General Comments: In Budyko-related research, the choice of E_P estimation method has long been an overlooked issue. The novelty of this manuscript lies in the in-depth investigation into the characteristics of E_P and its estimation methods under the Budyko framework. Furthermore, the authors apply this E_P to hydrological simulation and demonstrate its effectiveness by constructing the conversion function. The proposed approach is concise, has low data requirements, and demonstrates good practical value. Overall, the manuscript is well structured and methodologically sound, and is suitable for publication in HESS journal after moderate revision. My specific comments are as follows:

Response: We appreciate the reviewer's positive evaluation and constructive comments. All comments and suggestions have been considered and addressed point by point.

Q1: In a parametric Budyko model, the model parameter is commonly interpreted as representing catchment characteristics. In the conversion function approach with the adjustable Budyko E_P, the parameter is also involved. How should the role of this parameter be interpreted?

Response: Thanks for your insightful comment. In parametric Budyko models, the model parameter is commonly interpreted as representing catchment characteristics. Our previous study has shown that the Budyko model parameter is a lumped variable reflecting the integrative effects of the land-atmosphere system (Cheng et al., 2023). In practical applications, differences in E_P estimation methods often lead to variations in values of the Budyko model parameter. Under such circumstances, the parameter effectively plays a dual role: it not only characterizes catchment characteristics, but also compensates for biases in E_P estimation to some extent. When applying a parametric Budyko model with a conversion function used to adjust meteorological E_P (e.g., converting E_{P-Pen} by the linear function $aE_{P-Pen}+ b$), the Budyko model is extended in reality from a one-parameter form (n) to a three-parameter formulation (n, a, b), with these parameters jointly optimized during model calibration. Within the Budyko space, the model parameter n continues to control the curve shape, while a and b effectively move the data points horizontally closer to the Budyko curve by adjusting E_{P-Pen}.

Q2: There are many meteorological methods for estimating E_P now. Please further compare the differences and similarities between these E_P estimates and the Budyko E_P, as well as its applicability.

Response: We appreciate this valuable comment. The meteorological E_P is typically derived from atmospheric observations, using methods such as the Penman and Priestley-Taylor equations. Their physical meaning is generally associated with saturated surface conditions (open water surfaces or other idealized, homogeneous wet surfaces), under which evapotranspiration reaches its potential rate (also referred to as maximum or possible evapotranspiration). Compared with the meteorological E_P, the Budyko E_P represents a similar physical concept and likewise reflects the maximum evapotranspiration under saturated surface conditions. The difference is that Budyko

E_P does not assume an idealized, homogeneous evaporation surface, but instead corresponds to the catchment surface characterized by its actual vegetation, topography, and soil conditions. The Budyko E_P is derived from the coupled water-energy balance at the catchment scale and it is obtained within the Budyko framework using hydrological observations, such as precipitation and runoff. Due to surface heterogeneity, differences in spatial scale, and methodological discrepancies, Budyko E_P may differ in magnitude from meteorological E_P. Overall, Budyko E_P is more suitable for analyzing coupled water-energy processes at the catchment scale.

In the revised manuscript, we will further clarify both the consistency in physical interpretation and the differences between Budyko E_P and meteorological E_P.

Q3: In Figure 3, $E_{P\text{-}Bref}$ exceeds 3000 for many catchments. However, E_P values are typically below 2000 in related studies (e.g., Zomer et al., 2022). How to explain this discrepancy?
Zomer, R. J., Xu, J., and Trabucco, A.: Version 3 of the Global Aridity Index and Potential Evapotranspiration Database, Sci. Data, 9, https://doi.org/10.1038/s41597-022-01493-1, 2022.
Response: Thanks for your helpful comment. In the MOPEX catchments analyzed in this study, only two catchments have $E_{P\text{-}Bref}$ values exceeding 3000 mm yr^{-1}, and nine exceed 2000 mm yr^{-1}. Overall, 97.6% of the catchments have $E_{P\text{-}Bref}$ values below 2000 mm yr^{-1}. Therefore, the overall range of $E_{P\text{-}Bref}$ in this study is generally consistent with the E_P ranges reported in previous studies (Fig. R1). In the two catchments with $E_{P\text{-}Bref}$ exceeding 3000 mm yr^{-1}, annual precipitation is approximately 400 mm yr^{-1} and annual runoff less than 1 mm yr^{-1}. Under the constraints of the Budyko framework, such extremely low runoff levels lead to relatively large $E_{P\text{-}Bref}$ values.

Zomer et al. (2022) estimated E_P using the FAO-56 Penman-Monteith method (Allen et al., 1998), which is one widely used meteorological method for estimating E_P. Budyko E_P differs from Penman-Monteith E_P in both definition and estimation method, which can lead to differences in magnitude and also motivates the use of a conversion function. Specifically, Budyko E_P is obtained within the coupled water-energy balance framework using precipitation and runoff. As shown in Fig. 2, for a given level of precipitation, a substantial reduction in runoff corresponds to a marked increase in Budyko E_P; when runoff approaches very low values, Budyko E_P becomes extremely large.
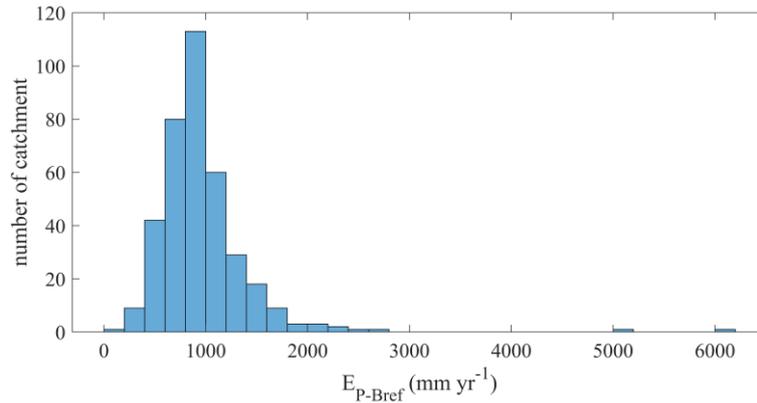
Figure R1: Frequency distribution of $E_{P\text{-}Bref}$ across the MOPEX catchments analyzed in this study

Q4: The intercept of the conversion function for $E_{P\text{-}Bref}$ is above 900 for the MOPEX catchments, whereas it reaches as high as 8000 for the CLP catchments. When fitting this conversion function, should the intercept be appropriately constrained?

Response: Thanks for your valuable comment. If the magnitude and physical meaning of the intercept is to be explicitly considered, additional constraints or boundary conditions would need to be introduced when constructing the conversion function. However, the conversion functions are derived empirically from the limited catchment samples in this study. From a mathematical perspective, the established empirical relationships are only valid within the range of $E_{P\text{-}Pen}$ values corresponding to the sample data. The form and expression of the conversion function may be changed when a broader range of catchment samples are incorporated. This would require further investigation.

Other minor comments and suggestions:

Q5: Line 112. Section 2.2 introduces three different evapotranspiration estimation methods and compares them. I suggest adding a schematic diagram of the methodological framework in this section to improve readability and logical clarity.

Response: Good suggestion. A methodological framework figure has been added (Fig. R2). In addition, a zero-parameter scheme was introduced during the revision to provide a more comprehensive comparison.
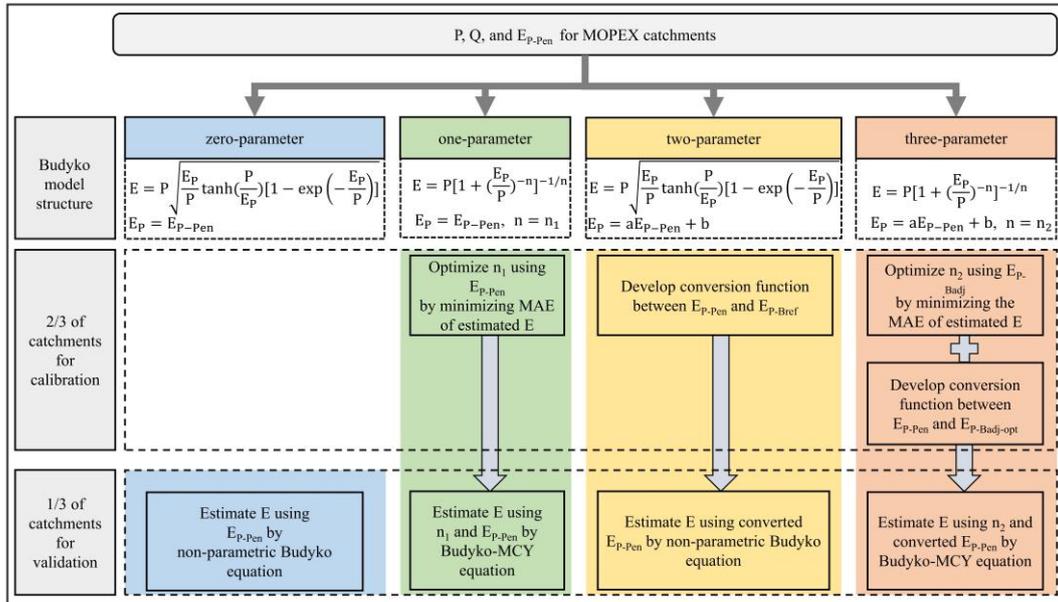
Figure R2: Methodological framework for E estimation with different Budyko equations and E_P formulations in this study

Q6: Line 175. I suggest also plotting the data points of water balance for the MOPEX catchments in Figure 2.

Response: The water balance data points for the MOPEX catchments are plotted in Fig. 2 as requested.
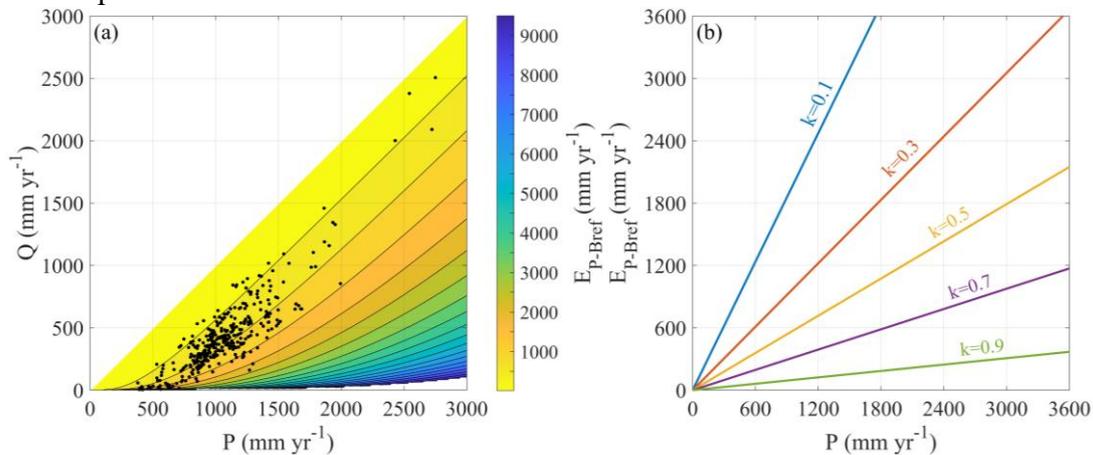

Figure 2: Relationship of $E_{P\text{-Bref}}$ with hydrological elements. k is the mean annual runoff coefficient (Q/P) for a catchment

Q7: Line 305. Two conversion functions were established, rather than one.

Response: Thanks for your careful review. This has been corrected.

Thanks again for the valuable time, suggestions, and comments!

References:

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration: Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper

No.56, Rome, Italy,

Cheng, C., Liu, W., Mu, Z., Zhou, H., and Ning, T.: Lumped variable representing the integrative effects of climate and underlying surface system: Interpreting Budyko model parameter from earth system science perspective, J. Hydrol., 620, 129379, https://doi.org/10.1016/j.jhydrol.2023.129379, 2023.

Zomer, R. J., Xu, J., and trabucco, A.: Version 3 of the Global Aridity Index and Potential Evapotranspiration Database, Sci. Data, 9, https://doi.org/10.1038/s41597-022-01493-1, 2022.