Response to Reviewer Comments: **Climate and Cryosphere Cause Water Yield Regime Shifts in the Upper Brahmaputra River basin**

Reviewer 2

Comment 2.1: The manuscript from Li et al. offers an analysis of the different drivers of hydrological regime shifts in the upper Brahmaputra, highlighting changing climate and glacier loss as major determinants. While the work is generally well written and shaped, there are some issues/suggestions to be considered before publication:

Reply: We thank the reviewer for their constructive comments and specifically for the suggestions on using the idea of "peak water" as a conceptual framework for understanding cryospheric contributions to river flow. **We will clarify some definitions, and give related evidence with "peak water" in the Results and Discussion section.** The reply to all comments is shown in the following.

General Comments

Comment 2.2: A conceptual framework would greatly help you to shape the storyline. Actually, there are several studies showing regime shifts associated with glacier loss (see Huss & Hoch, 2018; concept of "peak water"). I think that your work provides further evidence in that direction, showing the magnitude of hydrological glacier influence over spatial gradients, and offering an important analysis of the turning points in regime shifts.

Reply: We thank the reviewer for suggestions. We have now framed our analysis and discussion within the conceptual framework of "peak water" as suggested you. For example,

Revisions in Results:

Line 193–201: In contrast to positive contributions of climate, we find that WY caused by cryosphere exhibits a negative association with reduced total WY in recent years in the UYZR ($r = -0.39$, $p > 0.05$) and LSR ($r = -0.36$, $p > 0.05$) basins. The negative but weak relationship indicates that melt waters from cryospheric loss may compensate for low flow, and even mitigate water shortage risks, as suggested by Bibi et al. (2018) and Gleick and Palaniappan (2010). Also, the compensating effect from cryosphere is much stronger in the MYZR ($r = 0.47$, $p > 0.05$), and together with climate contributions, contributes to the increasing WY trend (Figure 4). Different from other regions, however, the HYZR basin shows a significantly positive relationship between cryospheric contributions and total WY ($r = 0.76$, $p < 0.05$), indicating that cryosphere instead of climate leads to the downward trend in headwaters. This signifies that in this region, cryospheric contributions have already passed a maximum supplying to river flow, due to decreased glaciers and snow under continuous warming, which is in agreement with Huss and Hock (2018).

Line 202–206: We further analyze the relationship of cryospheric contributions to total WY (RC_s) with temperature (Figure S6). In the HYZR basin, WY resulting from cryosphere continues to increase with temperature until a maximum is reached, beyond which cryospheric contribution to total WY begins to decrease. In addition, the compensating effect of melt waters also can be seen clearly in the UYZR, MYZR and LSR basins; WY caused by cryospheric loss keeps a positive relationship with the increase of temperature, further supporting the higher correlation in these basins (Figure 6).

Revisions in Discussion:

Line 225–234: However, climate, especially precipitation, remains the most important factor controlling the declining WY trend after the TP in most regions (Figure 6 and S5), and may lead to occurrence of turning points (Figure 3c+d), which is in agreement with previous studies (Li et al., 2021; Wang et al., 2021). This suggests the importance of precipitation and its projections on future hydrological process in mountainous watersheds (Lutz et al., 2014). Also, cryospheric contribution to mountainous hydrology is important – melt waters from glaciers and snow melting can alleviate water resources deficits, mainly caused by decreased precipitation in recent years (Figure 6). This finding is also supported by observed glacier runoff data (Yao et al., 2010) and several modeling studies (Lutz et al., 2014; Zhang et al., 2020; Wang et al., 2021). However, after glacier runoff reaches a maximum, defined as 'peak water' (Gleick and Palaniappan, 2010), cryospheric mass loss cannot sustain the rising meltwaters with atmospheric warming (e.g. the HYZR basin in the study). The decreased glacier areas and associated hydrological changes will substantially affect water resources management.

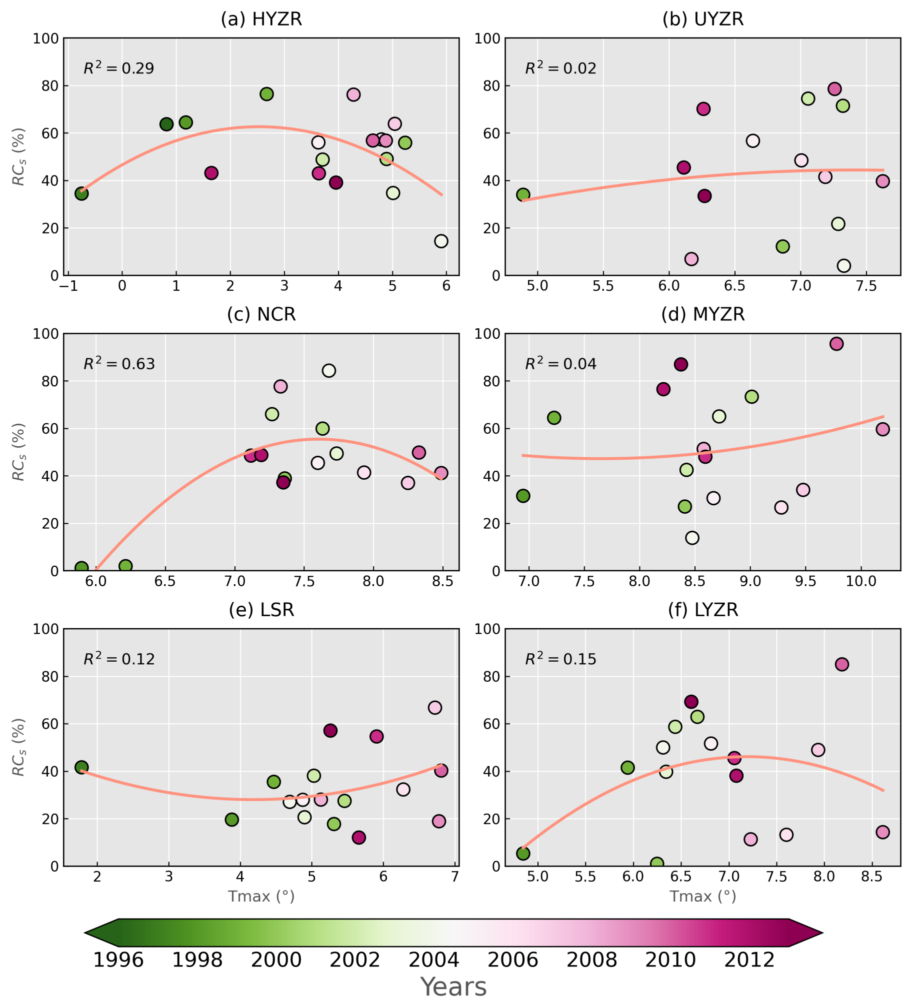

Figure S6. The relationship between cryospheric contributions to water yield deviations ($RC_s(t)$, see Methods in main text) and annual mean 2m maximum air temperature (T_{max}) using the polynomial fitting. The colorbar indicates the years after a TP in individual basins. R square here used to evaluate the fitting goodness is labelled in each panel.

Comment 2.3: I found the discussion a little bit lacking. As glaciers ad the climate are the major hydrological drivers, what will it happen when glaciers disappear and the climate has shifted? Also, you should stress that the "climate shifts" are changes in precipitation patterns in your work

Reply: We thank the reviewer for pointing this out.

We have added additional analysis and discussion of results within the framework of "peak water" as suggested in the previous comment.

Revisions in Results:

Line 196–201: Also, the compensating effect from cryosphere is much stronger in the MYZR ($r = 0.47$, $p > 0.05$), and together with climate contributions, contributes to the increasing WY trend (Figure 4). Different from other regions, however, the HYZR basin shows a significantly positive relationship between cryospheric contributions and total WY ($r = 0.76$, $p < 0.05$), indicating that cryosphere instead of climate leads to the downward trend in headwaters. This signifies that in this region, cryospheric contributions have already passed a maximum supplying to river flow, due to decreased glaciers and snow under continuous warming, which is in agreement with Huss and Hock (2018).

Line 202–206: We further analyze the relationship of cryospheric contributions to total WY (RC_s) with temperature (Figure S6). In the HYZR basin, WY resulting from cryosphere continues to increase with temperature until a maximum is reached, beyond which cryospheric contribution to total WY begins to decrease. In addition, the compensating effect of melt waters also can be seen clearly in the UYZR, MYZR and LSR basins; WY caused by cryospheric loss keeps a positive relationship with the increase of temperature, further supporting the higher correlation in these basins (Figure 6).

Revisions in Discussion:

Line 228–234: Also, cryospheric contribution to mountainous hydrology is important – melt waters from glaciers and snow melting can alleviate water resources deficits, mainly caused by decreased precipitation in recent years (Figure 6). This finding is also supported by observed glacier runoff data (Yao et al., 2010) and several modeling studies (Lutz et al., 2014; Zhang et al., 2020; Wang et al., 2021). However, after glacier runoff reaches a maximum, defined as 'peak water' (Gleick and Palaniappan, 2010), cryospheric mass loss cannot sustain the rising meltwaters with atmospheric warming (e.g. the HYZR basin in the study). The decreased glacier areas and associated hydrological changes will substantially affect water resources management.

Indeed, climate used in the DMC is represented by effective precipitation (eP, P-AET), which is mainly determined by precipitation. We have added related descriptions to highlight the importance of precipitation.

Revisions in Results:

Line 185–190: Results in Figure 6 show that, although the correlation varies greatly across basins ranging from 0.11 to 0.93 after the TP, climate typically is positively associated with total WY, in which the correlation is significant in half of basins ($p < 0.05$), again revealing the major role of climate in the hydrological trends in the entire UBR basin. Further analysis shows that, precipitation is much more important, because it exhibits the stronger reverse in trend compared with that in actual evaporation (Figure S5), which is also similar with direction changes in WY (Figure 4b).

Revisions in Discussion:

Line 215–218: However, climate, especially precipitation, remains the most important factor controlling the declining WY trend after the TP in most regions (Figure 6 and S5), and may lead to occurrence of turning points (Figure 3c+d), which is in agreement with previous studies (Li et al., 2021; Wang et al., 2021). This suggests the importance of precipitation and its projections on future hydrological process in mountainous watersheds (Lutz et al., 2014).

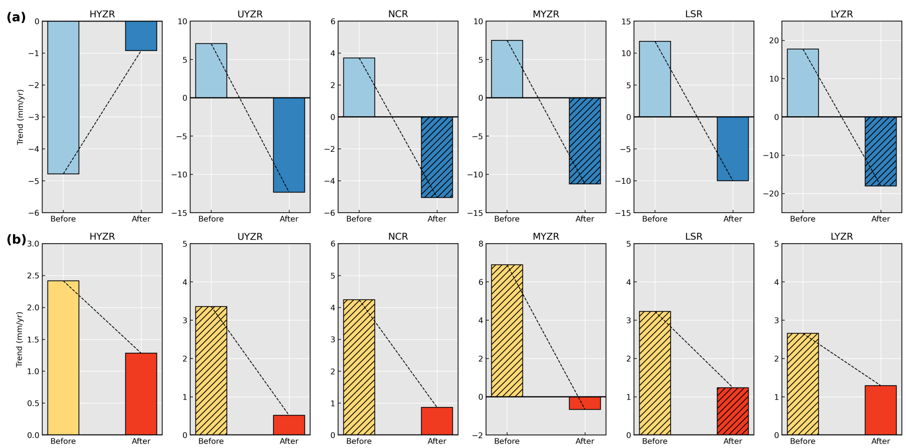

Figure S5. Direction of precipitation (a) and actual evaporation (b) changes. The black hatching represents the statistically significant trend ($p < 0.05$). The color of boxes represents the period before (light color) and after (dark color) the turning point (TP).

Comment 2.4: Why did you choose this particular type of analysis to estimate drivers of regime changes? This is not sufficiently explained in the text

Reply: Thank you for your suggestions. We will provide reasons for the use of DMC method in the Introduction and Methods sections.

Revisions in Introduction:

Line 47–51: Lastly, the present inadequate understanding of hydrological responses to complex interactions among climate, vegetation, and cryosphere limits the application of hydrological models in those glacier-fed watersheds (Pellicciotti et al., 2012). While, long-term observed runoff data and recent high-resolution precipitation records may give a pathway for using statistical methods to estimate runoff responses to warming in mountainous regions.

Revisions in Methods:

Line 101–108: The DMC used here is a plot of the cumulative data of one variable versus the cumulative data of another related variable in a concurrent period. It has previously been used to assess the individual effect of climate (Gao et al., 2011), forest disturbance (Wei and Zhang, 2010), wildfire (Hallema et al., 2018), and cryosphere (Brahney et al., 2017) on water resources. For the large and pristine UBR and other mountainous basins, climate, vegetation, and cryosphere play important roles in hydrology, and these three parts must be together considered to accurately estimate hydrological responses to warming. It is considerably hard to directly calculate the supply of melt waters to WY due to the lack of glacier monitoring, while long-term runoff observations and high-resolution climate and vegetation data make it possible to use the DMC technique, a data-driven statistical method, to estimate cryospheric contribution to WY.

Line 109–115: The selection of climate and vegetation indices used in the DMC technique is an important issue. Previous studies haves shown that effective precipitation (eP, P-AET) can reflect more information of climate on WY compared with individual P or AET, and be regarded as a reliable proxy to climate (Wei and Zhang, 2010; Zhang et al., 2019). LAI quantifies the amount of leaf area in an ecosystem and becomes an important variable reflecting vegetation structures and biophysical processes (Fang et al., 2019; Forzieri et al., 2020), and Li et al. (2021) has used LAI to investigate vegetation effects on seasonal hydrology in the UBR basin. Hence, we consider eP and LAI as the indices of climate and vegetation respectively, and use their time series as the inputs in the DMC model.

Line 116–118: To obtain cryospheric contribution to WY, we firstly build two types of DMC plots (see Figure S2) to assess the contribution of climate (eP) and vegetation (LAI), and then subtract the sum of estimated contributions from total WY deviations (results are shown in Figure 2). The calculation process of the DMC is shown as follows:

Comment 2.5: It seems that the drivers of regime shifts depend on the considered part of the catchment. In general, the influence from glaciers is higher in the upper part and that from precipitation is higher at downstream locations. I think that translating this information into "spatial gradients/turning points" would greatly improve the quality of your work. Is there any relationship between the glacier cover in the catchment and the role of glaciers in driving the magnitude and direction of regime shifts associated with glacier loss or precipitation changes?

Reply: The turning point is both controlled by climate and cryospheric loss, and thus it may be not possible to directly build relationships between turning points and cryospheric contributions. In addition, the limited data (we only access snow and glacier area in 2015) may hinder the analysis between glacier areas and cryospheric contributions from the DMC method.

But, Figure 1 in Huss and Hock (2018) recommended by the reviewer shows the responses of cryospheric contributions to river flow under global warming. Based on this, we try to link cryospheric contributions with temperature changes, and find a nonlinear relationship between them (see Figure S6). Related results and discussions are described in the main text.

Revisions in Results:

Line 202–206: We further analyze the relationship of cryospheric contributions to total WY (RC_s) with temperature (Figure S6). In the HYZR basin, WY resulting from cryosphere continues to increase with temperature until a maximum is reached, beyond which cryospheric contribution to total WY begins to decrease. In addition, the compensating effect of melt waters also can be seen clearly in the UYZR, MYZR and LSR basins; WY caused by cryospheric loss keeps a positive relationship with the increase of temperature, further supporting the higher correlation in these basins (Figure 6).

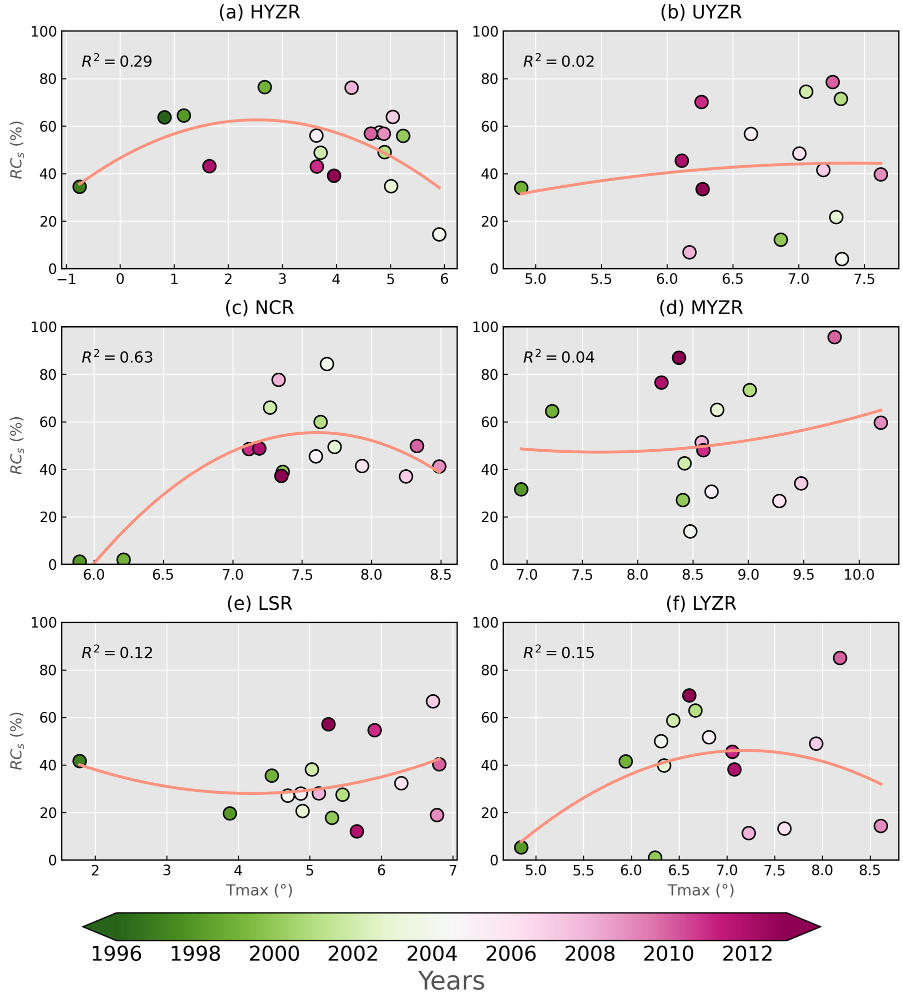

Figure S6 The relationship between cryospheric contributions to water yield deviations ($\Delta WY_s(t)$) and annual mean 2m maximum air temperature (T_{max}) using the polynomial fitting. R square used to evaluate the fitting goodness is labelled in each panel.

Revisions in Discussion:

Line 228–234: Also, cryospheric contribution to mountainous hydrology is important – melt waters from glaciers and snow melting can alleviate water resources deficits, mainly caused by decreased precipitation in recent years (Figure 6). This finding is also supported by observed glacier runoff data (Yao et al., 2010) and several modeling studies (Lutz et al., 2014; Zhang et al., 2020; Wang et al., 2021). However, after glacier runoff reaches a maximum, defined as 'peak water' (Gleick and Palaniappan, 2010), cryospheric mass loss cannot sustain the rising meltwaters with atmospheric warming (e.g. the HYZR basin in the study). The decreased glacier areas and associated hydrological changes will substantially affect water resources management.

Abstract

Comment 2.6: I suggest you to remove useless adverbs such as "however, nevertheless, etc.". Try

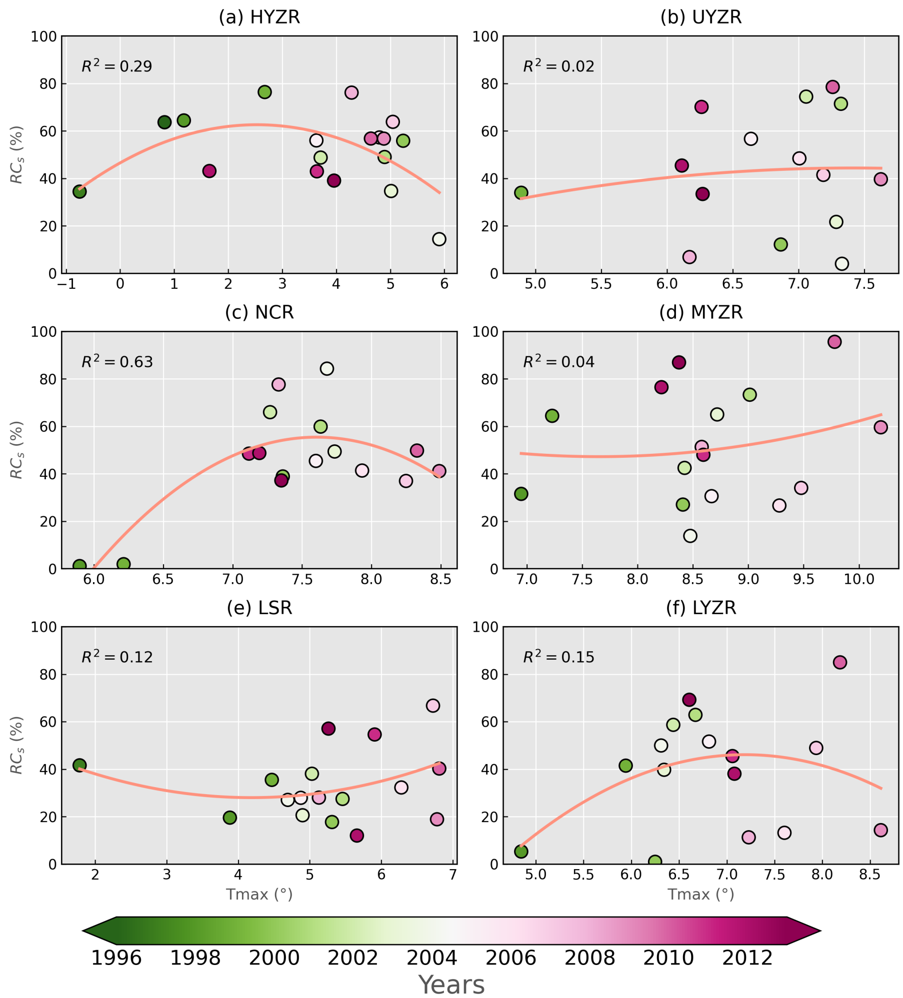

Figure S6 The relationship between cryospheric contributions to water yield deviations ($\Delta WY_s(t)$) and annual mean 2m maximum air temperature (T_{max}) using the polynomial fitting. R square used to evaluate the fitting goodness is labelled in each panel.

to shorten the abstract a little bit, e.g., discarding not essential sentences or summarizing some concepts

Reply: Thanks. We have rewritten the abstract (see below).

Comment 2.7: Line 15. Change "melt" with "loss". Cryospheric changes can increase the amount of available water, e.g. in rock glaciers

Reply: Thanks. We have rewritten the abstract (see below).

Comment 2.8: Line 18. Is it "stream head" correct word? I would delete the part ", as represented. . . downstream" in this sentence, useless for the abstract in my opinion.

Reply: Thanks. We have deleted the useless sentence for the abstract to ensure it convey main information to readers (see below).

Comment 2.9: Line 19. Delete "we found that"

Reply: Thanks. We have rewritten the abstract (see below).

Comment 2.10: Line 21. Delete "furthermore"

Reply: Thanks. We have rewritten the abstract (see below).

Comment 2.11: Line 23. Delete "however"

Reply: Thanks. We will delete it (see below).

Comment 2.12: Line 25. Delete "nevertheless, we found that"

Reply: Thanks. We have rewritten the abstract to strengthen its coherence (see below).

Comment 2.13: Line 28. What do you mean with "ecological restoration"? I would remove this word as "water management" is enough in this context. Either, you can use the word "water governance", which involves the management of water as well as the related ecosystems and resources

Reply: Thanks for your advice. We deleted "ecological restoration" throughout the manuscript (see below).

The revised abstract is shown:

Line 1–15: Although evidence of hydrological responses to climate is abundant, the reliable assessments of water yield (WY) in mountainous watersheds remain unclear due to intensified cryospheric changes. Here we examine long-term WY changes during 1982–2013 in the Upper Brahmaputra River (UBR) basin on the basis of annual runoff observations. Results show that hydrological regime shifts have occurred in the late 1990s; magnitude increases in WY range from ∼10% to ∼80%, while the directions of WY changes reverse from upward to downward after the late 1990s. We then use the double mass curve (DMC) technique to assess the effects of climate, vegetation, and cryosphere on WY regime shifts. Results show that climate and cryosphere together contribute to over 80% of magnitude increases of WY in the entire UBR basin, in which the role of vegetation is nearly negligible. The combined effects, however, are either offsetting or additive, leading to slight or substantial magnitude increases, respectively. Climate change, particularly precipitation decline leads to the downward WY trend in recent years, while melt waters from cryospheric changes may alleviate water shortage in some watersheds. In headwaters, however, cryospheric contributions to WY have declined due to reduced glaciers and snow under warming. Therefore, the combined effects of climate and cryosphere on WY should be considered in water resources management in mountainous watersheds, particularly involving co-benefits for upstream and downstream regions.

Introduction

Comment 2.14: Line 36. What do you mean with glacial snowmelt? Cryospheric drivers are snow and glaciers providing water across the melting process, i.e., glacier ice melt and snowmelt. Or do you mean the snowmelt occurring on the glacier surface? Please consider here the paper from Huss et al., 2017, which also includes the permafrost ice as a key component of the mountain cryosphere

Reply: Thank you pointing it out. We use **"glacier and snow melting"** throughout the revised manuscript, which will be calculated using the DMC method.

Comment 2.15: Line 36. It is actually unclear to a layman what the Third Pole is. Please clearly and concisely define it the first time you name it

Reply: Thanks. "Third pole" has the less role in the manuscript and also cause the confusion to the abbreviation of "turning point", so we plan to delete it.

Comment 2.16: Line 52. "direction of change…" of what?

Reply: We will use the following expression to replace it:

Line 30–31: For example, Fan and He (2015) highlighted the important role of precipitation in WY increases in the Salween and Mekong River basins.

Comment 2.17: Line 54. "glacial snow". See same comment of line 36.

Reply: Thanks. We will use **"glacier and snow melting"** throughout the manuscript.

Comment 2.18: Line 84-85. "a reference…modelling". You already provided this sentence 8 lines earlier. Please avoid repetition.

Reply: Thanks. We will delete the repeated expressions.

Results

Comment 2.19: Figure 3. I think the use of boxplots would greatly help interpretation.

Reply: We will use the boxplots to show the data distribution.

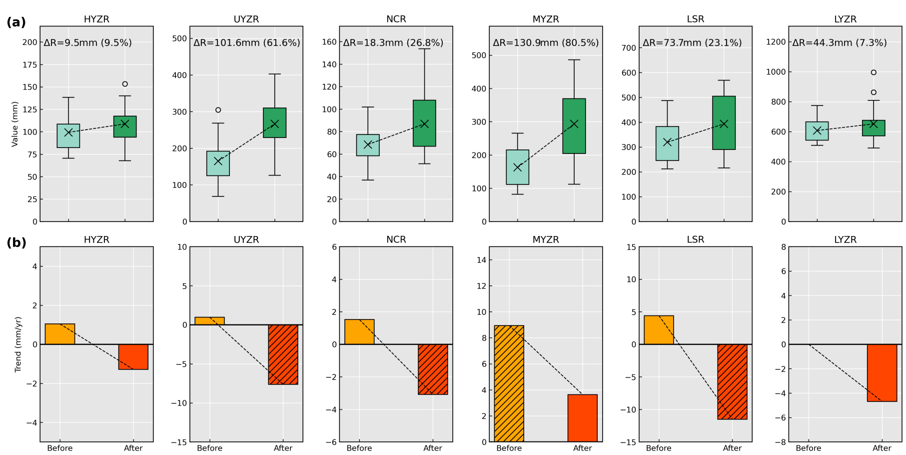

Figure 4. Water yield regime shifts over the entire UBR basin. (a) Magnitude of water yield changes. The colors of boxes represent before (light green) and after the turning point (TP) (green). Black "x" signals show the mean of water yield in each boxplot. (b) Direction of water yield changes. The black hatchings represent the statistically significant trend ($p < 0.05$).

Comment 2.20: Figure 5. I suggest you to provide the text and fitting lines for significant relationships only, to avoid figure overwhelming and help interpretation

Reply: Thanks for your suggestions. We have created the figure to avoid overwhelming as following.

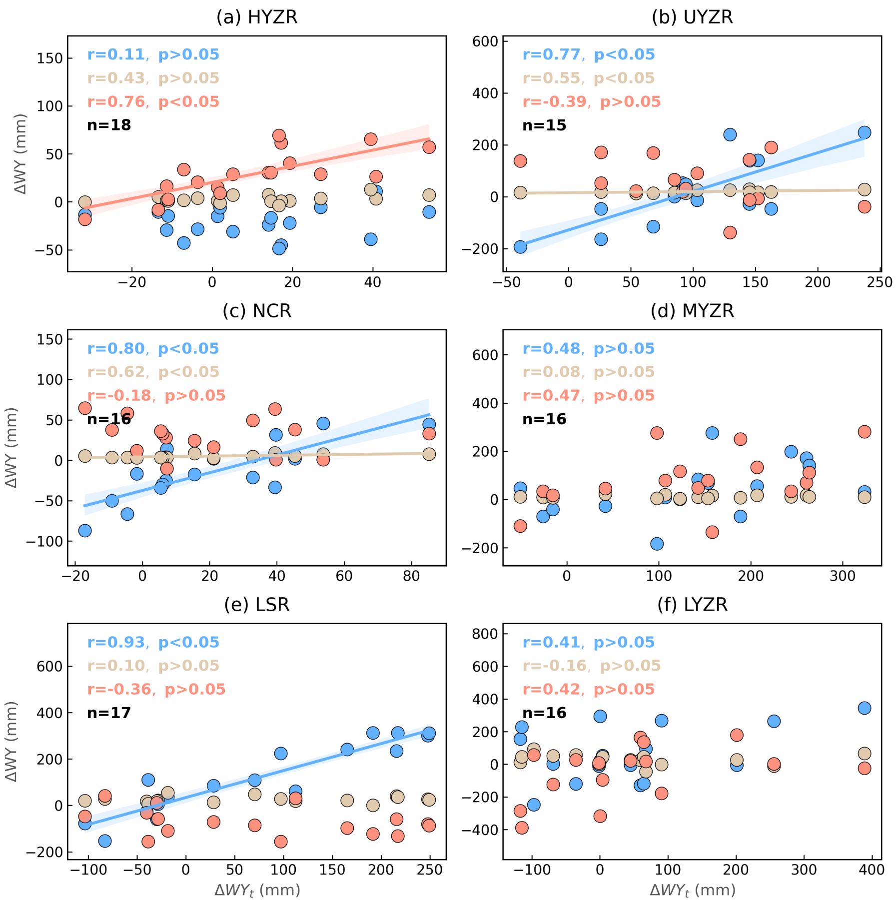

Figure 6. The relationship between time series of total water yield deviation ($\Delta WY_t(t)$, x-axis) and its components (y-axis) induced by climate ($\Delta WY_c(t)$, blue point), vegetation ($\Delta WY_v(t)$, tan point), and cryosphere ($\Delta WY_s(t)$, red point), respectively. The fitting line and its 95% confidence interval are shown only when p value < 0.05. n indicates the number of years after the TP, which is determined by the Pettitt method (See Table 1 and Figure 3c).

Discussion

Comment 2.21: I think that an important work to be considered, that may help contextualising your storyline, would be Huss & Hock (2018) providing the concept of "peak water". I suggest you to reshape the discussion around this work. Your results clearly show that the upper Brahmaputra has already surpassed the Peak Water and is now in declining phase of hydrological changes associated with glacier loss. This conceptualisation would also help you to better discuss the turning points that different areas experienced during distinct years. . . the presence of these turning points should be better discussed, as it is one of the strengths of the chosen methodology.

Reply: Thanks. We have linked the results with "peak water", as revealed in (Huss and Hock, 2018).

Revisions in Results:

Line 193–201: In contrast to positive contributions of climate, we find that WY caused by cryosphere exhibits a negative association with reduced total WY in recent years in the UYZR ($r = -0.39$, $p > 0.05$) and LSR ($r = -0.36$, $p > 0.05$) basins. The negative but weak relationship indicates that melt waters from cryospheric loss may compensate for low flow, and even mitigate water shortage risks, as suggested by Bibi et al. (2018) and Gleick and Palaniappan (2010). Also, the compensating effect from cryosphere is much stronger in the MYZR ($r = 0.47$, $p > 0.05$), and together with climate contributions, contributes to the increasing WY trend (Figure 4). Different from other regions, however, the HYZR basin shows a significantly positive relationship between cryospheric contributions and total WY ($r = 0.76$, $p < 0.05$), indicating that cryosphere instead of climate leads to the downward trend in headwaters. This signifies that in this region, cryospheric contributions have already passed a maximum supplying to river flow, due to decreased glaciers and snow under continuous warming, which is in agreement with Huss and Hock (2018).

Line 202–206: We further analyze the relationship of cryospheric contributions to total WY (RC_s) with temperature (Figure S6). In the HYZR basin, WY resulting from cryosphere continues to increase with temperature until a maximum is reached, beyond which cryospheric contribution to total WY begins to decrease. In addition, the compensating effect of melt waters also can be seen clearly in the UYZR, MYZR and LSR basins; WY caused by cryospheric loss keeps a positive relationship with the increase of temperature, further supporting the higher correlation in these basins (Figure 6).

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Line 228–234: Also, cryospheric contribution to mountainous hydrology is important – melt waters from glaciers and snow melting can alleviate water resources deficits, mainly caused by decreased precipitation in recent years (Figure 6). This finding is also supported by observed glacier runoff data (Yao et al., 2010) and several modeling studies (Lutz et al., 2014; Zhang et al., 2020; Wang et al., 2021). However, after glacier runoff reaches a maximum, defined as 'peak water' (Gleick and Palaniappan, 2010), cryospheric mass loss cannot sustain the rising meltwaters with atmospheric warming (e.g. the HYZR basin in the study). The decreased glacier areas and associated hydrological changes will substantially affect water resources management.

Comment 2.22: Line 309-311. This is not true! See works from Huss and Hoch (2018), and in general the latest IPCC report on the ocean and the cryosphere, chapter dedicated to mountain environments…

Reply: Thank you for pointing it out. In the original manuscript, we want to show that this study provides a more detailed analysis for water yield changes in the UBR basin. We have deleted it to avoid the confusion.

Comment 2.23: Line 330. Please change "retractration" with "loss" or "recession". Also the sentence is unclear as written

Reply: Thanks. We will use "glacier mass loss".

Comment 2.24: Line 338. What do you mean with "ecological restoration"? It is unclear why this would help ecological restoration in particular. It is a general issue of water governance, after all, not just restricted to ecological restoration.

Reply: We will use "water resources management" to indicate the implication of this study.

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