Responses to Comments from Anonymous Referee #1

General Comment: The manuscript titled "Characteristics of potential evapotranspiration and its estimation from hydrological observation in the Budyko framework", addresses the discrepancies between meteorologically derived potential evapotranspiration (E_P), specifically the Penman method, and the theoretical Budyko-derived E_P. The authors introduce a concept termed "Budyko E_P", which is inversely derived from observed precipitation (P) and runoff (Q) using both parametric and non-parametric Budyko equations. The manuscript presents a novel perspective and uses the extensive MOPEX dataset which provides a robust statistical basis for the analysis. However, according to the following comments, I recommend a major revision for this manuscript.

Response: We appreciate the reviewer's careful review and valuable comments. These comments have been very helpful in improving the clarity and overall quality of the manuscript. Our detailed responses to the specific comments are provided as follows.

Comment 1. There are significant conceptual concerns regarding the physical interpretation of the Budyko E_P and whether the improved performance is simply a result of mathematical fitting rather than physical insight.

Response: We thank the reviewer for raising concerns regarding the physical interpretation of Budyko E_P. The physical meaning of traditional E_P is generally associated with saturated surface conditions, under which evapotranspiration reaches its potential rate (also referred to as maximum or possible evapotranspiration), and it is typically defined for water surfaces or other homogeneous natural surfaces. Traditional E_P is usually estimated using meteorological data. For example, Penman E_P is typically based on the assumption of a small and wet surface, and its estimates are often comparable to pan evaporation under practical conditions (Brutsaert, 2015; Zhang and Brutsaert, 2021); Priestley-Taylor E_P emphasizes evapotranspiration processes over large-scale and uniformly wet surfaces, such as lakes or extensive wet regions (Priestley and Taylor, 1972; Assouline et al., 2016).

The classical Budyko framework describes the relationship among mean annual precipitation, potential evapotranspiration, and actual evapotranspiration (or streamflow) at the catchment scale. This relationship has been extensively validated by hydrological and meteorological observations across numerous catchments and has proven effective in characterizing long-term water-energy balance at the catchment scale (Budyko, 1974; Zhang et al., 2001; Wang and Tang, 2014; Yang et al., 2008). In Budyko-related studies, meteorologically derived E_P (e.g., from the Penman method) and observed precipitation (or its hydrologically equivalent form) are commonly used as input variables, and model performance is evaluated by comparing simulated streamflow with observations. Under practical observational conditions, precipitation and streamflow are the quantities that can be directly measured. Therefore, it is reasonable to infer that if the Budyko model is valid, then, under the same functional relationship, replacing the input variables with observed precipitation and streamflow will yield an output variable that is equivalent to E_P and represents a maximum evapotranspiration rate. Because this quantity is derived from the Budyko framework, we refer to it as Budyko E_P.

Budyko E_P represents catchment-scale potential evapotranspiration. Compared with traditional E_P, Budyko E_P shares the same physical meaning in that it represents the maximum evapotranspiration under corresponding saturated surface conditions, but differs in that the underlying surface is not assumed to be homogeneous and instead reflects the actual catchment characteristics, including diverse topography, soil, vegetation, and other factors. Due to differences in underlying surface conditions, spatial scales, and estimation methods, Budyko E_P may differ from E_P estimated using meteorological approaches. This discrepancy motivates the introduction of the conversion function approach. Accordingly, the improved performance obtained by converting meteorological E_P to Budyko E_P through the proposed conversion function and subsequently simulating actual evapotranspiration within the Budyko framework should not be attributed simply to mathematical fitting. Instead, it arises from a refined physical interpretation and effective estimation of E_P within the Budyko framework.

In the revised manuscript, we will further clarify the physical consistency and differences between Budyko E_P and traditional E_P.

Comment 2. Calculated E_P using the classic equations such as Penman is a climatic variable representing the atmospheric demand which is independent of moisture supply, but the Budyko E_P seems to be a fitted parameter. Thus, the authors may need to discuss if the Budyko E_P is yet a physical measure of atmospheric demand, or only a structural error-correction term. In this context, a discussion of how Budyko E_P relates to the surface energy balance, and whether it can be interpreted consistently across different climatic regimes, is necessary.

Response: Budyko E_P is not a fitted parameter or a structural error-correction term. Its physical meaning has been discussed in detail in our response to your Comment 1. In addition, E_P is not necessarily independent of water supply (P). Previous studies have shown that Penman E_P exhibits a negative correlation with P (Lintner et al., 2015), whereas Priestley–Taylor E_P is relatively independent of P (Chen and Buchberger, 2018). The Budyko E_P proposed in this study represents a form of E_P constrained jointly by P and Q at the catchment scale (see Fig. 2 in the manuscript). We are convinced that information relevant to E_P is implicitly contained in P and Q, from which E_P can be estimated through the Budyko framework.

With respect to "how Budyko E_P relates to the surface energy balance," we interpret the reviewer's question as referring to the relationship between Budyko E_P and surface net radiation. Budyko himself, in his original formulation of the Budyko framework, estimated E_P from net radiation (Budyko, 1974). Therefore, E_P inferred from the Budyko framework is necessarily related to net radiation. As discussed in our response to your Comment 1, Budyko E_P also incorporates the influence of catchment characteristics. Consequently, Budyko E_P reflects the combined effects of multiple factors, including but not limited to net radiation. Because the Budyko framework has been shown to be applicable across different climate regimes, the corresponding Budyko E_P can be interpreted as the catchment-scale upper limit of evapotranspiration under a given climatic condition, which also implies that Budyko E_P varies with climate.

Comment 3. It would be informative to explore how the results might change if the Budyko parameter (n) is estimated based on the watershed characteristics such as vegetation, soil, topography, etc., rather than treated as a purely fitting parameter.

Response: We thank the reviewer for this insightful suggestion. First, we agree that combining the conversion function approach with parameterization of the Budyko model based on catchment attributes is a promising direction that merits further exploration in future studies, and this point has been discussed in Section 4.3 of the manuscript. Second, previous studies have demonstrated that estimating Budyko model parameter based on catchment characteristics is an effective approach (Yang et al., 2009; Li et al., 2013; Xu et al., 2013; Ning et al., 2017; Alonso Vicario et al., 2024). Different from, or in parallel with, this line of research, the motivation of the present study is to develop a new approach that relies solely on routinely available hydrometeorological observations (precipitation, streamflow, and meteorological variables) to improve evapotranspiration simulation within the Budyko framework. At the same time, we have found that the effects of catchment characteristics are implicitly reflected in Budyko E_P.

Comment 4. Since the proposed method requires the runoff observed data (Equation 5), its applicability to ungauged basins is unclear. In addition, the authors should discuss how the method performs under non-stationary conditions.

Response: We thank the reviewer for raising concerns regarding the applicability of the proposed method. It should first be clarified that the data requirements of this method are consistent with those of traditional approaches based on the Budyko framework, as it similarly relies on precipitation and streamflow observations over multiple years. In fact, without streamflow observations, not only is the proposed method difficult to apply directly, but most hydrological models, including the Budyko framework itself, also cannot be implemented, because model parameter generally needs to be calibrated using observed streamflow data. Future investigations into the spatial variability of the conversion function and its regionalization characteristics are expected to further extend the potential applicability of this approach to ungauged catchments.

Regarding the application of the conversion function approach under non-stationary conditions, we have provided a brief outlook in Section 4.3 of the Discussion. The Budyko framework was originally developed under steady-state conditions and is primarily applicable at mean annual scales, at which changes in water storage (ΔS) can be approximately neglected and the catchment water balance can be characterized by long-term mean precipitation, streamflow, and evapotranspiration (Budyko, 1974). The conversion function approach proposed in this study is coupled with the Budyko framework for hydrological simulation; therefore, its applicable scale is consistent with that of the Budyko framework and is mainly limited to steady-state conditions at mean annual scales. As noted in our outlook, if ΔS were to be explicitly incorporated into the Budyko framework, Budyko E_P could potentially be extended to annual-scale calculations, thereby enabling the estimation of annual runoff or annual evapotranspiration. The specific performance of the conversion function approach under non-stationary conditions remains to be explored in future studies.

Comment 5. In Equation 7, do the parameters "a" and "b" depend on the climate characteristics (for example, aridity index) across the US? In Figure 5, if the points represent different aridity indices it would be helpful to assess whether the outliers from the linear regression correspond to particular climate types.

Response: We thank the reviewer for raising this valuable idea. The parameters "a" and "b" correspond to a specific linear regression function. Following your suggestion, we colored the scatter points in Fig. 5 according to the aridity index ($E_{P\text{-}Pen}/P$), as shown in Fig. R1. The results indicate clear differences in the degree of scatter under different hydroclimatic conditions. Catchments with a lower aridity index (i.e., more humid catchments) tend to cluster more closely around the regression line, whereas those with a higher aridity index (i.e., drier catchments) exhibit substantially greater dispersion and are more prone to forming outliers that deviate from the regression relationship. This suggests that: (1) when a linear relationship is adopted, a single regression equation cannot adequately represent catchments across the full range of dry–wet conditions, and it may be more appropriate to establish separate conversion functions for different aridity regimes; and (2) nonlinear forms of the conversion function could also be considered.

Furthermore, considering the influence of regional differences in the complementary relationship for evapotranspiration as well as the effects of catchment characteristics on Budyko E_P, the conversion function proposed in this study should be regarded as an initial attempt. More in-depth investigations are required in future work.

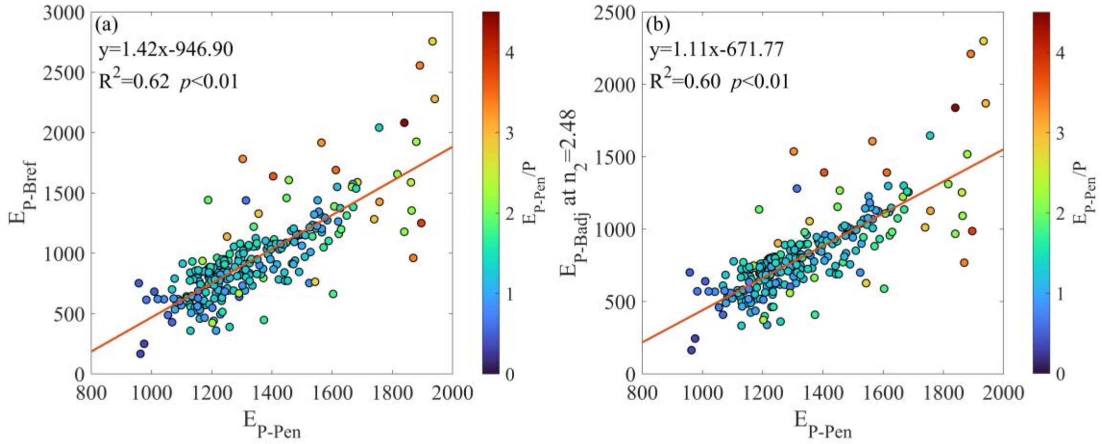

Fig.R1. The conversion functions of $E_{P\text{-}Pen}$ established for the MOPEX calibration catchments. Panels (a) and (b) show the conversion function from $E_{P\text{-}Pen}$ to the reference Budyko E_P and the optimized adjustable Budyko E_P, respectively. Points are colored by the aridity index ($E_{P\text{-}Pen}/P$).

Comment 6. Page 2, Line 41: the word “Potential” has been repeated twice and should be corrected.

Response: We apologize for this oversight and thank the reviewer for pointing it out. The repeated word “Potential” will be removed in the revised manuscript.

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

Reference:

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