Supplement of

Catchments do not strictly follow Budyko curves over multiple decades but deviations are minor and predictable

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This supplement provides additional details of the analysis that are carried out in this study.

S1 Movement of catchments in Budyko space between subsequent 20-year periods

S2 Mean 20-year changes in hydro-climatic variables across studied catchments between subsequent 20-year periods with consistent sample sizes

S3 Dependency between $I_{E,\mathrm{i}}$ and median $\varepsilon_{IE\omega}$ for two selected example catchments

S4 Three additional examples of well-known river basins

S5 Comparative analysis of median $\varepsilon_{IE\omega}$ with respect to topographic characteristics and climatic indices of study catchments

S1 Movement of catchments in Budyko space between subsequent 20-year periods

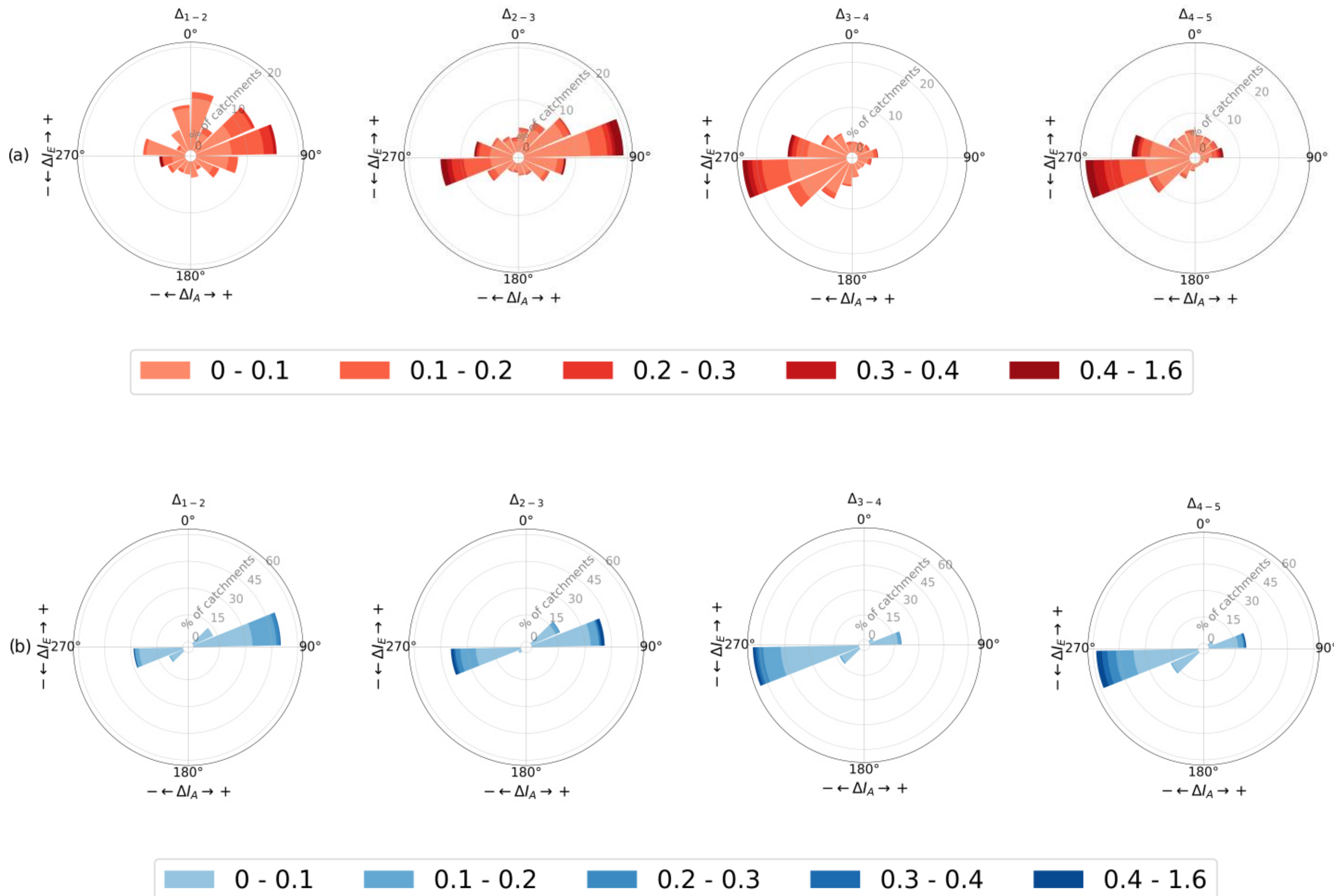

Figure S1: Rose diagrams depicting the movement of catchments in the Budyko space between two subsequent 20-year periods over a 100-year study period. The colour gradients represent the intensity of movement. Each bar present a direction range of 22.5 degree a) Roses illustrating total change b) Roses illustrating change attributed solely due to variations in the I_A

The differences in I_A between the individual time periods, represented by movement along the x-axis of the I_A-I_E Budyko space, and differences in I_E, expressed by movement along the y-axis, led to characteristic directions and magnitudes of actual movement of individual catchments in the I_A-I_E Budyko space, inferred from observations of ΔI_A and ΔI_E, between the individual 20-year periods (Jaramillo and Destouni, 2014; van der Velde et al., 2014).

The right-ward direction of movement, represented by angles $0 < \alpha < 180^{o}$ in the I_A-I_E Budyko space, reflects a shift towards overall more arid conditions for the majority of catchments in the early 20th century, which is followed by a clear left-ward movement (180 < α < 360°) towards more humid conditions for the later parts of the century. This pattern of observed movement is contrasted by the expected movement in the I_A-I_E Budyko space, inferred from ΔI_E. The directions of expected movement (Fig. S1b) exhibit comparable pattern with Fig. S1a. Overall, movement towards somewhat more arid conditions between the first time periods (0 < α < 45°) and towards more humid conditions later on (225 < α < 270°) can be seen. If individual catchments, in response to ΔI_A, followed their specific curves defined by ω, the movement directions resulting from observed ΔI_E (Fig. S1a) would not only have to be constrained to the ranges 0 < α < 45° and 225 < α < 270° but they would be equal to those resulting from expected ΔI_E. As a consequence, Fig. S1a and Fig. S1b would have to show identical pattern. By inversion, the difference between the Fig. S1a and Fig. S1b illustrates that not all catchments follow their specific curves and thus suggests the presence of vertical deviations $\varepsilon_{IE\omega} \neq 0$ from expected I_E.

S2 Mean 20-year changes in hydro-climatic variables across studied catchments between subsequent 20-year periods with consistent sample size

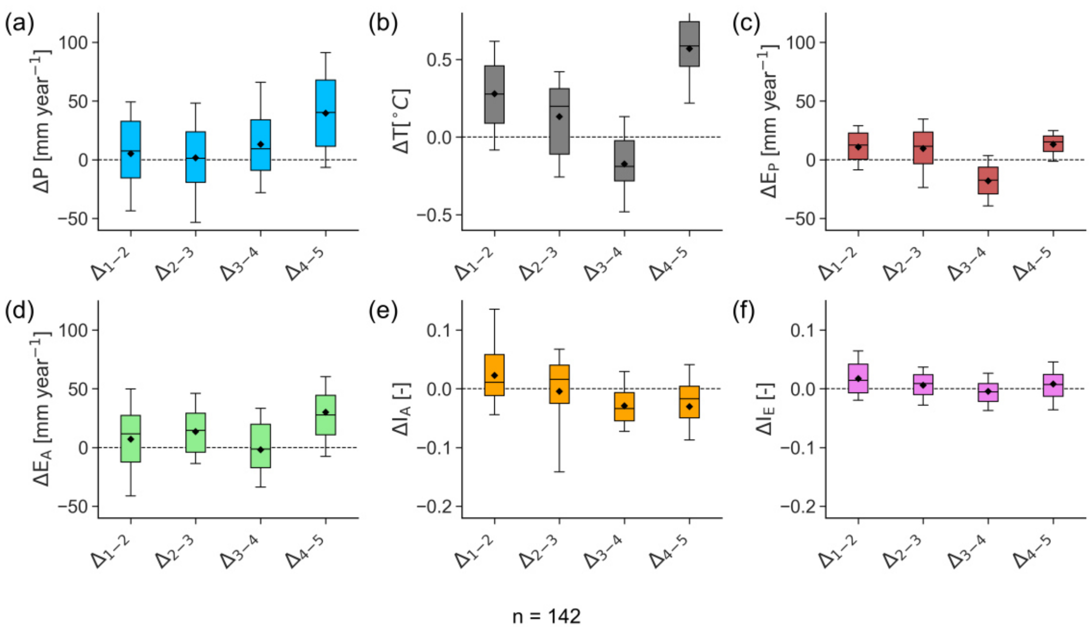

Figure S2: Mean 20-year changes in hydro-climatic variables for the studied catchments between two consecutive periods. a) Precipitation *P*, b) Temperature *T*, c) Potential evaporation E_P, d) Actual evaporation E_A, e) Aridity index I_A, and f) Evaporative index I_E. The boxes represent the 25th to 75th quantiles, while whiskers extend to the 10th and 90th quantiles. Diamonds denote the arithmetic mean. 'n' indicates the number of catchments included in the comparison between two respective periods. Outliers have been removed for improved visualization

S3 Dependency between $I_{E,i}$ and median $\varepsilon_{IE\omega}$ for two selected example catchments

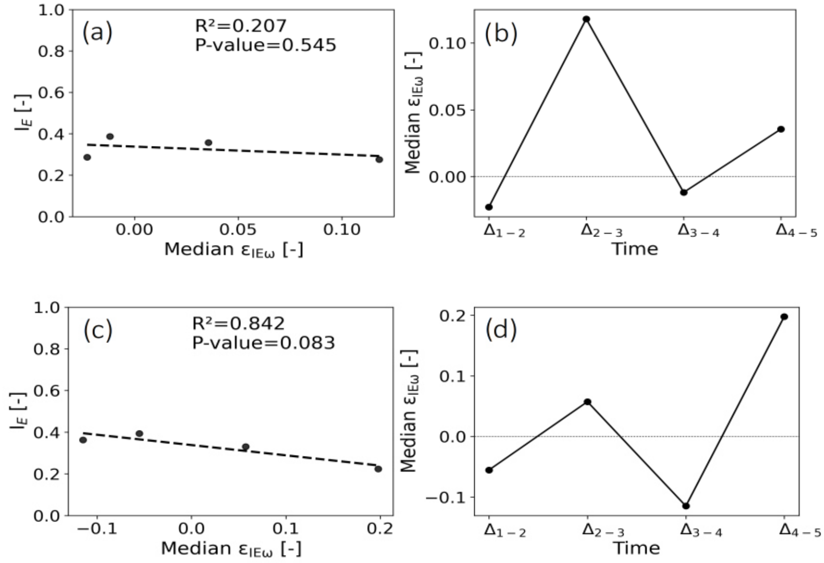

Figure S3: a) Correlation between I_E and median $\varepsilon_{IE\omega}$ (a and c) and temporal evolution of median $\varepsilon_{IE\omega}$ (b and d) for the Save River (top) and Kaituna River (bottom) catchments, respectively

S4 Three additional examples of well-known river basins

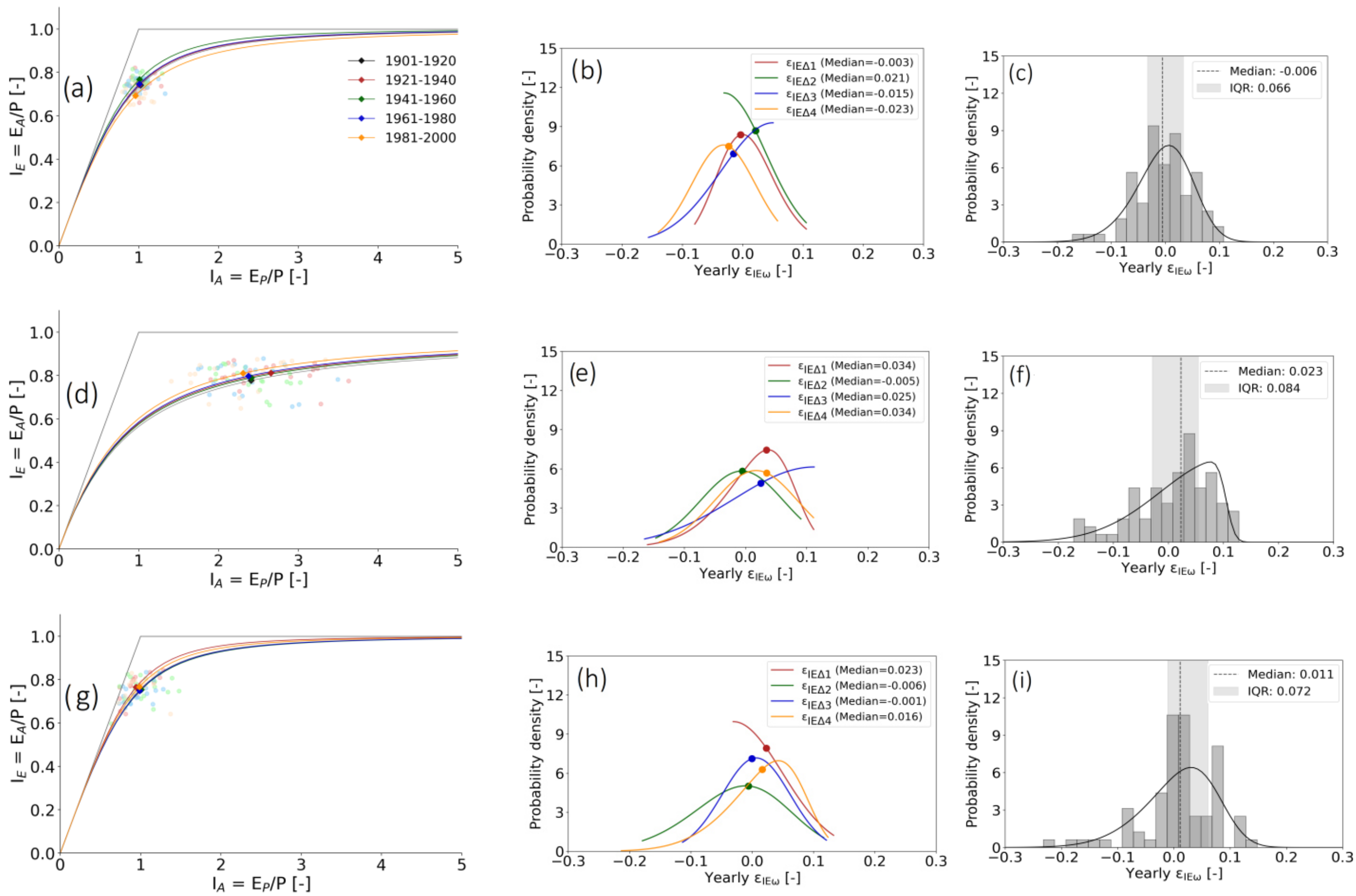

Figure S4: Mean annual position of catchments (light colour dots) in Budyko space along with long-term mean (dark colour dots) and predictive parametric Budyko curves (left column). Individual distribution of deviations ($\varepsilon_{IE\Delta1}$, $\varepsilon_{IE\Delta2}$, $\varepsilon_{IE\Delta3}$ and $\varepsilon_{IE\Delta4}$) with long term median deviation $\epsilon_{IE\omega}$ values (middle column) and long-term marginal distribution of annual deviations along with long-term median values of $\varepsilon_{IE\omega}$ and IQR of $\varepsilon_{IE\omega}$ values (right column) for five example catchment: Parana River (a-c), Snake River (d-f), Elbe River (g-i)

In the case of Parana River basin (Argentina; 891832 km^2; ID AR_0000001), tagged as "Stable" on basis of all four 20-year distributions ("o o o o"), the marginal distribution has a median deviation $\varepsilon_{IE\omega}$ ~ -0.006 with a narrow IQR ~ 0.066 (Fig. S4c). Similarly, the Snake River (Fig. S4d-f), the largest tributary to the Columbia river system (US; 156061 km^2; ID US_0008712), was also tagged as "Stable", in spite of some more pronounced fluctuations over the four periods with a median $\varepsilon_{IE\omega}$ ~ 0.023 but a slightly higher IQR ~ 0.084 (Fig. S4F). The Elbe River (Germany; 90277 km^2; ID DE_0000724) exhibits somehow similar distributions of $\varepsilon_{IE\omega}$. The four median deviations varies between -0.006 to 0.023 (Fig. S4h) and the annual spread remains very low IQR ~ 0.072 (Fig. S4i). As a consequence this river basin was tagged as "Stable", too.

S5 Comparative analysis of median $\varepsilon_{IE\omega}$ with respect to topographic characteristics and climatic indices of study catchments

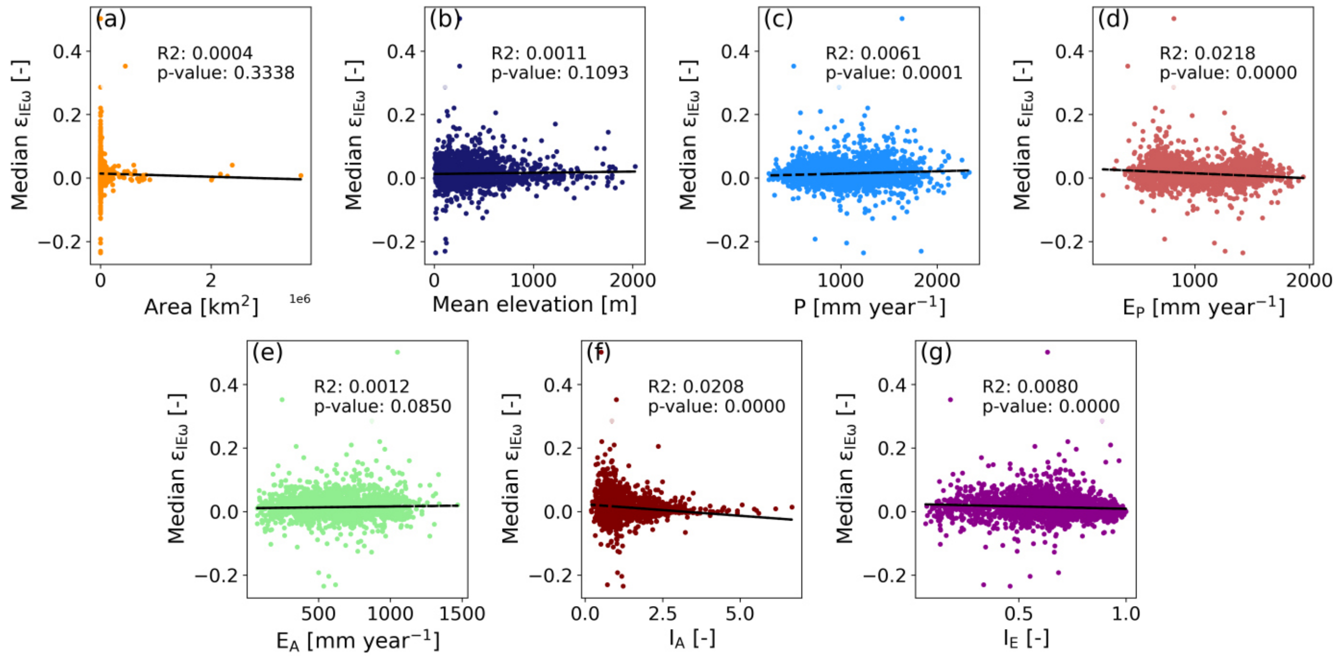

Figure S5: A comparative analysis of median $\varepsilon_{IE\omega}$ in relation to topographic characteristics and climatic indices of study catchments a) Area, b) Mean elevation, c) Precipitation *P*, d) Potential Evaporation E_P, e) Actual Evaporation E_A, f) Aridity Index I_A, and g) Evaporative Index $_{IE}$

The scatter subplots (Fig. S5a-g), examining the relationship between median deviation $\varepsilon_{IE\omega}$ and topographic characteristics (Area and mean elevation) along with climatic indices of catchments (*P, E_P, E_A, I_A, and I_E*), consistently demonstrate weak or negligible associations. Specifically, the R^2 values are consistently low, ranging from 0.00004 to 0.0218. These values suggest a limited impact by topographic features and climatic indices on the variability of median deviation $\varepsilon_{IE\omega}$. Furthermore, the majority of associated p-values falling below the conventional significance level of 0.05 (Fig. S5c-d,f-g) indicate an overall statistical significance in these relationships. Notably, weak R^2 values and non-significant p-values for topographic characteristics (Area and mean elevation), further highlight the absence of a substantial link with median deviation $\varepsilon_{IE\omega}$. Even in the case of seemingly a bit stronger relationships with climatic indices like *P, E_P, I_A*, and I_E, statistically significant findings only account for a small fraction of the variability in median deviation $\varepsilon_{IE\omega}$. Both of the R^2

and p-values collectively supports the notion that neither topographic characteristics nor climatic indices exhibit a meaningful relationship with median deviation $\varepsilon_{IE\omega}$ for the analysis in this study.

References

Jaramillo, F. and Destouni, G. 2014. Developing water change spectra and distinguishing change drivers worldwide. Geophysical Research Letters 41(23), 8377-8386, https://doi.org/10.1002/2014gl061848.

van der Velde, Y., Vercauteren, N., Jaramillo, F., Dekker, S.C., Destouni, G. and Lyon, S.W. 2014. Exploring hydroclimatic change disparity via the Budyko framework. Hydrological Processes 28(13), 4110-4118, https://doi.org/10.1002/hyp.9949.