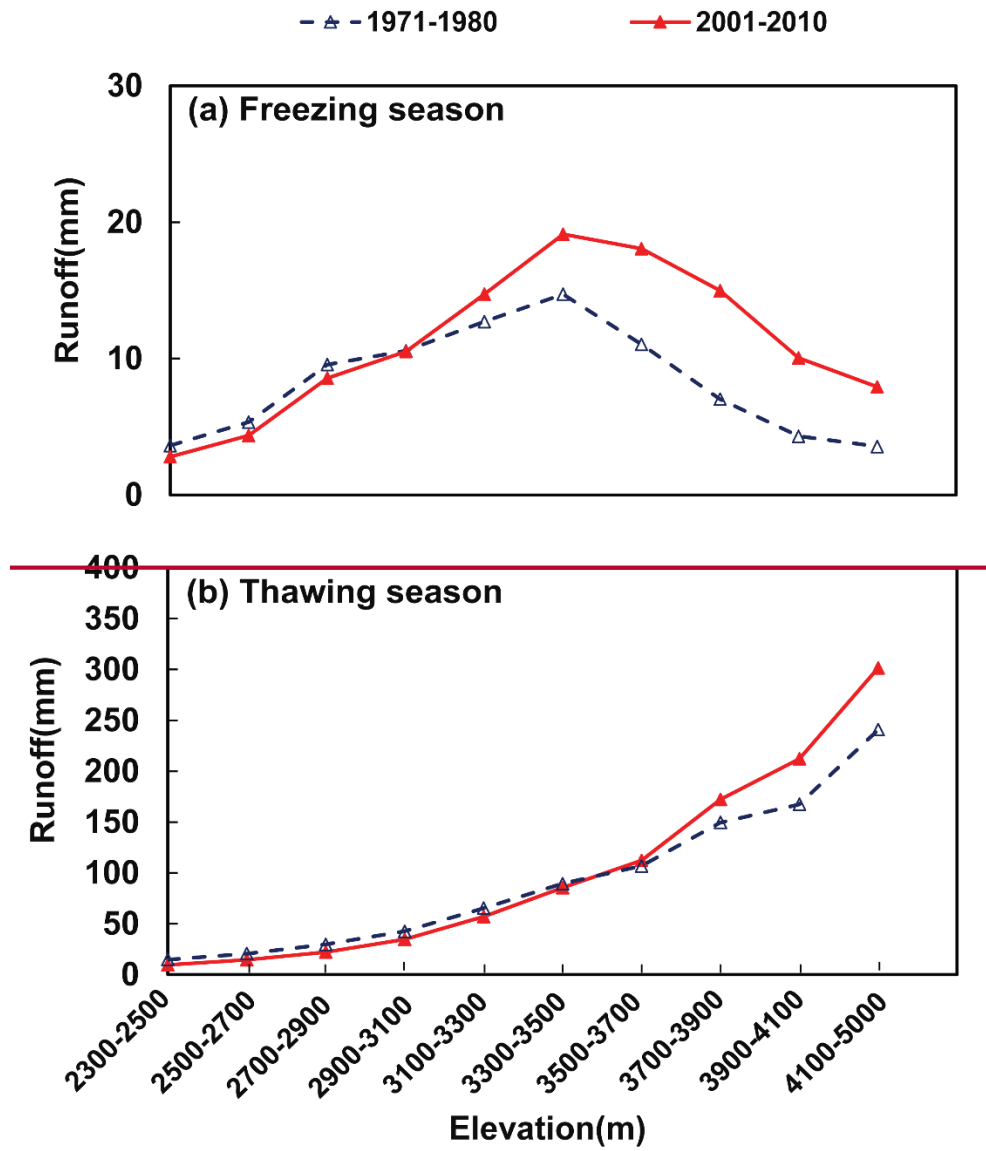


Figure 14. Changes of the annual water storage (equivalent water depth) during the period of 1971-2013: (a) the liquid soil water storage of the top 0-3 m layer; (b) the ice water storage of the top 0-3 m layer; (c) the groundwater storage



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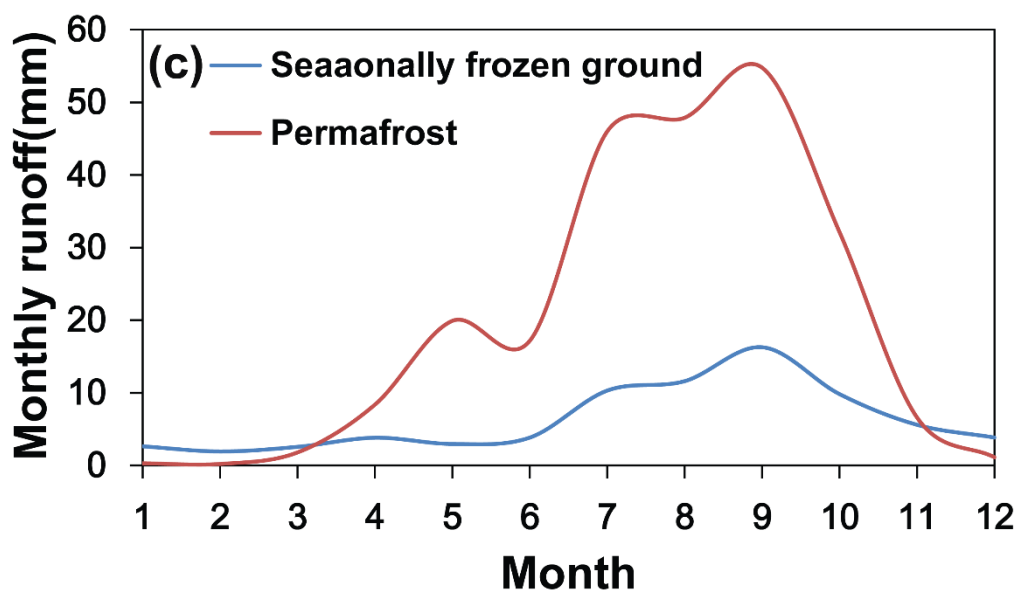
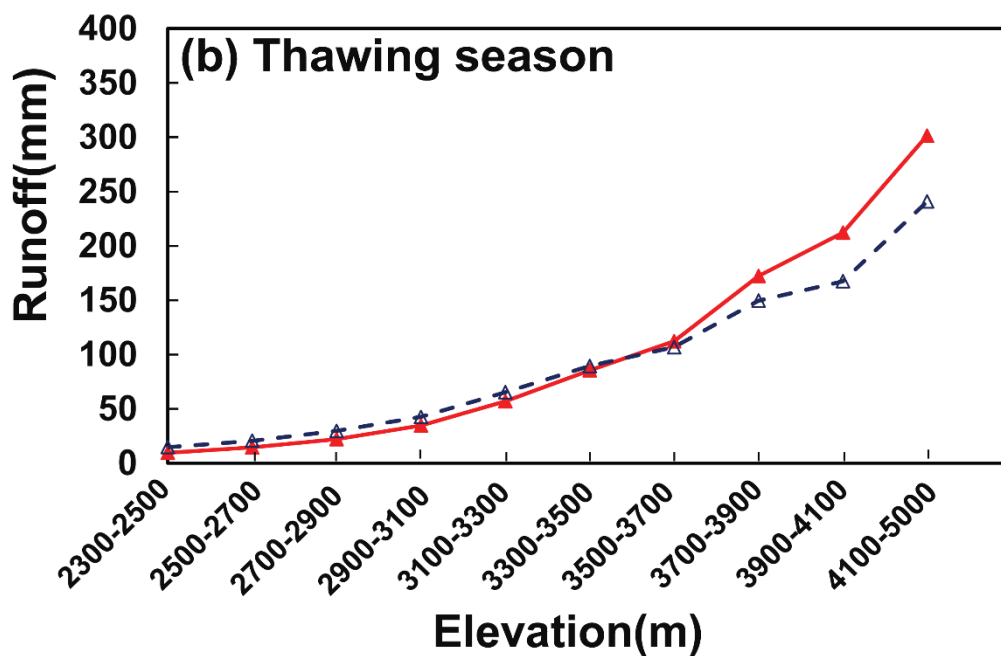
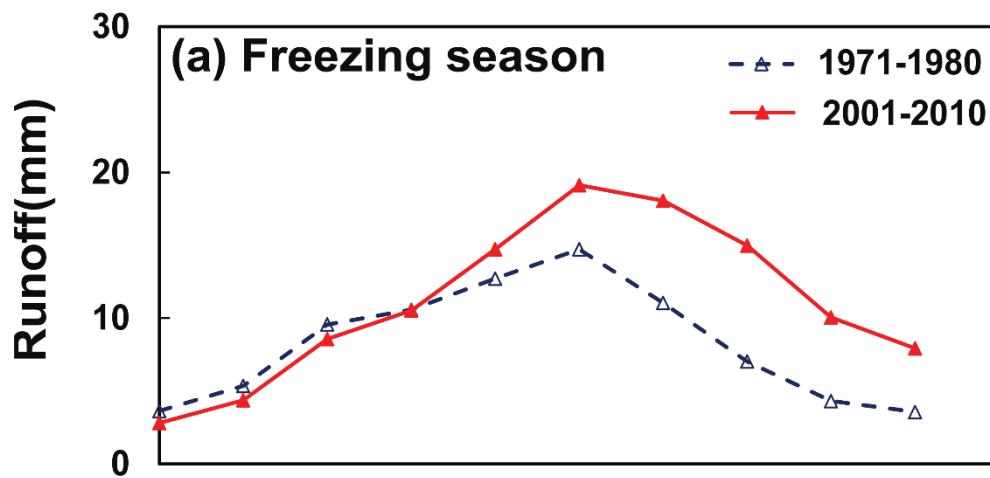


Figure 15. Model simulated ~~changes of~~ runoff change with elevation: (a) in the freezing season, (b) in the thawing season, and (c) seasonal pattern of the runoff: ~~(e)~~ in the permafrost areas, (d) and in the seasonally frozen ground areas in the period of 2001-2010.

**Table list:**

Table 1 Major parameters of the GBEHM model

Table 2 Changes in annual basin water balance and runoff components in different seasons

1033 Table 1 Major parameters of the GBEHM model

Parameters	Coniferous Forest	Shrub	Steppe	Alpine Meadow	Alpine Sparse Vegetation	Desert
Surface retention capacity (mm)	30.0	25.0	10.0	15.0	15.0	5.0
Surface roughness (Manning coefficient)	0.5	0.3	0.1	0.1	0.1	1.0
Soil reflectance to visible light	0.20	0.20	0.20	0.28	0.14	0.11
Soil reflectance to near-infrared radiation	0.225	0.225	0.225	0.28	0.225	0.225
Leaf reflectance to visible light	0.105	0.105	0.105	0.105	0.105	—
Leaf reflectance to near-infrared radiation	0.35	0.58	0.58	0.58	0.58	—
Leaf transmittance to visible light	0.05	0.07	0.07	0.07	0.07	—
Leaf transmittance to near-infrared radiation	0.10	0.25	0.25	0.25	0.25	—
Maximum Rubisco capacity of top leaf ( $10^{-5} \text{ mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ )	6.0	6.0	3.3	3.3	3.0	—
Plant root depth (m)	2.0	1.0	0.40	0.40	0.1	0.0
Intrinsic quantum efficiency ( $\text{mol} \cdot \text{mol}^{-1}$ )	0.08	0.08	0.05	0.05	0.05	—
Canopy top height (m)	9.0	1.9	0.3	0.3	0.2	—
Leaf length (m)	0.055	0.055	0.3	0.3	0.04	—
Leaf width (m)	0.001	0.001	0.005	0.005	0.001	—
Stem area index	0.08	0.08	0.05	0.05	0.08	—

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1035 Table 2 Changes in annual basin water balance and runoff components in different seasons

Decade	Precipitation (mm/yr)	Actual evaporation (mm/yr)	Simulated runoff (mm/yr)	Observed runoff (mm/yr)	Runoff ratio (observed)	Runoff ratio (simulated)	Runoff components (mm/yr)					
							Freezing season (from November to March)			Thawing season (from April to October)		
							T	G	S	T	G	S
1971-1980	439.1	280.8	154.5	143.8	0.33	0.35	18.5	0.0	0.0	136.0	3.5	13.5
1981-1990	492.8	300.0	186.2	174.1	0.35	0.38	20.2	0.0	0.0	166.1	3.1	28.2
1991-2000	471.0	306.1	160.1	157.4	0.33	0.34	20.4	0.0	0.0	139.7	3.8	19.2
2001-2010	504.3	317.4	177.9	174.3	0.35	0.35	27.2	0.0	0.0	150.7	3.7	25.8

1036 Note: T means total runoff, G means glacier runoff and S means snowmelt runoff.

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