Note: Adjustments in response to the comments from Reviewer 2 are highlighted in yellow in the revised manuscript.

Reviewer 2

We would like to thank the referee once again for their continued review and thoughtful comments. We greatly appreciate the time and effort taken in further refining our manuscript and for providing additional valuable insights. We have carefully considered these additional comments in the revised manuscript.

We have separated the different comments (*shown in italic*) and provide our replies below. Text in the original manuscript is shown in '*italic*' and revised text in '***bold***'.

Reviewer comment:

The revised manuscript "Catchments do not strictly follow Budyko curves over multiple decades but deviations are minor and predictable" is a very improved version of the earlier manuscript. I feel that all the reviewers' comments have been very well addressed, with complete and detailed answers and well-chosen adjustments made accordingly to the manuscript.

I feel the introduction is very complete and interesting; the method is a lot clearer, with the choices made better explained and discussed. The figures are clear, complete and the adjustments made help to better show the richness of the results. I believe that this manuscript is very well integrated into the current literature and the current stakes surrounding models' robustness for predictions. This article would be an interesting contribution to the field, and I recommend it for publication.

Reply:

We are thankful for the encouraging remarks made by the reviewer on our manuscript. We are pleased that the reviewer found our approach and reflections valuable to the field.

Reviewer comment:

I would thank the authors for adding more perspective to the results by showing the effect on discharge changes / I_E (%), which are easier to understand than changes in the median. I would maybe specify more clearly that these changes in Q are changes due to the deviation to the curve only (if I understood correctly). There is a predicted change along the Budyko curve, what the authors evaluate is the part that is not predicted due to a deviation to the curve.

Reply:

We highly appreciate the reviewer's thoughtful comment. We have clarified this point in our revised manuscript that the changes in Q presented in our analysis are solely attributable to deviations from the expected parametric Budyko curve. We have modified the caption of Figure 7c as follows:

p. 17, lines 485-487 (Results):

"Figure 7: a) Temporal stability, b) long-term median $\varepsilon_{IE\omega}$ values map of aggregated long-term marginal distributions for the study catchments, and c) change in Q as a result of long-term median $\epsilon_{IE\omega}$ values. Histogram and cumulative density of changes in Q, and change in Q across different I_A bins are presented as two insets. ***Change in Q reflect the change due to median deviations $\varepsilon_{IE\omega}$ from the***

expected parametric Budyko curve only (i.e., excluding any change resulting from a change in aridity and its associated movement along the expected curve)*.Catchments highlighted with a black border represent the 5 selected examples from Fig. 6, while those outlined in red denote three additional selected example catchments shown in the Supplement (Fig. S5). The boxes represent the 25th to 75th percentiles, while whiskers extend to the 10th and 90th percentiles. Diamonds denote the arithmetic mean, and outliers are not shown."*

Reviewer comment:

Also, how is the median value of deviation interpreted? A unit for the median could be interesting to understand the order of magnitude analysed. Is it a relative variation in I_E? Or an absolute variation in I_E? If it is the latter, the regional aggregation of median distributions (l 539) would need to be further discussed.

Reply:

We thank the reviewer for this insightful comment. The deviation ($\varepsilon_{IE\omega}$) is dimensionless because it represents the absolute difference between observed evaporative index and predicted evaporative index (Eq. (4)). Concerning the regional marginal distribution of deviations, these are not based on aggregation of median deviations but rather on aggregating yearly deviations for each catchment within a defined latitude-aridity index bins. To clarify this, the following modifications have been made in the revised manuscript as follows:

p. 3, lines 75-76 (Introduction):

"Where $\varepsilon_{IE\omega}$ is defined as the ***absolute*** *difference between the observed evaporative index ($I_{E,o}$) and the predicted evaporative index (I_E) derived from the expected parametric Budyko curve,* ***making it dimensionless****."*

p. 6, line 143 (Methods):

"Figure 2: A schematic representation of a catchment movement in Budyko space between two long-term time periods T_i and T_{i+1}. Case A: Catchment A moves along the same Budyko curve from the first period T_i to the next period T_{i+1} (i.e., $\omega_i = \omega_{i+1}$). Case B: Catchment B has deviated from its expected parametric Budyko curve (i.e., $\omega_i \neq \omega_{i+1}$), ***resulting in deviation $\varepsilon_{IE\omega,i+1}$ (Eq.(4))****"*

p. 19-20, lines 545-548 (Results):

"For a more regional evaluation, ***the yearly $\varepsilon_{IE\omega}$ values for individual catchments were aggregated into regional marginal distributions of $\varepsilon_{IE\omega}$ stratified according to the long-term mean aridity index I_A and varied latitude bands (Fig. 9a). These regional distributions capture the variability of yearly $\varepsilon_{IE\omega}$ across regions with the median $\varepsilon_{IE\omega}$ serving as a robust measure of central tendency****. The general pattern found across most regions with available data are broadly consistent. 16 out of 20 regions are characterized by median deviations $\varepsilon_{IE\omega}$ that do not exceed ± 0.02. Similarly, no consistent directional pattern in the magnitude of regional median $\varepsilon_{IE\omega}$ could be identified either (Fig. 9b). For higher latitude regions beyond ±30°, the minor fluctuations in median $\varepsilon_{IE\omega}$ bear no evidence for a relationship with I_A. On the other hand, the data suggest that the spread around the regional medians consistently decreases with increasing I_A across all latitude bands except 50° N–90° N band as shown by the sequence of IQR in Fig. 9c. This indicates that catchments in more humid regions across the study domain are subject to more pronounced annual water storage fluctuations."*

Reviewer comment:

L 78 : missing a parenthesis for the e.g.

Reply:

We thank the reviewer for pointing this out. We have added a parenthesis at the end of this sentence in revised manuscript.

Reviewer comment:

L 160: 'Ti', not very clear it is a notation. Maybe be more explicit (noted Ti for the ith period) or refer to Table 1. At minima, write T_i and not Ti, as done later on. Otherwise, it's a very good paragraph.

Reply:

We thank the reviewer for highlighting this point. In the revised manuscript, we have updated both the text and title of Table 1 to explicitly define T_i as the i^{th} 20-year period and referred to Table 1 for clarification. The revisions are incorporated as under:

p. 7, line 161 (Methods):

"Here, we have sub-divided the available data records of each catchment into up to five individual 20-year periods ***over the last century, denoted as T_i (Table 1), where T_i represents the i^{th} 20-year period.*** *This 20-year period was chosen deliberately to balance the need for a sufficiently long period to minimize the impact of storage changes, while preserving the temporal sequence in the data that allowed us to place each catchment into a specific temporal stability category (as described in Step-4)."*

p. 7, line 170 (Methods):

"Table 1: Symbols used in this study to present 20-year periods ***(T_i),*** *changes between subsequent 20-year periods, and distributions of deviations."*

Reviewer comment:

L 503: "decrease in the seasonality": what does it mean

Reply:

We thank the reviewer for highlighting the need for clarification regarding the decrease in seasonality. Seasonality refers to Seasonality Index (SI) of liquid precipitation input (rainfall + snowmelt), calculated by using the equation proposed by Gao et al. (2014), which describes how precipitation is distributed over the year. A higher SI indicates that most of the precipitation falls within a few months, while a lower SI value signifies a more even distribution throughout the year.

We have added a clarification of this point in the revised manuscript as follows:

p. 18, lines 497-500 (Results):

"In contrast, 7 % of the catchments were tagged as "Alternating" and a dependency between $I_{E,i}$ and $\varepsilon_{IE\omega}$ could not be ruled out. A characteristic example for this type of catchments is the Kaituna

catchment (New Zealand; 706 km^2, ID NZ_0000003) in Fig. 6j-l. This catchment features major fluctuations with median $\varepsilon_{IE\omega}$ between -0.115 and 0.198. In addition, although no systematic evolution of median $\varepsilon_{IE\omega}$ over time was evident (Fig. S4d), the data suggest the potential presence of a dependency on $I_{E,i}$ as shown in Fig. S4c. The pronounced alternating behaviour of the $\varepsilon_{IE\omega}$ fluctuations between -0.115 and 0.198, could not be readily explained by factors such as land use changes as estimated from the Hilda+ gridded land cover product (Winkler et al., 2021), ***Seasonality Index (SI) of liquid precipitation input (i.e., rainfall + snowmelt), Parde Coefficients or median rainfall intensity (Fig. S3a,c,e-f). The SI was calculated using the formula proposed by Gao et al. (2014). A higher SI value indicates that most of the precipitation falls within a few months, while a lower value reflects more evenly distributed precipitation throughout of the year.*** *This suggests that other additional drivers, or a combination of drivers, influence this catchment's alternating behaviour."*

p. 18, lines 505-508 (Results):

"The remaining 102 catchments (4 %) were tagged as "Shift", as they exhibit a rather consistent shift of median $\varepsilon_{IE\omega}$ over time. This can be seen for a selected example in Fig. 6m-o.The median $\varepsilon_{IE\omega}$ in this catchment of the Zschopau River (Germany; 1544 km2; ID DE_0000027) does not only significantly vary between -0.055 and 0.037 but it does so rather systematically into one dominant direction after $\varepsilon_{IE\Delta 1}$ ("+ - ++"; Fig. 6n). ***This shift aligns with a gradual decrease in the 20-year Seasonality Index (SI) (Fig. S3e) of liquid precipitation input (i.e., rainfall + snowmelt). In the Zschopau river catchment, this decrease in SI towards the end of the century signifies a shift towards a more evenly distributed precipitation pattern. These changes coincide with an increase in forest cover towards the end of century, as estimated from Hilda+ data (Fig. S3b)****. Additionally, Renner et al. (2014) and Renner and Hauffe (2024) reported a gradual recovery of forests in the Zschopau catchment during this period, which may further contribute to the observed shift."*