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Characteristics of potential evapotranspiration and its estimation from hydrological observation in the Budyko framework

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Abstract. Potential evapotranspiration (E_P) is one of input variables in the Budyko framework, yet the diverse estimation methods cause discrepancies in its values. This raises a question about whether there exists a kind of E_P specially satisfying the Budyko framework. Based on the relationships among variables in the Budyko models and the deterministic value of E_P with known mean annual precipitation and runoff, we uncover the characteristics of E_P and its estimation method from hydrological observation in the Budyko framework. Accordingly, we introduce the concept of Budyko E_P. The non-parametric and parametric Budyko equations correspond to the reference and the adjustable Budyko E_P, respectively. For the Model Parameter Estimation Experiment catchments, the reference Budyko E_P is higher in the central and southern contiguous United States and lower in the northeastern and northwestern regions. The linear conversion functions are established from the meteorological E_P to the reference and optimized adjustable Budyko E_P separately. When estimating actual evapotranspiration (E) by Budyko models with the same data resources, employing two conversion functions with the meteorological E_P reduces the mean absolute error of E estimation by 33 % and 35 %, respectively, compared to using the optimized Budyko model parameter with the meteorological E_P. Further investigation suggests that the complementary relationship for evapotranspiration is one factor affecting the expression of the region-specific conversion function. Future in-depth exploration of the spatiotemporal differences in conversion functions will advance E estimation and the applications of Budyko E_P.

1 Introduction

Potential Potential evapotranspiration (E_P) refers to the maximum evaporation that can be achieved at a certain land surface with unlimited water supply (Thornthwaite, 1948), and it is an important basic parameter in hydrology, meteorology, agriculture, ecology, and other fields. The origin of E_P can be traced back to Ol'dekop (1911), with the term "maximum evaporation" being used to characterize the maximum evaporation capacity of a catchment. Nearly 40 years later, Thornthwaite (1948) introduced the concept of "potential evaporation" and proposed the first easily implemented method for E_P estimation based on basic meteorological observations. Subsequently, various meteorological equations have been proposed for E_P estimation, including the Penman (1948), Hamon (1960), Priestley and Taylor (1972), Hargreaves and Samani (1982), and Penman-Monteith (Allen et al., 1998) equations.

The Budyko framework is a classic approach for describing the coupled water-energy balances in a catchment. The original Budyko models were non-parametric and the most representative one was proposed by Budyko (1974). Subsequent studies have added one or more adjustable model parameters to the Budyko models to explain the influence of catchment characteristics (Zhang et al., 2004; Yang et al., 2008; Wang and Tang, 2014; Fu, 1981; Zhang et al., 2001). Typically, the Budyko-related studies use known precipitation (P) and meteorological E_P for the estimation and change attribution of actual evapotranspiration (E) or runoff (Q). Despite the long history of research on E_P, its definitions and estimation methods remain diverse in practical applications (Yang et al., 2019; Tu and Yang, 2022; Allen et al., 2021; Zhou and Yu, 2024;

Mccoll, 2020; Liu et al., 2021; Granger, 1989). Consequently, the choice of E_P estimation methods in the Budyko framework has become increasingly complex (see Table S1).

The Budyko equations include both non-parametric and parametric forms. For the non-parametric Budyko equations, Budyko (1958, 1974) originally recommended using net radiation as a proxy for E_P; however, E_P has also been estimated using the Penman method (Yin et al., 2019). For a given P, different E_P inputs directly lead to different E estimates. This sensitivity was already recognized by Pike (1964), who showed that the temperature-based E_P approach used in the non-parametric Budyko equation proposed by Turc (1954) underestimated E, and therefore recommended the Penman E_P and accordingly modified the Turc equation. For the parametric Budyko equations, previous studies have primarily focused on the model parameter, intending to improve E estimation by enhancing the accuracy of parameter estimation (Zhang et al., 2004; Yang et al., 2007; Cheng et al., 2022; Li et al., 2013). However, the model parameter has no prior physical meaning (Greve et al., 2015; Sposito, 2017), and it typically requires calibration using known P, E_P, and Q. In Budyko-based hydrological simulations, the use of multiple E_P estimation methods renders P the only well-defined input. In this case, the Budyko model parameter essentially balances the influence of different E_P on P partitioning. That is, the parameter value varies with the E_P estimation method applied, which makes it somewhat arbitrary. This undoubtedly undermines the Budyko framework's consistency and standardization in practical applications. Therefore, a question naturally arises: Is there a kind of E_P that is specially suitable for the Budyko framework?

The Budyko framework is expressed in a functional form, in which the values of the function and the independent variables are constrained by a specific functional relationship. In the Budyko framework, P and E_P are the independent variables, and E (or Q) is the dependent variable. Typically, P and Q can be directly observed, and E can be obtained from the water balance equation. If P and Q (or E) are known, this implies that E_P must satisfy the constraints imposed by the Budyko framework and cannot take arbitrary values. This indicates an intrinsic linkage between E_P and hydrological variables, suggesting the possibility of estimating E_P through the Budyko framework when P and Q are specified. Since such E_P is derived from the Budyko framework, it can be referred to as the Budyko E_P, which shares the same temporal and spatial scales as the hydrological variables therein. An important feature of the Budyko E_P is that it fully conforms to the requirements of the Budyko framework. In practice, ensuring that E_P derived from other methods embodies the feature of the Budyko E_P should theoretically enhance the accuracy of E estimation.

Therefore, the aim of this study is to define and calculate the Budyko E_P, and to investigate E estimation in the Budyko framework from the perspective of this E_P. To this end, we first explore the relationships between E_P and hydrological elements and propose a method to calculate the Budyko E_P under the Budyko framework. The reference and adjustable Budyko E_P are obtained by the non-parametric and parametric Budyko equations, respectively. Then, we calculate the reference Budyko E_P at the mean annual scale for the Model Parameter Estimation Experiment (MOPEX) catchments and explore its spatial pattern. Further, the linear conversion functions are established from the meteorological E_P to the reference Budyko E_P and the optimized adjustable Budyko E_P separately. Finally, the performance of the conversion functions in E estimation is investigated.

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2 Theory, methods, and materials

2.1 Budyko E_P and its calculation

Budyko (1958, 1974) postulated that E/P at the mean annual catchment scale was mainly determined by E_P/P and proposed the original non-parametric Budyko equation:

$$\frac{E}{P} = \sqrt{\frac{E_P}{P}\tanh\left(\frac{E_P}{P}\right)^{-1}\left[1-\exp\left(-\frac{E_P}{P}\right)\right]}\,, \tag{1}$$

Since the water storage variation can be approximately ignored at the mean annual scale, the original non-parametric Budyko model can equivalently describe the relationship between runoff coefficient (Q/P) and E_P/P:

$$\frac{Q}{P} = 1-\sqrt{\frac{E_P}{P}\tanh\left(\frac{E_P}{P}\right)^{-1}\left[1-\exp\left(-\frac{E_P}{P}\right)\right]}\,, \tag{2}$$

For a given catchment, both P and Q are definite observations over a given period. Based on the P and Q data, E_P can be determined using Eq. (2), which we designate as the reference Budyko E_P (hereafter denoted as $E_{P\text{-}Bref}$). The $E_{P\text{-}Bref}$ is calculated by P and Q with clear meanings and definite values, indicating that the $E_{P\text{-}Bref}$ itself also has a well-defined value. Subsequent studies have added an adjustable model parameter to the Budyko framework to incorporate the effects of catchment characteristics; thus many parametric Budyko equations have been developed (Zhang et al., 2004; Yang et al., 2008; Wang and Tang, 2014; Fu, 1981; Zhou et al., 2015). In the parametric Budyko equations, E_P is related to P, Q, and the model parameter. Given P and Q, the Budyko E_P varies with the values of the Budyko model parameter, which we refer to as the adjustable Budyko E_P.

Take the Budyko-MCY equation (Choudhury, 1999; Mezentsev, 1955; Yang et al., 2008) as an example:

$$\frac{E}{P} = \frac{1}{\left[1+\left(\frac{E_P}{P}\right)^{-n}\right]^{1/n}}\,, \tag{3}$$

$$\frac{Q}{P} = 1-\frac{1}{\left[1+\left(\frac{E_P}{P}\right)^{-n}\right]^{1/n}}\,, \tag{4}$$

where n is the model parameter ranging from (0,+∞) and it regulates the allocation of P to E and Q.

According to Eq. (4), the adjustable Budyko E_P ($E_{P\text{-}Badj}$) based on the Budyko-MCY equation can be expressed as:

$$E_{P-Badj} = P\left[\left(1-\frac{Q}{P}\right)^{-n}-1\right]^{-1/n}\,, \tag{5}$$

2.2 Conversion function and E estimation

When using the meteorological E_P in the Budyko framework, the optimized Budyko model parameter for all study catchments can be obtained by minimizing the error of estimated E against observed E (i.e., the water balance-based E). The optimized model parameter with both the meteorological E_P and P can yield a reasonable simulation of E (Zhang et al., 2004;

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Potter et al., 2005; Donohue et al., 2011; Zhang and Brutsaert, 2021; Zhang et al., 2010). Typically, when auxiliary data on catchment characteristics of both climate and land surface are available, using time-varying or catchment-specific model parameters derived from empirical formulas tends to yield better performance in E estimation (Ning et al., 2019; Chen et al., 2022; Han et al., 2011; Li et al., 2013).

Without auxiliary information, it can be expected that the simulation of E could be further improved by employing the Budyko E_P, as it is better suited to the Budyko framework compared with the meteorological E_P. Therefore, by establishing and using the conversion function from the meteorological E_P to the Budyko E_P, the converted meteorological E_P would be more closely aligned with the Budyko E_P, and help to improve the accuracy of E simulation with Budyko models. Following Zhang and Brutsaert (2021), the meteorological E_P is estimated based on the Penman equation (Penman, 1948; Brutsaert, 1982) in this study and is denoted as $E_{P\text{-}Pen}$:

$$E_{P-Pen} = \frac{\Delta}{\Delta+\gamma}(R_n - G)/\lambda + \frac{\gamma}{\Delta+\gamma} f(u_2)(e_s - e_a)/\lambda, \quad (6)$$

where Δ is the slope of the saturated vapor pressure with respect to the air temperature (kPa °C^{-1}). γ is the psychometric constant (kPa °C^{-1}). R_n is the net radiation (MJ m^{-2}). G is the soil heat flux (MJ m^{-2}) (usually being ignored at the daily scale). λ is the latent heat of vaporization (2.45 MJ kg^{-1}). The wind function $f(u_2)$ can be represented as $f(u_2)=0.26(1+0.54u_2)$ (Brutsaert, 1982), where u_2 is the wind speed at a height of 2 meters (m s^{-1}). e_s and e_a are the saturated and actual air vapor pressures (kPa), respectively.

To test this idea and compare the performance of E estimation using the meteorological E_P versus Budyko E_P, we randomly divide the study catchments into two subsets: 2/3 for calibration and 1/3 for validation. Following the traditional practice in Budyko-related studies, we obtain the optimized Budyko-MCY model parameter (n_1) with known P, $E_{P\text{-}Pen}$, and Q by minimizing the mean absolute error (MAE) of the estimated E for the calibration catchments, and then apply n_1 and $E_{P\text{-}Pen}$ in the Budyko-MCY equation (Eq. (3)) to estimate E for the validation catchments.

When using $E_{P\text{-}Bref}$, we first establish the conversion function from $E_{P\text{-}Pen}$ to $E_{P\text{-}Bref}$ based on their relationship for the calibration catchments. This conversion function is then extrapolated to the validation catchments to convert $E_{P\text{-}Pen}$. Finally, the converted $E_{P\text{-}Pen}$ is used to estimate E under the non-parametric Budyko equation (Eq. (1)) for the validation catchments.

When using $E_{P\text{-}Badj}$, both the Budyko-MCY model parameter (n_2) and the conversion function are obtained with the goal of minimizing the MAE of the estimated E for the calibration catchments. The corresponding $E_{P\text{-}Badj}$ at n_2 is referred to as the optimized $E_{P\text{-}Badj}$ ($E_{P\text{-}Badj\text{-}opt}$). The conversion function, which shows the relationship between $E_{P\text{-}Badj\text{-}opt}$ and $E_{P\text{-}Pen}$, is then extrapolated to the validation catchments to convert $E_{P\text{-}Pen}$. Finally, the converted $E_{P\text{-}Pen}$ and n_2 are used to estimate E for the validation catchments with the Budyko-MCY equation (Eq. (3)).

2.3 Hydrometeorological data

We take the MOPEX catchments as an example to calculate the Budyko E_P, establish the conversion function, and explore the potential application of the conversion function in E estimation. The MOPEX dataset contains daily P, Q, E_P (based on

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pan evaporation), and maximum and minimum temperatures of 438 catchments during 1948-2003 (Duan et al., 2006), which are widely used in the catchment hydrological research (Wang and Hejazi, 2011; Xu et al., 2013; Kim et al., 2023; Ghotbi et al., 2020). Since the collected meteorological dataset is available from 1979 to 2021, this study uses the MOPEX dataset for the overlapping period, i.e., from 1979 to 2003. Daily-scale MOPEX data are aggregated to annual data, and catchments with continuous annual data for less than 11 years are removed. Therefore, 373 catchments are left for further analysis (Fig. 1). After examination, these catchments all satisfy the water balance constraint (i.e., Q<P) at the mean annual (≥11 years) scale. The time window of 11 years is selected because previous research showed that water storage variation can be approximately ignored at time scales longer than 11 years, so E can be obtained from P minus Q (Han et al., 2020; Shao et al., 2021).

The gridMET dataset supplies gridded meteorological data at a 4-km resolution covering the contiguous United States during 1979-2021 (Abatzoglou, 2013). The daily meteorological variables include the minimum and maximum air temperature, wind speed, vapor pressure deficit, and downward shortwave radiation, which enables E_P estimation by multiple meteorological equations (Ficklin et al., 2015; Abatzoglou and Ficklin, 2017; Mcevoy et al., 2020). The daily gridded $E_{P\text{-}Pen}$, calculated based on the gridMET dataset, is aggregated to the annual scale and averaged over multiple years. The resulting mean annual $E_{P\text{-}Pen}$ is then spatially averaged over each MOPEX catchment. To ensure comparability, the temporal coverage of $E_{P\text{-}Pen}$ is aligned precisely with that of the Budyko E_P for each catchment.

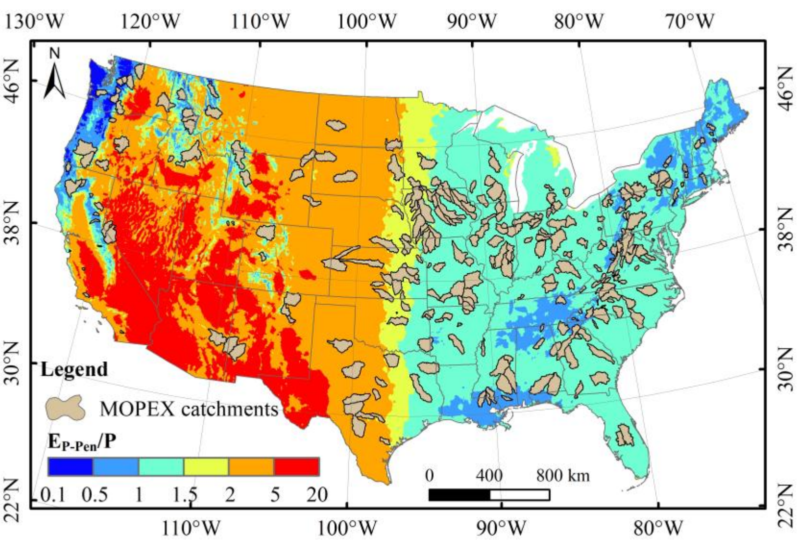

Figure 1: Spatial distribution of 373 MOPEX catchments. $E_{P\text{-}Pen}/P$ is used to indicate the dryness index.

3 Results

3.1 Relationship of E_P with P and Q in the Budyko framework

$E_{P\text{-}Bref}$ derived from the non-parametric Budyko equation is closely related to P and Q, as shown in Fig. 2. Overall, when the runoff coefficient (k=Q/P) is large, $E_{P\text{-}Bref}$ tends to be small; as P increases and Q decreases (i.e., k decreases), $E_{P\text{-}Bref}$

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becomes larger (Fig. 2(a)). When k is held constant, $E_{P\text{-}Bref}$ increases linearly with P (Fig. 2(b)). A smaller k corresponds to a larger slope of the P-$E_{P\text{-}Bref}$ line, indicating that $E_{P\text{-}Bref}$ is more sensitive to P. When P is constant, the smaller the k, the larger the $E_{P\text{-}Bref}$, and correspondingly the larger $E_{P\text{-}Bref}$/P, which indicates the limited P is converted more to E and less to Q in a drier climate. For a larger k (usually corresponding to wetter catchments), $E_{P\text{-}Bref}$ is less affected by P. Therefore, it can be concluded that $E_{P\text{-}Bref}$ is closely related to the hydrological elements, with its variation largely affected by the runoff coefficient of the catchment.

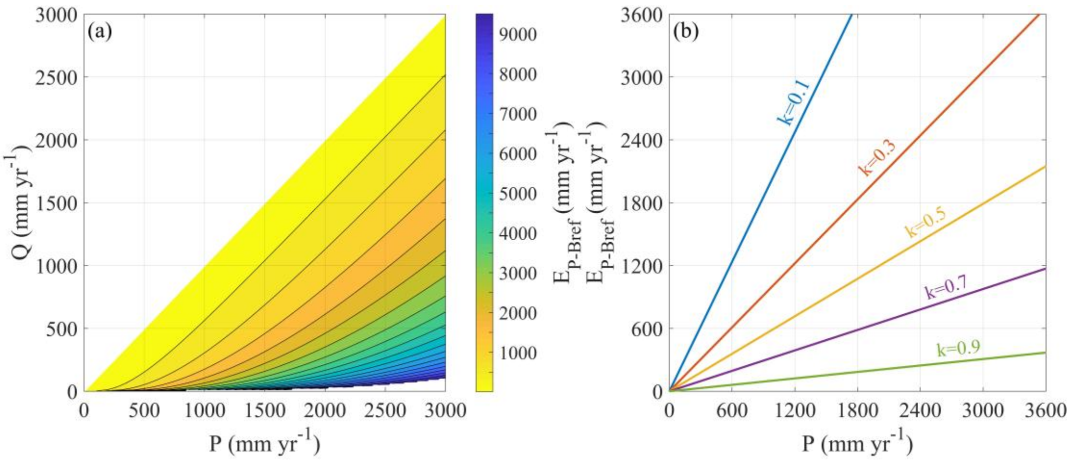

Figure 2: Relationship of $E_{P\text{-}Bref}$ with hydrological elements. k is the mean annual runoff coefficient (Q/P) for a catchment.

3.2 Spatial distribution of the reference Budyko E_P

The spatial distribution of $E_{P\text{-}Bref}$ across the MOPEX catchments shows that the high $E_{P\text{-}Bref}$ values are predominantly found in the central and southern areas, while low values in the northeastern and northwestern regions (Fig. 3). $E_{P\text{-}Bref}$ values in the vast majority of catchments range from 166 to 2756 mm yr^{-1}. Only two catchments with mean annual Q less than 1 mm yr^{-1} have $E_{P\text{-}Bref}$ values exceeding the upper limit, both of which are located in the central contiguous United States. This is consistent with the results that a very low runoff coefficient leads to a substantially large Budyko E_P (Fig. S1). Therefore, we retain 371 catchments with $E_{P\text{-}Bref}$ less than 2756 mm yr^{-1} for subsequent E estimation.

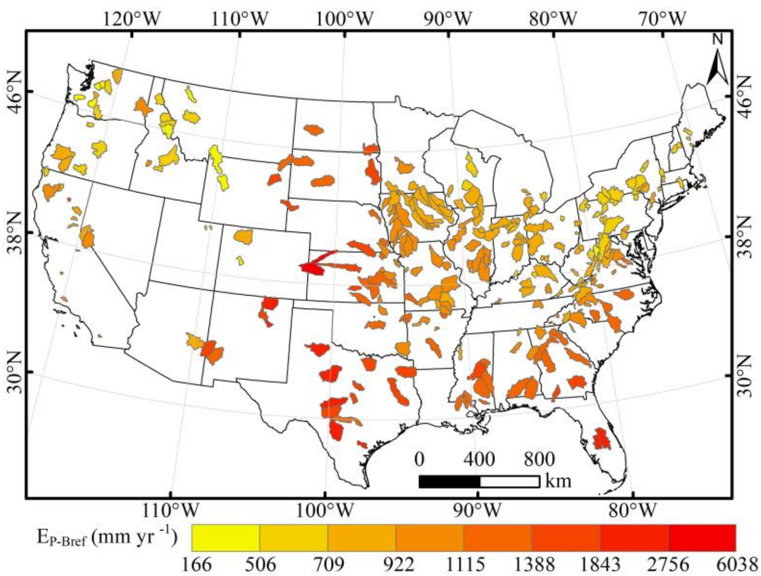

Figure 3: Spatial distribution of $E_{P\text{-}Bref}$ for 373 MOPEX catchments.

3.3 E estimation by the conversion function

Following the traditional practice in the Budyko-based E estimation studies, we obtain the optimized value of the Budyko–MCY model parameter (n_1=1.25) for the MOPEX calibration catchments (Fig. 4(a)). The parameter calibration is performed by minimizing the MAE of the estimated E against the water balance-based E for the calibration catchments. The optimized model parameter n_1 is then extrapolated to the MOPEX validation catchments to estimate E. It is found that the MAE of E estimation is 90.30 mm yr^{-1} and the R^2 is 0.46 (Fig. 4(b)). Although using $E_{P\text{-}Pen}$ and the optimized Budyko model parameter generally provides acceptable E estimation, we observe an underestimation of E at larger values and an overestimation at lower ones.

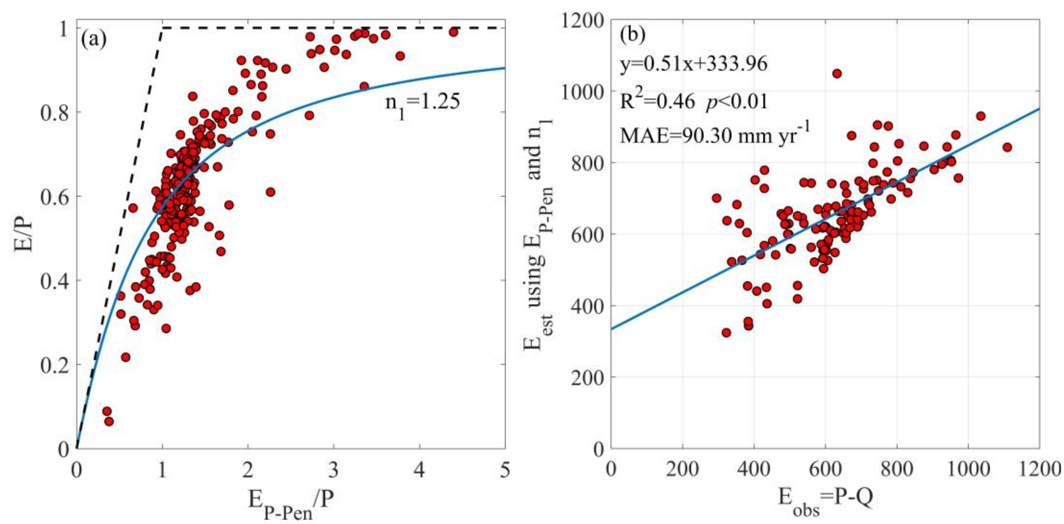

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Figure 4: (a) The distribution of data points for the MOPEX calibration catchments in the Budyko space and (b) the comparison of estimated E (E_{est}) based on the Budyko-MCY equation using E_{P-Pen} and the optimized model parameter n_1 against the water balance-based E (E_{obs}) for the MOPEX validation catchments.

In this study, we analyze the relationships and constraint conditions of the variables within the Budyko framework and introduce the concept of Budyko E_P. Using the same data resources as the traditional Budyko-based E estimation studies, we further explore the available data information to establish the conversion function from the meteorological E_P to the Budyko E_P, aiming to further improve the accuracy of E estimation.

Considering the scatter distribution characteristics between the Budyko E_P (including both the reference and adjustable Budyko E_P) and E_{P-Pen} (Figs. 5(a) and 5(c)), the conversion function takes a linear form:

$$E_{P-Budyko} = aE_{P-meteor} + b \,, \tag{7}$$

where $E_{P-Budyko}$ represents the Budyko E_P, which comprises E_{P-Bref} and E_{P-Badj}. $E_{P-meteor}$ represents the meteorological E_P, which refers to E_{P-Pen} in this study. The coefficients a and b are the slope and intercept of the linear regression equation, respectively.

A linear conversion function is established based on the relationship between E_{P-Pen} and E_{P-Bref} for the MOPEX calibration catchments, i.e., E_{P-Bref}=1.42E_{P-Pen}-946.90 (Fig. 5(a). This conversion function is then extrapolated to convert E_{P-Pen} and then to estimate E using the non-parametric Budyko equation (Eq. (1)) for the MOPEX validation catchments. The results show that the MAE of estimated E decreases from 90.30 mm yr^{-1} (when using the optimized model parameter and E_{P-Pen}) to 60.41 mm yr^{-1}, and the R^2 increases from 0.46 to 0.72. When estimating E using the adjustable Budyko E_P, a conversion function from E_{P-Pen} to $E_{P-Badj-opt}$ is established for the MOPEX calibration catchments, i.e., $E_{P-Badj-opt}$=1.11E_{P-Pen}-671.77 (Fig. 5(c)). Extrapolating this conversion function to the MOPEX validation catchments and combining it with the Budyko-MCY equation (Eq. (3)) slightly improve the accuracy of E estimation compared to using E_{P-Bref}, with the MAE of 59.05 mm yr^{-1} and the R^2 of 0.74 (Fig. 5(d)). In summary, compared to using the optimized model parameter and meteorological E_P, the MAEs of E estimation with the reference and adjustable Budyko E_P decrease by 33 % and 35 %, respectively. This demonstrates the effectiveness of the Budyko E_P and conversion function in catchment E estimation.

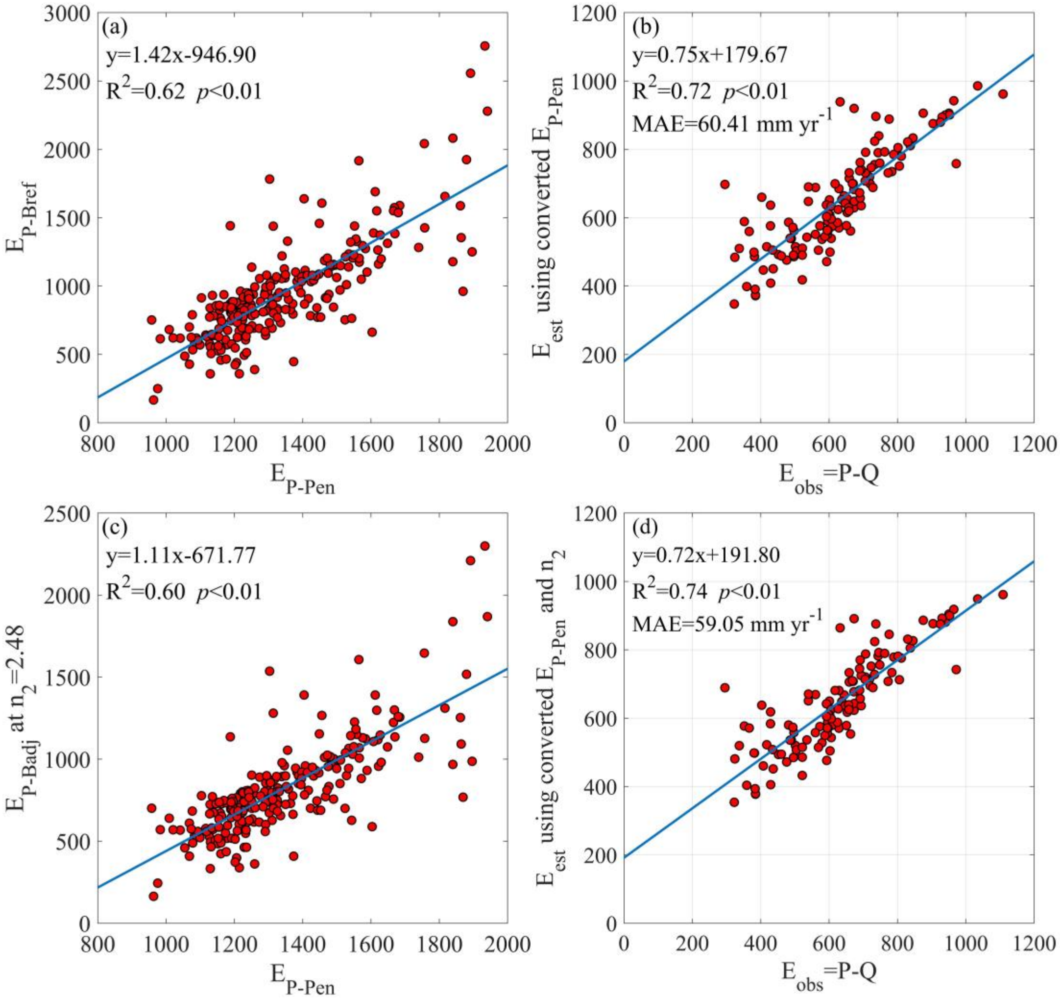

Figure 5: The conversion functions of $E_{P\text{-}Pen}$ in the MOPEX calibration catchments and the performance of E estimation in the MOPEX validation catchments. Panels (a-b) show the conversion function from $E_{P\text{-}Pen}$ to the reference Budyko E_P and the corresponding E estimation performance, respectively. Panels (c-d) display the conversion function from $E_{P\text{-}Pen}$ to the optimized adjustable Budyko E_P and the corresponding E estimation performance, respectively.

4 Discussion

4.1 Characteristics of the Budyko E_P

E_P has traditionally been estimated using meteorological approaches, which is generally based on the relationships of E_P with energy balance and aerodynamic processes. This has led to the development of various meteorological methods for E_P estimation. By examining the water balance characteristics in a catchment, this study suggests that the E_P value, which specially satisfies the Budyko framework, is deterministic for a given catchment with known values of P and Q. Consequently, we introduce the concept of Budyko E_P and propose its inversion-based calculation method. This inversion

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logic is conceptually similar to the idea that runoff variability integrates and conveys information about rainfall inputs, allowing P to be inferred from Q under the physical constraints of the catchment water balance (Manoj et al., 2025). Calculated from catchment-scale P and Q data within the Budyko framework, the Budyko E_P fully conforms to the framework's spatial and temporal scales. It characterizes the atmospheric evaporative demand as manifested in terrestrial hydrological processes in the context of land-atmosphere coupling.

Since the Budyko E_P is derived from the Budyko framework, clarifying its relationship with E is crucial for determining the appropriate E_P values when using the Budyko models. Therefore, we derive the partial derivatives of E with respect to E_P ($\partial E/\partial E_P$) under the non-parametric Budyko equation (Eq. (S9)) and the Budyko-MCY equation (Eq. (S15)), respectively. The variations of these two types of $\partial E/\partial E_P$ with P and E_P (or E_P/P) are shown in Fig. 6. For the non-parametric Budyko equation, the response of E to changes in E_P can be divided into two situations. When P and E_P vary inversely (e.g., $\partial P/\partial E_P$=-1), E increases with E_P under humid conditions but decreases with E_P under dry conditions (Fig. 6(a)). When E_P and P are relatively independent ($\partial P/\partial E_P$=0) (Fig. 6(b)) or vary in the same direction (e.g., $\partial P/\partial E_P$=1) (Fig. 6(c)), $\partial E/\partial E_P$ varies with climatic conditions but remains positive in both humid and dry environments, indicating that E always increases with E_P. In particular, when E_P and P are relatively independent, $\partial E/\partial E_P$ in the non-parametric Budyko equation is solely a function of E_P/P, whereas in the Budyko-MCY equation it depends on both E_P/P and n. In this case, the derivative remains positive for both equations (Fig. 6(d)).

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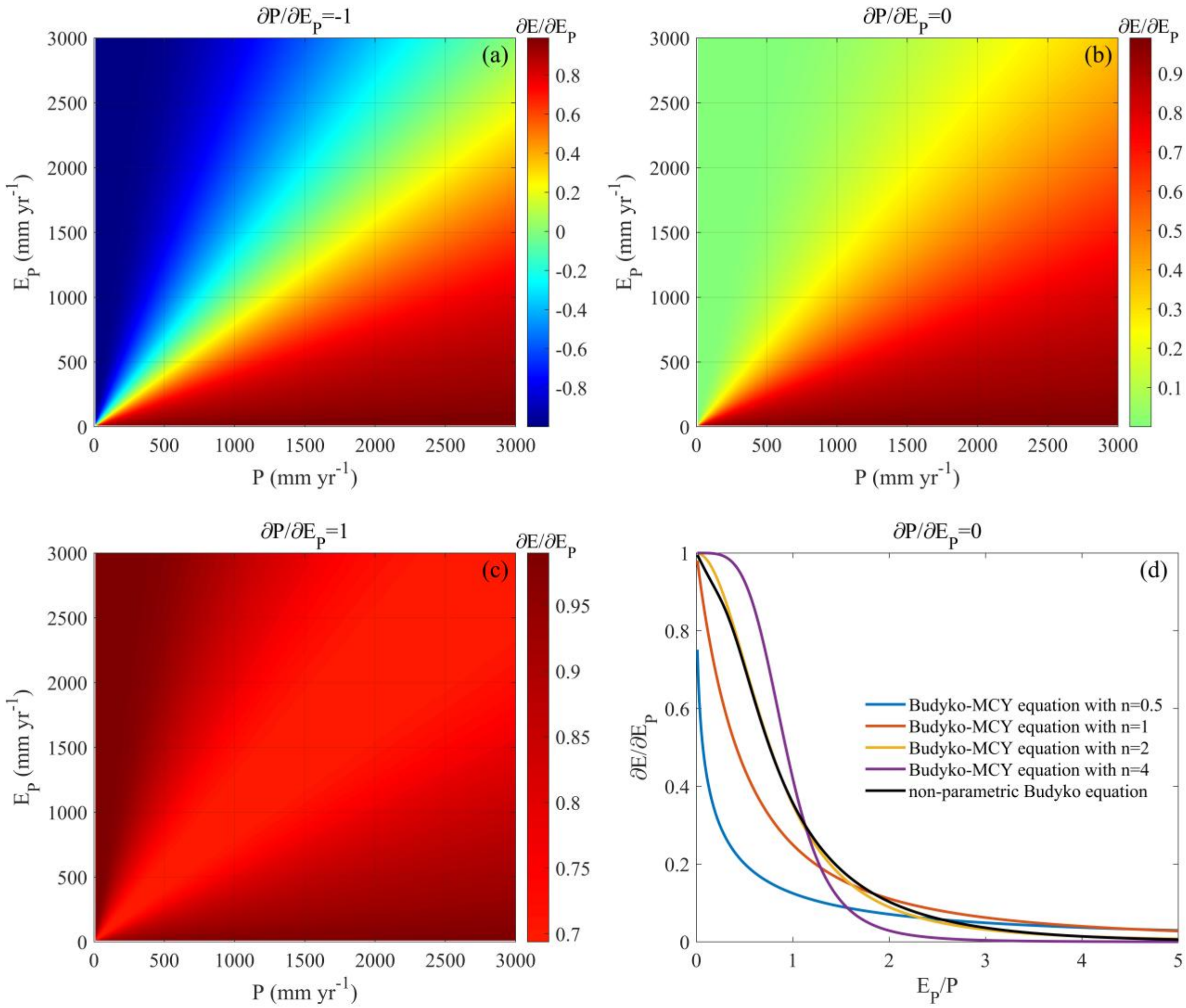

Figure 6: Variations of $\partial E/\partial E_P$ derived from the original non-parametric Budyko equation (Eq. (1)) and the Budyko-MCY equation (Eq. (3)) under varying $\partial P/\partial E_p$ conditions. Panels (a-c) illustrate $\partial E/\partial E_P$, derived from the non-parametric Budyko equation, under conditions where P and E_P are negatively correlated, independent, and positively correlated, respectively, while panel (d) additionally includes the results from the Budyko-MCY equation (with different parameter values) under the condition $\partial P/\partial E_p=0$.

4.2 Form of conversion function and its spatial variation

Budyko E_P, E, and P satisfy the constraints of the Budyko framework. When estimating E by the Budyko models, the theoretical value of $E_{P\text{-meteor}}$ should match that of Budyko E_P. However, in most cases, $E_{P\text{-meteor}}$, such as $E_{P\text{-pen}}$, does not coincide with Budyko E_P. The purpose of developing a conversion function for $E_{P\text{-meteor}}$ is to reduce its discrepancies with Budyko E_P, ensuring that the E_P input into the Budyko model exhibits the characteristics of Budyko E_P. This enhances E estimation without the need for additional data or catchment-specific adjustments to the model parameter. In this study, $E_{P\text{-Pen}}$ and Budyko E_P show positive correlations across MOPEX catchments in the spatial process. However, the regression

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lines do not follow the 1:1 line, indicating the differences between $E_{P\text{-}Pen}$ and Budyko E_P in both magnitudes and trends (Figs. 5(a) and 5(c)). If $E_{P\text{-}Pen}$ is used directly in the Budyko model without conversion, it will not yield the E estimates with the minimum MAE. This highlights the necessity of incorporating a conversion function when using $E_{P\text{-}meteor}$ in the Budyko framework. Such necessity becomes particularly pronounced when the slope of the linear conversion function is negative, because in this case low $E_{P\text{-}meteor}$ values correspond to high Budyko E_P values and vice versa.

It is found that the slopes of the linear conversion functions from $E_{P\text{-}Pen}$ to Budyko E_P are positive (Figs. 5(a) and 5(c)) for the MOPEX catchments. However, we observe a significant negative correlation between $E_{P\text{-}Pen}$ and $E_{P\text{-}Bref}$ for catchments in the Chinese Loess Plateau (CLP) and the conversion function is $E_{P\text{-}Bref}$=-5.90$E_{P\text{-}Pen}$+ 8272.20, implying a negative conversion relationship (Fig. 7(a)). As a further illustration, the relationship between $E_{P\text{-}Pen}$ and $E_{P\text{-}Bref}$ is also clearly contrasted between the two catchment groups in Fig. S2. This indicates that the slope and intercept of the linear conversion function may vary with the hydroclimatic conditions of catchments. A preliminary analysis indicates that the complementarity relationship between E and $E_{P\text{-}Pen}$ is an important factor affecting the specific expression of the conversion function. To be specific, a strong complementary relationship between E and $E_{P\text{-}Pen}$ exists for catchments in the Chinese Loess Plateau in the spatial process (Fig. 7(b)), where $E_{P\text{-}Bref}$ is significantly negatively correlated with $E_{P\text{-}pen}$. In contrast, no significant evidence of such a complementary relationship is observed for the MOPEX catchments in the spatial process (Fig. 7(d)), where $E_{P\text{-}Bref}$ is significantly positively correlated with $E_{P\text{-}Pen}$ (Fig. 7(c)). Considering the spatial differences of the complementary relationships, the form and expression of the conversion function need to be adjusted accordingly. Although the dry/wet climate conditions are considered to have affected the performance of the complementary relationships (Roderick and Farquhar, 2002; Golubev et al., 2001; Han et al., 2014), its spatial differentiation characteristics may also be shaped by other factors. How the complementary relationship between E and $E_{P\text{-}Pen}$ influences the relationship between Budyko E_P and $E_{P\text{-}Pen}$ merits more in-depth analysis.

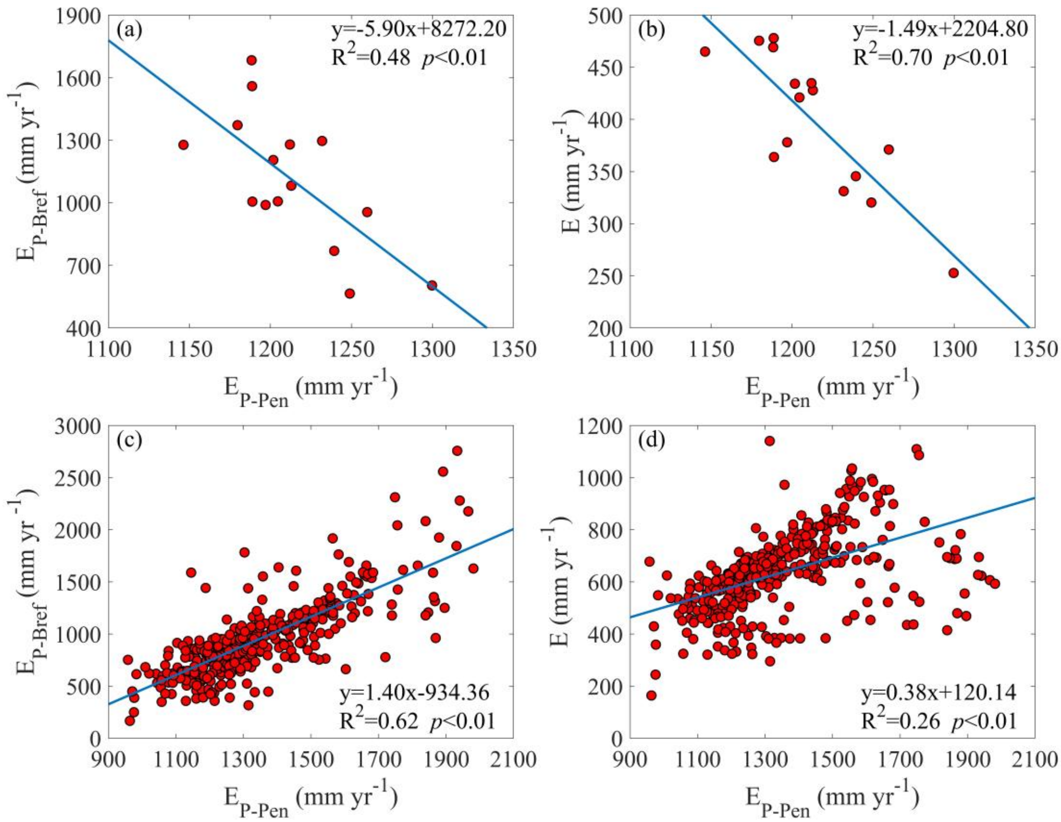

Figure 7: Relationships among $E_{P\text{-}Pen}$, $E_{P\text{-}Bref}$, and E for 15 catchments in the Chinese Loess Plateau and 371 MOPEX catchments, respectively. Panels (a-b) show the results of the catchments in the Chinese Loess Plateau and the data is from Cheng et al. (2023). Panels (c-d) show the results of the MOPEX catchments.

Worth noting, the MOPEX catchments are less distributed across the arid western United States, where $E_{P\text{-}Pen}$ values are generally higher. In Fig. 7(d), E shows a certain degree of negative correlation with $E_{P\text{-}Pen}$ for higher $E_{P\text{-}Pen}$, indicating that the complementary relationships for evapotranspiration may exist in arid regions. Additionally, it is important to emphasize that the values of E and E_P in this study are multi-year averages, so their relationships (including the complementary relationships) reflect their variations across different catchments (i.e., in the spatial process). Based on 192 data pairs of annual E and pan evaporation from 25 catchments (each having data over different periods) across the contiguous United States, Ramírez and Hobbins (2005) concluded that significant complementary relationships for evapotranspiration existed in the contiguous United States. Considering the insignificant complementary relationships in the spatial process (Fig. 7(d)), their results highlight the complementary relationships for evapotranspiration in the interannual process. The distinctions and connections between the complementary relationships for evapotranspiration in the spatial and temporal processes require further exploration, which will help to understand the differences in conversion functions under varying spatiotemporal conditions. Moreover, under certain conditions, Budyko E_P and E may also display a complementary relationship, which is an aspect worth considering. The conversion function can be established in both spatial and interannual processes, and its formulation varies across regions and is influenced by different complementary relationships for evapotranspiration in spatiotemporal processes and other factors.

4.3 Implications and perspectives of the Budyko E_P and the conversion function

The Budyko E_P not only shows the relationship between E_P and the water balance or hydrological elements in a catchment but also breaks through the conventional thinking of E_P estimation solely from the meteorological perspective, thus providing a new angle to understand E_P. This study further examines the performance of the Budyko E_P in estimating E at the catchment scale. Without relying on auxiliary data such as climate, vegetation, topography, and soil characteristics, we established a conversion function from meteorological E_P to Budyko E_P, achieving E estimates that outperform those obtained with fixed Budyko model parameter. Previous studies have shown that when auxiliary data are available, empirical functions for the model parameter derived from such data often yield more accurate E estimates than using a fixed parameter (Huang et al., 2024; Xu et al., 2013; Ning et al., 2019). Notably, the conversion function method establishes a direct link between meteorological E_P and Budyko E_P, simplifying the estimation process by eliminating the need for auxiliary data, thereby improving its practicality while maintaining accuracy, particularly in regions where auxiliary data are scarce or where complex regional conditions pose challenges to developing a unified parameter function (Chen et al., 2023; Cheng et al., 2022).

Future research on the Budyko E_P and the corresponding conversion function could address the following aspects. First, by incorporating water storage variation, Budyko E_P can be calculated at the annual scale, which would enable its application in annual Q or E estimation. Second, further investigation of the complementary relationship of evapotranspiration under different spatial and temporal conditions will help advance the precise expression of the conversion functions. Third, similar to the parameter-function approach, the conversion function could also be parameterized when auxiliary data are available, which would further improve the accuracy of E estimation.

5 Conclusions

Traditional meteorological methods of E_P estimation generally link E_P to meteorological elements and different meteorological equations lead to changes in E_P values. This study uncovers the connection between E_P and the components of the catchment water balance, and propose the concept of Budyko E_P under the Budyko framework and calculate its mean annual values by P and Q data. The reference and adjustable Budyko E_P are obtained based on the non-parametric and parametric Budyko equations, respectively. To facilitate the use of Budyko E_P in hydrological simulations, we developed conversion functions from $E_{P\text{-}Pen}$ to both the reference and the optimized adjustable Budyko E_P. Using the converted $E_{P\text{-}Pen}$ in Budyko models significantly improves the accuracy of E estimation for the MOPEX catchments, compared to using $E_{P\text{-}Pen}$ directly with the optimized Budyko model parameter. By extracting deeper information from the same inputs, our method enhances the performance of Budyko models in hydrological simulations without increasing data demand.

Further investigation suggests that the region-specific conversion function needs to be adjusted according to the spatial differentiation of the complementary relationships for evapotranspiration, as shown in the MOPEX and Chinese Loess Plateau catchments. When the complementary relationships for evapotranspiration are prominent, applying the conversion function becomes particularly important when estimating E using the Budyko model. This study further clarifies the relationships among variables in the Budyko framework and proposes the Budyko E_P calculation method. The results improve the estimation accuracy of land evapotranspiration and promote the understanding of the relationship between E and E_P.

Code availability. The code used for all analyses is available from the authors upon request.

Data availability. All data used in this study are publicly available. The Model Parameter Estimation Experiment (MOPEX) data are available from Duan et al. (2006). The gridMET data (Abatzoglou, 2013) can be accessed at http://www.climatologylab.org/gridmet.html.

Supplement. The supplement related to this article is available online at: ….

Author contributions. CC carried out the main analyses and prepared the initial manuscript; WL offered conceptual direction and overall supervision; RC assisted with investigation and visualization; ZM and HZ supported data collection and manuscript reviewing; XH and ZL contributed methodological assistance; HF provided support in reviewing and refining the manuscript. All the authors have read and agreed to the submitted version of the paper

Competing interests. The contact author has declared that none of the authors has any competing interests.

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