Reviewer 1

We would like to thank the referee for the very constructive comments. We greatly appreciate the time and effort taken in thoroughly reviewing our manuscript and for providing valuable and insightful perspectives on our research. We will carefully consider these comments in the revision of the 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**'. Line numbers mentioned in our reply refer to the original manuscript version.

Reviewer comment:

I commend the authors for their manuscript "Catchments do not strictly follow Budyko curves over multiple decades, but deviations are minor and predictable". The hypothesis that the manuscript aims to test is that changes in trajectories in Budyko space are unpredictable, which is in itself a fundamental question in studies dealing with the Budyko framework. The probabilistic approach used to test the hypothesis is elegant, brings some clarity, and puts in context the different recent results of other studies. I enjoyed reading the manuscript, from the introduction to the conclusions. Their finding is also comforting for the field. I also appreciate the reflections on the latest research on the matter.

Reply:

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

Reviewer comment:

I have some suggestions for improvement below, but, in general, I have a rather positive perspective of the manuscript in terms of the scientific method, knowledge gap identification, novelty, approach, and implications. My only disappointment is the lack of exploration of the reason behind the shifting, variable, or alternating nature of some catchments, although the authors explicitly state that this is not the study's objective. Although not the sole aim of the manuscript, it would be indeed interesting to get some potential explanations for the different groups of Table 2. Under what conditions or drivers can catchments shift, variate or alternate?

Reply:

We highly appreciate the positive feedback and thoughtful suggestions. Although it is indeed not the primary scope of the paper, we acknowledge that exploring the reasons behind the shifting, variable, or alternating nature of catchments would indeed be a valuable and interesting addition.

We examined the example catchments shown in Fig. 6 (in the manuscript) to explore potential factors influencing the fluctuations.

For the Sava River, classified here as variable, previous work by Levi et al. (2015) suggests that the relatively wide range of $\varepsilon_{IE\omega}$ fluctuations (IQR ~ 0.11; Fig.6i) can be largely attributed to hydropower developments and the associated changes in hydropower production levels, which disrupt natural flow regimes by increasing runoff during high demand and altering seasonal flow patterns (RenÖFÄLt et al., 2009; Lee et al., 2023).

In the case of the Kaituna River (Fig.6k), 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 of liquid precipitation, Parde Coefficients or median rainfall intensity (Fig. R1a,d,g-h). This suggests that some additional drivers, or a combination of drivers, might be influencing the catchment alternating behaviour.

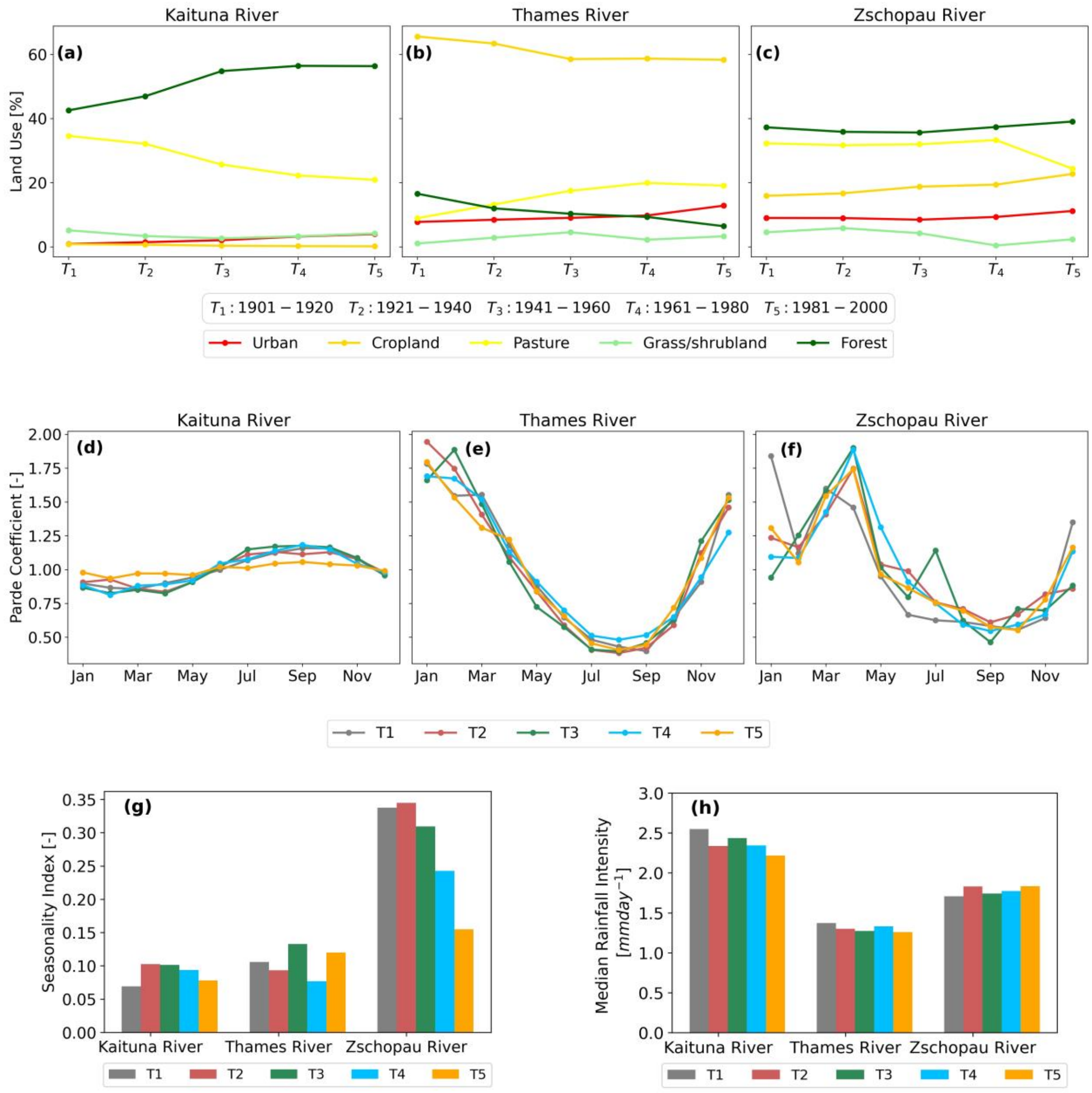

Figure R1: Land use changes (a-c), Parde Coefficients (d-f), seasonality indices (g), and median rainfall intensity (h) for three catchments (Kaituna, Thames, and Zschopau) across five 20-year periods (T_1–T_5).

In addition, we examined the Thames River in the UK, which also exhibited an alternating sequence of negative $\varepsilon_{IE\omega}$, i.e. reduced evaporation, and positive $\varepsilon_{IE\omega}$, i.e. increased evaporation (Fig.R2). These fluctuations were found qualitatively consistent with land use changes from *Hilda+* data (Fig. R1b). From T_1 to T_2, a ~5% decrease in forest cover likely contributed to negative $\varepsilon_{IE\omega}$. Between T_2 and T_3, the positive $\varepsilon_{IE\omega}$ correlates with a 4.3% increase in pasture and a 1.7% increase in grass/shrubland, with negligible change in forest cover. The subsequent decrease in evaporation from T_3 to T_4 coincides with a 1% reduction in forest cover and a ~2.5% decrease in grass/shrubland. However, during the final period (T_4 to T_5), vegetation changes cannot explain the observed alternating behaviour.

The shifting behaviour of $\varepsilon_{IE\omega}$ for the Zschopau River (Fig. 6n) into one dominant direction after $\varepsilon_{IE\Delta 1}$ coincides with a gradual decrease in the seasonality of liquid precipitation input (i.e. rainfall + snowmelt; Fig.R1g), combined with an increase in forest cover (*Hilda+* data) towards the end of century (Fig.R1c). Renner et al. (2014); Renner and Hauffe (2024) also reported a gradual forest recovery in the Zschopau catchment during this period, which could further contribute to the observed shift.

While some of these explorations suggests potentially plausible correlations with land use changes and seasonality of liquid precipitation, the available data is insufficient to draw robust conclusions. Given the limited data support, we chose not to include these potential explanations in the manuscript to avoid introducing overly speculative elements.

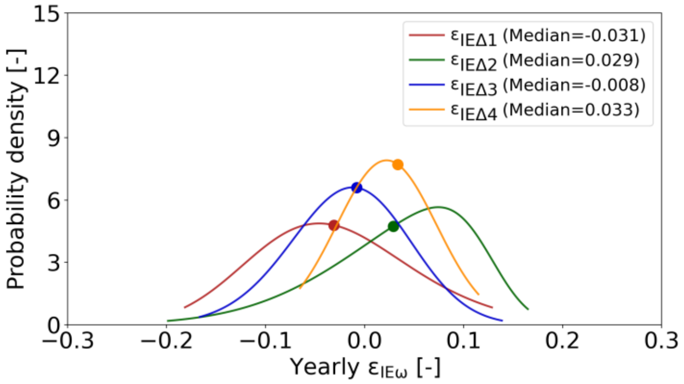

Figure R2: Individual distribution of deviations ($\varepsilon_{IE\Delta 1}$, $\varepsilon_{IE\Delta 2}$, $\varepsilon_{IE\Delta 3}$ and $\varepsilon_{IE\Delta 4}$) for Thames River in the UK

Reviewer comment:

Title: The title says that most catchments deviate, but the conclusion states "62% do not significantly deviate", which is contradicting.

Reply:

Please note that we have made the deliberate choice to formulate the title as “Catchments do not strictly follow….”. This is more general than “Most catchments do not strictly follow…” and does not directly imply a majority.

Indeed, our analysis suggests that, based on Wilcoxon Signed Rank Tests, for 62% of the catchments the median deviations were not significantly different from zero. However, it is important to note that minor deviations were still observed in most catchments even though they were not classified as significant based on this specific statistical test. It would probably too naive to assume that $\varepsilon_{IE\omega} = 0$ and that catchments therefore strictly follow their curves, as also demonstrated, for example, by (Reaver et al., 2022). We therefore prefer to reflect this in the title of the paper. We believe this title conveys the key message of this research work. However, we will clarify this point in discussion part of the revised manuscript.

Reviewer comment:

l. 69 Climate is not the only driver; do not forget changes in water and land use, which have been broadly found to drive the trajectory of movement in Budyko space.

Reply:

We completely agree. We will expand the statement in lines 68-72 as follows:

"*Recently, it was also argued that catchments should not be necessarily expected to follow their long-term average, catchment specific parametric Budyko curves when subject to climatic perturbations, expressed as changes in I_A (Berghuijs and Woods, 2016; Jaramillo et al., 2018; Jaramillo et al., 2022; Reaver et al., 2022). Such deviations ($\varepsilon_{IE\omega}$) from the expected parametric Budyko curve, were previously referred to as residual or landscape-driven,* ***indicating that many factors other than I_A, such as human-induced changes in water and land use (e.g., afforestation, deforestation, irrigation, reservoir construction) can and do also play a role (Donohue et al., 2007; Wang and Hejazi, 2011; Destouni et al., 2012; Sterling et al., 2012; van der Velde et al., 2014; Jaramillo and Destouni, 2015; Levi et al., 2015; Nijzink et al., 2016; Daly et al., 2019; Gan et al., 2021; Hrachowitz et al., 2021)***

Reviewer comment:

Fig. 2- The use of symbols in variables became too confusing at some point. The subindices in the variables are long and have a long set of characters, as shown in Fig. 2. Maybe this can be simplified in some way. In the same way, the critical variable $\varepsilon_{IE\omega}$ is not explicitly shown in Fig. 2. There are also some inconsistencies, e.g., $\varepsilon_{IE\Delta j}$. Why "j"? I would avoid the i+1 subindex in the figure so that it agrees with the variables called in the text.

Reply:

We agree with that observation. Given the multi-decadal periods involved, simplifying the notations is quite challenging. However, we will revisit the figure and try to make it simpler without losing clarity. We will explicitly show $\varepsilon_{IE\omega}$ in the revised figure and address any inconsistencies throughout the revised manuscript.

Reviewer comment:

Fig. 5. $\varepsilon_{IE\Delta}$ does not agree with its expression in Fig. 2. This also brings confusion. Please double-check these issues across the manuscript.

Reply:

We thank the reviewer for pointing this out. We will correct that and ensure consistency in use of symbols throughout the revised manuscript.

Reviewer comment:

L. 186 Why are the time periods consecutive? I see no problem in comparing the changes from, for example, T_1 to T_4. These new permutations would give even more robustness to the statements of deviation or not deviation.

Reply:

We do, in principle, agree and considered this approach in the initial phase of the research. However, we chose to proceed with comparing consecutive periods for the following reasons:

1. The use of the most recent 20-year period as the baseline allows to explore the temporal stability of changes. Meaning, is there a systematic pattern over time, as reflected in the classes “Alternating and Shifts” or can the fluctuations be assumed to be random, as reflected in the classes “Stable” and “Variable”? Using permutations of different periods and thus not preserving the temporal sequence would make such a distinction problematic. We believe that such a classification is necessary for the interpretation of any type of future estimates of $I_{E.}$ For catchments in the classes “Alternating” and “Shift”, historical data indicate a change of the underlying distributions which need to be considered for any type of future estimation. In the absence of further information, it is then plausible to assume that the most recent distributions are more representative as baseline for predictions.
2. In many cases, we do not have complete data for five 20-year periods across the full 100-year timeframe. As only 159 out of 2,387 catchments include the full 100-year period for Δ_{1-2}, while 889 catchments have data for Δ_{2-3}, and the number increase to 1916 for Δ_{3-4}, and 2269 for Δ_{4-5}. This distribution shows that for most catchments, only two or three 20-year periods are available, making changes to the baseline period less impactful.

In any case, we will include this in the discussion part of our revised manuscript.

Reviewer comment:

L. 200 ω is both the Budyko and PDF scaling parameters, which is also confusing.

Reply:

We thank the reviewer for this observation. In the revised manuscript, we will replace the scale parameter ω of Skew Normal Distribution with λ to avoid confusion.

Reviewer comment:

Fig. 3 Mention the example of the basin you are showing here.

Reply:

This figure is not based on real data and is intended for illustration purpose only. We will clarify this in the revised manuscript.

Reviewer comment:

Fig. 6. Can you classify the catchments with the classification of Table 2? This helps understand which ones correspond to which. Also, why did you choose these catchments? I would also put the name of the catchment in the plots.

Reply:

Excellent suggestion. In the revised manuscript, we will mention both the class and names of each catchment in the plots. The selected example catchments were chosen as they provide a good representation of the different categories used in this research.

Reviewer comment:

L. 395 The answer to your finding about the Sava River may be found in Levy et al. (2015); hydropower development.

Reply:

We thank the reviewer for pointing us to that paper. We will include this information in the discussion section of the revised manuscript.

Reviewer comment:

Fig. 8 Any use for the palette change in Fig. 8a?

Reply:

The palette in Fig. 8a differs from that in Fig. 8b to match the palette used in Fig. 7b. This was done to maintain consistency and help the reader to better understand the figures. In contrast, Fig. 8b uses a single colour as the interquartile range (IQR) values are all positive, and thus a more varied colour palette was not necessary. The choice of colour is just random. We will clarify the use of the different colour schemes in the figure caption.

Reviewer comment:

Discussion: I would like to know the thoughts from the authors on the future use of the framework for identifying human modifications to the water cycle, as it has largely been used to date. Maybe some recommendations on the way forward for this goal could be included in the discussion.

For instance, the fact that most basins do not deviate does not necessarily mean that the Budyko framework (and the authors' approach) cannot be used to continue identifying human drivers of change. In fact, such identification relies on the deviations to recognize drivers of change. A way forward can be the categorization of the authors into stable, variable, alternating, and shifting categories and to focus analysis on some of these groups.

Reply:

We completely agree that despite the minor deviations observed in the majority of catchments, the Budyko framework remains useful for identifying human-driven changes. Indeed, deviations are key for recognizing these drivers of change. Categorizing catchments into ”Stable”, “Variable”, “Alternating” and “Shift” could guide a targeted future research. For example, catchments in the “Alternating” and “Shift” categories may in the past either have been subject to more substantial human interference than those in the other categories or they may be more *sensitive* to human-induced changes. Further investigations into the drivers of these deviations could enhance our understanding of how these human-induced changes influence catchments responses differently in different environments. We will incorporate and discuss this this perspective in the revised manuscript.

Reviewer comment:

Could the authors provide a list in Supplementary on the catchments that fall in each of the categories (if this is not already mentioned).

Reply:

We thank the reviewer for this suggestion. A detailed summary table, including the list of catchments with their respective categories, is available in a separate repository available at: https://doi.org/10.5281/zenodo.10925966. We will add this to our data availability statement.

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