1. Comments from Editor

The revised material adequately incorporates most of the reviewer's comments, and should be suitable for publication in TC with further revision. Most revisions stem from points raised by the referee's comments, but there is still a question that remains in relation to tc-2016-289 with respect to code availability, data used, and scripts used to perform the modelling. Most figures also need some work to generate a common look and feel. The revisions are for the most part minor, but will take some time.

General comments

With respect to Referee #1

1. Referee #1 makes the general comment that taliks are to be expected, and you responded that talik development is not substantial and include a figure. However, I do not see that you addressed the question in the paper. Please incorporate the finding into your results, and discuss the implications in your discussion. I agree with the reviewer that taliks are often expected when permafrost changes to seasonally frozen ground. I wonder if the lack of taliks is a relict of modelling and therefore an underestimate, or if there is a likely explanation that is physically based. The relevant figure is probably best included in your supplementary material.

2. Referee #1 [13]: Your reply is adequate, but you need a line of explanation in the manuscript to reflect your answer.

With respect to Referee #2

1. Referee #2 [Q1]: The important issue is raised here that an assumption of zero heat flux is simply not intuitive, and I expect that this assumption will continue to raise questions. Indeed, Fig. 12b seems to suggest a bottom-up degradation of permafrost as thaw depths are comparatively invariant. Top-down thaw would lead to more widespread talik development as expected by Referee #1. Is this pattern of permafrost degradation highlighted in Fig. 12b a function of the model calibration and spin up, or is it related to actual increases in freezing season air temperatures whereas summer thaw season air temperatures are relatively stable. This is an issue that needs to be addressed clearly.

2. We need a paper that is strong, and without distractions so that the important points shine through. I strongly suggest that you revise the manuscript with the general assumption that there is a geothermal heat flux, and abandon any comparison with a model scenario that does not include such a flux. This is a major revision that will affect figures and text. Are there no deep boreholes in the region, or heat flux models for the region, from which to obtain an estimate? If so, please look into using them. Your estimate of 0.2 W/m2 seems reasonable, but how does this compare with published values for QTP (e.g. Wu et al., 2010, Global and Planetary Change: 72: 32-38)?

3. Referee #2 [Q37]: Please re-visit the text with respect to this question and include discussion about temperature inversion. The effect is not related to vegetation or soil conditions, but relates to accumulation of cold, dense air in valleys. Bonnaventure et al. (2012), Permafrost and Periglacial Processes, 23: 52-68) incorporated inverted surface lapse rates in their model of Yukon Territory permafrost distribution, and it may be a useful reference for you.

4. Referee #2 [Q39]: Regarding annual averages, please indicate in the text why you did not use annual averages, but instead had to rely on measurements from specific dates. Please discuss any implications due to this choice.

With respect to code, data and scripts

Your novel approach was of interest to the reviewers, and will be to other readers who will want to apply the approach to new areas, or test model-to-model results, or examine the reproducibility of experiments, uncertainties, and goodness of fit. I suggest that you indicate where the model code, data, and scripts used are publicly available.

With respect to figures and tables

1. The figures require a common appearance so the work does not look like the figures were drafted by different co-authors. This includes figures in the supplementary material.

2. Use similar colours to show similar things. For example, simulation and observation should keep the same color coding in all figures. See Fig 5 versus Figs. 4 and 6.

3. Some figures have boxes around panels, while others do not. Please be consistent.

4. Graph axes: tic marks inside or outside? Some figure panels are only enclosed on 2 sides, while the majority have 4 sides.

5. Font sizes are often too small: Fig. 2; Fig. 3; Fig. 4; Fig. 6; Fig. 7; Fig. 11, panels c, d, and e; Fig. 12; Fig. 13.

6. Fig. 15 fonts and overall scale is much larger than the rest.

7. Axes labels, panel titles, and tables: Label/title and text within brackets need to be separated by a space. E.g., "Depth(m)" becomes "Depth (m)" or "(a)T1 (2011-09-25,4132 m)" becomes "(a) T1 (2011-09-25,4132 m)". Carefully check Fig.2b , Fig. 3; Fig. 5; Fig. 6; Fig. 7 (Precipitation); Fig. 9; Fig. 10a; Fig. 11; Fig. 12; Fig. 13 (Actual evapotranspiration); Fig. 14; Fig. 15.

8. A period "." Is required at the end of the last sentence of most figure captions.

Specific comments

Throughout: change passive tense to active tense. E.g. line 415, change “an increasing trend of active layer thickness in the permafrost regions was observed (3.5 cm/10yr),which had a significantly positive correlation with annual mean air temperature.” to “ Simulated active layer thickness in permafrost regions increased (3.5 cm·decade), and correlates positively with annual mean air temperature (p=XXXX).” Indicate the level of significance.

Throughout: Please carefully reduce the word count. This is a long manuscript that can be written more succinctly.

Throughout: Please refer to “supplementary material” rather than “supplemental file” or supplement material”.

Throughout: please convert cm values to either mm or m.

Throughout the text, figures, and tables: please be consistent in how units are related to each other. E.g., “mol·m-2·s-1” versus “mol/m2/s”. The former is preferred.

Throughout: “Soil temperature” is used throughout, but you really mean “ground temperatures”. Soil implies weathering, etc., that is unlikely at great depths. This change likely affects figures, captions, and the main text.

Line 1. Suggest changing title to “entitled “Change in Frozen Soils and the Effects on Regional Hydrology, Upper Heihe Basin, Northeastern Qinghai-Tibetan Plateau”

Line 38: Change “degradation” to reduction in permafrost extent”. Existing text could imply that ground ice in permafrost is contributing to groundwater recharge.

Lines 58 to 63: Sentence are still not clear. Perhaps change to: “Intensive field observations on frozen soils were typically carried out a small spatial scales over short periods. Consequently, regional patterns and long-term trends are not captured. Long-term meteorological and hydrological observations are available, but they do not provide information on soil freezing and thawing processes …”

Lines 69 to 72. Both reviewers took issue with this sentence. It is still too vague. Please delete “by simplified ways” and provide some explanation of the simplifications.

Lines 86. Change to “Consequently, cryospheric …”

Line 88. What is meant by “thin and warm”? Report thicknesses and temperature ranges published in the literature.

Line 163. Change “based on the” to “from a”

Lines 274-275. Delete sentence and work idea into text on Line 279.

Line 279. Change to “… with a constant thickness of 10 cm to try to replicate the maximum freezing depths according to field observations.”

Line 342. Uncertainties in the simulations may relate to the estimates of ground heat capacity and thermal conductivity derived according to Farouki (1981), but the results are similar to the findings of Ou et al. (2016) …”

Lines 384 to 387. Change to “Compared to the decadal mean for 1971 to 1980, mean air temperature for the 2001 to 2010 period increased by approximately 1.2 °C, with a larger increase in the freezing season (1.4 °C) than in the thawing season (1.1 °C) (Figure 9 and Table S2).

Lines 465 to 472. These sentence are not well written and do not read easily. Please revise.

Line 478. Delete comma after frozen ground.

Lines 477 to 480. Change “decreased, which led” to “decreased, leading”

Line 482. Change “in the permafrost area and seasonally frozen soils” to “from the entire basin”.

Lines 494 to 496. Re-write and combine sentences so that it reads more easily.

Lines497 to 499. Delete the first 2 sentences and change to “Figure 15 shows the large difference in runoff variation with elevation between the freezing and thawing seasons.”

Line 526. Change order of words: “soil liquid” to “liquid soil’.

Lines 555 to 557. Indicate the year the decrease was observed.

Lines 582 to 585. Include potential for temperature inversion in this discussion.
Line 586: change “lateral heat” to laterally advected heat”

Line 589: Change “when high groundwater flow rate events occur” to “where groundwater flow rates are high.”

Figure 1.White background conveys no information/context for meteorological stations. If you show the colorized DEM (elevation) for the whole panel, the study area will

remain obvious due to the encircling black polygon.

Figure 3. Too much wasted space. Try to reduce figure size. Move panel titles inside of the panels. Keep temperature scales the same; really only need 4 degrees of freedom in each figure, or keep a uniform temperature range of -2 to 4 °C. Depth scale range in e and f are half of a-d. for comparative purposes it would be helpful if all depth scales were the same range, 2-44 m. Panel e, "°C" is offset below the axis title.

Figure 4. Figure labels: second and subsequent words are not to be capitalized. E.g., "Soil Depth (m)" becomes "Soil depth (m)". Dates shown on x-axis are annual. Simplify labels to show only the year. Axis title can be changed to "Year". Change color scale in panels a and b so that the 0 °C isotherm is clear. Color scale used in Fig. 12 is good. Plotting the isotherm as a black line would also help. In caption change "Simulation-Observation" to "difference (simulation – observation).".

Figure 5. Use annual increments on x-axis, label every 2nd or 5th year, and title "Year".

Figure 6. Panels are all too small and time series lines too thin. Does not reproduce well as a result. Perhaps move panel titles inside the panel to give more room. Show monthly tic marks, but label every second one, or label "J F M A M J J A S O N D". Figure caption: change "… Sunny slope station." To "…Sunny Slope station (2014 calendar year). Root mean square errors are indicated."

Figure 7. Indicate within every panel if it is a Calibration or Validation period, and perhaps enclose each pair in a box. Change caption to "…the Yingluoxia gauge, (b) the Qilian gauge, and (c) the Zhamashike gauge. For each gauge, the upper and lower panels show the calibration and validation periods, respectively. Nash-Sutcliffe efficiency and relative error coefficients are indicated."

Figure 8. Plot tic marks for each year. No need to indicate "-01" for month. X-axis title "Year". Change caption to "comparison of simulated monthly evapotranspiration with a remote-sensing-derived estimate (Wu, 2013) for the period of 2002 to 2012."

Figure 9. Y-axes in both panels should share the same scaling ratio so that the figure highlights the fact that freezing season temperatures are increasing at greater rates than thawing season temperatures. Time series labels: Space between depth interval and unit. Change caption to "Simulated ground temperature changes in: (a) … and (b) …". Include a line about the linear regressions. What is the statistical significance of the slopes?

Figure 10. Panel b time series labels: change "Frozen depth of Seasonally frozen ground" to "Seasonally frozen depth"". Change "Active layer thickness of permafrost" to "Thaw depth". Change caption text to "… annual maximum depths of seasonally frozen ground and thaw above permafrost." Include a line about the linear regressions. What is the

statistical significance of the slopes?

Figure 11. Tic marks on panels d and e are not visible. Panel d: Capitalize “Sunny”. Change caption to “Distribution of permafrost and seasonally frozen ground for two periods: (a) 1971-1980 and (b) 2001-2010. (c) Area where permafrost degraded to seasonally frozen ground between the two periods. Percentage of permafrost area for the two periods with respect to elevation on slopes that are (d) sunny or (e) shaded. Note that (d) and (e) share a legend.”

Figure 12. Change caption to ”Spatially averaged monthly ground temperatures simulated from 1971 to 2013 for two elevation intervals: (a) seasonally frozen ground between 3300 and 3500 m; (b) permafrost that degraded to seasonally frozen ground between 3500 and 3700 m.” Show annual tic marks on x-axis, but perhaps label every 2nd or 5th year.

Figure 13. This figure needs work. Caption says actual evapotranspiration but the data are for simulated evapotranspiration. It is not clear which two panels are paired together. Labels are missing. Tic mark intervals and labels are different though time scale ranges are the same. Change caption to “Runoff and simulated evapotranspiration in (a) the freezing season and (b) the thawing season.” Either report trend lines and significance in caption or in the figure, or remove the trend lines. Are trend lines in the left-hand side panels for the simulated or observed data? This needs to be clear.

Figure 14. These are simulation results. Are these basin-averaged? Change caption to “(Basin averaged?) Annual water storage (equivalent water depth) changes simulated over the period of 1971 to 2013 for: (a) liquid water in the top layer of the ground (0-3 m); (b) ice in the top layer of the ground (0-3 m); (c) and ground water.” Indicate if trend lines are significant.

Figure 15. Needs work. Look and feel is quite different than other figures. Panel a is missing a properly scaled and labeled x-axis. There is a typo in panel c. Change caption to “Model simulated runoff changes from the 1971-1980 period to the 2001-2010 period with elevation for (a) the freezing season and (b) the thawing season, and (c) monthly averaged seasonal runoff in permafrost and seasonally frozen ground for the period of 2001 to 2010.

Table 2. Several column headings show words that are split across lines.

Figure S1. Capitalize “simulation” in legend. Add line to caption “Legend in (a) applies to all panels.

Figure S2. Change “Obs” to “Observations”. X-axis time scale should be adjust to even spacing by months.

Figure S3. Tic marks on x-axis should indicate years, with every 2nd or 5th labelled. Figure caption should be re-worded in a similar manner as Figure 12.

2. Author's responses

The revised material adequately incorporates most of the reviewer's comments, and should be suitable for publication in TC with further revision. Most revisions stem from points raised by the referee's comments, but there is still a question that remains in relation to tc-2016-289 with respect to code availability, data used, and scripts used to perform the modelling. Most figures also need some work to generate a common look and feel. The revisions are for the most part minor, but will take some time.

Reply: Thanks for handling our manuscript and the suggestions to revise the manuscript. Following comments from the editor, we have substantially revised our manuscript. The details are given bellow.

General comments

With respect to Referee #1

1. Referee #1 makes the general comment that taliks are to be expected, and you responded that talik development is not substantial and include a figure. However, I do not see that you addressed the question in the paper. Please incorporate the finding into your results, and discuss the implications in your discussion. I agree with the reviewer that taliks are often expected when permafrost changes to seasonally frozen ground. I wonder if the lack of taliks is a relict of modelling and therefore an underestimate, or if there is a likely explanation that is physically based. The relevant figure is probably best included in your supplementary material.

Reply: Thanks for your suggestion. We have added the relevant result in the supplementary material as Figure S5.

We added a sentence in section 4.2 as "Figure S5, illustrating the taliks simulated in the period of 2001-2010, shows that the taliks were mainly located on the edge of the permafrost area and the development of taliks was not significant." (Please see line 430-432 in the revised clean version manuscript).

We also discussed the talik development in the manuscript as "The laterally advected heat flux may increase the thawing of permafrost, especially in areas with high groundwater flow rates (Kurylyk et al., 2016; Sjöberg et al., 2016). Not considering the lateral heat flux may lead to an underestimation of talik development and thawing rates of permafrost." (Please see line 583-586 in the revised clean version manuscript)

2. Referee #1 [13]: Your reply is adequate, but you need a line of explanation in the manuscript to reflect your answer.

Reply: Thank you for this comment. We have added a sentence as "Uncertainties in the simulations may be related to the ground heat capacity and thermal conductivity estimated according to Farouki (1981), and the results are similar to the findings by Ou et al. (2016) using the Northern Ecosystem Soil Temperature (NEST) model." (Please see line 349-352 in the revised clean version manuscript)

With respect to Referee #2

1. Referee #2 [Q1]: The important issue is raised here that an assumption of zero heat flux is simply not intuitive, and I expect that this assumption will continue to raise questions. Indeed, Fig. 12b seems to suggest a bottom-up degradation of permafrost as thaw depths are comparatively invariant. Top-down thaw would lead to more widespread talik development as expected by Referee #1. Is this pattern of permafrost degradation highlighted in Fig. 12b a function of the model calibration and spin up, or is it related to actual increases in freezing season air temperatures whereas summer thaw season air temperatures are relatively stable. This is an issue that needs to be addressed clearly.

Reply: Thank you for this comment. We considered a geothermal heat flux and re-run the model. The related figures and texts are updated.

We realized that the thaw depths changed slowly comparing with the frozen depths. The main reason may be the effect of geothermal heat flux. Air temperature increase in the freezing season (0.41℃ decadal^{-1}) is much larger than the thawing season (0.26℃ decade^{-1}), which may be another reason. We have updated the related results in the revised manuscript and explained as "The thaw depths changed slowly compared with the frozen depths as shown in Figure 10, which may be primarily due to the geothermal heat flux. Additionally, the faster increase in the air temperature in the freezing season (0.41 ℃ decade-1) than in the thawing season (0.26 ℃ decade-1) may be another reason." (Please see line 441-445 in the revised clean version manuscript).

2. We need a paper that is strong, and without distractions so that the important points shine through. I strongly suggest that you revise the manuscript with the general assumption that there is a geothermal heat flux, and abandon any comparison with a model scenario that does not include such a flux. This is a major revision that will affect figures and text. Are there no deep boreholes in the region, or heat flux models for the region, from which to obtain an estimate? If so, please look into using them. Your estimate of 0.2 W/m2 seems reasonable, but how does this compare with published values for QTP (e.g. Wu et al., 2010, Global and Planetary Change: 72: 32-38)?

Reply: As mentioned above, we considered a geothermal heat flux and re-run the model. There are no deep boreholes in the study area. We estimated upward geothermal heat flux as 0.14 W m^{-2} at a depth of 50 m by the average geothermal gradient at 4 boreholes (T1-T4) shown in Figure 3, which is reasonable comparing with the observations along Qinghai-Tibet Highway/Railway in the interior QTP (vary from 0.02 W m^{-2} to 0.16 W m^{-2}) from the published literature (Wu et al., 2010), Please see line 275-280 in the revised clean version manuscript.

We have deleted comparison with a model scenario that does not include such a flux and revised the related part in the manuscript.

3. Referee #2 [Q37]: Please re-visit the text with respect to this question and include discussion about temperature inversion. The effect is not related to vegetation or soil conditions, but relates to accumulation of cold, dense air in valleys. Bonnaventure et al. (2012), Permafrost and Periglacial Processes, 23: 52-68) incorporated inverted surface lapse rates in their model of Yukon Territory permafrost distribution, and it may be a useful reference for you.

Reply: We have modified the text as "Sub-grid topography may also affect the frozen soil simulation. For example, active layer thickness is different between the low-elevation valleys and higher-elevation slopes due to the temperature inversion caused by the accumulation of cold air in valleys (Bonnaventure et al., 2012; Zhang et al., 2013; O'Neill et al., 2015)." (Please see line 579-583 in the revised clean version manuscript).

4. Referee #2 [Q39]: Regarding annual averages, please indicate in the text why you did not use annual averages, but instead had to rely on measurements from specific dates. Please discuss any implications due to this choice.

Reply: We have no data to estimate the annual average soil temperature profiles due to lack of continuous measurement. We have added a sentence to explain as "We used the observations at specific dates instead of annual averages due to lack of continuous measurement." (Please see line 154-155 in the revised clean version manuscript).

With respect to code, data and scripts

Your novel approach was of interest to the reviewers, and will be to other readers who will want to apply the approach to new areas, or test model-to-model results, or examine the reproducibility of experiments, uncertainties, and goodness of fit. I suggest that you indicate where the model code, data, and scripts used are publicly available.

Reply: We have added a sentence in the Acknowledgements as "All data for this paper are properly cited and referred in the reference list. The model code with a working example is freely available from our website (https://github.com/gb03/GBEHM) or upon request from the corresponding author (yangdw@tsinghua.edu.cn)" (Please see line 638-641 in the revised clean version manuscript). And we will continue to work on the website in the future.

With respect to figures and tables

1. The figures require a common appearance so the work does not look like the figures were drafted by different co-authors. This includes figures in the supplementary material.

Reply: Thank you for this comment. We have revised all the figures.

2. Use similar colours to show similar things. For example, simulation and observation should keep the same color coding in all figures. See Fig 5 versus Figs. 4 and 6.

Reply: We have modified the figures to using red colors for simulation and black color for observation.

3. Some figures have boxes around panels, while others do not. Please be consistent.

Reply: We have changed all the figures to keep them consistent.

4. Graph axes: tic marks inside or outside? Some figure panels are only enclosed on 2 sides, while the majority have 4 sides.
Reply: We have modified the figures and make all tic marks inside.

5. Font sizes are often too small: Fig. 2; Fig. 3; Fig. 4; Fig. 6; Fig. 7; Fig. 11, panels c, d, and e; Fig. 12; Fig. 13.
Reply: We have modified the figures to use larger fonts.

6. Fig. 15 fonts and overall scale is much larger than the rest.
Reply: We have modified the figure and used the same font size as other figures.

7. Axes labels, panel titles, and tables: Label/title and text within brackets need to be separated by a space. E.g., "Depth(m)" becomes "Depth (m)" or "(a)T1 (2011-09-25,4132 m)" becomes "(a) T1 (2011-09-25,4132 m)". Carefully check Fig.2b , Fig. 3; Fig. 5; Fig. 6; Fig. 7 (Precipitation); Fig. 9; Fig. 10a; Fig. 11; Fig. 12; Fig. 13 (Actual evapotranspiration); Fig. 14; Fig. 15.
Reply: We have revised as suggested.

8. A period "." Is required at the end of the last sentence of most figure captions.
Reply: We have revised as suggested.

Specific comments

1. Throughout: change passive tense to active tense. E.g. line 415, change "an increasing trend of active layer thickness in the permafrost regions was observed (3.5 cm/10yr),which had a significantly positive correlation with annual mean air temperature." to " Simulated active layer thickness in permafrost regions increased (3.5 cm·decade), and correlates positively with annual mean air temperature (p=XXXX)." Indicate the level of significance.
Reply: We have changed passive tense to active tense in the whole manuscript.

2. Throughout: Please carefully reduce the word count. This is a long manuscript that can be written more succinctly.
Reply: Thank you for this comment. We have tried our best to reduce the length of the manuscript.

3. Throughout: Please refer to "supplementary material" rather than "supplemental file" or supplement material".
Reply: We have revised as suggested.

4. Throughout: please convert cm values to either mm or m.
Reply: We have converted cm values to m.

5. Throughout the text, figures, and tables: please be consistent in how units are related to each other. E.g., "mol·m-2·s-1" versus "mol/m2/s". The former is preferred.
Reply: We have revised as suggested.

6. Throughout: "Soil temperature" is used throughout, but you really mean "ground temperatures". Soil implies weathering, etc., that is unlikely at great depths. This change likely affects figures, captions, and the main text.
Reply: We have used ground temperature instead of soil temperature as suggested.

7. Line 1. Suggest changing title to "entitled "Change in Frozen Soils and the Effects on Regional Hydrology, Upper Heihe Basin, Northeastern Qinghai-Tibetan Plateau"
Reply: We have changed the title as suggested.

8. Line 38: Change "degradation" to reduction in permafrost extent". Existing text could imply that ground ice in permafrost is contributing to groundwater recharge.
Reply: We have revised as suggested (Please see line 38-39 in the revised clean version manuscript).

9. Lines 58 to 63: Sentence are still not clear. Perhaps change to: "Intensive field observations on frozen soils were typically carried out a small spatial scales over short periods. Consequently, regional patterns and long-term trends are not captured. Long-term meteorological and hydrological observations are available, but they do not provide information on soil freezing and thawing processes …"
Reply: Thanks for this suggestion. We have revised as suggested (Please see line 58-63 in the revised clean version manuscript)

10. Lines 69 to 72. Both reviewers took issue with this sentence. It is still too vague. Please delete "by simplified ways" and provide some explanation of the simplifications.
Reply: We have changed this sentence as "but they simplify the flow routing using linear scheme." (Please see 71-72 in in the revised clean version manuscript).

11. Lines 86. Change to "Consequently, cryospheric …"
Reply: We have revised as suggested (Please see line 86-87 in the revised clean version manuscript).

12. Line 88. What is meant by "thin and warm"? Report thicknesses and temperature ranges published in the literature.
Reply: We modified this sentence as **"**the thickness of permafrost on the Qinghai-Tibetan Plateau ranges 1-130 m and the temperature varies from -0.5 to -3.5 °C (Yang et al., 2010)" (Please see line 87-89 in the revised clean version manuscript).

13. Line 163. Change "based on the" to "from a"
Reply: We have delete this sentence to reduce the length of the manuscript.

14. Lines 274-275. Delete sentence and work idea into text on Line 279.
Reply: We have revised as suggested (Please see line 284-286 in the revised clean version manuscript)

15. Line 279. Change to "… with a constant thickness of 10 cm to try to replicate the maximum freezing depths according to field observations."
Reply: We have revised as suggested (Please see line 284-286 in the revised clean version manuscript)

16. Line 342. Uncertainties in the simulations may relate to the estimates of ground heat capacity and thermal conductivity derived according to Farouki (1981), but the results are similar to the findings of Ou et al. (2016) …"
Reply: We have revised as suggested (Please see line 349-352 in the revised clean version manuscript)

17. Lines 384 to 387. Change to "Compared to the decadal mean for 1971 to 1980, mean air temperature for the 2001 to 2010 period increased by approximately 1.2 °C, with a larger increase in the freezing season (1.4 °C) than in the thawing season (1.1 °C) (Figure 9 and Table S2).
Reply: We have revised as suggested (Please see line 393-396 in the revised clean version manuscript)

18. Lines 465 to 472. These sentence are not well written and do not read easily. Please revise.
Reply: We have revised these sentences as suggested (Please see line 481-486 in the revised clean version manuscript).

19. Line 478. Delete comma after frozen ground.
Reply: We have revised as suggested (Please see line 492 in the revised clean version manuscript)

20. Lines 477 to 480. Change "decreased, which led" to "decreased, leading"
Reply: We have revised as suggested (Please see line 491-494 in the revised clean version manuscript)

21. Line 482. Change "in the permafrost area and seasonally frozen soils" to "from the entire basin".
Reply: We have revised as suggested (Please see line 496 in the revised clean version manuscript)

22. Lines 494 to 496. Re-write and combine sentences so that it reads more easily.
Reply: We have revised as suggested (Please see line 462-464 in the revised clean version manuscript)

23. Lines497 to 499. Delete the first 2 sentences and change to “Figure 15 shows the large difference in runoff variation with elevation between the freezing and thawing seasons.”

Reply: We have revised as suggested (Please see line 506-507 in the revised clean version manuscript)

24. Line 526. Change order of words: “soil liquid” to “liquid soil’.

Reply: We have revised as suggested (Please see line 533-534 in the revised clean version manuscript)

25. Lines 555 to 557. Indicate the year the decrease was observed.

Reply: We have indicate the year the decrease was observed in the manuscript (Please see line 560 in the revised clean version manuscript).

26. Lines 582 to 585. Include potential for temperature inversion in this discussion.

Reply: We have revised as suggested (Please see line 579-583 in the revised clean version manuscript)

27. Line 586: change “lateral heat” to laterally advected heat”

Reply: We have revised as suggested (Please see line 583 in the revised clean version manuscript)

28. Line 589: Change “when high groundwater flow rate events occur” to “where groundwater flow rates are high.”

Reply: We have revised as suggested (Please see line 584 in the revised clean version manuscript)

29. Figure 1. White background conveys no information/context for meteorological stations. If you show the colorized DEM (elevation) for the whole panel, the study area will remain obvious due to the encircling black polygon.

Reply: We have revised this figure as suggested (Please see Figure 1 in the revised clean version manuscript).

30. Figure 3. Too much wasted space. Try to reduce figure size. Move panel titles inside of the panels. Keep temperature scales the same; really only need 4 degrees of freedom in each figure, or keep a uniform temperature range of -2 to 4 °C. Depth scale range in e and f are half of a-d. for comparative purposes it would be helpful if all depth scales were the same range, 2-44 m. Panel e, “°C” is offset below the axis title.

Reply: We have revised this figure as suggested (Please see Figure 3 in the revised clean version manuscript).

31. Figure 4. Figure labels: second and subsequent words are not to be capitalized. E.g., “Soil Depth (m)” becomes “Soil depth (m)”. Dates shown on x-axis are annual. Simplify labels to show only the year. Axis title can be changed to “Year”. Change color scale in panels a and b so that the 0 °C isotherm is clear. Color scale used in Fig. 12 is good. Plotting the isotherm as a black line would also help. In caption change "Simulation-Observation" to "difference (simulation – observation).".

Reply: We have revised this figure as suggested (Please see Figure 4 in the revised clean version manuscript).

32. Figure 5. Use annual increments on x-axis, label every 2nd or 5th year, and title "Year".

Reply: We have revised this figure as suggested (Please see Figure 5 in the revised clean version manuscript).

33. Figure 6. Panels are all too small and time series lines too thin. Does not reproduce well as a result. Perhaps move panel titles inside the panel to give more room. Show monthly tic marks, but label every second one, or label "J F M A M J J A S O N D". Figure caption: change "… Sunny slope station." To "…Sunny Slope station (2014 calendar year). Root mean square errors are indicated."

Reply: We have revised this figure as suggested (Please see Figure S2 in the revised supplement materials).

34. Figure 7. Indicate within every panel if it is a Calibration or Validation period, and perhaps enclose each pair in a box. Change caption to "…the Yingluoxia gauge, (b) the Qilian gauge, and (c) the Zhamashike gauge. For each gauge, the upper and lower panels show the calibration and validation periods, respectively. Nash-Sutcliffe efficiency and relative error coefficients are indicated."

Reply: We have revised this figure as suggested (Please see Figure 6 in the revised clean version manuscript).

35. Figure 8. Plot tic marks for each year. No need to indicate "-01" for month. X-axis title "Year". Change caption to "comparison of simulated monthly evapotranspiration with a remote-sensing-derived estimate (Wu, 2013) for the period of 2002 to 2012."

Reply: We have revised this figure as suggested (Please see Figure S3 in the revised supplement materials).

36. Figure 9. Y-axes in both panels should share the same scaling ratio so that the figure highlights the fact that freezing season temperatures are increasing at greater rates than thawing season temperatures. Time series labels: Space between depth interval and unit. Change caption to "Simulated ground temperature changes in: (a) … and (b) …". Include a line about the linear regressions. What is the statistical significance of the slopes?

Reply: We have revised this figure as suggested and the statistical significance is shown in the figure (Please see Figure 7 in the revised clean version manuscript).

37. Figure 10. Panel b time series labels: change "Frozen depth of Seasonally frozen ground" to "Seasonally frozen depth"". Change "Active layer thickness of permafrost" to “Thaw depth”. Change caption text to “… annual maximum depths of seasonally frozen ground and thaw above permafrost.” Include a line about the linear regressions. What is the statistical significance of the slopes?

Reply: We have revised this figure as suggested and the statistical significance is shown in the figure (Please see Figure 8 in the revised clean version manuscript).

38. Figure 11. Tic marks on panels d and e are not visible. Panel d: Capitalize “Sunny”. Change caption to “Distribution of permafrost and seasonally frozen ground for two periods: (a) 1971-1980 and (b) 2001-2010. (c) Area where permafrost degraded to seasonally frozen ground between the two periods. Percentage of permafrost area for the two periods with respect to elevation on slopes that are (d) sunny or (e) shaded. Note that (d) and (e) share a legend.”

Reply: We have revised this figure as suggested (Please see Figure 9 in the revised clean version manuscript).

39. Figure 12. Change caption to ”Spatially averaged monthly ground temperatures simulated from 1971 to 2013 for two elevation intervals: (a) seasonally frozen ground between 3300 and 3500 m; (b) permafrost that degraded to seasonally frozen ground between 3500 and 3700 m.” Show annual tic marks on x-axis, but perhaps label every 2nd or 5th year.

Reply: We have revised this figure as suggested (Please see Figure 10 in the revised clean version manuscript).

40. Figure 13. This figure needs work. Caption says actual evapotranspiration but the data are for simulated evapotranspiration. It is not clear which two panels are paired together. Labels are missing. Tic mark intervals and labels are different though time scale ranges are the same. Change caption to “Runoff and simulated evapotranspiration in (a) the freezing season and (b) the thawing season.” Either report trend lines and significance in caption or in the figure, or remove the trend lines. Are trend lines in the left-hand side panels for the simulated or observed data? This needs to be clear.

Reply: We have revised this figure as suggested and the statistical significance is shown in the figure (Please see Figure 11 in the revised clean version manuscript).

41. Figure 14. These are simulation results. Are these basin-averaged? Change caption to “(Basin averaged?) Annual water storage (equivalent water depth) changes simulated over the period of 1971 to 2013 for: (a) liquid water in the top layer of the ground (0-3 m); (b) ice in the top layer of the ground (0-3 m); (c) and ground water.” Indicate if trend lines are significant.

Reply: We have revised this figure as suggested the statistical significance is shown in the figure (Please see Figure 12 in the revised clean version manuscript).

42. Figure 15. Needs work. Look and feel is quite different than other figures. Panel a is missing a properly scaled and labeled x-axis. There is a typo in panel c. Change caption to “Model simulated runoff changes from the 1971-1980 period to the 2001-

2010 period with elevation for (a) the freezing season and (b) the thawing season, and (c) monthly averaged seasonal runoff in permafrost and seasonally frozen ground for the period of 2001 to 2010.

Reply: We have revised this figure as suggested (Please see Figure 13 in the revised clean version manuscript).

43. Table 2. Several column headings show words that are split across lines.

Reply: We have revised this table as suggested (Please see Table 2 in the revised clean version manuscript).

44. Figure S1. Capitalize "simulation" in legend. Add line to caption "Legend in (a) applies to all panels.

Reply: We have revised this figure as suggested (Please see Figure S1 in the revised supplement materials).

45. Figure S2. Change "Obs" to "Observations". X-axis time scale should be adjust to even spacing by months.

Reply: We have revised this figure as suggested (Please see Figure S4 in the revised supplement materials).

46. Figure S3. Tic marks on x-axis should indicate years, with every 2nd or 5th labelled. Figure caption should be re-worded in a similar manner as Figure 12.

Reply: We have revised this figure as suggested (Please see Figure S6 in the revised supplement materials).

3. Author's changes in manuscript

1. Re-run the model with consideration of the geothermal heat flux in the bottom boundary and update the related texts and figures.

2. Move Figure 6 and Figure 8 in the previous version to the supplement materials in order to reduce the length of the manuscript.

3. Add figure in the supplement materials to show the taliks.

4. Modified all the figures according to the comments.

5. Modified the manuscript according to the suggestions of a native speaker and reduce the manuscript length.

6. Add introductions about model code availability and data used in the Acknowledgement.

Change in Frozen Soils and ~~Its~~ the Effects 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 (QTP), which is characterized by high elevations 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) changes ~~of~~ in frozen ground and ~~its~~ the effects on hydrology in the upper Heihe basin, which is located ~~in~~ on the northeastern ~~Qinghai-Tibetan Plateau~~QTP. The model was carefully validated ~~carefully~~ against data obtained from multiple ground-based observations. Based on the model simulations, we analyzed the changes ~~of~~ in frozen soils and their effects on the hydrology. The results showed that the permafrost area shrank by ~~9~~8.~~5~~8% (approximately ~~600~~ 500 km^2), especially in areas with elevations between 3500 m and 3900 m. The maximum frozen depth of seasonally frozen ground decreased at a rate of approximately 0.0~~5.2~~32 ~~c~~m·decade^{-1}~~/10yr~~, and the active layer thickness over the permafrost increased by approximately ~~about~~ 0.~~3~~04~~.5~~ 3 ~~c~~m·decade^{-1}~~/10yr~~. Runoff increased significantly during the cold season~~s~~ (November-March) due to the increase in liquid soil moisture caused by rising soil temperatures. Areas ~~where~~ in which permafrost changed into seasonally frozen ground at high elevations showed especially large increases in runoff. Annual runoff increased due to increased precipitation, the base flow increased due to changes in frozen soils~~permafrost degradation~~, and the actual evapotranspiration increased significantly due to increased precipitation and soil warming. The groundwater storage showed an increasing trend, indicating~~which indicated~~ that a reduction in permafrost extent enhanced the

groundwater recharge~~ was enhanced mainly due to the reduction in permafrost extent degradation of permafrost in the study area~~.

KEYWORDS: permafrost; seasonally frozen ground; soil moisture; ~~soil ~~ground temperature; 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 elevations ~~altitudes~~ (Hinzman et al., 2013; Cheng and Wu, 2007). Changes in frozen soils can greatly affect ~~the~~ land-atmosphere interactions 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 impacts on regional hydrology is important for water resources management and ecosystem protection in cold regions.

Previous studies based on either 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~~ as well as in northeastern China (Liu et al., 2003; Duan et al., 2017). A few studies reported that permafrost thawing might reduce river runoff (here, ~~This paper defines the~~ runoff is defined as all liquid water flowing out of the study area~~.~~), especially ~~in~~ on the ~~Qinghai-Tibetan Plateau~~Qinghai-Tibetan Plateau (e.g., Qiu, 2012; Jin et al., 2009). Intensive field observations of frozen soils have typically been performed at small spatial scales over short periods. Consequently, regional patterns and long-term trends have not been captured.~~Intensive field 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 the l~~Long-term meteorological and hydrological observations are~~a~~ available, but they ~~did~~ do not provide information ~~detailed data~~ on soil freezing and thawing processes (McClelland et al., 2004; Liu et al., 2003; Niu et al., 2011). Therefore, 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 vertical soil freezing-thawing processes, but they~~VIC model~~ simplify~~ies~~ the flow routing using ~~a~~ linear schemes. ~~ized Saint-Venant equation, and CLM model uses a linear transport scheme~~ ~~they represen t the flow routing at the catchment scale by simplified ways simple linearized Saint-Venant equation or linear transport scheme.~~ Subin et al. (2013) and Lawrence et al. (2015) used the CLM model to simulate ~~the~~ global changes ~~of~~ in permafrost. Cuo et al. (2015) used the VIC to simulate frozen soil changes~~degradation~~ and ~~its~~ their hydrological impacts at the plot scale in the headwaters 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 for ~~to apply to~~ regional investigations~~appications~~~~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~~ to better understand~~ing~~ ~~of~~ the frozen soil changes and their impacts on ~~the~~ regional ~~hydrology~~ hydrologic processes and water resources.

The ~~Qinghai-Tibetan Plateau~~Qinghai-Tibetan Plateau (QTP) is known as Asia's water tower, and runoff changes on the plateau have significant impacts on water security in downstream regions (Walter et al., 2010~~),~~); hence, ~~which~~ such changes have ~~received an increasing amount of~~attracted considerable~~a wide~~ attention in recent years (Cuo et al., 2014). The ~~Qinghai-Tibetan Plateau~~QTP is characterized by high elevations and a cold climate.~~-~~ Consequently, ~~Cryospheric~~ cryospheric processes have great impacts on its hydrological processes (Cheng and Jin, 2013; Cuo et al., 2014). ~~In contrast with the Arctic and Subarctic, t~~The thickness of permafrost on the ~~Qinghai-Tibetan Plateau~~QTP ~~is~~ varies from 1 to 130 m, and the temperature ranges~~varies from~~ between -0.5 and -3.5 ℃ (Yang et al., 2010)~~relatively thin and warm, and the frozen depth of the seasonally frozen soils is also relatively shallow~~. Compar~~ing~~ed with the Arctic and Subarctic soils~~As a result~~, the frozen soils on the ~~Qinghai-Tibetan Plateau~~QTP are more sensitive to increased air temperature ~~rising~~ (Yang et al., 2010), and ~~the~~ changes ~~of~~ in the frozen soils may have more significant impacts on the regional hydrology.

~~An evident~~Clear increases in the annual and seasonal air temperatures ~~has~~ have been observed ~~in~~ on the ~~Qinghai-Tibetan Plateau~~QTP (Li et al., 2005; Liu and Chen, 2000; Zhao et al., 2004). Several studies have shown ~~the~~ changes ~~of~~ in frozen soils based on long-term observations. For example, Cheng and Wu (2007) analyzed the

~~borehole observations of~~ soil temperature profiles from boreholes ~~profiles~~ on the ~~Qinghai-Tibetan Plateau~~QTP 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~~ observed a decreasing trend of freezing depth in the seasonally frozen soils ~~using observations~~ at 50 stations. Several studies have analyzed the relationship between ~~the~~ changes ~~of~~ in frozen soils and river discharge using observational~~the observed~~ data (Zhang et al., 2003; Jin et al., 2009; Niu et al., 2011). However, the spatio-temporal characteristics of the long-term changes in frozen soils are not sufficiently clear. Based on comprehensive field experiments (Cheng et al., 2014), a hydrological model coupling cryospheric processes and hydrological processes has been developed (Yang et al., 2015; ~~–~~Gao ~~et~~ et al., 2016). This model 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~~QTP.

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

2. Study Area and Data

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, representing a drainage area of 10,009 km^2, are located on the northeastern ~~Qinghai-Tibetan Plateau~~QTP at ~~an~~ elevations of

2200 to 5000 m~~ with a drainage area of 10,009 km^2~~. T~~T~~he upper reaches of this river 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 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 the remaining portion~~other parts~~ of the study area. Glaciers are found at ~~an ~~elevations above 4000 m, and cover ~~covering~~ approximately 0.8% of the upper Heihe basin. ~~There are two tributaries (East and West Tributaries) in t~~The upper Heihe basin, contains two tributaries,~~on which two~~ each with a hydrological station~~s are located, namely~~, i.e., Qilian (on the eastern tributary) and Zhamashike (on the western tributary). The outlet of the upper Heihe basin also features ~~has ~~a hydrological station, namely, Yingluoxia (see Figure 1).

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 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 elevation-dependent temperature gradient ~~with~~

~~elevation which was~~ provided by the HiWATER experiment (Li et al., 2013).

The land surface data used to run the model include land use, topography, leaf area index, and soil parameters. The topography data were obtained from the Shuttle Radar Topography Mission (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~~);~~) and ~~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 were estimated based on remote sensing data (Wu et al., 2012; Wu, 2013).

The ~~F~~field observation data used in this study include~~s~~ river discharge, soil temperature, frozen depth, soil moisture and borehole observations. Daily river discharge data were obtained from the Hydrology and Water Resources Bureau of Gansu Province. The CMA provided d~~D~~aily 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~~.

We obtained ~~G~~ground ~~T~~temperature observations from six boreholes, whose location are shown in Figure 1, ~~were provided by~~from Wang et al. (2013). We used the observations at specific dates instead of annual averages~~s~~ ~~is~~due to lack of~~difficulty in~~

continuous measurement. 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. 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~~ the distributed eco-hydrological model GBEHM (geomorphology-based ecohydrological model), which was developed 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)~~. The GBEHM is a spatial distributed model for large-scale river basins. It employs ~~the~~ geomorphologic properties to reduce the lateral two-dimensions into one-dimension for flow routing within a sub-catchment, which greatly improves the computational efficiency while retaining the spatial heterogeneity in water flow paths at the basin scale. 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~~, slope gradient, slope aspect, soil type and vegetation type (Yang et al., 2015).

The hillslope is the basic unit ~~for~~ in the hydrological simulation~~, upon which~~of 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 of 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 unit~~s~~ corresponding to each grid. Exchange between the groundwater and the river water is calculated using Darcy's law (Yang et al., 1998, 2002; Cong et al., 2009).

The model runs with a time step of 1 hour. Runoff generated from the grid is the lateral inflow into the river ~~at~~ over 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 the GBEHM includes glacier ablation, snow melting, and soil freezing and thawing.

(1) Glacier ablation

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

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

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

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

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

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

$$M = \frac{Q_M}{L_f} dt \tag{3}$$

where dt is the time step used in the model (s) and L_f is the latent heat of fusion (J·/kg^{-1}).

(2) Snow melt

A multi-layer snow cover model is used to describe the mass and energy balance of snow cover. The snow parametrization of snow is based on Jordan (1991), and two constituents, namely, ice and liquid water, are used to describe 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 Lehnin, 2002):

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

where C_s is the heat capacity of snow (J·m^{-3}·K^{-1}); T_s is the temperature of the snow layer (K); ρ_i is the density of ~~the~~ ice (kg·/m$^{3\text{-}3}$); θ_i is the volumetric ice content; K_s is the thermal conductivity of snow (W·m^{-1}·K^{-1}); L_f is the latent heat of ice fusion (J·/kg^{-1}) ; I_R is the radiation transferred into the snow layer (W·/m$^{2\text{-}2}$); and Q_R is the energy delivered ~~brought~~ by rainfall (W·/m$^{2\text{-}2}$), which is only considered for the top snow layer. The solar radiation transfer in the snow layers and the snow albedo are simulated using the SNICAR model, which is solved using the method developed by Toon et al. (1989). Eq. (4) is solved using an implicit centered finite difference method, and a Crank-Nicholson scheme is employed.

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

$$\frac{\partial \rho_i \theta_i}{\partial t} + M_{iv} + M_{il} = 0 \tag{5}$$

$$\frac{\partial \rho_l \theta_l}{\partial t} + \frac{\partial U_l}{\partial z} + M_{lv} - M_{il} = 0 \tag{6}$$

where ρ_l is the density of the liquid water (kg·m^{-3}~~/m^3~~); θ_l is the volumetric liquid water content; U_l is the liquid water flux (kg·m^{-2}·s^{-1}); M_{iv} is the mass of ice that ~~is changed~~changes into vapour within a time step (kg·m^{-3}·s^{-1}); M_{il} is the mass of ice that ~~is changed~~changes into liquid water within a time step (kg·m^{-3}·s^{-1}); and M_{lv} is the mass of liquid water that ~~is changed~~changes into vapour within a time step (kg·m^{-3}·s^{-1}). The liquid water flux of the snow layer is calculated as follows (Jordan, 1991):

$$U_l = -\frac{k}{\mu_l}\rho_l^2 g \tag{7}$$

where k is the hydraulic permeability (m^2), μ_l is dynamic viscosity of water at 0 °C ~~℃~~ (1.787· ~~×~~ 10^{-3} N· s·/m$^{2\text{-}2}$), ρ_l is the density of liquid water (kg·/m$^{3\text{-}3}$) and g is gravitational acceleration (m·/s$^{2\text{-}2}$). The water flux of the bottom snow layer is considered snowmelt runoff.

(3) Soil freezing and thawing

The energy balance of the soil layer is solved as follows (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 (J·m^{-3}·K^{-1}); T is the temperature (K) of the soil layers; z is the vertical depth of the soil (m); θ_i is the volumetric ice content; ρ_i is the density ~~the~~ of ice (kg·~~/~~m^{-3}); λ_s is the thermal conductivity (W·m^{-1}·K^{-1}); ρ_l is the density of liquid water (kg·~~/m^3~~m^{-3}); and c_l is the specific heat of liquid water (J·kg^{-1}·K^{-1}). In addition, q_l is the water flux between different soil layers (m·~~/~~s^{-1}) 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 follows:

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

where K is the unsaturated soil hydraulic conductivity (m·~~/~~s^{-1}); K_{sat} is the saturated soil hydraulic conductivity (m·~~/~~s^{-1}); θ_l is the volumetric liquid water content; θ_s is the saturated water content; θ_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~~ that is calculated using soil temperature as follows (Wang et al., 2010):

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

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 uppermosttop surface soil layer. When the ground is not covered by snow, the heat flux from the atmosphere into the uppermost top soil layer is expressed as follows (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 (W·-m^{-2}); S_g is the solar radiation absorbed by the uppermost top soil layer (W-·m^{-2}); L_g is the net long wave radiation absorbed by the ground (W-·m^{-2}), H_g is the sensible heat flux from the ground (W-·m^{-2}); λE_g is the latent heat flux from the ground (W-·m^{-2}); and Q_R is the energy delivered brought by rainfall (W·/m$^{2-2}$). When the ground is covered by snow, the heat flux into the uppermost top soil layer is calculated as follows:

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

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

There are The values of geothermal heat flux obtained from the observations along Qinghai-Tibet Highway/Railway in the interior QTP vary from 0.02 W m^{-2} to 0.16 W m^{-2} in the published literature (Wu et al., 2010), but there is no data available observations of the geothermal heat flux for the northeastern QTP. To simulate the permafrost we consider an underground depth of 50 m. We assume anthe bottom boundary condition as upward thermal heat flux at the bottom boundary and estimate its value asto be of 0.1642 W·m^{-2}-$^{-2}$ at a depth of 50 m (Estimated usingby the average geothermal gradient from the 4 boreholes (T1-T4) shown in Figure 3, which is reasonable based on a comparison ~~comparing~~ with the observations (0.02 W·m^{-2} to 0.16 W·m^{-2}) ~~in~~from the interior of the QTP (Wu et al., 2010)~~).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 better capturing the maximum frozen depth according to the field observations.~~ The 1.7 m topsoil layer ~~of 1.7 m~~ is subdivided into 9 layers. The first layer is 0.05 ~~c~~m, and the soil layer thickness increases with depth linearly from 0.05 ~~c~~m to 0.3~~0~~ ~~c~~m ~~up to the~~at a depth~~s~~ of 0.8 m and ~~later~~ then decreases linearly with depth to 0.1~~0~~ ~~c~~m ~~up to the~~at a depth~~s~~ of 1.7 m. There are 12 soil layers with a constant thickness of 0.1 m from 1.7 m to 3.0 m ~~with a constant thickness of 10 cm~~to try to replicate the maximum freezing depths according to field observations. From the depth of 3 m to 50 m, there are 18 layers with thicknesses increasing exponentially from 0.1~~0~~ ~~c~~m 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

To initialize the model, we first estimated the soil temperature profiles based on the assumption that there is a linear relationship between the ground~~soil~~ temperature at a given depth below the surface and elevation ~~at the same depth below surface~~. This temperature-elevation ~~The~~ relationship ~~between groundsoil temperature at a specific~~

~~depth and elevation~~ is estimated from the observed ground~~soil~~ temperatures ~~at~~ in 6 boreholes (see Figure 1). Next, the model had a ~~500~~ 500-year spin up run to specify the initial values of the hydrological variables (e.g., soil moisture, ~~soil temperature,~~ soil ice content, ground temperature, and groundwater table) by repeating the atmospheric forcing data from 1961 to 1970.

This study used ~~T~~the period of 2002 to 2006 ~~was used~~ for model calibration and the period of 2008 to 2012 ~~was~~ for model validation. The daily ground~~soil~~ temperature at the Qilian station and the frozen depths at the Qilian and Yeniugou stations were used to calibrate the ground surface~~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 Rubsico capacity of the top leaf based on the remote sensing evapotranspiration data. Table 1 shows the major parameters used in the model.

~~Simulation case without the frozen soil scheme~~ ~~(~~We also ~~designed A a~~ simulated the hydrological processes~~ion case~~ without the frozen soil scheme ~~in order is designed~~ to investigate the impact of frozen soils ~~on the hydrological processes~~. In this case, the phase transition of soil water between the solid and the liquid is not considered, although the ground~~soil~~ temperature is still simulated. Other processes are simulated ~~as~~ in the same manner as in the normal run.

4. Results

4.1 Validation of the hydrological model

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

Figure 3 shows the comparison of the model-simulated and observed ground~~soil~~ temperature profiles at the six boreholes. The model generally captured the vertical distribution of the ground~~soil~~ temperature at T1, T2, T3 and T4 in the permafrost area, but the temperatures were overestimated~~overestimations were produced~~ above 20 m depth for T1 and T3. Good agreement between the simulated and observed ground~~soil~~ temperature profiles below the depth of 20 m is probably due to fitting of initial values. Therefore,~~This implies that~~ the deep ground temperatures ~~in the deep groundsoil is~~ are stable, which is confirmed by the comparison of temperature profiles in different years, as shown in Figure S1 in the supplementary material~~supplemental file~~. Figure S1 also illustrates that the temperatures above 20 m have ~~shows~~ shown significant increasing trends ~~in~~ over 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, which is located in seasonally frozen ground, the simulated ground~~soil~~ temperature profile did not agree well with ~~that~~ the observed profile at depths of 4-20 m. This error might also be related to ~~the~~ heterogeneity ~~of~~ in the ground~~soil~~ properties, especially the thermal conductivity and heat capacity, since no such information ~~is~~ was available. The model simulation agrees well with the borehole observations at T7, which is located ~~at~~ in the transition zone from permafrost to seasonally frozen ground. Therefore,~~This indicates that~~ the model can identify the boundary ~~of~~ between the permafrost and ~~the~~ seasonally frozen ground.

We also validated the model simulation of the freezing/thawing cycles based on long-term observations of ground~~soil~~ temperature and frozen depth. Figure 4 compares the simulated ground~~soil~~ temperature with the observed temperature at the Qilian station, which is located in ~~the~~ seasonally frozen ground (observed daily ground~~soil~~ temperature data are available from 2004 ~~on~~). Generally, the model simulations accurately captured the seasonal changes in the ground~~soil~~ temperature profile. Validation of the ground~~soil~~ temperature at different depths (0.05 ~~c~~m, 0.1~~0~~ ~~c~~m, 0.2~~0~~ ~~c~~m, 0.4~~0~~ ~~c~~m, 0.8~~0~~ ~~c~~m, 0.16~~0~~ ~~c~~m, and 0.32~~0~~ ~~c~~m) showed that the root mean square error (RMSE) decreases with increasing depth. The RMSE ~~were~~ was approximately 2.5 ℃ for the uppermost ~~top~~ three depths (0.5 ~~c~~m, 0.10 ~~c~~m and 0.2~~0~~ ~~c~~m). The RMSE for depths of 0.4~~0~~ cm and 0.8~~0~~ ~~c~~m were 1.7 ℃ and 1.5 ℃, respectively, and the RMSE for a depth of 3.2 m was 0.9 ℃ ~~at a depth of 3.2 m~~. Uncertainties in the simulations may be related to the ground heat capacity and thermal conductivity estimated according to Farouki (1981), and~~but~~ the results are similar to~~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 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 0.50 cm at the Yeniugou station. In general, the validation of groundsoil temperature and frozen depth indicates that the model effectively captured well the freezing and thawing processes in the upper Heihe basin.

Furthermore, we used the The the observed hourly liquid soil moisture at the A'rou Sunny Slope station was used for an additional independent validation. Figure 6S2 in the supplementary material shows the comparison between the simulated and observed liquid soil moisture at different depths from January 1 to December 31 in, 2014. This comparison By comparing with the observed liquid soil moisturedemonstrates, we can see that the model simulation of liquid soil moisture is reasonable.

Figure 76 compares the model simulated and the observed daily streamflow discharge at the Yingluoxia, Qilian and Zhamashike stations. The model simulations agreed well with the observations. The model simulations captured the flood peaks and the magnitude of base flow in both of the calibration and validation periods. For the Yingluoxia, Qilian and Zhamashike stations,In the calibration period, the Nash-Sutcliffe efficiency (NSE) coefficients were 0.64, 0.65 63 and 0.702 for the Yingluoxia, Qilian and Zhamashike stations, respectively, in the calibration period; in the validation period, the NSE values wereand 0.6564, 0.60, and 0.7573, respectively, in the validation period. The relative error (RE) was within 10% for both the calibration and validation periods (see Figure 76). Figure 8S3 in the supplementary material shows the comparison of the model-simulated monthly actual evaporation data and the 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~~9.~~0~~1 mm in the calibration period and ~~6~~7.~~3~~1 mm in the validation period.

We also compared ~~The~~ the ~~model~~ model-simulated river discharges with and without the frozen soil scheme ~~were compared~~. Table S1 in the supplementary material shows that the model with the frozen soil scheme achieves a better simulation of the daily hydrograph than the model without the frozen soil scheme. Figure ~~S2~~ S4 in the supplementary ~~supplement~~ material shows that the model without the frozen soil scheme ~~overestimated~~ overestimates the river discharge in the freezing season and ~~underestimated~~ underestimates flood peaks in the warming season.

4.2 Long-term changes in frozen soils

In the upper Heihe basin, the ground surface starts to freeze ~~freezing~~ in November and begins to thaw~~thawing initiates~~ in April (Wang et al., 2015a). From November to March, the ground surface temperature is below 0℃ in both the permafrost and seasonally frozen ground regions, and precipitation mainly falls in the period from April to October. Therefore, to investigate the changes in frozen soils and their hydrological impact, 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~~ over the past 50 years ~~was~~ were reported in a previous study (Wang et al., 2015b). Compared to the decadal mean for 1971 to 1980, the annual mean air temperature for the 2001 to 2010 period was approximately 1.2 ℃ higher, with a larger increase in the freezing season (1.4 ℃) than in the thawing season (1.1 ℃) (Table S2).~~Table S2 in the supplement material shows that annual mean air temperature increased by approximately 1.2℃ 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℃) than in the thawing season(1.1℃) between these two periods.~~

Figure ~~9~~ 7 shows the changes in the basin-averaged ground~~soil~~ temperature in the freezing and thawing seasons. The ground~~soil~~ temperature increased in all seasons, especially ~~in~~ over the past 30 years. The increasing trend of ground~~soil~~ temperature was larger in the freezing season than in the thawing season. In the freezing season (Figure ~~9~~7(a)), the top layer ground~~soil~~ temperature was lower than the deep layer ~~soil~~ temperature. The linear trend of the top layer (0-0.5 m) ground~~soil~~ temperature was 0.~~48~~49 ℃·~~/~~decade^{-1}~~10yr~~ and the trend of the deep layer (2.5-3 m) ~~soil~~ temperature was 0.~~34~~32 ℃·decade^{-1}/~~10yr~~. The ground~~soil~~ temperature in the deep layer (2.5-3 m) changed from -~~1~~0.~~1~~7 ℃ in the 1970s to approximately 0 ℃ in the most recent decade. In the thawing season (~~see~~ Figure ~~9~~7(b)), the increasing trend of the top layer (0-0.5 m) ground~~soil~~ temperature (0.29 ℃·decade^{-1}/~~10yr~~) was greater than ~~the trend~~that of the deep layer (2.5-3 m) ~~soil~~ temperature (0.~~21~~22 ℃·decade^{-1}/~~10yr~~). The warming trend ~~is~~ was larger in shallow ground layerss~~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 ℃ for at least two consecutive years (Woo, 2012). This study differentiated permafrost from seasonally frozen ground based on the simulated vertical ground~~soil~~ temperature profile in each grid. For each year in each grid, the frozen ground condition was determined by searching the ground~~soil~~ temperature profile within a four-year window from the previous three years to the current year. Figure ~~10~~ 8 shows the change in permafrost area during 1971-2013. As shown in Figure ~~10~~8(a), the permafrost areas decreased by approximately ~~9~~8.~~5~~8% (from ~~6445~~ 5700 km^2 in the 1970s to ~~5831~~ 5200 km^2 in the 2000s), indicating an evident decrease in~~degradation of~~ the permafrost extent in the upper Heihe basin in the past 40 years.

Figure ~~10~~ 8 (b) shows the changes in the basin-averaged maximum frozen depth ~~for~~ in the seasonally frozen ground areas and active layer thickness ~~over~~ in the permafrost areas. The basin-averaged annual maximum frozen depth showed a significant decreasing trend (0.0~~5.2~~32 ~~c~~m·decade^{-1}~~/10yr~~). In addition, the maximum frozen depth had a significantly negative correlation with the annual mean air temperature (r = -0.~~73~~71). ~~An increasing trend of~~ Simulated active layer thickness in the permafrost regions ~~was observed~~increased (0.0~~3.5~~43 ~~c~~m·decade^{-1}~~/10yr~~), ~~which had~~and correlated ~~a significantly~~ positively~~ correlation~~ with the annual mean air temperature (p = 0.005).

Figure ~~11~~ 9 shows the frozen soil distributions in the periods of 1971 to 1980 and ~~in the period of~~ 2001 to 2010. Comparing the frozen soil distributions of the two periods, we observed major changes in the frozen soils ~~were observed~~ on ~~the~~ sunny slopes at elevations between 3500 and 3~~7~~900 m, especially in the west tributary, where large areas of permafrost changed into seasonally frozen ground. Figure S55, illustrating shows the taliks simulated in the period of 2001-2010, shows that the taliks were mainly located on the edge of the permafrost area and the development of taliks was not significantwhich indicates that talik development was not significant in the upper Heihe basin.

Figure 12 10 shows the monthly mean soil ground temperatures over for the areas with elevations between 3300 and 3500 m and over areas with elevations between 3500 and 3700 m in the upper Heihe basin. In the areas with elevations between 3300 and 3500 m located in the seasonally frozen ground region, as shown in Figure 1210(a), the frozen depth decreased, and the groundsoil temperature in the deep layer (with depths greater than 2 m) increased. Figure 1210(b) shows that the increase in groundsoil temperature was larger in the area with higher elevation (3500-3700 m). This figure shows that the thickness of the permafrost layer decreased as the groundsoil temperature increased, and the permafrost changed into seasonally frozen ground after 2000. The thaw depths changed slowly comparinged with the frostfrozen depths as shown in Figure 120, which may be primarily the effect ofdue to the geothermal heat flux mainly. Additionally, the Ffaster rising ofincrease in the air temperature rise fasterchain the freezing season (1.40.41? ℃℃ decadeyear^{-1}) was much larger thanin in the thawing season (1.10.26? ℃ decadeyear^{-1}) may be another reason.

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 exhibited had the same decadal variation; however the annual evapotranspiration maintained an increasing trend since starting in the 1970s which that was consistent with the rising air temperature and soil warming. Although the actual evapotranspiration increased, the runoff ratio remained stable during the past 4 decades because of the increased precipitation.

Figure 11 and Table 2 show tThe 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 exhibited showed a significant increasing trends in the freezing season and in the thawing season. Therefore, This indicates that the model simulation effectively well reproduced the observed long-term changes. In the freezing season, since there was no glacier melt andor snow melting (see Table 2), the 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 1614% of the total runoff, and whereas glacier runoff contributed only a small fraction of the total runoff (approximately 2.42%). Therefore, rRainfall runoff was the major component of the total runoff in the thawing season, and the runoff increase in the thawing season was mainly due to increased rainfallprecipitation and snowmelt. As shown in Figure 1311, the actual evapotranspiration increased significantly in both seasons due to increased precipitation and groundsoil warming. The increasing trend of the actual evapotranspiration was higher greater in the thawing season than in the freezing season.

Figure 14 12 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 11 (a), exhibiting with a correlation coefficient of 0.8079. The annual ice water storage in the top 0-3 m soil layers showed a 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 has increases increased with the frozen soil degradation.

5. Discussion

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

We have plotted the Llong-term changes of in the spatially averaged liquid soil moistures in the region areas with elevations between 3300 and 3500 m and in the region areas with elevations between 3500 and 3700 m are shown in Figure S3 S6 in the supplementary supplement material. In the seasonally frozen ground with at elevations 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 byincreased slightly due to the decrease in the frozen depth, as shown in Figure 10(a). At elevations of 3500-3700 m, the liquid soil moisture in the deep soil layer increased significantly since the 1990s,, due to permafrost changed to seasonally frozen ground 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 as shown in Figure 12 (b), due to the change of the permafrost into the seasonally frozen ground, as shown in Figure 10 (b). This 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 changes was were the primary 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 frozen depth of the seasonally frozen ground decreased, leadingwhich led to to increased increases in the 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 1513(c) shows the seasonal pattern of runoff in from the entire basinthe permafrost area and seasonally frozen soils. From April to October (the thawing season), runoff in the permafrost area is was much larger than in the seasonally frozen soilsground, ; however, but in the freezing season runoff in the permafrost area is was lower than in the seasonally frozen soilsground. Figure S4 S7 in the supplementary supplement material shows runoff changes from a typical area (with elevations between of 3500-3700 m) that featuredwhere covered by the permafrost in during the period of 1971 to 1980 and that changed into the seasonally frozen ground in during the period of 2001 to 2010. This illustrates that the thawing of the permafrost increased the runoff in the freezing season and slowed recession processes in autumn.

Figure S~~2~~4 illustrates ~~T~~the increase in freezing season runoff and the shift in the seasonal flow patterns~~ are also illustrated~~ simulated by the model ~~simulation~~ without the 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 from the rainfall and was mainly rainfall runoff, as shown in Table 2. The increased runoff mainly came from increaseddue to precipitation and snowmeltincrease 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 seasons.~~ Figure 13 shows the large difference in runoff variation with elevation between the freezing and thawing 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~~9) was relatively small. The areas with elevations of 3500 ~~to~~ -3900 m showed larger changes in runoff. This pattern 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~~9). 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 areas of ~~the~~ seasonally frozen ground. In the thawing season, runoff increased with elevation due to the increase in precipitation with increasing elevation, and the magnitude of the runoff increase was mainly determined by magnitude of the ~~increased~~ precipitation increase

(Gao et al., 2016). Precipitation in the region with elevations below 3100 m was low, ~~but~~ and the air temperature was high. Hence, ~~R~~runoff in this region ~~decreased~~ was lower during 2001-2010 ~~compared to~~than during 1971-1980 because of ~~higher~~ greater evapotranspiration.

5.2 Comparison with the previous similar studies

In this study, the model simulation showed that the thawing of 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~~ the impact of the frozen soil thawing ~~the thaw of frozen soils~~ on runoff ~~had~~ varied regional~~ characteristics~~ly. In the upper Heihe basin (see Figure ~~15~~13), ~~thaw of frozen soils led to increased runoff at higher elevations but led to decreased runoff at lower elevations during the freezing season. This implies that~~the change ~~of~~ in the freezing season runoff was strongly affected by the change ~~of the~~from permafrost to seasonally frozen ground~~degradation~~ in the ~~higher~~ higher-elevation region ~~but~~ and by the evaporation increase in the ~~lower~~ lower-elevation region due to rising ~~the~~ air temperature~~ rising~~. However, runoff at the basin scale mainly came from the ~~higher~~ higher-elevation regions.

This study also showed that the thawing of frozen soils increased the liquid soil ~~liquid~~ moisture in the upper Heihe basin, which is consistent with the finding of Subin et al. (2013) using the CLM model ~~simulation~~ to simulate ~~in~~ northern high-latitude permafrost regions, and the findings of Cuo et al. (2015) using the VIC model to ~~simulation~~ simulate ~~at~~ 13 sites on the ~~Tibetan Plateau~~QTP. In contrast,~~However,~~ Lawrence et al. (2015) found that permafrost thawing ~~caused~~ reduced soil moisture ~~drying~~ based on CLM model simulations ~~for~~ of the global permafrost region. This finding 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~~simulated the soil moisture changes in the active layer of permafrost ~~in~~ over large areas with coarse spatial resolution. Unlike those studies, ~~This~~ this study ~~revealed~~ investigated the spatio-temporal variability ~~of~~ in soil moisture ~~with~~ using a high spatial resolution and analyzed the ~~correlations~~ impacts~~with~~ of ~~the change in~~ frozen soil~~s~~ changes.

~~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 area~~s~~ ~~in~~ of the Yellow River basin. ~~This~~ These results ~~is~~ are different from those in the present study, possibly due to the difference ~~of~~ in the hydrogeological structure and ~~the~~ soil hydraulic parameters ~~in~~ between the source area of the Yellow River ~~from those~~and ~~in~~ the upper Heihe basin. Wang et al. (2015a) estimated the increasing trend of the maximum frozen depth in the seasonally frozen ground to be 0.04 m·decade^{-1} during 1972-2006 in the Heihe River basin ~~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 results ~~GBEHM model simulation~~ in this study. The increase in groundwater storage illustrated in this study is also consistent with the findings 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. Guo et al. (2013) reported that the permafrost area for the whole ~~Qinghai-Tibetan Plateau~~QTP decreased from approximately ~~about~~ 175.0×~~×~~ 10^4 km^2 in 1981 to 151.5×~~×~~ 10^4 km^2 in 2010, 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 of the ~~,~~Q~~inghai-~~T~~ibetan~~ P~~lateau~~ 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~~ along the southern portion of the Qinghai~~–~~-Tibet Highway, from 1975 to 1996. Compared with the borehole observations by Wang et al. (2013) shown in Figure 2, ~~this~~ our model slightly overestimated the soil temperature in permafrost areas, ~~which might~~possibly ~~–~~leading to an 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 simulation of the ~~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 uncertainty in the~~the estimations of~~ radiation and surface albedo estimates due to the complex topography, vegetation cover and soil moisture distribution, thereby~~which may introduce~~ introducing uncertainties into the estimated ground temperature and ~~thermal~~ soil heat flux~~ into the deep layers~~. The uncertainty in the simulation of soil heat-water transfer processes might result from the soil water and heat parameters and the bottom boundary conditions of heat flux. For example, the soil depth and the fraction of rock in soil ~~may~~ can greatly affect the ground~~soil~~ temperature simulation. Permafrost degradation is closely related to the thermal properties of rocks and soils, the geothermal flow and the initial ground~~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^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. 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~~ between the low-elevation valleys and higher-elevation slopes due to the ~~different vegetation conditions, soil organic layers and shading by surroundings~~ temperature inversion caused by the~~due to~~ accumulation of cold air in valleys (Bonnaventure et al., 2012; Zhang et al., 2013; O'Neill et al., 2015). ~~This is not well considered in this study.~~ ~~The present study does not consider~~ ~~Figure S5 in the supplementary material shows there is~~

~~non-significant talik development in permafrost area. For discontinuous permafrost,~~ ~~t~~The ~~llL~~aterally advected heat ~~lateral heat~~ flux ~~that~~ may increase the thawing ~~rate~~ of permafrost, especially in areas with high groundwater flow rates (Kurylyk et al., 2016; Sjöberg et al., 2016)~~,~~. Not considering the lateral heat flux may lead ~~and~~ ~~this effect is not considered in the present study.~~ to an underestimation of talik development and~~This may lead to underestimation of~~ thawing rates of ~~discontinuous~~ permafrost~~,~~. ~~especially when high groundwater flow rate events occur.~~ In addition, uncertainties ~~from~~ in the input data, particularly ~~the~~ solar radiation (which is estimated using interpolated sunshine hour data from a limited number of observational stations) and precipitation (which is also interpolated ~~by~~ based on observations at these stations), may also influence the results of the model simulation. Due to the complexity of the distributed model and the large number of model parameters, quantifying the ~~it is challenge to quantify~~ overall simulation uncertainty is challenging. This work will be done in ~~the~~ a future study.

6. Conclusions

This work carefully validated a ~~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 effects of the frozen soil~~s~~ changes on the hydrological processes were explored. Based on these analyses, we have reached the ~~the~~ following conclusions ~~can be drawn~~:

(1) The model simulation suggests that ~~9~~8.~~5~~8% of the permafrost areas degraded into seasonally frozen grounds in the upper Heihe River basin during ~~the period of 1~~1971 ~~to~~-2013, ~~which~~ predominantly ~~occurred at~~ between ~~the~~ elevations ~~between~~ of 3500 m and 3900 m. The results indicate that the~~The~~ decreasing trend of the annual maximum frozen depth of the seasonally frozen ground ~~annual maximum frozen depth~~ is ~~estimated to be~~ 0.0~~5.2~~32 ~~c~~m·decade^{-1}~~/10yr for the seasonally frozen grounds~~, which is consistent with previous observation-based studies at the plot scale. Additionally, our work indicates that ~~The~~ the increasing trend of active layer thickness in the permafrost regions is ~~estimated to be~~ 0.0~~3.5~~43 ~~c~~m·decade^{-1}~~/10yr in the permafrost regions~~.

(2) The m~~M~~odel~~-~~-simulated ~~trends in~~ runoff trends agree with the observed trends. In the freezing season (November-March), based on the model simulation, runoff was mainly sourced ~~by~~ from subsurface flow, which increased significantly in the higher elevation regions where significant frozen soil changes occurred. This finding implies that the runoff increase in the freezing season is primarily caused by frozen soil changes (permafrost degradation and reduced~~decrease of~~ ~~the~~ seasonally frozen depth). In the thawing season (April-October), the model simulation indicates that runoff was mainly ~~came~~ sourced from rainfall and showed an increasing trend at ~~the~~ higher elevations, which can be explained by the ~~increased~~ increase in precipitation. In both the freezing and thawing seasons, the ~~model~~ model-simulated runoff decreased in the ~~lower~~ lower-elevation regions, which can be explained by increased evaporation due to ~~the~~ rising air temperatures.

(3) The ~~Model~~ model-simulated changes in soil moisture and ground~~soil~~ temperature

indicates that the annual storage of the liquid water increased, especially in the most recent three decades, due to frozen soil the changes in frozen soils. The Aannual ice water storage in the top 0-3 m of soil showed a significant decreasing trend due to soil warming. The Model model simulated annual groundwater storage had an increasing trend, which is consistent with the changes observed by the GRACE satellite. This indicated thatherefore, —groundwater recharge in the upper Heihe basin has increasedwas enhanced in recent decades.

(4) The Mmodel 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 throughout the study period.

For a better understanding of the 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 that might be related to the soil properties, the high spatial heterogeneity, and the assumption of zero geothermal heat flux at the lower boundary, all of which also warrant further investigation in the future.

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~~their constructive comments, which greatly improved the manuscript.~~ All data for this paper are properly cited and referred in the reference list. The model code with a working example is freely available from our website (https://github.com/gb03/GBEHM) or upon request from the corresponding author (yangdw@tsinghua.edu.cn).

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~~-~~**Figure caption:**

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

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

Figure 3. Comparison of the simulated and the observed soil temperature at borehole observation sites, and the observed data is provided by Wang et al. (2013).

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

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

Figure 6. Comparison of the simulated and the observed daily river discharge at: (a) the Yingluoxia Gauge, (b) the Qilian Gauge, and (c) the Zhamashike Gauge. For each gauge, the upper and lower panels show the calibration and validation periods, respectively. Nash-Sutcliffe efficiency and relative error coefficients are indicated.~~Comparison of the simulated and the observed hourly liquid soil moisture at the A'rou Sunny Slope station~~

Figure 7. ~~Figure 7.~~ Simulated ground temperature changes in: (a) the freezing season (from

November to March) (b) the thawing season (from April to October).

~~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 calibration period, and the bottom panel is the validation period for each gauge))~~

Figure 8. Change of the frozen soils in the upper Heihe basin: (a) areas of permafrost and basin averaged annual air temperature; (b) the basin averaged annual maximum depths of seasonally frozen ground and thaw above permafrost.~~Comparison of the simulated and the remote sensing estimated actual evapotranspiration provided by Wu (2013) in the period of 2002~2012~~

Figure 9. Distribution of permafrost and seasonally frozen ground for two periods: (a) 1971-1980 and (b) 2001-2010; (c) Area where permafrost degraded to seasonally frozen ground from (a) to (b); Percentage of permafrost area with respect to elevation on the (d) sunny and (e) the shaded slopes for the two periods. Note that (d) and (e) share a legend.

~~Changes of the mean soil temperature in different seasons: (a) the freezing season (from November to March) (b) the thawing season (from April to October)~~

Figure 10. Spatially averaged monthly ground temperatures simulated from 1971 to 2013 for two elevation intervals: (a) seasonally frozen ground between 3300 and 3500 m; (b) permafrost that degraded to seasonally frozen ground between 3500 and 3700 m.

~~Change of the frozen soils in the upper Heihe basin: (a) areas of permafrost and basin averaged annual air temperature; (b) the basin averaged annual maximum frozen depth of the seasonally frozen ground and the annual maximum thaw depth of the permafrost~~

Figure 11. Runoff and simulated evapotranspiration in (a) the freezing season and (b) the thawing season. Trend lines are for simulated data. The up two panels are for freezing season and the lower

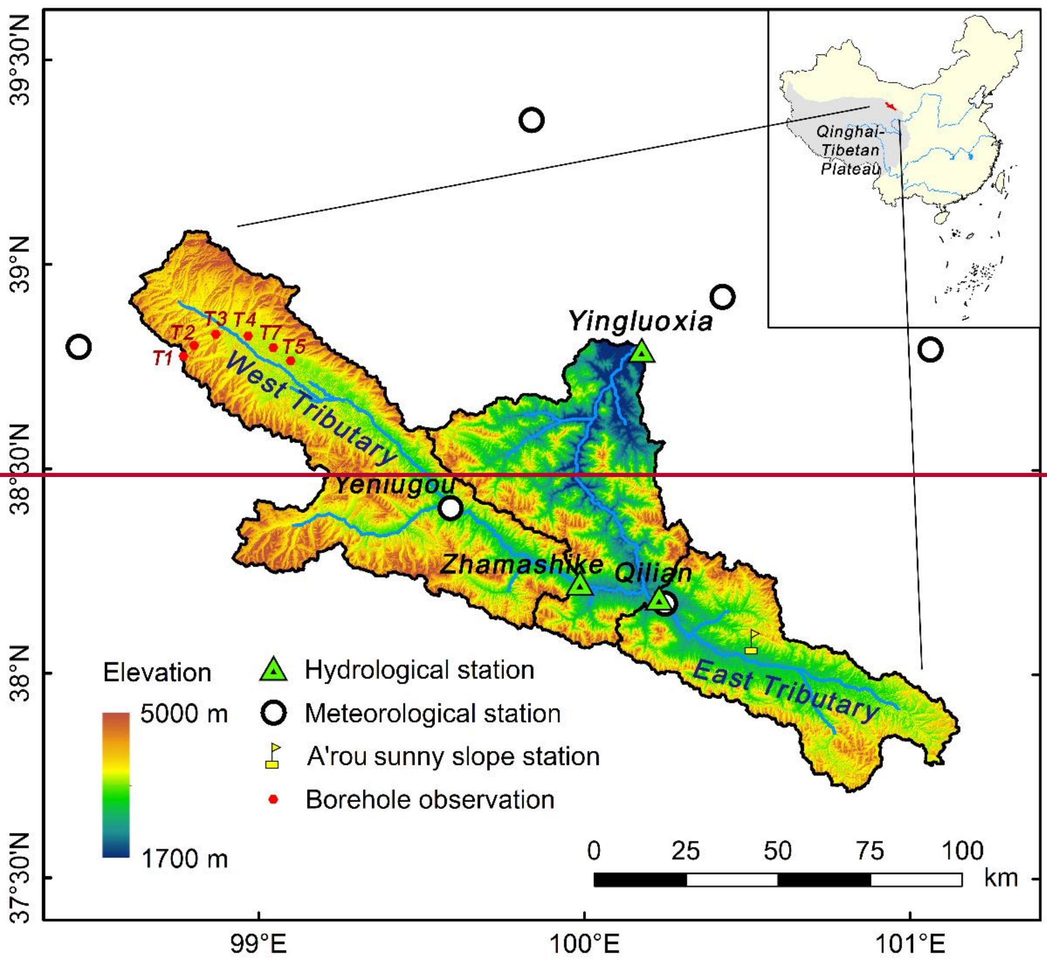
two panels are for thawing season.~~Distribution of permafrost and seasonally frozen ground: (a) distribution in the period of 1971-1980; (b) distribution in the period of 2001-2010; (c) Areas where where permafrost changed into seasonally frozen ground (d) percentage of areas of permafrost on sunny slope; (e) percentage of areas of permafrost on shaded slope (the same legend as (d))~~

Figure 12. Basin averaged annual water storage (equivalent water depth) changes simulated over the period of 1971 to 2013 for: (a) liquid water in the top layer of the ground (0-3 m); (b) ice in the top layer of the ground (0-3 m); (c) and ground water. ~~Spatial averaged monthly soil temperature during the period of 1971-2013 in different elevation intervals: (a) the seasonally frozen ground with elevation between 3300-3500 m; (b) the areas where permafrost changed to seasonally frozen ground with elevation between 3500-3700 m~~

Figure 13. Model simulated runoff changes from the 1971-1980 period to the 2001-2010 period with elevation for (a) the freezing season and (b) the thawing season, and (c) monthly averaged seasonal runoff in permafrost and seasonally frozen ground for the period of 2001-2010.~~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.~~



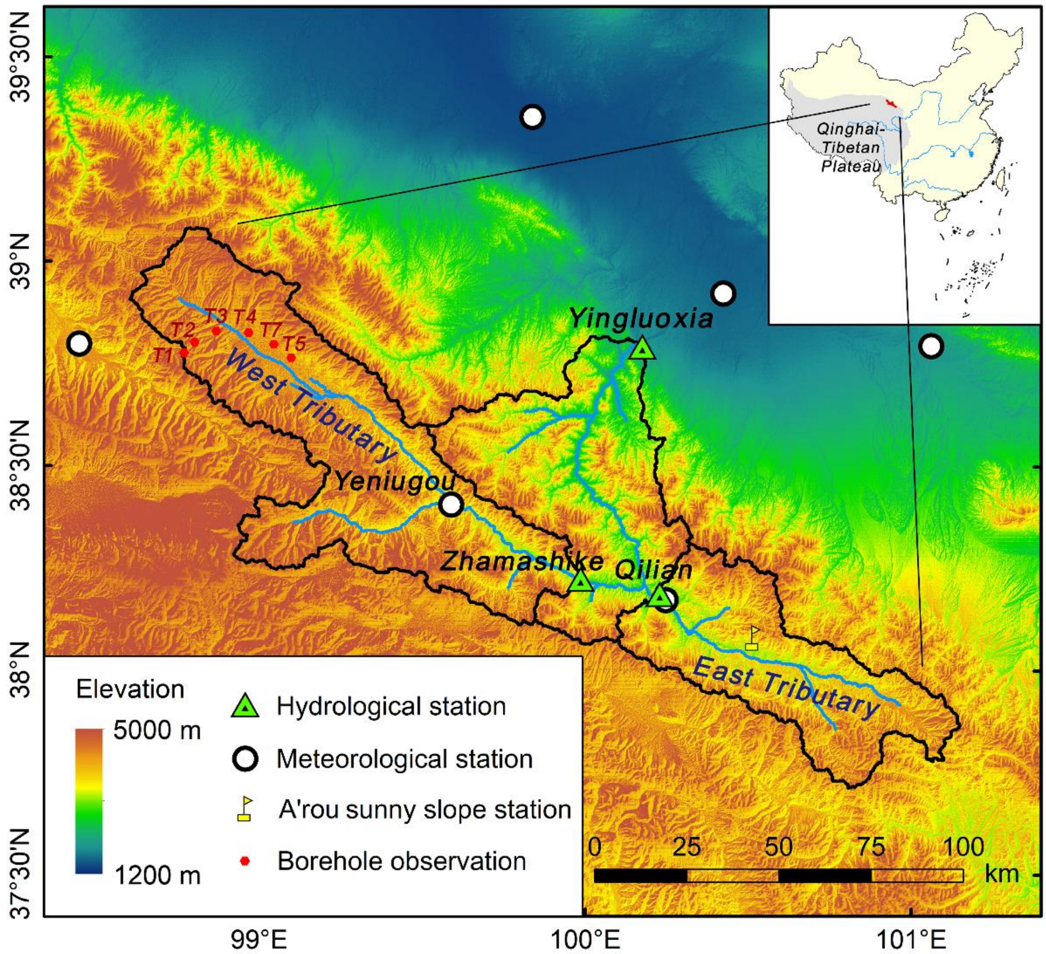
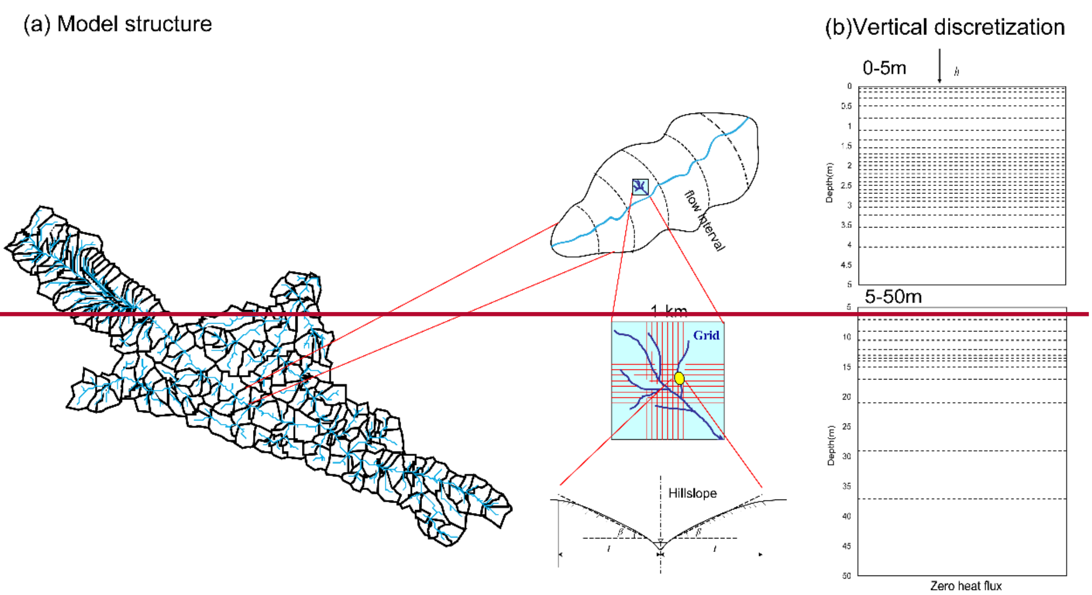


Figure 1. The Study area, hydrological stations, borehole observation and flux tower stations.



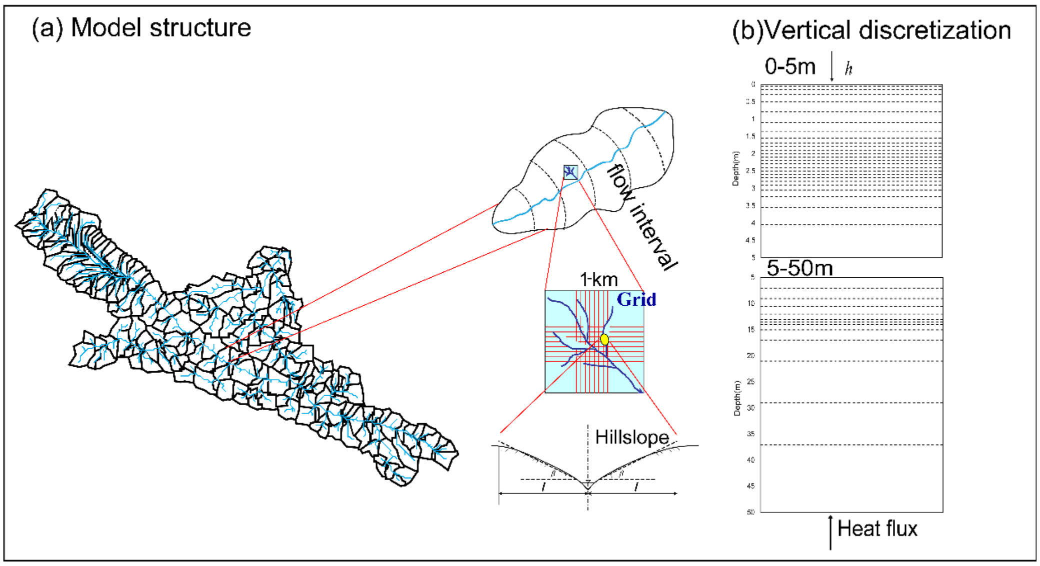
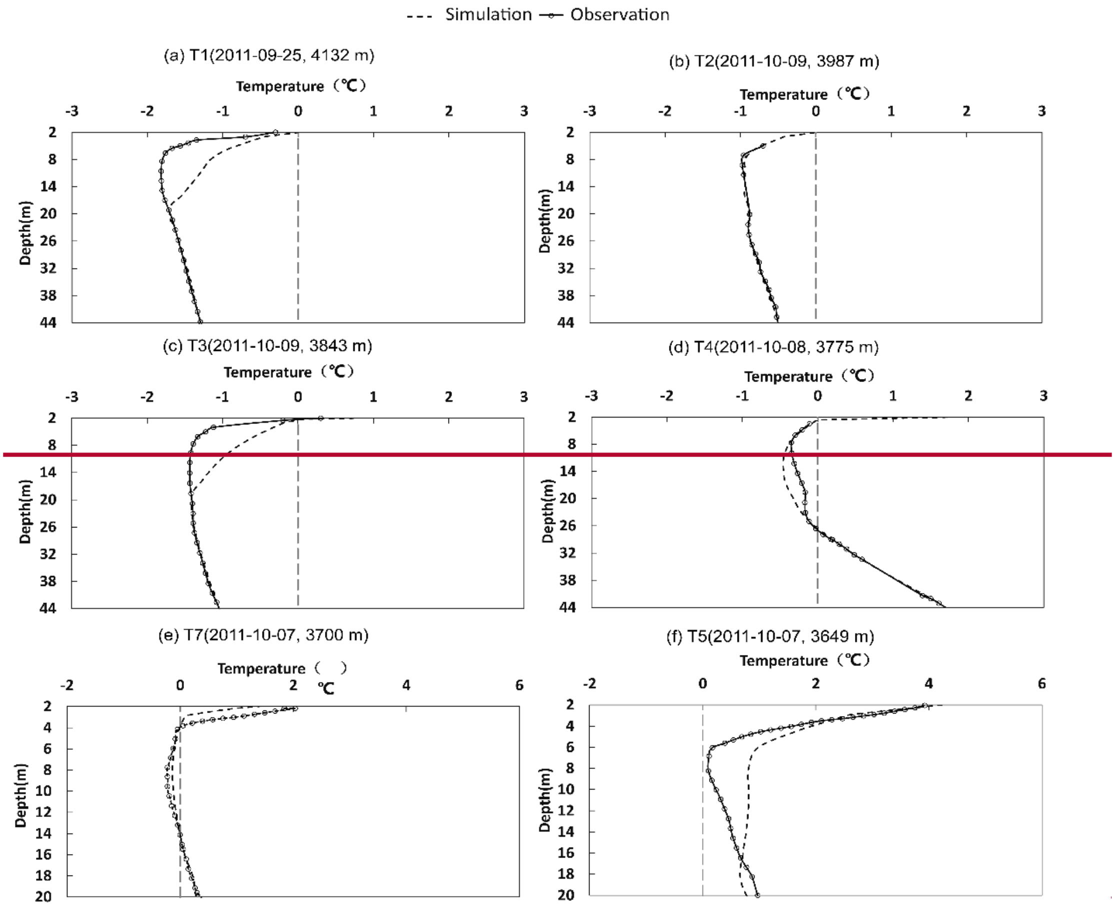


Figure 2. Model structure and vertical discretization of soil column.



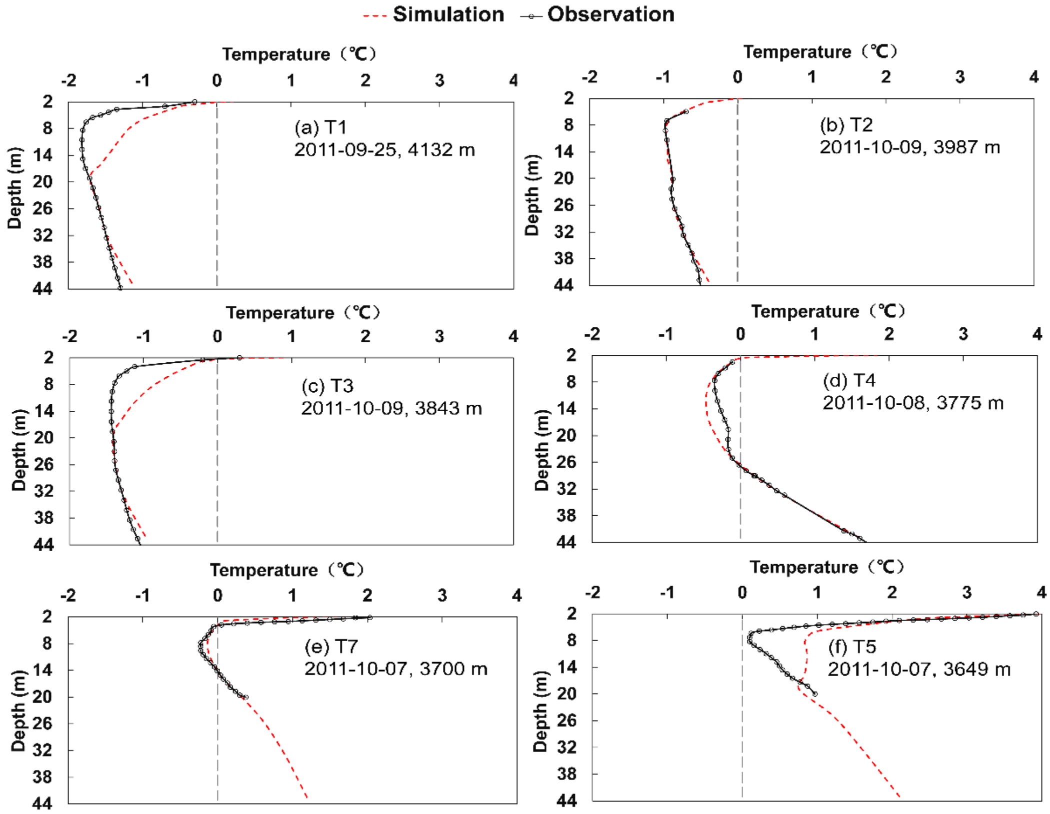
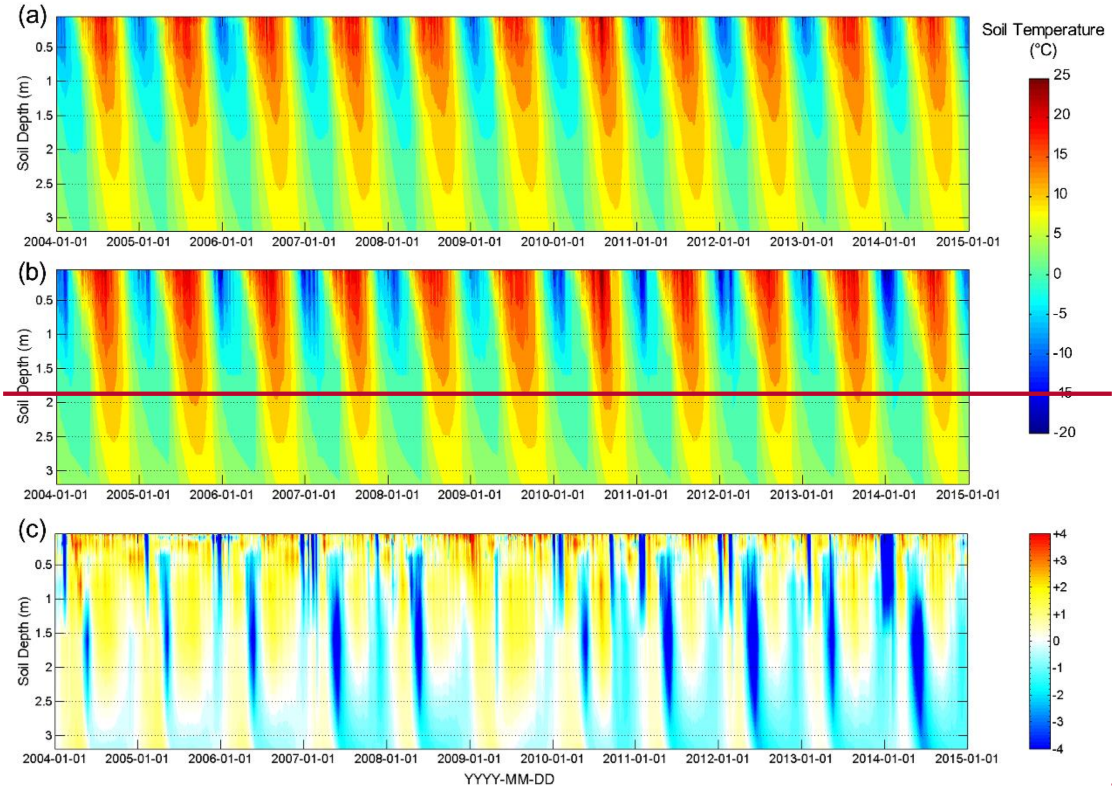


Figure 3. Comparison of the simulated and the observed soil temperature at borehole

observation sites, and the observed data is provided by Wang et al. (2013).



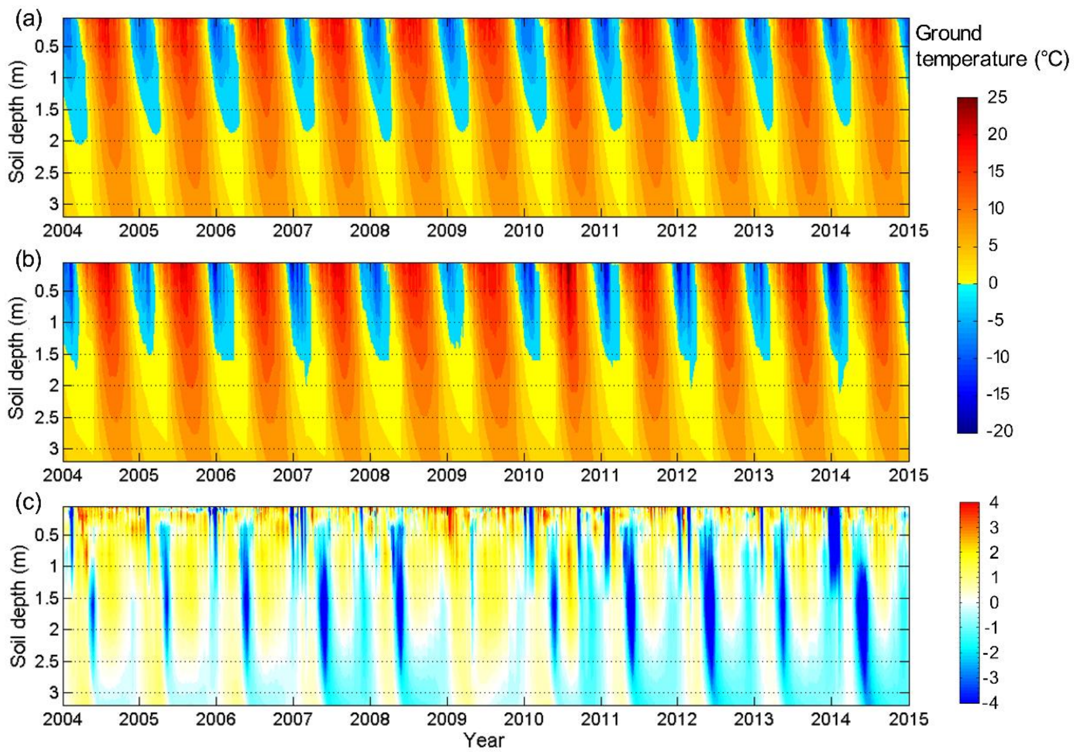
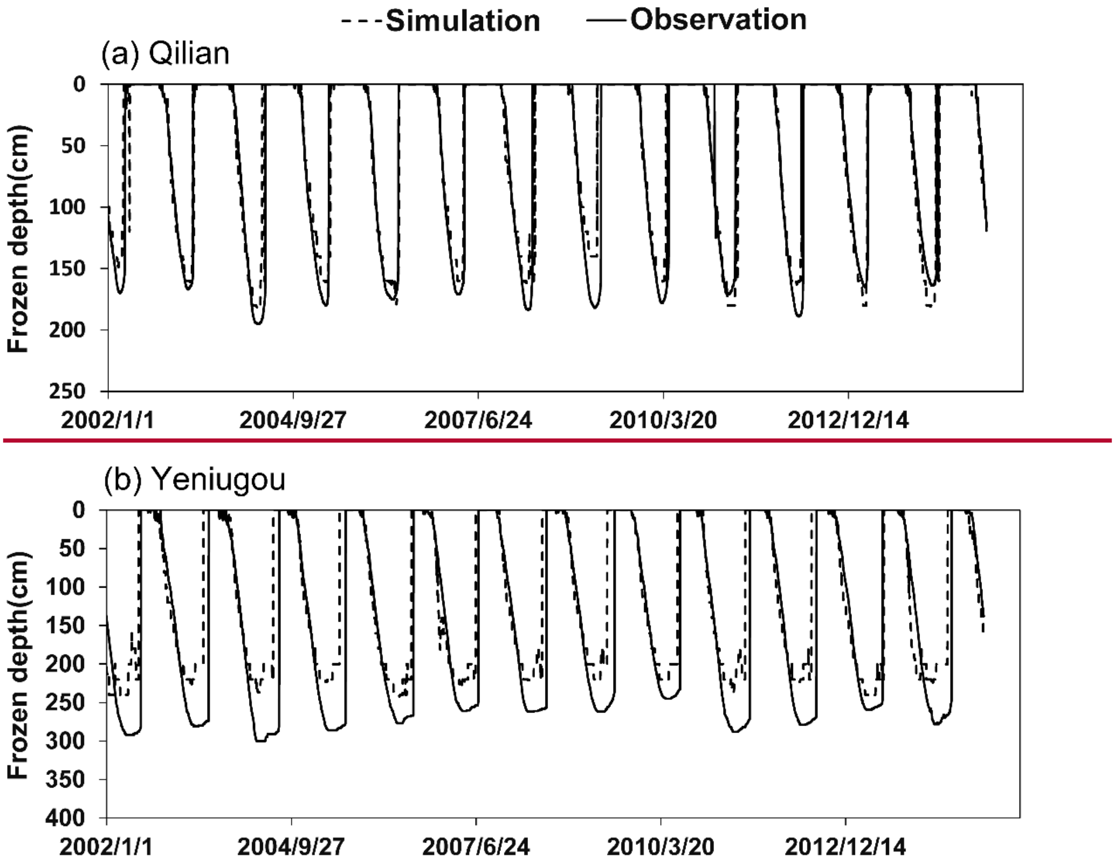


Figure 4. Daily soil temperature at the Qilian station: (a) observation; (b) simulation; (c) difference ~~the~~ (simulation ~~and the-~~ observation)~~Simulation-Observation~~.



- - - Simulation
—— Observation
(a) Qilian
Frozen depth(cm)
0
50
100
150
200
250
2002/1/1
2004/9/27
2007/6/24
2010/3/20
2012/12/14
(b) Yeniugou
Frozen depth(cm)
0
50
100
150
200
250
300
350
400
2002/1/1
2004/9/27
2007/6/24
2010/3/20
2012/12/14

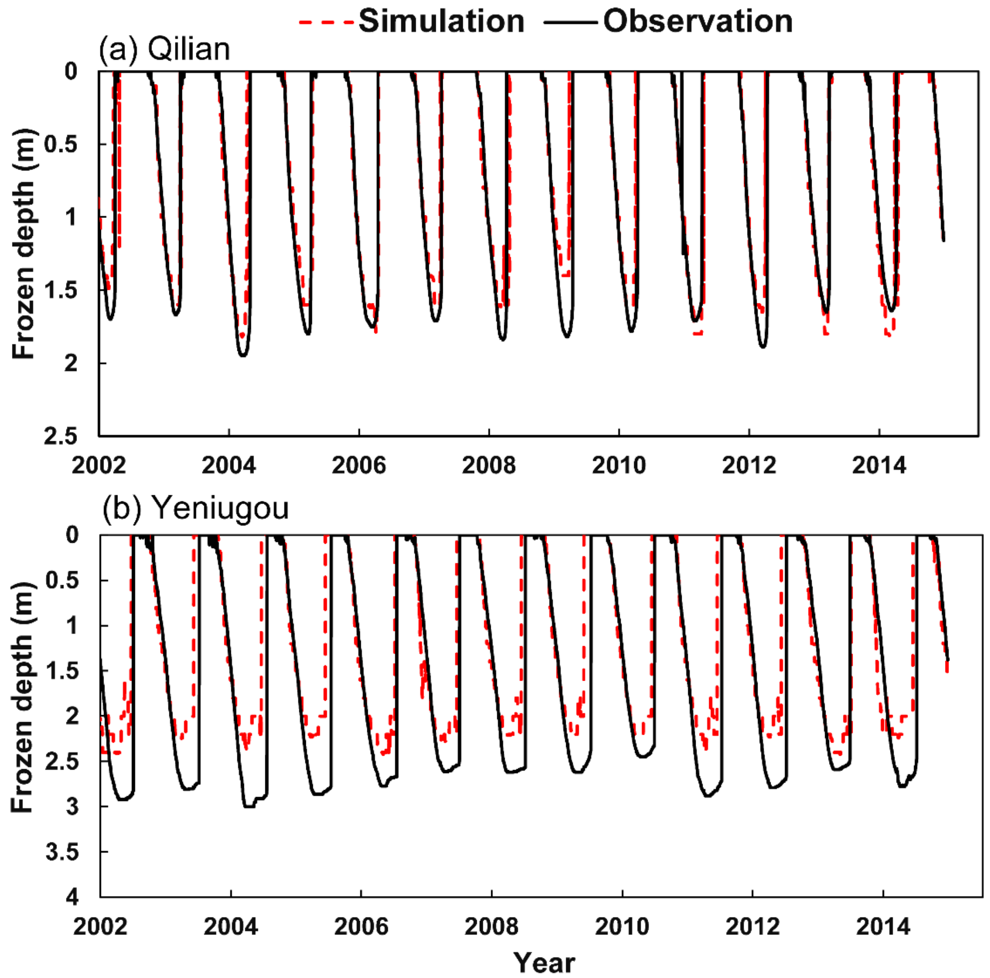


Figure 5. Comparison of the simulated and observed daily frozen depths during the period of 2002-2014 at: (a) the Qilian station, (b) the Yeniugou station.

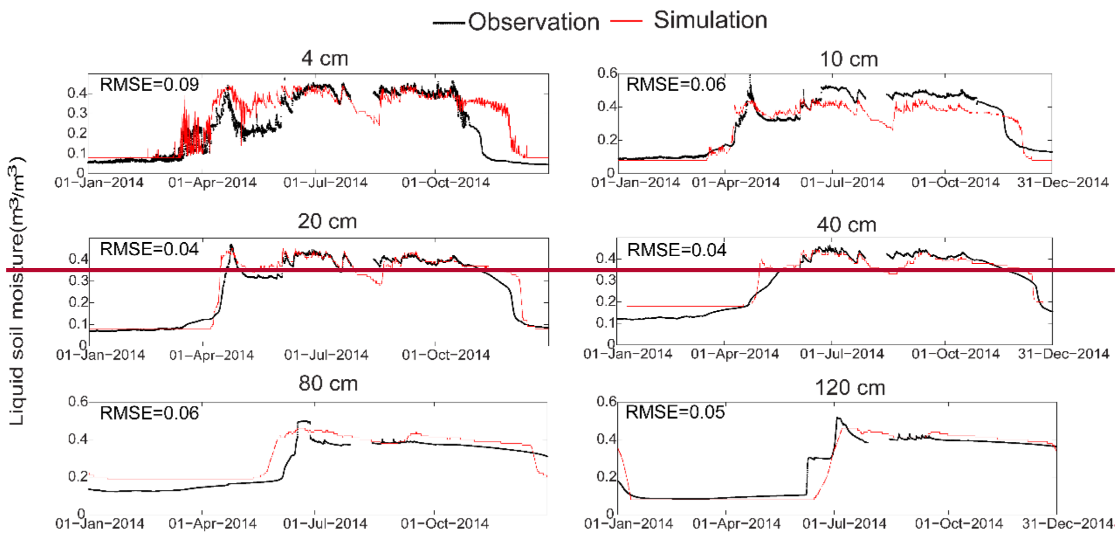
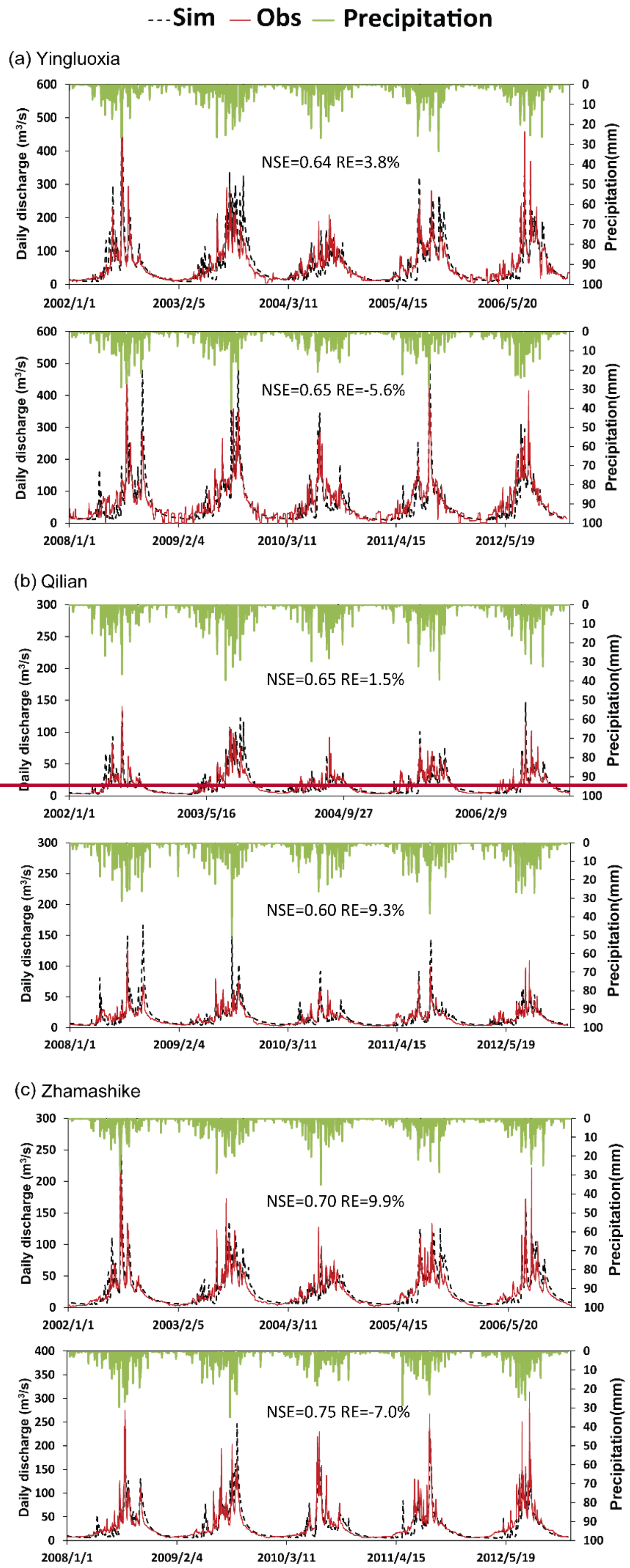


Figure 6. Comparison of the simulated and the observed hourly liquid soil moisture at the A’rou Sunny (Slope station


Sim
Obs
Precipitation
(a) Yingluoxia
NSE=0.64 RE=3.8%
NSE=0.65 RE=-5.6%
(b) Qilian
NSE=0.65 RE=1.5%
NSE=0.60 RE=9.3%
(c) Zhamashike
NSE=0.70 RE=9.9%
NSE=0.75 RE=-7.0%
Daily discharge (m3/s)
Precipitation(mm)
2002/1/1
2003/2/5
2004/3/11
2005/4/15
2006/5/20
2008/1/1
2009/2/4
2010/3/11
2011/4/15
2012/5/19
2003/5/16
2004/9/27
2006/2/9

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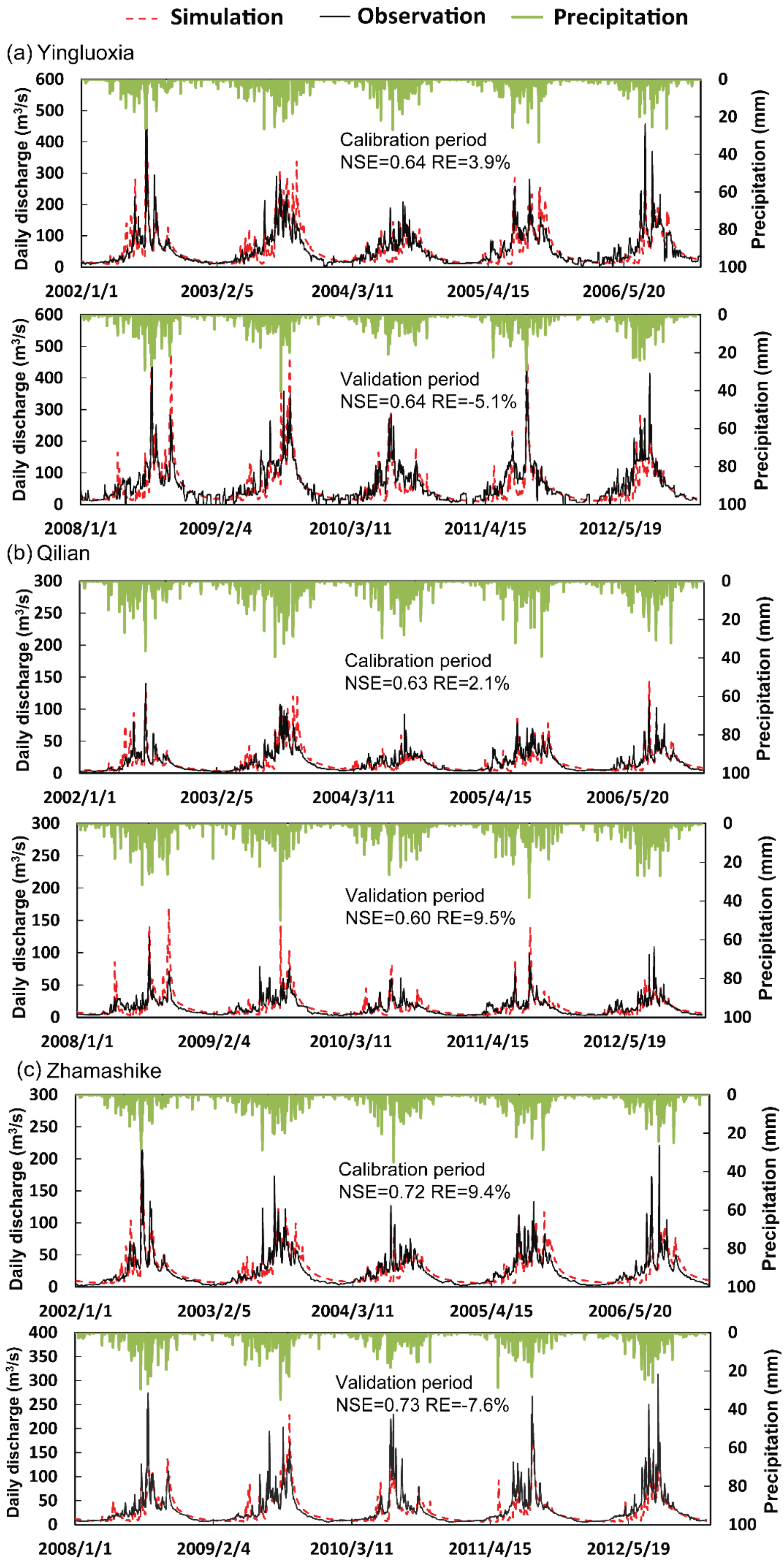
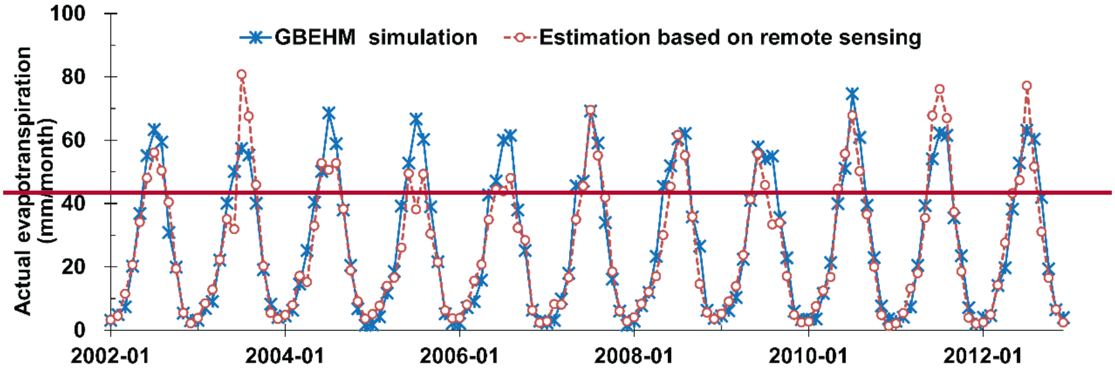
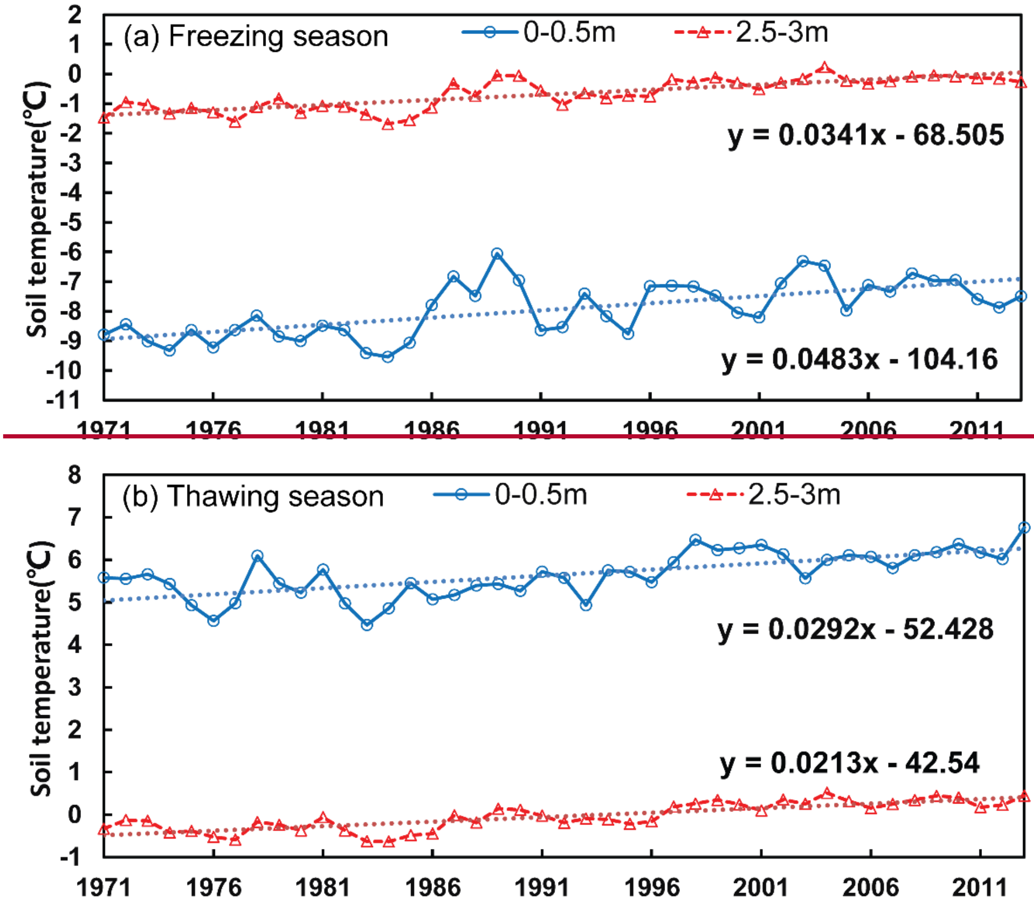


Simulation
Observation
Precipitation
(a) Yingluoxia
Calibration period
NSE=0.64 RE=3.9%
Validation period
NSE=0.64 RE=-5.1%
(b) Qilian
Calibration period
NSE=0.63 RE=2.1%
Validation period
NSE=0.60 RE=9.5%
(c) Zhamashike
Calibration period
NSE=0.72 RE=9.4%
Validation period
NSE=0.73 RE=-7.6%
Daily discharge (m³/s)
Precipitation (mm)
2002/1/1
2003/2/5
2004/3/11
2005/4/15
2006/5/20
2008/1/1
2009/2/4
2010/3/11
2011/4/15
2012/5/19

Figure ~~7~~6. Comparison of the simulated and the observed daily river discharge at: (a) the Yingluoxia Gauge, (b) the Qilian Gauge, and (c) the Zhamashike Gauge. For each gauge, the upper and lower panels show the calibration and validation periods, respectively. Nash-Sutcliffe efficiency and relative error coefficients are indicated. ~~(The upper panel is calibration period, and the bottom panel is the validation period for each gauge)).~~



~~Figure 8. Comparison of the simulated and the remote sensing estimated actual evapotranspiration provided by Wu (2013) in the period of 2002~2012~~


(a) Freezing season
0-0.5m
2.5-3m
y = 0.0341x - 68.505
y = 0.0483x - 104.16
Soil temperature(℃)
(b) Thawing season
0-0.5m
2.5-3m
y = 0.0292x - 52.428
y = 0.0213x - 42.54
Soil temperature(℃)
1971 1976 1981 1986 1991 1996 2001 2006 2011

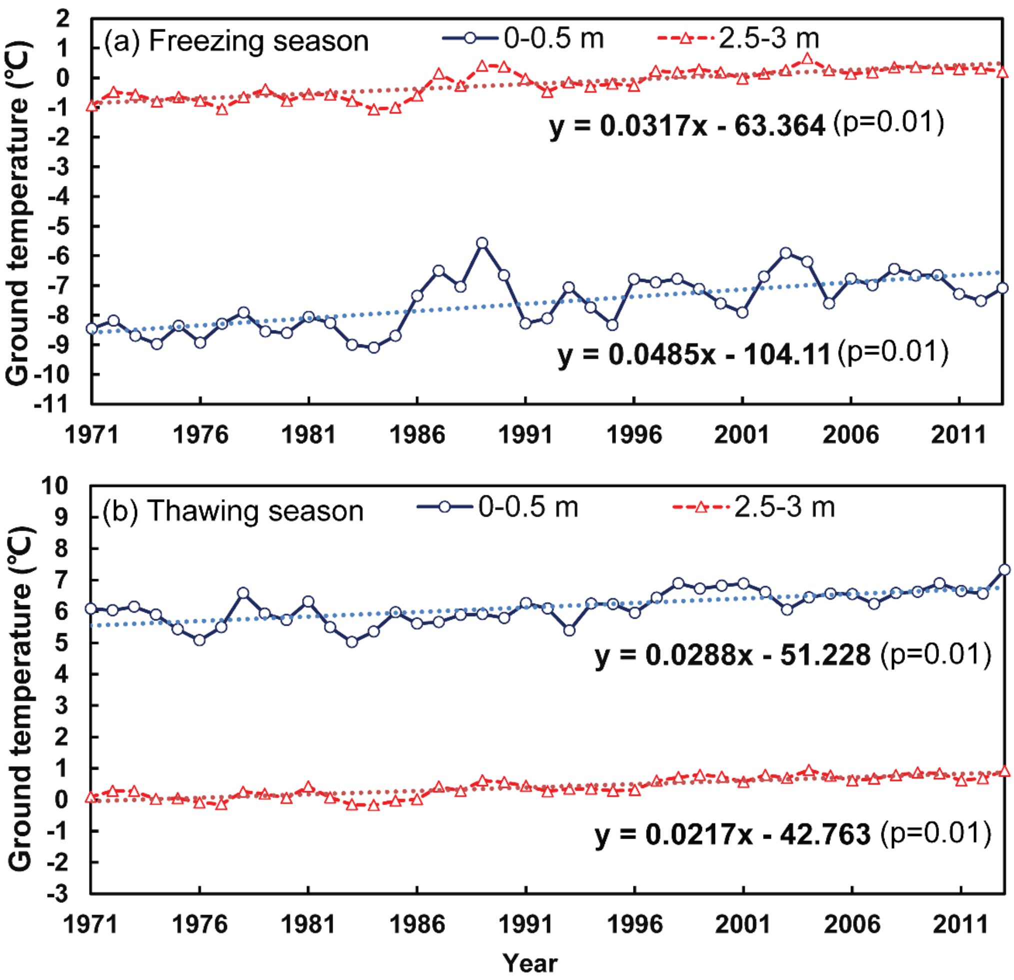


Figure 97. Simulated ground temperature changes in:Changes of the mean soil temperature in different seasons: (a) the freezing season (from November to March) (b) the thawing season (from April to October). p indicates the significance level level of the slope.

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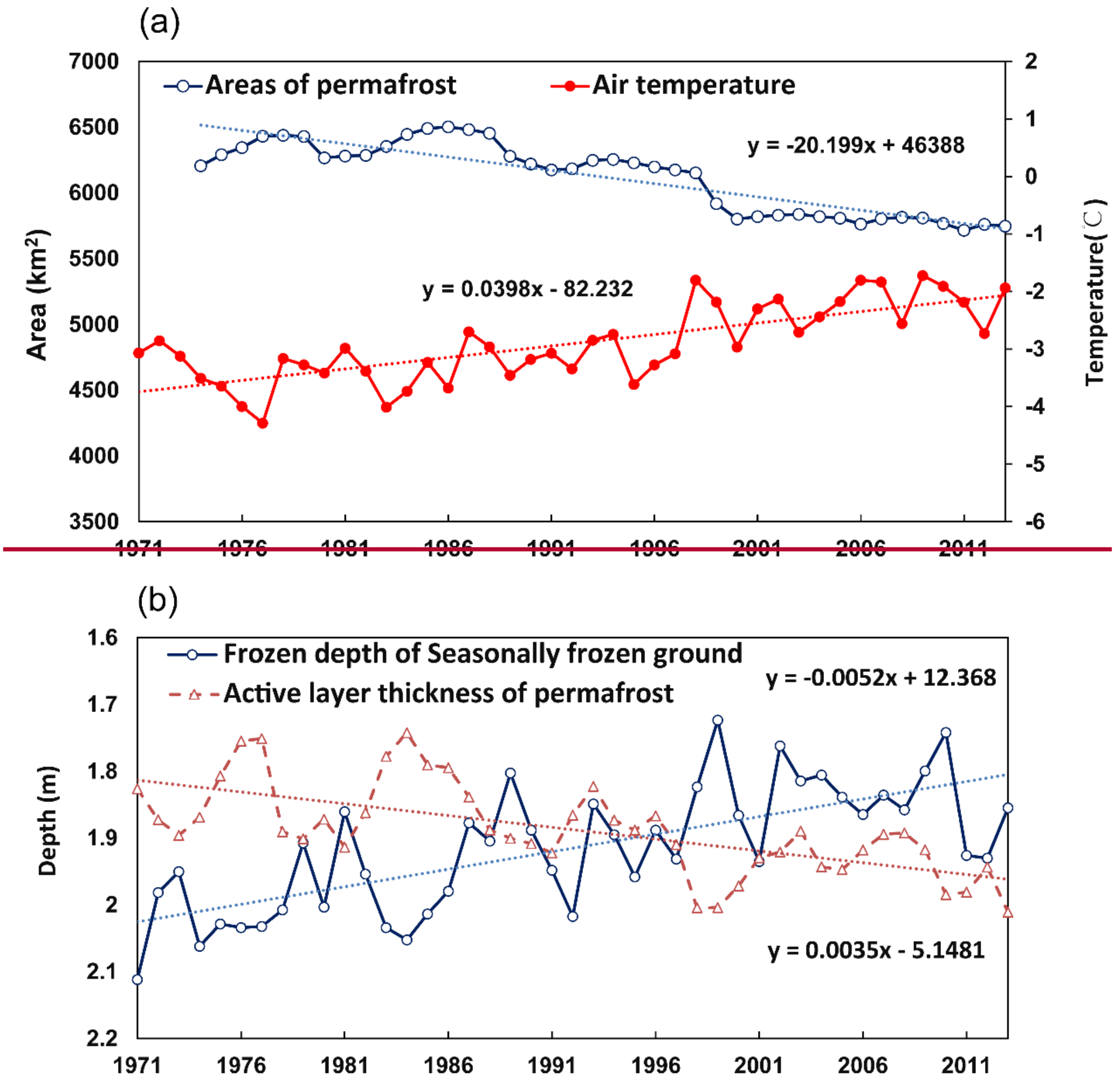

(a)
Areas of permafrost
Air temperature
y = -20.199x + 46388
y = 0.0398x - 82.232
Area (km²)
Temperature(℃)
(b)
Frozen depth of Seasonally frozen ground
Active layer thickness of permafrost
y = -0.0052x + 12.368
y = 0.0035x - 5.1481
Depth (m)

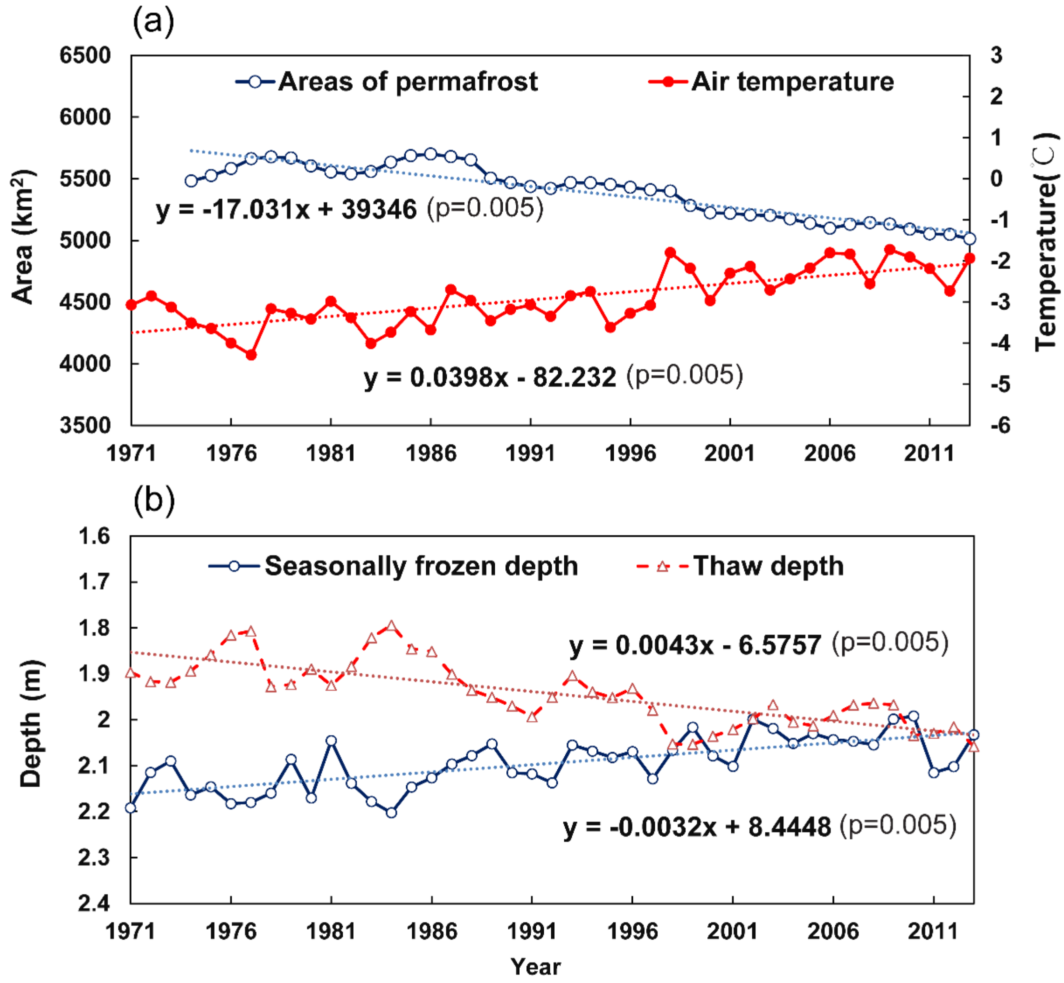
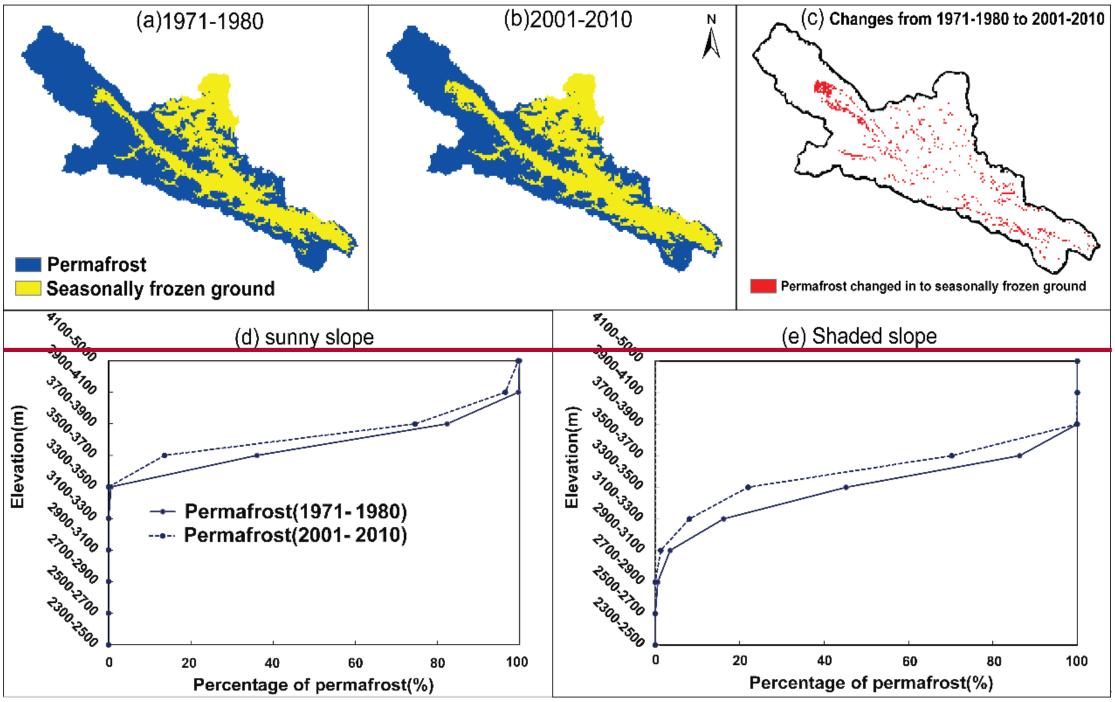


Figure ~~10~~8. Change of the frozen soils in the upper Heihe basin: (a) areas of permafrost and basin averaged annual air temperature; (b) the basin averaged annual maximum depths of seasonally frozen ground and thaw above permafrost. ~~p indicates the significance level level of the slope.~~

~~frozen depth of the seasonally frozen ground and the annual maximum thaw depth of the permafrost~~



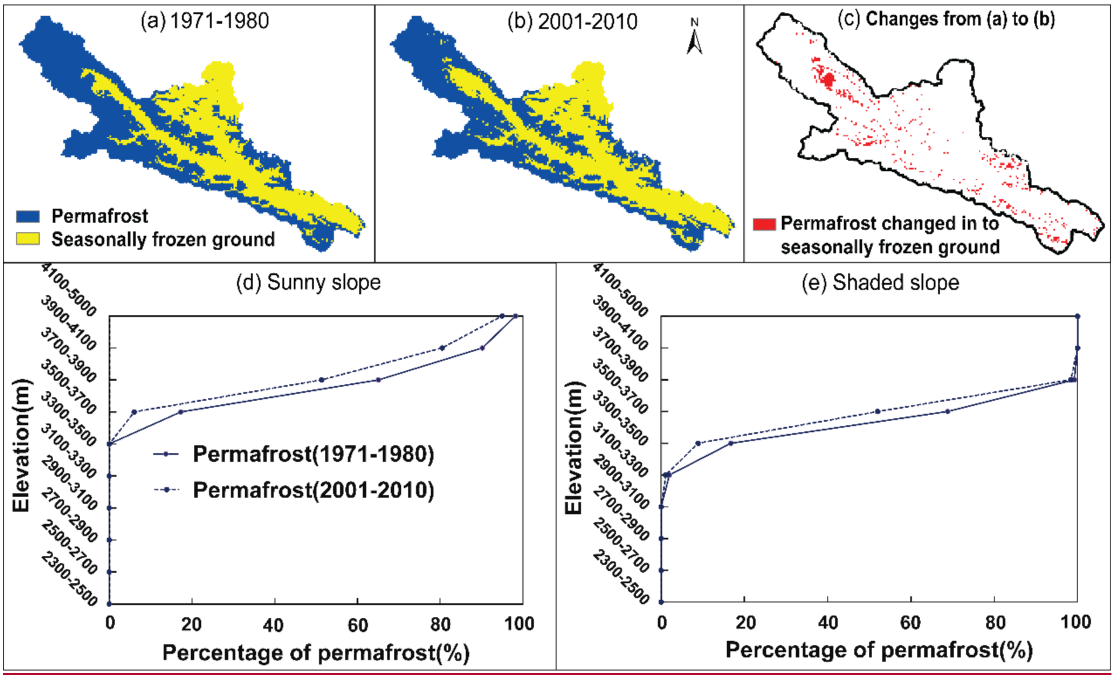
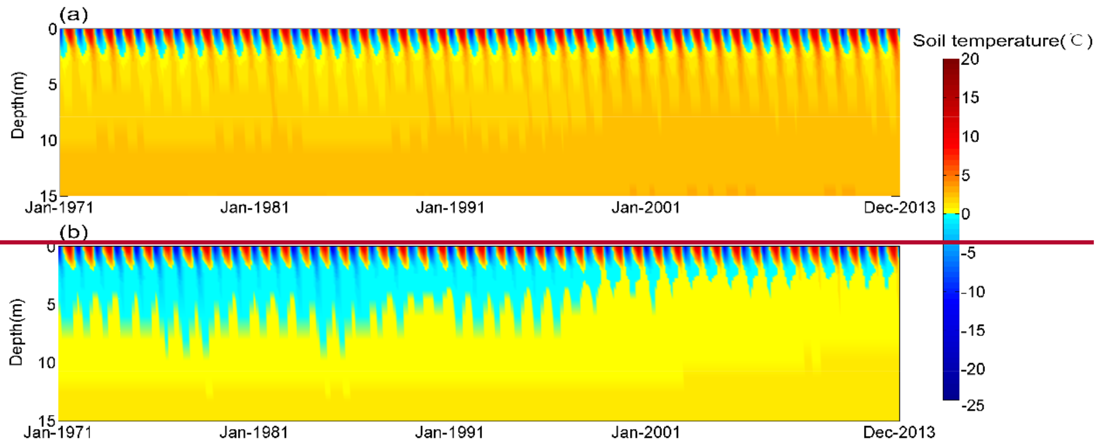


Figure ~~11~~9. Distribution of permafrost and seasonally frozen ground for two periods: (a) 1971-1980 and (b) 2001-2010;~~.~~ (c) Area where permafrost degraded to seasonally frozen ground from (a) to (b)~~between the two periods~~;~~.~~ Percentage of permafrost area ~~for the two periods~~ with respect to elevation on the ~~slopes that are~~ (d) sunny~~–~~ and~~or~~ (e) the shaded slopes for the two periods. Note that (d) and (e) share a legend.~~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))~~



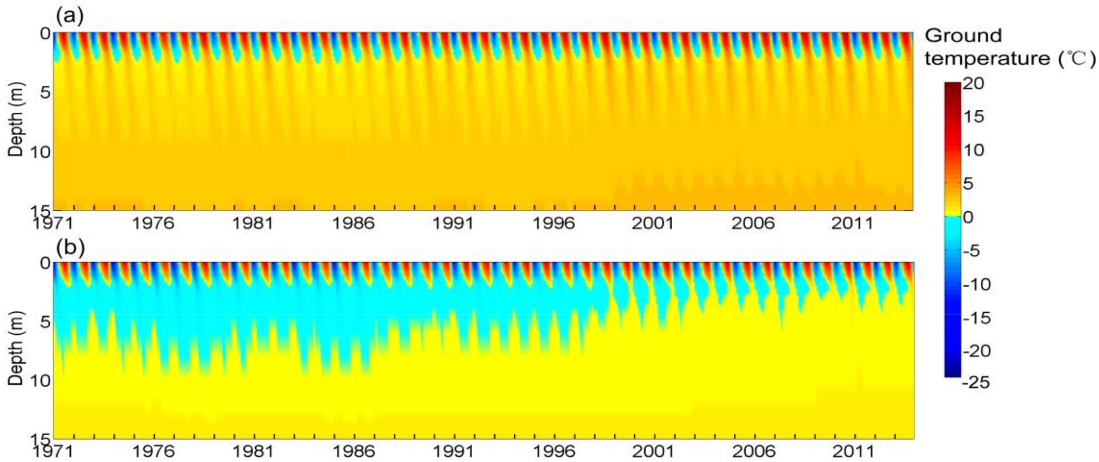
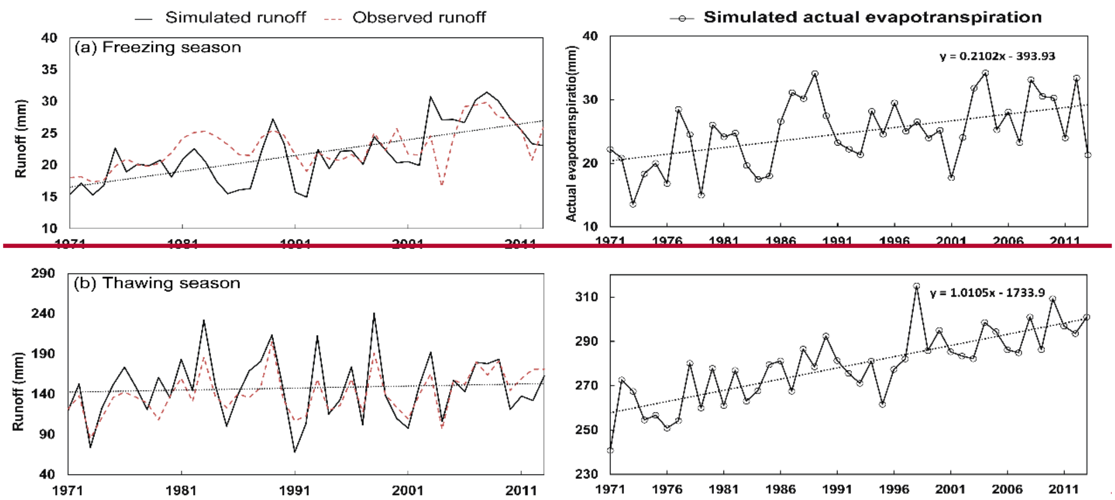


Figure 1~~2~~0. Spatially averaged monthly ground temperatures simulated from 1971 to

2013 for two elevation intervals: (a) seasonally frozen ground between 3300 and 3500 m; (b) permafrost that degraded to seasonally frozen ground between 3500 and 3700 m.~~Spatial averaged monthly soil temperature during the period of 1971-2013 in different elevation intervals: (a) the seasonally frozen ground with elevation between 3300-3500 m; (b) the areas where permafrost changed to seasonally frozen ground with elevation between 3500-3700 m~~



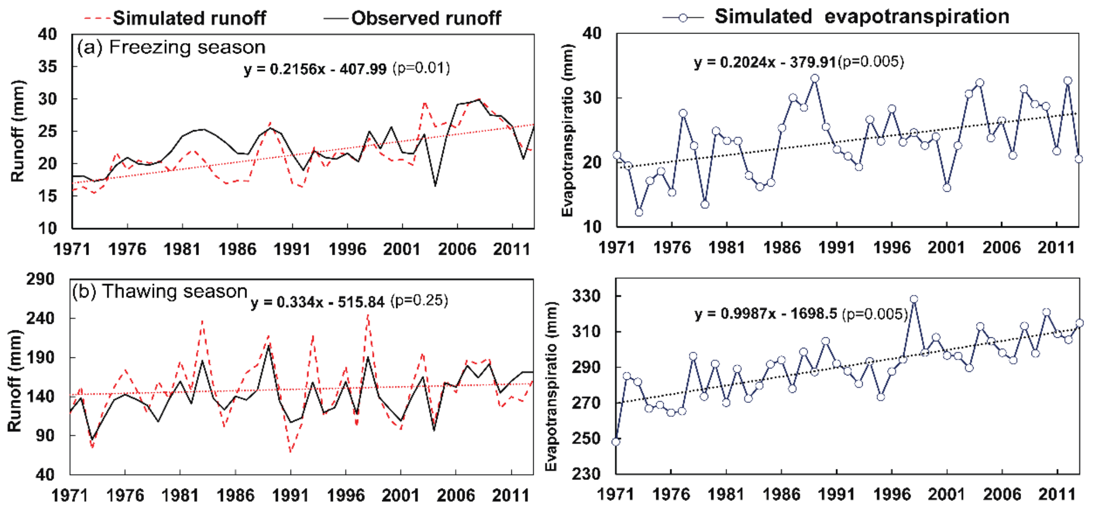
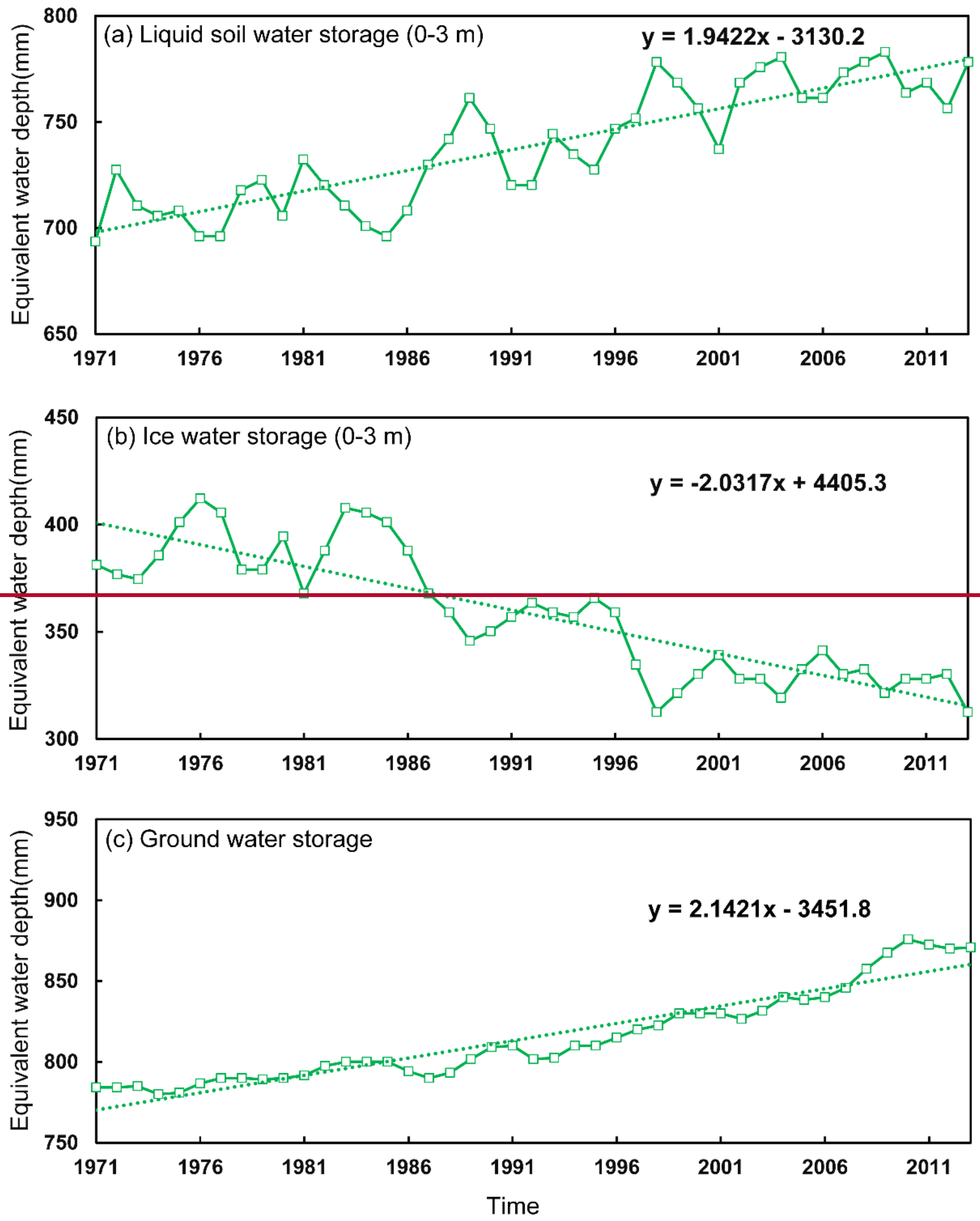


Figure 1~~3~~1. Runoff and simulated evapotranspiration in (a) the freezing season and

(b) the thawing season. Trend lines are for simulated data. The up two panels are for freezing season and the lower two panels are for thawing season. p indicates the significance level level of the slope. Trend lines are for the simulated data. Changes of the runoff and actual evapotranspiration: (a) in the freezing season; (b) in the thawing season



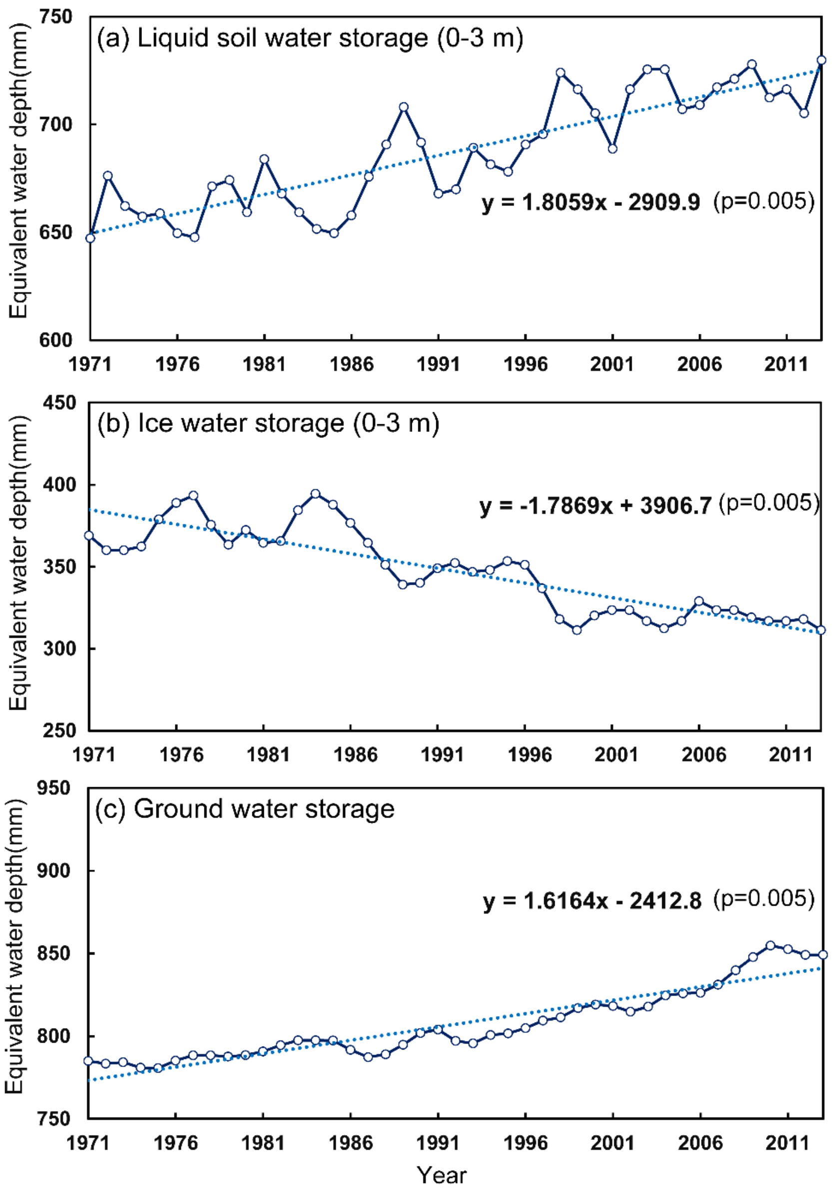


Figure 142. Basin averaged annual water storage (equivalent water depth) changes simulated over the period of 1971 to 2013 for: (a) liquid water in the top layer of the ground (0-3 m); (b) ice in the top layer of the ground (0-3 m); (c) and ground water. p indicates the significance level level of the slope.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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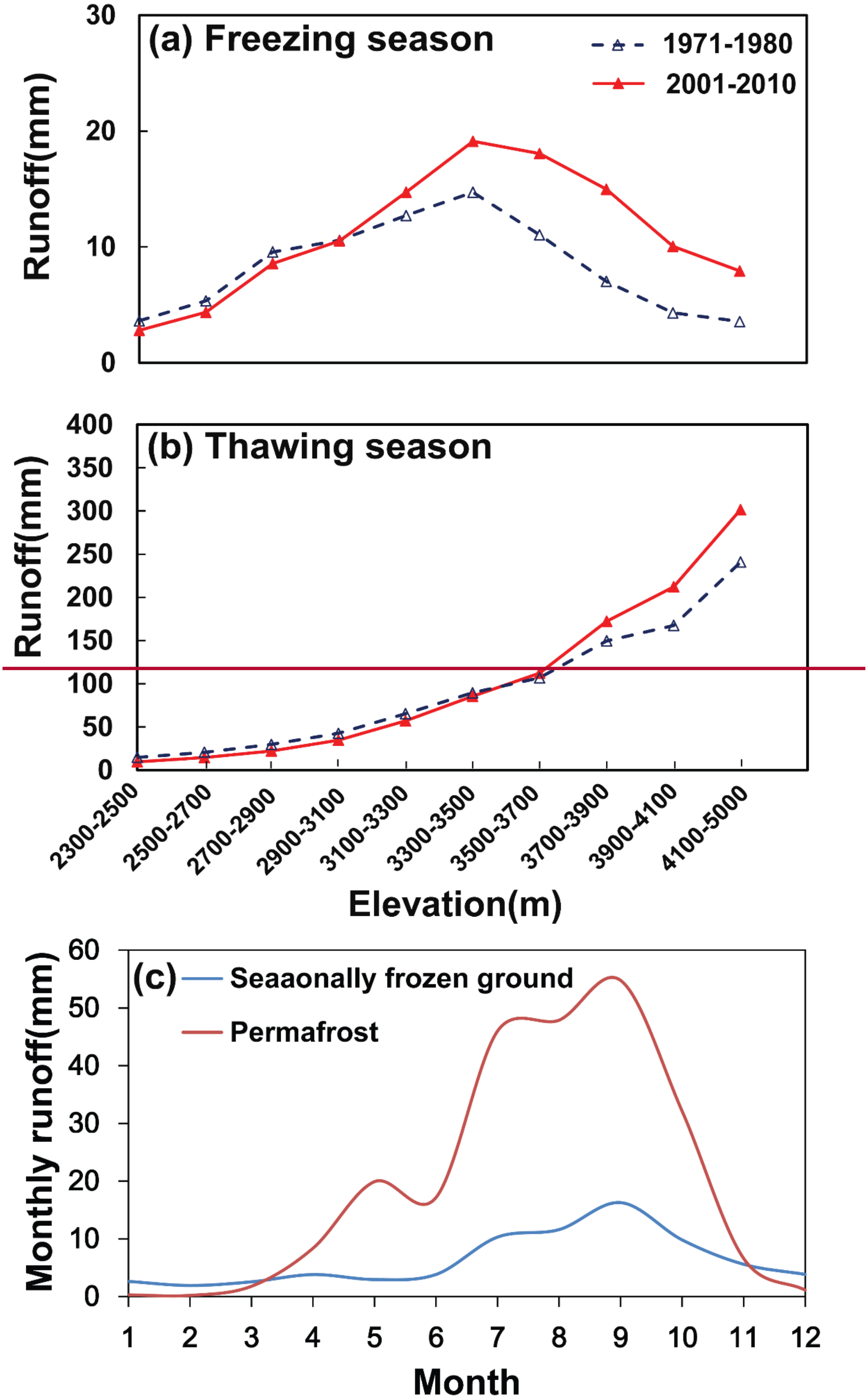

(a) Freezing season
1971-1980
2001-2010
Runoff(mm)
0
10
20
30
(b) Thawing season
Runoff(mm)
0
50
100
150
200
250
300
350
400
2300-2500
2500-2700
2700-2900
2900-3100
3100-3300
3300-3500
3500-3700
3700-3900
3900-4100
4100-5000
Elevation(m)
(c)
Seaaonally frozen ground
Permafrost
Monthly runoff(mm)
0
10
20
30
40
50
60
1
2
3
4
5
6
7
8
9
10
11
12
Month

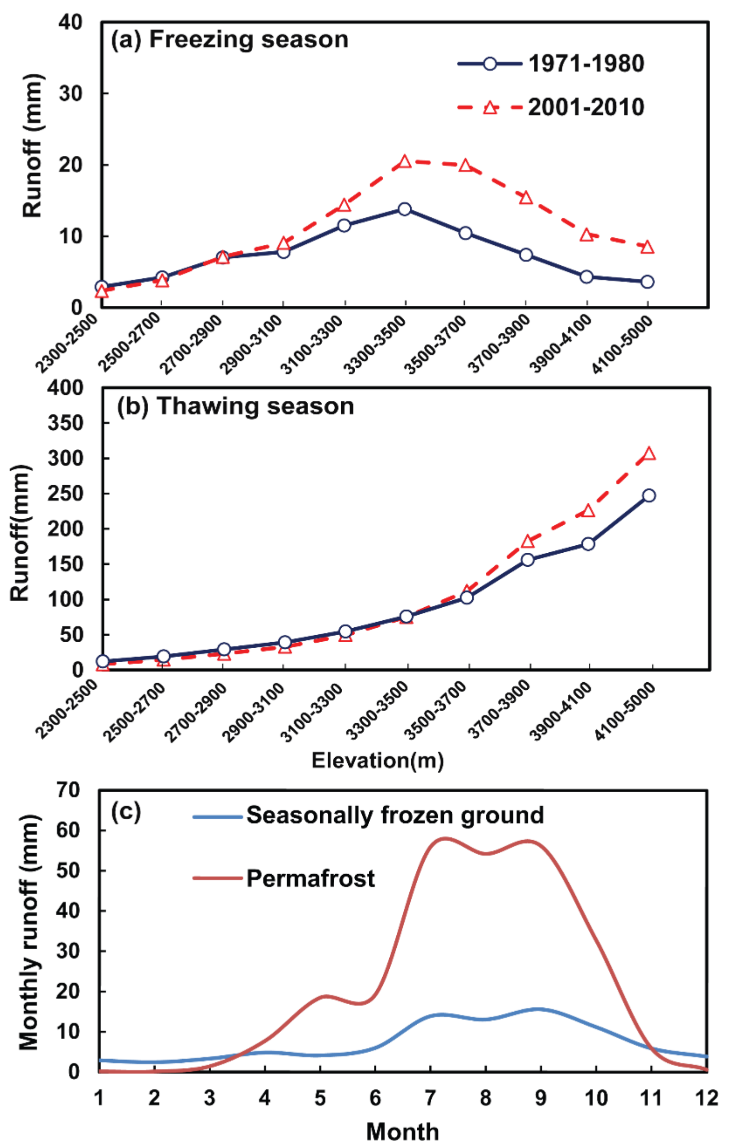

Figure 1~~5~~3. Model simulated runoff changes from the 1971-1980 period to the 2001-2010 period with elevation for (a) the freezing season and (b) the thawing season, and (c) monthly averaged seasonal runoff in permafrost and seasonally frozen ground for the period of 2001 ~~to~~ -2010.

~~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.~~

Table list:

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} mol·m^{-2}·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 (mol·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	—

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

Decade	P~~recipitation~~ (mm/yr)	~~Actual evaporation~~E (mm/yr)	Sim ~~imulated runoff~~ R (mm/yr)	Obs ~~bserved runoff~~ R (mm/yr)	Runoff ratio (~~obs~~Obser~~ved~~)	Runoff ratio~~–~~ (~~sim~~Sim~~ulated~~)	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	28~~0~~2.~~8~~1	15~~4~~4.~~5~~1	143.8	0.33	0.35	18.5	0.0	0.0	13~~6~~5.~~0~~6	3.5	13.~~5~~8
1981-1990	492.8	300.~~0~~8	1~~86~~88.~~2~~5	174.1	0.35	0.3~~8~~8	20.~~2~~5	0.0	0.0	16668.~~1~~0	3.1	~~28~~27.~~2~~8
1991-2000	471.0	30~~6~~7.~~1~~6	16~~0~~1.~~1~~9	157.4	0.33	0.3~~4~~4	20.~~4~~5	0.0	0.0	13941.~~7~~4	3.8	~~19~~18.~~2~~4
2001-2010	504.3	31~~7~~9.~~4~~0	1~~77~~80.~~9~~6	174.3	0.35	0.3~~5~~6	2~~7~~6.2	0.0	0.0	15~~0~~4.~~7~~3	3.7	~~25~~24.~~8~~1

Note: P means precipitation, E means actual evaporation, R means runoff, T means total runoff, G means glacier runoff and S means snowmelt runoff, Sim means simulation and Obs means observation.

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