Responses to the comments from Reviewer #1

We are very grateful to the reviewer for the positive and careful review. The thoughtful comments have helped improve the manuscript. The reviewer's comments are italicized and our responses immediately follow.

General Comments: The paper presents an analysis of the impacts of climate change and two ecological factors (CO2 physiological forcing and land cover change) for the streamflow extremes of the Sanjiangyuan region. The methodology used and the conclusions drawn are sound, and the manuscript is well structured. However, some questions needed to be explained clearly and the English writing of this manuscript needs improvement.

Response: Thanks for the positive comments. We have made extensive modifications to our manuscript for clarification, and have proofread and edited the English carefully. Please see our responses below.

Lin17 on page 2: '~700' change to '700'

Lin40 on page 4: 'Global temperature has been increasing' change to 'Global temperature has increased'

Response: Revised as suggested. (L40 in the revised manuscript)

Lin 61-62 on page 5: The statement by the authors that 'Thus, it is necessary to assess their combined impacts on the projection of streamflow extremes at different warming levels' is confusing. This sentence needs to be clarified with more evidence to prove the veracity of the statements. In addition, the entire paragraph can be rephrase.

Response: Thanks for the suggestion. The necessity to assess the combined impacts of CO_2 physiological forcing and land cover change is due to their contrary influences on the terrestrial hydrology. We have rephrased the paragraph as follows:

"... In addition to climate change, recent works reveal the importance of the ecological factors (e.g., the CO_2 physiological forcing and land cover change) in modulating the streamflow and its extremes. For example, the increasing CO_2 concentration is found to alleviate the decreasing trend of future streamflow at global scale through decreasing the vegetation transpiration by reducing the stomatal conductance (known as the CO_2 physiological forcing) (Fowler et al., 2019; Wiltshire et al., 2013; Yang et al., 2019; Zhu et al., 2012). Contrary to the CO_2 physiological forcing, the vegetation greening in a warming climate is found to have a significant role in exacerbating hydrological drought, as it enhances transpiration and dries up the land (Yuan et al., 2018b). However, the relative contributions of CO_2 physiological forcing and vegetation greening to the changes in terrestrial hydrology especially the streamflow extremes are still unknown, and whether their combined impact changes at different warming levels needs to be investigated." (L51-71)

Lin 63-66 on page 5: The reasoning behind the choice of the streamflow extremes over the Sanjiangyuan regions needs to be explained.

Response: Thanks for the comment. The reason for the choice of the streamflow extremes over the Sanjiangyuan region is explained from two aspects in the revised manuscript as follows:

1) "Hosting the headwaters of the Yellow river, the Yangtze river and the Lancang-Mekong river, the Sanjiangyuan region is known as the "Asian Water Tower" and concerns 700 million people over its downstream areas. Changes in streamflow and its extremes over the Sanjiangyuan region not only influence the local ecosystems, environment and water resources, but also affect the security of food, energy, and water over the downstream areas." (L72-77)

2) "Both the regional climate and ecosystems show significant changes over the Sanjiangyuan region due to global warming (Bibi et al., 2018; Kuang and Jiao, 2016; Liang et al., 2013; Yang et al., 2013; Zhu et al., 2016), which makes it a sound region to investigate the role of climate change and ecological change (e.g., land cover change and CO2 physiological forcing) in influencing the streamflow and its extremes (Cuo et al., 2014; Ji and Yuan, 2018; Zhu et al., 2013)." (L77-83)

If historical changes in climate and ecology have significantly altered the terrestrial hydrology over the regions, the terrestrial hydrology also need analysis.

Response: Thanks for the comment. Actually, we have analyzed the terrestrial hydrological changes including the precipitation, evapotranspiration, total runoff and terrestrial water storage at different warming levels in section 3.1 and Figure 4. The results suggest that the regional hydrological cycle is accelerating in a warming climate. Please see the text in the last paragraph in section 3.1.

At the same time, the characteristics of basin of the headwaters of the Yellow river *and Yangtze river should be provided, such as area and discharge.*

Response: Thanks for the suggestion. We have added a brief introduction to the characteristics of the study domain in the revised manuscript as follows:

"The Sanjiangyuan region is located at the eastern part of the Tibetan Plateau (Figure 1a), with the total area and mean elevation being 3.61×10^5 km^2 and 5000 m respectively. It plays a critical role in providing freshwater, by contributing 35%, 20% and 8% to the total annual streamflow of the Yellow, Yangtze and Lancang-Mekong rivers (Li et al., 2017; Liang et al., 2013). The source regions of Yellow, Yangtze and Lancang-Mekong rivers account for 46%, 44% and 10% of the total area of the Sanjiangyuan individually, and the Yellow river source region has a warmer climate and sparser snow cover than the Yangtze river source region." (L115-122)

Lin 67-72 on page 5: Does CO2 physiological forcing has a significant influence on the terrestrial hydrology and its extremes in Sanjiangyuan or other high-land areas? It would be better to add some related literature.

Response: Thanks for the suggestion. We have added some related literature as suggested: "And the CO_2 physiological forcing is revealed to cause equally large changes in regional flood extremes as the precipitation over the Yangtze and Mekong rivers (Fowler et al., 2019)." (L94-96)

Reference:

Fowler, M. D., Kooperman G. J., Randerson, J. T. and Pritchard M. S.: The effect of plant physiological responses to rising CO2 on global streamflow, Nat. Clim. Change, 9, 873-879, https://doi.org/10.1038/s41558-019-0602-x, 2019.

Lin 91-94 on page 6: Streamflow observations are daily or monthly streamflow observations? It seem monthly streamflow in this work.

Response: Yes, we used monthly streamflow to evaluate the model. We have clarified it as: "Monthly streamflow observations ..., were used to evaluate the streamflow simulations." (L123-125)

Lin 107-109 on page 7: In this study, 11 models in CMIP6 that can reproduce the increased precipitation over the Sanjiangyuan, were chosen for the analysis. Please give more explanation why only precipitation was considered. In addition, can those models correctly simulate the temperature, specific humidity, etc.?

Response: Thanks for the suggestion. We have evaluated the performance of CMIP6 models in representing the trends of other meteorological variables as suggested. Figure R1 shows that the ensemble mean (right panel) and each of the 11 CMIP6 model (left model) chosen in this research can reproduce the sign of historical trends of other meteorological forcings. We have revised the description to avoid misleading information: "... Then, models were chosen for the analysis when the simulated meteorological forcings (e.g., precipitation, temperature, humidity, and shortwave radiation) averaged over the Sanjiangyuan region have the same trend signs as the observations during 1979-2014. Table 1 shows the 11 CMIP6 models that were finally chosen in this study." (L139-145)

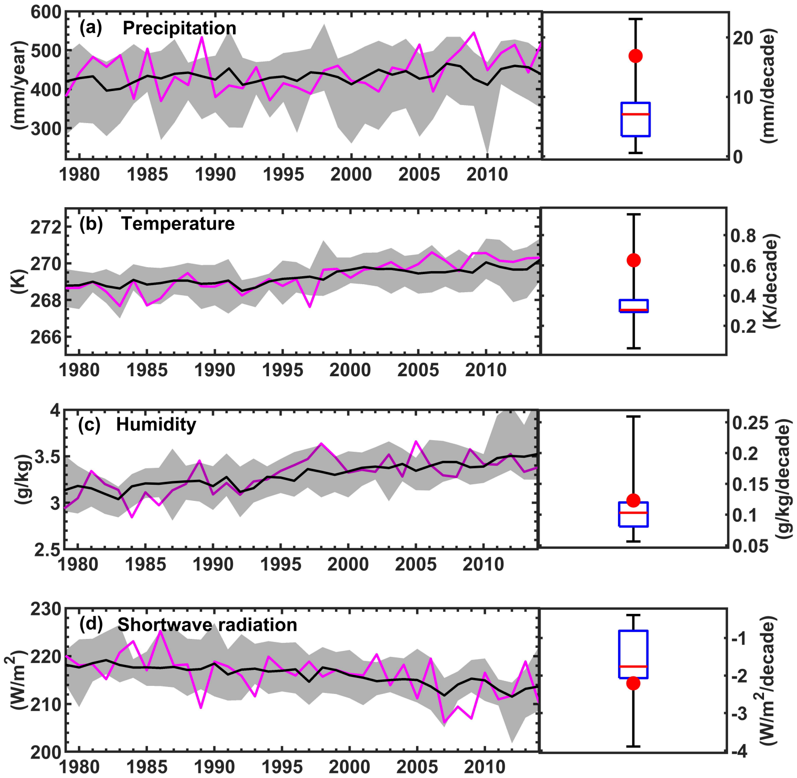

Figure R1. (a) Observed (purple line) and CMIP6 model simulated (black line) annual mean precipitation during 1979-2014. Shadings are ranges of all 11 CMIP6 models. The observed precipitation trends during 1979-2014 is shown by red circle on the right panel, while simulated trends of 11 CMIP6 models are shown by the boxplot. (b), (c) and (d) are the same as (a) but for temperature, humidity and shortwave radiation respectively.

Lin 143-148 on page 7: It is important to show the structure of the model and how it handles the various hydrological processes as mentioned in this part. Maybe you can *insert a figure of the structure of the eco-hydrological model.*

Response: Thanks for the suggestion. Detailed model introduction and a new Figure 2 have been added in the revised paper as suggested:

"Figure 2 shows the structure and main ecohydrological processes in CSSPv2. The CSSPv2 is rooted in the Common Land Model (CoLM; Dai et al., 2003) with some improvements at hydrological processes. CSSPv2 has a volume-averaged soil moisture transport (VAST) model, which solves the quasi-three dimensional transportation of the soil water and explicitly considers the variability of moisture flux due to subgrid topographic variations (Choi et al., 2007). Moreover, the Variable Infiltration Capacity runoff scheme (Liang et al., 1994), and the influences of soil organic matters on soil hydrological properties were incorporated into the CSSPv2 by Yuan et al. (2018a), to improve its performance in simulating the terrestrial hydrology over the Sanjiangyuan region. Similar to CoLM and Community Land Model (Oleson et al., 2013), vegetation transpiration in CSSPv2 is based on Monin-Obukhov similarity theory, and the transpiration rate is constrained by leaf boundary layer and stomatal conductances. Parameterization of the stomatal conductance (g_s) in CSSPv2 is

$$g_s = m \frac{A_n}{P_{CO_2} / P_{atm}} h_s + b\beta_t$$

where the m is a plant functional type dependent parameter, A_n is leaf net photosynthesis ($\mu\, mol\, CO_2\, m^{-2}\, s^{-1}$), P_{CO_2} is the CO_2 partial pressure at the leaf surface (Pa), P_{atm} is the atmospheric pressure (Pa), h_s is the lead surface humidity, b is the minimum stomatal conductance ($\mu\, mol\, m^{-2}\, s^{-1}$), while β_t is the soil water stress function. Generally, the stomatal conductance decreases with the increasing of CO_2 concentration. Generally, the stomatal conductance decreases with the increasing of CO_2 concentration." (L182-207)

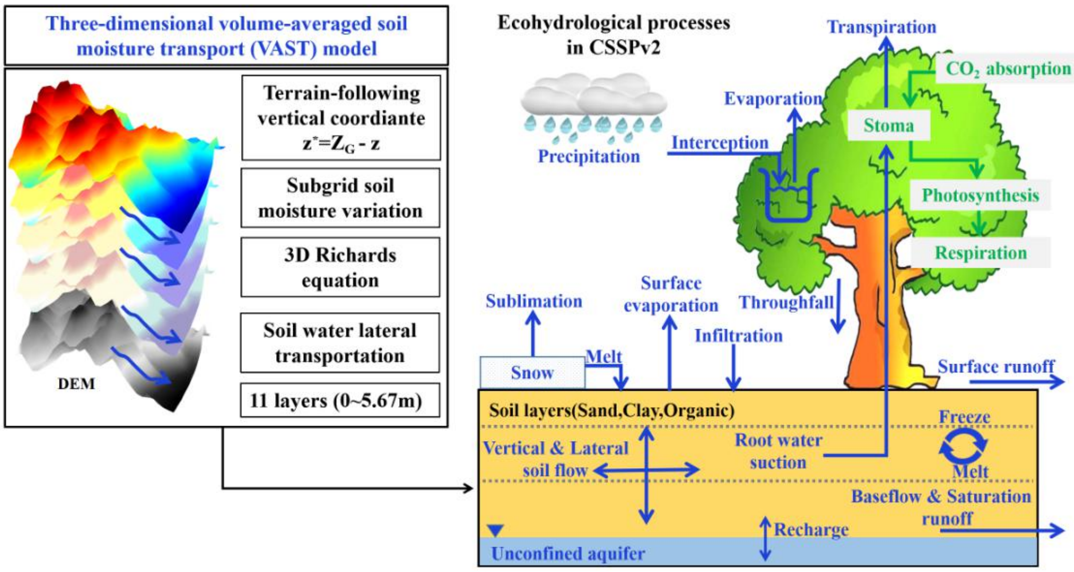

Figure 2. Main ecohydrological processes in the Conjunctive Surface-Subsurface Process version 2 (CSSPv2) land surface model.

Lin 196-198 on page 11: 'the ensemble means of CMIP6 simulations can reproduce the historical increasing trends of temperature, precipitation, and LAI reasonably well.' As shown in the figure.1(d), the ensemble means of CMIP6 seem to hardly simulate the trend of the precipitation. Please give more explanations for this.

Response: Thanks for the suggestion. The previous statement " ... reproduce the historical increasing trends of ..." may cause some misunderstanding. We have revised it as: "As shown in Figures 1b-1e, observations (pink lines) show that the annual temperature, precipitation and growing season LAI increase at the rates of 0.63°C/decade ($p=0$), 16.9 mm/decade ($p=0.02$), and 0.02 m^2/m^2/decade ($p=0.001$) during 1979-2014 respectively. The ensemble means of CMIP6 simulations (black lines) can generally capture the historical increasing trends of temperature (0.30 °C/decade, $p=0$), precipitation (7.1 mm/decade, $p=0$) and growing season LAI (0.029 m^2/m^2/decade, $p=0$), although the trends for precipitation and temperature are underestimated." (L266-273)

Lin 207-218 on page 11: In this paragraph, the author used different indices to measure the performance of models including ling-Gupta efficiencies, correlation coefficient, and root mean squared error (RMSE). A simple introduction of those indices can be added in section 2. In addition, the statistical results of the indices in this study can be presented in a table.

Response: Thanks for the suggestion. We have added a brief description of the indices used in the research as: "Correlation coefficient (CC) and root mean squared error (RMSE) were calculated for validating the simulated monthly streamflow, annual evapotranspiration and monthly terrestrial water storage. The King-Gupta efficiency (KGE; Gupta et al., 2009), which is widely used in streamflow evaluations, was also calculated. Above metrics were calculated as follows:

$$CC = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}}$$

$$KGE = 1 - \sqrt{(1 - CC)^2 + (1 - \frac{\sigma_x}{\sigma_y})^2 + (1 - \frac{\bar{x}}{\bar{y}})^2}$$

where x_i and y_i are observed and simulated variables in a specific month/year i individually, and $\bar{x}$ and $\bar{y}$ are the corresponding monthly/annual means during the evaluation period n. The σ_x and σ_y are standard deviations for observed and simulated variables, respectively. The KGE ranges from negative infinity to 1, and model simulations can be regard as satisfactory when the KGE is larger than 0.5 (Moriasi et al., 2007)." (L211-224)

The statistical results of the indices are now shown in Table 3.

Table 3. Performance for CSSPv2 model simulations driven by the observed meteorological forcing (CMFD/CSSPv2) and the bias-corrected CMIP6 historical simulations (CMIP6_His/CSSPv2). The metrics include correlation coefficient (CC), root mean squared error (RMSE), and Kling-Gupta efficiency (KGE). The KGE is only used to evaluate streamflow.

Variables	Experiments	CC	RMSE	KGE
Monthly streamflow at TNH station	CMFD/CSSPv2	0.95	165 m^3/s	0.94
	CMIP6_His/CSSPv2	0.76	342 m^3/s	0.71
Monthly streamflow at ZMD	CMFD/CSSPv2	0.93	169 m^3/s	0.91

station	CMIP6_His/CSSPv2	0.82	257 m^3/s	0.81
Monthly terrestrial water storage anomaly over the Sanjiangyuan region	CMFD/CSSPv2	0.7	22 mm/month	-
	CMIP6_His/CSSPv2	0.4	24 mm/month	-
Annual evapotranspiration over the Sanjiangyuan region	CMFD/CSSPv2	0.87	14 mm/year	-
	CMIP6_His/CSSPv2	0.47	13 mm/year	-

Lin 254-255 on page 13: No significant changes? As shown in Figure 4b, the frequency of wet extremes tends to increase by 25%. Please give more explanation.

Response: Thanks for the comment. We have clarified this as: "No statistically significant changes are found ..., as the uncertainty ranges are larger than the ensemble means." (L332-334)

Lin 261-264 on page 14: 'Moreover, the frequency of dry extremes tends to decrease significantly ..' It seem that the dry extremes over the Yangtze river also need further analysis at different global warming levels. P2lease clarify.

Response: Thanks for the suggestion. Although the dry extremes over the Yangtze river source region decrease significantly, contributions from the climate change and ecological factors cannot be distinguished due to the small changing magnitude. We have clarified it as:

"Although the frequency of dry extremes also tends to decrease significantly by 35%, 44%, 34% at the three warming levels, the changes are much smaller than those of the wet extremes. Moreover, contributions from climate change and ecological change are both smaller than the uncertainty ranges (not shown), suggesting that their impacts on the changes of dry extremes over the Yangtze river headwater region are not distinguishable. Thus, we mainly focus on the dry extremes over the Yellow river and the wet extremes over the Yangtze river in the following analysis." (L338-345)

Lin 298-300 on page 15: Please clarify this sentence.

Response: Thanks for the suggestion. We have revised this sentence and moved it to the front of detailed description of the importance of CO_2 physiological forcing and land cover change:

"Although the contribution from climate change (red bars in Figures 7a-7b) is greater than the ecological factors (blue and cyan bars in in Figures 7a-7b), influences of CO_2

physiological forcing and land cover change are nontrivial. ... Over the Yellow river, the combined impact of the two ecological factors ... reduces the increasing trend of dry extremes caused by climate change (red bars) by 18~22% at 1.5 and 2.0 °C warming levels, while intensifies the dry extremes by 9% at 3.0°C warming level. ... Over the Yangtze river, ... increases the wet extremes by 9% at 1.5°C warming level while decreases the wet extremes by 12% at 3.0°C warming level." (L371-385)

Lin 321-323 on page 11: A section on uncertainties should be included. Climate model and eco-hydrological model are sources of uncertainties. For example, according to Fig 2, the simulations tend to underestimate the high flow, which will inevitably affect the results.

Response: Thanks for the suggestion. We do agree with the reviewer that both global climate models (GCMs) and hydrological models are sources of uncertainties. Actually, we have used the bootstrap method to estimate the uncertainty caused by GCMs. We have added detailed information for the uncertainty estimations as follows:

"The relative changes in frequency of dry/wet extremes between the reference period and different warming periods were first calculated for each GCM under each SSP scenario, and the ensemble means were then determined for each warming level. To quantify the uncertainty, the above calculations were repeated by using the bootstrap 10,000 times, and 11 GCMs were resampled with replacement during each bootstrap (Christopher et al., 2018). The 5% and 95% percentiles of the total 10,000 estimations were finally taken as the 5~95% uncertainty ranges." (L257-263)

We do not add a new section to discuss the uncertainties, because analysis of uncertainties that caused by GCMs is already included in the results and only the robust changes are taken into consideration in this research.

"However, the dry extreme frequency will further increase to 77% and 125% at the 2.0 and 3.0°C warming levels and the results become significant (Figure 5b)."(L329-332).

"No statistically significant changes are found for the wet extremes at all warming levels over the Yellow River headwater region, as the uncertainty ranges are larger than the ensemble means."(L332-334)

However, we have added some discussions on the uncertainties caused by land surface hydrological model, as only one land surface model was used in this work. “Although we used 11 CMIP6 models combined with two SSP scenarios to reduce the uncertainty of future projections caused by GCMs, using a single land surface model may result in uncertainties (Marx et al., 2018). However, considering the good performance of the CSSPv2 land surface model over the Sanjiangyuan region and the dominant role of GCMs’ uncertainty (Zhao et al., 2019; Samaniego et al., 2017), uncertainty from the CSSPv2 model should have limited influence on the robust of the result.” (L447-453)

Figure 1.(d) ‘growthing season leaf area index’ , while Line 483 ‘growing season leaf area index’?

Response: We have corrected the ‘growthing season leaf area index’ as ‘growing season leaf area index’ in the revised Figure 1.

Figure 4.(1) ‘Simulated monthly streamflow climatology’ change ‘Simulated monthly streamflow’

Response: Revised as suggested.