A DETAILED LIST OF RESPONSES
TO REVIEWER #1

General comments:

It's my pleasure to review this manuscript. The TRSR region is important for water resource security and of interest to researchers because of its complex hydrological processes. This study conducts a systematic modeling work on this region, and analyze the contribution of runoff components and the hydrological response to climate change and human activities. The results are helpful for understanding the hydrological processes in this important region, which make this manuscript worth publishing. Overall, the manuscript is written well and easy to follow. However, I have some concern about the results, especially for the snow and glacier simulations. I recommend to accept the manuscript after moderate revisions to address following issues.

Response: We appreciate the positive assessment of our manuscript. Your insightful comments have enhanced our paper considerably. Below is a point-by-point response to your review.

Specific comments:

1. The description of model:
A module representing glacier processes was integrated into the model, and the authors described them in detail. The snowmelt contributes more than glacier runoff in most of the basins, but the simulation of snow processes was not introduced in the Method section. I think this might be due to that the snow module has been included in the VIC model, and the authors only introduced the extension module. Nonetheless, since the simulation of snow processes is equally important as glacier, I suggest the authors to add some description on the snow simulation.

Response: We thank the reviewer for this advice. We have added additional information about snow simulation to the revised manuscript, as follows:

"The critical elements of this model that are particularly relevant to its application in cold regions include (1) a two-layer energy-balance model that simulates accumulation and melt of ground snow and a simplified single-layer model of the ground snowpack energy balance that simulates melt, sublimation, drip and release of intercepted snow from the canopy (Cherkauer and Lettenmaier, 1999; Cherkauer and Lettenmaier, 2003; Storck and Lettenmaier, 1999); and (2) a frozen soil algorithm that calculates the soil ice contents within each vegetation type and the effects of frozen soil on infiltration and runoff (Cherkauer and Lettenmaier, 1999; Cherkauer and Lettenmaier, 2003)."

References

Cherkauer, K. A. and Lettenmaier, D. P.: Hydrologic effects of frozen soils in the upper

Mississippi River basin, J. Geophys. Res.-Atmos., 104, 19599-19610, https://doi.org/10.1029/1999jd900337, 1999.
Cherkauer, K. A. and Lettenmaier, D. P.: Simulation of spatial variability in snow and frozen soil, J. Geophys. Res.-Atmos., 108, https://doi.org/10.1029/2003jd003575, 2003.
Storck, P. and Lettenmaier, D. P.: Predicting the effect of a forest canopy on ground snow accumulation and ablation in maritime climates, 67th Western Snow Conference, edited by C. Troendle. Colo. State Univ., pp. 1–12.

2. Definition of the runoff component:
The authors estimated the contribution of runoff components in each basin, which is an important result. However, the result would be confusing if the definition of runoff component was not clarified. Is the runoff component defined based on the contribution of each water source in the total water input, or the proportion of each component in the streamflow? The amount of river water should be smaller than the sum of each water source due to evaporation loss. How does the model consider this? I suggest the authors to clearly clarify the definition of runoff components. The authors can refer to a recent review on this issue ("A meta-analysis based review of quantifying the contributions of runoff components to streamflow in glacierized basins").

Response: We thank the reviewer very much for this advice; it is indeed our negligence that the definition of runoff components is not clearly clarified, which would easily cause readers' misunderstanding. As He et al. (2021) stated, different definitions of runoff components could lead to different calculation results, and the same terminology in different studies might refer to different runoff components, thus preventing a comprehensive comparison of contributions of runoff components across different glacierized basins. In this study, the runoff component is defined as the proportion of each component in the streamflow, and the total runoff is divided into three components: glacier, rainfall, and snowmelt runoff. Glacier runoff represents the sum of glacier melt water and rainfall from the glacier area (Wang et al., 2021). Rainfall runoff represents the runoff induced by rainfall, and snowmelt runoff represents the runoff induced by snow melting. And we use the runoff simulated in the model when calculating contributions. Rainfall runoff and snowmelt runoff are calculated by the original VIC model, taking into consideration the contributions to infiltration and base flow as well as evapotranspiration losses, including canopy interception evaporation, vegetation transpiration, and bare soil evaporation. Glacier runoff is calculated by a degree-day algorithm, ignoring infiltration and evapotranspiration. We have edited the text of the method section of the revised manuscript to provide more detail, as follows:

"It is very important to define runoff components clearly (He et al., 2021). In this study, the runoff component is defined as the proportion of each component in the streamflow and the total runoff is divided into three components: glacier, rainfall, and snowmelt runoff. Glacier runoff represents the sum of glacier melt water and rainfall from glacier area (Wang et al., 2021). Rainfall runoff represents the runoff induced by rainfall and snowmelt runoff represents the runoff induced by snow melting.”

References

He, Z., Duethmann, D., and Tian, F.: A meta-analysis based review of quantifying the contributions of runoff components to streamflow in glacierized basins, J. Hydrol., 603, https://doi.org/10.1016/j.jhydrol.2021.126890, 2021.

Wang, Y., Xie, X., Shi, J., and Zhu, B.: Ensemble runoff modeling driven by multi-source precipitation products over the Tibetan Plateau, Chin. Sci. Bull., 66, 4169-4186, https://doi.org/10.1360/tb-2020-1557, 2021.

3. Validation of snow/glacier simulation:

It is good to involve snow and glacier simulation into the hydrological model, but the results could be unreasonable if the snow and glacier simulation are not validated by any measurement dataset. In my opinion, the contribution of glacier runoff in source Yangtze River (Zhimenda station) was significantly overestimated, and my approximate estimation is as follows: The mean annual runoff at Zhimenda station was about 160mm/a, so the glacier runoff should be 13.92mm/a (if the authors define the runoff component by the proportion in the streamflow). Considering the glacier area is 0.81%, the runoff generation in glacier area is 13.92/0.81%=1700mm/a. Excluding the precipitation (about 400mm/a), the glacier meltwater would be more than 1.3m/a, which is significantly higher than the estimation from existed glacier studies (0.5m/a). Besides, if the runoff component was defined by the water source definition, the glacier mass meltwater estimated in similar way would even be larger than 4m/a.

Nonetheless, I agree with the authors that the meltwater has little influence on the streamflow due to the small glacier area. But I just think that if snow and glacier simulations are not verified, the benefit of using a glacier hydrological model would be reduced.

Response: We thank the reviewer for these comments. We fully agree with the reviewer’s assertion that the benefit of using a glacier hydrological model would be reduced if snow and glacier simulations are not verified. However, as to why snowmelt runoff and glacier runoff have not been verified, we make the following three responses:

(i) There is a lack of measured data of snowmelt and glacier runoff. Although some studies have calibrated and verified the snowmelt and glacier runoff, the data used in most studies are glacier outlines, snow cover area, or snow water equivalent derived from remote sensing data collected during several different time periods (Chen et al., 2017; Han et al., 2019; Sun and Su, 2020) rather than direct measured data of snowmelt and glacier runoff, which will inevitably bring some uncertainty to the simulation results (Zhao et al., 2019).

(ii) Actually, the observed total runoff includes glacier and snowmelt runoff; the simulation performance of snowmelt and glacier runoff can be reflected by evaluating the simulation results of VIC-Glacier on total runoff to a certain extent. As shown in Figure 2, the model achieved reasonably satisfactory results, with NSE exceeding 0.68

at all stations.
(iii) By comparing with previous studies, it is found that the research results on the proportion of glacier and snowmelt runoff in this study are within a reasonable range. Taking Zhimenda Station as an example, Wang et al. (2021) found that during 1984–2015, glacier runoff contributed 9% to the total runoff at Zhimenda Station; Han et al. (2019) and Zhang et al. (2013) estimated glacier runoff accounted for 5% and 6.5% in 2003–2014 and 1961–2009, respectively. These results are close to the conclusion in this study that glacier runoff accounts for 8.7% during 1984–2018 at Zhimenda Station.

Regarding the reviewer's concern that the contribution of glacier runoff as a source to the Yangtze River (Zhimenda Station) was significantly overestimated, we don't know which time period they are referring to during which the mean annual runoff at Zhimenda Station is about 160 mm/a, which is much higher than the 100 mm/a we obtained during 1984–2018. And the glacier runoff calculated based on the mean annual runoff of 100mm/a is 8.7 mm/a rather than 13.82 mm/a.

References

Chen, X., Long, D., Hong, Y., Zeng, C., and Yan, D.: Improved modeling of snow and glacier melting by a progressive two-stage calibration strategy with GRACE and multisource data: How snow and glacier meltwater contributes to the runoff of the Upper Brahmaputra River basin?, Water Resour. Res., 53, 2431-2466, https://doi.org/10.1002/2016wr019656, 2017.

Han, P., Long, D., Han, Z., Du, M., Dai, L., and Hao, X.: Improved understanding of snowmelt runoff from the headwaters of China's Yangtze River using remotely sensed snow products and hydrological modeling, Remote Sens. Environ., 224, 44-59, https://doi.org/10.1016/j.rse.2019.01.041, 2019.

Sun, H. and Su, F.: Precipitation correction and reconstruction for streamflow simulation based on 262 rain gauges in the upper Brahmaputra of southern Tibetan Plateau, J. Hydrol., 590, 125484, https://doi.org/10.1016/j.jhydrol.2020.125484, 2020.

Wang, Y., Xie, X., Shi, J., and Zhu, B.: Ensemble runoff modeling driven by multi-source precipitation products over the Tibetan Plateau, Chin. Sci. Bull., 66, 4169-4186, https://doi.org/10.1360/tb-2020-1557, 2021.

Zhang, L., Su, F., Yang, D., Hao, Z., and Tong, K.: Discharge regime and simulation for the upstream of major rivers over Tibetan Plateau, J. Geophys. Res.-Atmos., 118, 8500-8518, https://doi.org/10.1002/jgrd.50665, 2013.

Zhao, Q., Ding, Y., Wang, J., Gao, H., Zhang, S., Zhao, C., Xu, J., Han, H., and Shangguan, D.: Projecting climate change impacts on hydrological processes on the Tibetan Plateau with model calibration against the glacier inventory data and observed streamflow, J. Hydrol., 573, 60-81, https://doi.org/10.1016/j.jhydrol.2019.03.043, 2019.

4. Designation of climate change scenarios:
The authors set four scenarios to analyze the hydrological response to the climate

change. In my understanding, the scenarios designation seems more likely a sensitivity analysis between runoff and T and P, but the attribution analysis has shown the result that the precipitation is the most important factor. So we can expect the sensitivity analysis would give similar conclusion. If the aim of setting scenarios is to predict the runoff change in the future, why not directly use the projection climate data such as CMIP6?

Response: We very much appreciate these comments providing a different perspective related to the purpose of designating climate change scenarios. After discussing this point amongst the co-authors, we would prefer to retain original analysis for the following reasons:

(i) Hydrologic models driven by hypothetical climate change scenarios or global climate models (GCMs) have long been commonly used to predict the response of future runoff to climate change (Su et al., 2016).

(ii) The reliability of hydrological model simulation depends largely on the accuracy of meteorological forcing data (Sun and Su, 2020). Although GCMs have been greatly improved over time, their output cannot be directly applied to climate change prediction and related research at the watershed scale due to their inherent systematic deviation and coarse spatiotemporal resolution, so downscaling and deviation correction have become essential steps in using GCM output data, which would introduce uncertainty into the research results (Piani et al., 2010; Wood et al., 2004).

(iii) The hypothetical climate change scenarios are easy to design and apply; however, this does not mean that such scenarios can be assumed at will, but must be designed according to the possible range of future precipitation and temperature changes in previous studies. For example, Lutz et al. (2014) predicted the future precipitation and temperature of QTP would change –10% to 20% and 1°C–3°C under the RCP4.5 and RCP8.5 scenarios from the CMIP5 multi-model ensemble, respectively. Su et al. (2016) estimated the annual precipitation would increase by 5.0–10.0% in 2011–2040 and 10.0–20.0% in 2041–2070 under RCP2.6, RCP4.5, and RCP8.5 scenarios at the plateau scale, and annual temperature was projected to increase for all scenarios, with the greatest warming in the northwest (2.0–4.0 °C) and least in the southeast (1.2–2.8 °C). Zhao et al. (2019) predicted the temperature of QTP would increase by 0.11 °C (for RCP2.6) and 0.31 °C (for RCP4.5) per decade. Extending these analyses, we chose precipitation changes from −20% to +20% at a step of 10% and temperature changes from −1°C to 1°C at a step of 0.5 °C to analyze the impact of future climate change on runoff.

(iv) Sensitivity analysis is often used to identify the governing factors for a certain process simulated (Xu et al., 2004). Actually, without sensitivity analysis between climate factors (e.g., precipitation and temperature) and runoff, we can still roughly know the relationship between them, such as the fact that rainfall runoff is subject to precipitation change and glacier runoff depends on temperature change. Hypothetical climate change scenarios are made for the purpose of predicting how runoff will change in the future according to the possible range of future climate factors, which is exactly their practical significance. As mentioned in the conclusion of the original manuscript, "Considering the fact that a simultaneous increase of precipitation and temperature is the most likely future climate change scenario, we expect that the total runoff, rainfall runoff, and glacier runoff will increase in the future, while the snowmelt runoff will remain basically unchanged." If this part is taken as sensitivity analysis, we could analyze only how runoff will change with precipitation and temperature change, instead of discussing that the most likely climate change scenario in the future is warming and wetting, and we would not draw a conclusion about how runoff will change in the future. Therefore, we think these hypothetical climate change scenarios are not just simple sensitivity analysis, but can be used to predict future runoff changes to a certain extent.

References

Lutz, A. F., Immerzeel, W. W., Shrestha, A. B., and Bierkens, M. F. P.: Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation, Nat. Clim. Change, 4, 587-592, https://doi.org/10.1038/nclimate2237, 2014.

Piani, C., Weedon, G. P., Best, M., Gomes, S. M., Viterbo, P., Hagemann, S., and Haerter, J. O.: Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models, J. Hydrol., 395, 199-215, https://doi.org/10.1016/j.jhydrol.2010.10.024, 2010.

Su, F., Zhang, L., Ou, T., Chen, D., Yao, T., Tong, K., and Qi, Y.: Hydrological response to future climate changes for the major upstream river basins in the Tibetan Plateau, Global Planet. Change, 136, 82-95, https://doi.org/10.1016/j.gloplacha.2015.10.012, 2016.

Sun, H. and Su, F.: Precipitation correction and reconstruction for streamflow simulation based on 262 rain gauges in the upper Brahmaputra of southern Tibetan Plateau, J. Hydrol., 590, 125484, https://doi.org/10.1016/j.jhydrol.2020.125484, 2020.

Wood, A. W., Leung, L. R., Sridhar, V., and Lettenmaier, D. P.: Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs, Clim. Change, 62, 189-216, https://doi.org/10.1023/B:CLIM.0000013685.99609.9e, 2004.

Xu, C., Hu, Y., Chang, Y., Jiang, Y., Li, X., Bu, R., and He, H.: Sensitivity analysis in ecological modeling, J. Appl. Ecol., 15, 1056-1062, 2004.

Zhao, Q., Ding, Y., Wang, J., Gao, H., Zhang, S., Zhao, C., Xu, J., Han, H., and Shangguan, D.: Projecting climate change impacts on hydrological processes on the Tibetan Plateau with model calibration against the glacier inventory data and observed streamflow, J. Hydrol., 573, 60-81, https://doi.org/10.1016/j.jhydrol.2019.03.043, 2019.