Applicability of 12 PET estimation methods in different climate regions in China
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ABSTRACT
Potential evapotranspiration (PET) is a comprehensive factor that characterises climate change, and considering the numerous methods to calculate PET, it is difficult to objectively select a method according to the requirements. In this study, the applicability of 12 commonly used PET estimation methods in China was studied. Based on temperature and humidity, China is divided into 11 temperature zones (TZ) and 5 arid and humid regions (AHRs). The study used the FAO Penman–Monteith (P-M) method as the standard, and the applicability of the 12 methods was analysed using four factors: correlation, annual mean values, seasonal distribution, and parameter characteristics. The results show that the radiation-based methods have the best monthly correlation with the P-M method, the temperature-based methods are second best, and mass-transfer-based methods perform the worst. Among these, the P-T method is the best, and the Hamon method is the worst. The Kharrufa and Abtew methods have the better applicability in higher TZs, whereas the Harg method has the least applicability. The seasonal distribution of radiation-based methods (excluding the Jensen method) in the different AHRs and different TZs is better than that of temperature-based and mass-transfer-based methods. According to the evaluation results of all factors, the Rohwer, P-T, and Mark methods are recommended when the data conditions are not conducive for the P-M method.

Key words | applicability, China, mass transfer, potential evapotranspiration, radiation, temperature

HIGHLIGHTS
- There are many methods to calculate PET, while it is difficult to choose objectively according to the needs.
- The applicability of 12 commonly used PET estimation methods in China was studied from four aspects.
- Variation range of the national annual value estimated is 288.72–1355.1 mm.
- The P-M method and energy-based methods have the highest monthly correlation.
- The Rohwer, P-T, and Mark methods are recommended.
INTRODUCTION

Due to the increasing impact of human activities in recent decades, the global climate has undergone drastic changes (Cong et al. 2010; Bao et al. 2012; Ahn & Merwade 2014; Li et al. 2015). According to the ‘IPCC Global Warming 1.5 °C Special Report’ released by the IPCC, the global average temperature is increased by 1 °C than it was before industrialisation and is expected to rise by 1.5 °C between 2030 and 2052 (IPCC 2018). Other meteorological parameters, such as relative humidity, wind speed, and net radiation, show different trends in different regions (Jiang et al. 2010; Espadafor et al. 2011; Jiménez et al. 2012; Valipour 2015a, 2015b; Zheng et al. 2016; Zhang & Li 2017). For example, relative humidity has decreased in Spain and China, while exhibiting an upward trend in Iranian coastal areas. Wind speed has been declining in China, whereas the global ocean wind speed is on the rise. Although net radiation is declining globally, a small upward trend is exhibited in the ocean (Azorin et al. 2015; Wang et al. 2019). In China, due to the large differences in geographical environments, the differences in climate change trends are more observable (Zhang & Cong 2014). For example, although the overall temperature in China shows an increasing trend, a downward trend exists in the northeast region. The overall wind speed shows a downward trend; however, the change in wind speed in the southeast area of the Tibetan Plateau is not evident, whereas in other areas, an increasing wind speed trend has been observed (Huang et al. 2016). The water cycle is an important component of the climate system, and climate change impacts on the water cycle elements will inevitably lead to the temporal and spatial changes of regional or basin water resources (Yang et al. 2015). The potential evapotranspiration (PET) plays an important climatic role in the water cycle and is a comprehensive meteorological factor. It is a key variable in the methods or models that predict climate change impacts on water resources, and simulation accuracy directly affects the prediction rationality (Douglas et al. 2009). Climate change directly or indirectly affects the extent and spatio-temporal distribution of PET (Wang et al. 2017; Dinipashoh et al. 2019), which necessitates an estimation study of PET in the context of climate change.

Currently, approximately 50 methods or models are used worldwide to estimate PET, which can be divided into the following four categories: (1) temperature-based methods, (2) mass-transfer-based methods, (3) radiation-based methods, and (4) comprehensive methods (Singh & Xu 1997). These methods are derived experimentally or theoretically, with different test conditions, required input data, and applicability in different regions.

The most internationally accepted method for estimating PET is the FAO Penman–Monteith (FAO P-M) formula. It is internationally recognised as the most effective method to estimate PET and has been shown to provide accurate estimations under different conditions (Allen et al. 1998). The P-M method was used to calculate PET in China, and the results confirmed its suitability in China (Liu et al. 2012). However, this formula requires a large amount of meteorological input data, such as maximum, minimum, and mean air temperatures, wind speed, relative humidity, and solar radiation. In practical applications, because the data are limited or the accuracy of the data is not sufficient, especially in remote areas, PET calculations are limited and cannot be estimated (Er-Raki et al. 2010). Simple empirical methods require less data. For example, the Linacre method only requires temperature, altitude, and latitude data; the Abtew method only needs total solar radiation data. These methods can accurately estimate PET and are widely used (Ye et al. 2009). Determining the applicability of the PET equations, the variety of data types required, and the extensive expertise required to properly use the various equations makes it difficult to select the appropriate method for further research on practical applications (Xu & Singh 2000). Therefore, it is necessary to study the applicability of various PET estimation methods under different conditions and provide the basis for the selection of PET for further research.

PET applicability analysis began in the 1990s, with a large-scale systematic study focussing on dozens of commonly used methods for estimating PET, such as Priestley–Taylor (P-T), Thornthwaite (Th), Blaney–Criddle (BC), Hargreaves (Harg), Jensen–Haise (JH), P-T, Penman, and Turc (Tu). Practically, fewer than ten methods for
estimating PET were typically used in most studies (Table 1; Foroud et al. 1989; Shi et al. 2008; Valipour 2014). In the study of PET estimation methods, Xu Chongyu’s research was the most representative, and it evaluated the estimation effect of three types of PET estimation formulas based on mass transfer, radiation, and temperature (Xu & Singh 2000; Xu & Singh 2001). In 2002, Xu Chongyu (Xu & Singh 2002) cross-compared these three types of PET estimation methods and found that the difference between the types of formulas in the same category is small. A comparison of the different categories showed that the radiation-based methods are the best, the temperature-based methods are better, and the mass-transfer-based methods perform the worst. This outcome is consistent with the conclusions of most studies (Tabari et al. 2013; Valipour et al. 2017).

The selection of study areas for PET research are primarily determined using geographically divided watersheds, regions, and administrative divisions at various levels (Lu et al. 2005; Kisi 2007; Sepaskhah & Razzaghi 2009; Ye et al. 2009; Ma et al. 2019), single arid or humid regions, and single temperature zones (TZs) (Table 1; Liu & Lin 2005; Azhar & Perera 2010; Xu et al. 2013; Heydari et al. 2015; Li et al. 2016), whereas comparative analysis is insufficient in multiple arid and humid regions (AHRs) and TZs (Valipour et al. 2017). In China, although many studies have been investigated the applicability of PET estimation methods, few studies have divided the study areas based on the TZ and AHR classifications and performed comparative analyses of the different types of PET estimation methods. However, China is a vast geographical area that extends from north to south across a tropic zone to a frigid zone, and from east to west, which includes humid and arid regions, with widely varied geographical environments. Hence, evaluating the applicability of PET estimation methods according to different AHRs and TZs is necessary.

Therefore, based on existing research, this study selected the 12 methods for estimating PET, based on temperature, mass transfer, and radiation; divided China into 5 AHRs and 11 TZs; and used the FAO P-M formula as the standard. This study analysed the applicability of the 12 different methods in China using four factors: correlation, annual mean values, seasonal distribution, and parameter characteristics. The results provide a basis for the selection of PET estimations.

| Study area                              | Documents                                      | Number of methods |
|-----------------------------------------|-----------------------------------------------|-------------------|
| Geographically divided watersheds,     | Kisi (2007)                                   | 3                 |
| regions, and administrative divisions at | Zou et al. (2014)                              | 4                 |
| various levels                         | Li et al. (2017)                               | 6                 |
| Henan Province, China                  | Zhao et al. (2015a)                            | 6                 |
| Hanjiang River Basin, China            | Zhao et al. (2015b)                            | 6                 |
| Haihe River Basin, China               | Valipour (2015a, 2015b)                       | 22                |
| Haihe River Basin, China               | Ye et al. (2009)                               | 5                 |
| 31 provinces in Iran                   |                                               |                   |
| Tibetan Plateau, China                 |                                               |                   |
| Single arid or humid region            | Douglas et al. (2009)                          | 3                 |
| Wetland area of Florida, USA           | Lu et al. (2005)                               | 6                 |
| Humid regions in the southeastern United States | Heydari et al. (2015)                             | 1                 |
| Arid regions in Iran                   | Sepaskha & Razzaghi (2009)                     | 2                 |
| Semiarid regions in Iran               | Azhar & Perera (2010)                         | 10                |
| Arid regions in Australia              | Liu & Lin (2005)                              | 1                 |
| Semiarid regions in northern China     | Xu et al. (2013)                              | 3                 |
| Humid regions in eastern China         | Li et al. (2016)                              | 6                 |
| Arid regions in the northwestern China | Er-Raki et al. (2010)                          | 3                 |
| Semiarid areas                         |                                               |                   |
| Single temperature zone                | Gunston & Batchelor (1983)                     | 1                 |
| Tropical countries                    | Chen et al. (2018)                             | 3                 |
| Temperate Inner Mongolia, China        | Shi et al. (2008)                             | 3                 |
| Temperate mixed forest in Changbai Mountain, China |            |                   |
| Multiple AHRs and TZs                  | Valipour et al. (2017)                         | 15                |
STUDY AREA AND METHODS

Study area

China is a vast territory with a wide range of meteorological conditions. From the southeast coast to the northwest inland area, there is a difference in the annual average relative humidity of more than 50%. From the southernmost islands of the South China Sea Islands to the northernmost Heilongjiang Mohe, the annual average temperature difference can reach more than 28 °C. PET is affected by temperature and humidity; therefore, dividing the entire country into different AHRs and TZs can allow better analysis of the impacts on PET by these two factors.

Data

This study uses conventional observation data from 228 weather stations from the China Meteorological Data Network (http://data.cma.cn/) from 1960 to 2013 (there is no meteorological data for Taiwan Province and the South China Sea Islands), including the daily maximum temperature, average temperature, minimum temperature, daylight hours, wind speed at 10 m, relative humidity, and solar radiation. Due to the extremely uneven distribution of meteorological stations in China and the limited meteorological stations selected in this study, no meteorological stations were located in some TZs, which are plateau cold zones and cold temperate zones. Therefore, in this study, only nine TZs with stations are discussed, and the specific distribution is shown in Figure 1 and Table 2.

Methods

Model comparison and statistical error analysis

The correlation coefficient is the linear correlation degree between study variables, and the root-mean-square error is
a measure of the deviation between the observed and true values. In this study, the correlation coefficient and root-mean-square error were used to measure the correlation and deviation between 12 PET methods and the P-M method.

\[
R^2 = 1 - \frac{\sum_{i=1}^{n} (PETPM_i - PET_{i,m})^2}{\sum_{i=1}^{n} (PETPM_i - PETPM)^2},
\]

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (PETPM_i - PET_{i,m})^2},
\]

where \(R^2\) is the correlation coefficient (dimensionless), PETPM is the calculated value of the P-M formula (mm); PET_{i,m} is the calculated value of the \(m\) method (12 methods total, mm), PET_{i,m} is the average value of the P-M formula (mm), and RMSE is the root-mean-square error (dimensionless).

**PET methods**

A total of 13 methods for estimating PET were used, including the benchmark method FAO P-M formula and four temperature-based, two mass-transfer-based, and six radiation-based methods (Table 3).

The standard method used in this study for estimating PET is the FAO Penman–Monteith formula (P-M formula) recommended by the United Nations Food and Agriculture Organization. This method is based on the principle of energy balance and aerodynamics, and it has a complete theoretical basis, high precision, and high applicability among many PET estimation formulas; therefore, it can be used as a benchmark method for the applicability analysis of other methods.

\[
E_P = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T_a + 273} U_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34) U_2}
\]

where \(E_P\) is the PET (mm/d); \((E_P)\) units are the same in the subsequent formulas; \(G\) is the soil heat flux density (MJ/(m\(^2\) d)); \(R_n\) is the net radiation on the surface of the crop (MJ/(m\(^2\) d)); \(\gamma\) is the dry–wet constant (kPa/C); \(T_a\) is the daily average temperature (°C) at a height of 2 m; \(e_s\) is the saturated vapour pressure (kPa); \(e_a\) is the actual vapour pressure (kPa); \(\Delta\) is the slope of the temperature-saturated water pressure curve \(T\) (kPa/°C); and \(U_2\) is the wind speed of 2 m (m/s). When the \(G\) value is small, it is neglected in the process.

**RESULTS AND DISCUSSION**

This study analyses the applicability of 12 PET methods in different arid and humid zones and TZs in China using four factors: correlation analysis, annual mean values, intra-seasonal distribution, and parameter adjustments.

**China**

**Correlation analysis**

The monthly correlation coefficients of all the methods were above 0.89 (Table 4), indicating their good correlation with the FAO P-M method in calculating PET on a national scale. The monthly correlation coefficients between the radiation-based methods and the FAO P-M method are above 0.96. This is significantly greater than the correlation coefficient values between the temperature and mass-transfer-based methods and the FAO P-M method because the radiation-based methods also consider the temperature factor. The best correlation was obtained by using the Door method, and the least correlated were by the Rohwer and Penman methods based on the temperature and mass transmission methods. Before and after the adjustment, excluding the Linacre and Kharrufa methods, the correlation between other methods and the P-M method remained unchanged.
The PET value calculated using the FAO P-M method was 884.41 mm. The multiyear PET mean value calculated using various methods before adjusting the parameters fluctuated on both sides of the PET calculated by the FAO P-M method (288.73–1,355.10 mm). After the parameters were adjusted, the values obtained using the various methods

### Table 3 | Methods of estimating PET

| Classification | Estimation methods | Estimation formula | Initial value |
|----------------|--------------------|--------------------|---------------|
| Methods based on temperature | Blaney & Criddle (1950) | \( EP = kp(0.46T_a + 8.13) \) | \( k = 0.87 \) |
| | Linacre (1977) | \( EP = \frac{mT_m}{100 - A + 15(T_a - T_d)} \) | \( m = 500 \) |
| | Kharrufa (1985) | \( EP = aP^2 \) | \( a = 0.34 \), \( b = 0.55 \) |
| | Hamon (1961) | \( EP = \frac{bD^2}{Pt} \) | |
| Methods based on mass-transfer | Rohwer (1962) | \( EP = c(1 + 0.27U_2)(e_i - e_a) \) | \( c = 0.44 \) |
| | Penman (1948) | \( EP = d(1 + 0.98/100U_2)(e_i - e_a) \) | \( d = 0.35 \) |
| Methods based on radiation | Priestley & Taylor (1972) | \( EP = \frac{R_s}{\lambda} \) | \( f = 1.26 \) |
| | Makkink (1957) | \( EP = g \frac{(R_n - G)}{\lambda} \) | \( g = 0.61 \) |
| | Abtew (1996) | \( EP = K \frac{R_s}{\lambda} \) | \( K = 0.53 \) |
| | Hargreaves (1975) | \( EP = n(T + 17.8) \frac{R_s}{\lambda} \) | \( n = 0.0135 \) |
| | Doorenbos & Pruitt (1977) | \( EP = a \left( \frac{R_s}{\lambda} \right)^2 + \beta \) | \( \beta = -0.3 \) |
| | Jensen & Haise (1965) | \( EP = C_7(T - T_x) \frac{R_s}{\lambda} \) | \( C_7 = 0.025 \) |

\( \lambda \) is the reactant influence coefficient; \( p \) is the percentage of daytime hours as a percentage of the daytime hours; \( T_d \) is the dew point temperature (°C); \( h \) is the site elevation (m); \( A \) is the latitude (°); where the site is located; \( T \) is the daytime duration (h); \( R_s \) is the saturated water vapour density term; \( R_s \) is the short-wave radiation (MJ/(m² d)); in the Doorenbos & Pruitt (1977) formula, \( a = 1.066 - 0.13 \times 10^{-2}R_h + 0.045U_2 - 0.20 \times 10^{-3}R_h \times U_2 - 0.135 \times 10^{-2}R^2 - 0.11 \times 10^{-2}U_2^2; T_x \) is the temperature constant, this study considers -3 °C; removes the selected parameters that need to be adjusted (experience coefficients are not explained), and other symbols have the same meaning as formula 3.

### Table 4 | Correlation coefficients of different methods and the P-M method

| MBTMT | BC | BC-ap | Linacre | Linacre-ap | Kharrufa | Kharrufa-ap |
|-------|----|-------|---------|------------|----------|--------------|
| \( R^2 \) | 0.91 | 0.91 | 0.95 | 0.89 | 0.90 | 0.92 |
| MBTMT | Hamon | Hamon-ap | Rohwer | Rohwer-ap | Penman | Penman-ap |
| \( R^2 \) | 0.91 | 0.91 | 0.89 | 0.89 | 0.89 | 0.89 |
| MBR | P-T | P-T-ap | Mak | Mak-ap | Abtew | Abtew-ap |
| \( R^2 \) | 0.97 | 0.97 | 0.98 | 0.98 | 0.96 | 0.96 |
| MBR | Harg | Harg-ap | Door | Door-ap | Jensen | Jensen-ap |
| \( R^2 \) | 0.98 | 0.98 | 0.99 | 0.99 | 0.96 | 0.96 |

\( R^2 \), correlation coefficient; MBTMT, methods based on temperature and mass-transfer; MBR, methods based on radiation.

### Annual mean values

The PET value calculated using the FAO P-M method was 884.41 mm. The multiyear PET mean value calculated using various methods before adjusting the parameters fluctuated on both sides of the PET calculated by the FAO P-M method (288.73–1,355.10 mm). After the parameters were adjusted, the values obtained using the various methods...
were close to those obtained by the FAO P-M method (Table 5). Before the adjustment, the value calculated by the P-T method was closest to the value calculated by the FAO P-M method (a 43.41 mm difference), and the value calculated using the Hamon method was the most conflicting from the value calculated by the FAO P-M method (up to 595.68 mm). The amount and percentage of change in PET calculation methods based on temperature and mass transfer before and after the adjustment were significantly greater than those based on radiation. The temperature-based Hamon method showed a change of >600 mm, and the percentage change was as high as 200%. With other methods based on temperature and mass transfer other than Rohwer, a change of >200 mm and a percentage change of >100% were observed. The radiation-based methods other than the Abtew method showed a change of approximately 300 mm, and the remaining radiation-based methods showed a change of <200 mm, with the percentage change being within 50% (Figure 2).

The FAO P-M method resulted in a decrease in the calculated value of PET with increasing humidity in different AHRs (Table 6), which is consistent with the negative correlation between the FAO P-M formula and humidity. The increase in the humid region (5-HR) value relative to the subhumid region (4-SHR) is primarily due to higher temperatures in the humid region compared with the subhumid region; therefore, the PET value increased slightly with an increase in humidity. Among the different TZs (Table 6), PET increased with an increase in temperature in the plateau (TZ1-3), the temperate zone (TZ4-5), and the tropical zone (TZ6-9).

### Seasonal distribution

The PET calculated by the FAO P-M formula is evenly distributed during the year, with the summer > spring > autumn > winter values, and no negative values appear in winter (Figure 3). In the temperature-based methods, both the BC and Linacre methods result in lower PET in spring, higher PET in autumn, and more moderate value in summer and winter. The Kharrufa and Hamon methods result in lower PET values in spring and winter, and higher PET values in summer; moreover, the seasonal distribution is variable. The seasonal distribution of PET according to the Rohwer and Penman methods is comparable and consistent with that of the FAO P-M method. The radiation-based P-T, Mak, Harg, and Door methods show nearly the same seasonal distribution as the FAO P-M method. The proportion of the PET estimation values calculated using the Abtew method is greater in winter and lower in summer, whereas that of the Jensen method is greater in summer and lower in winter, and after parameter adjustment, negative values appear in the winter. The seasonal distributions of all methods except the Jensen method, which shows negative values in winter after adjustment, are essentially unchanged following adjustment, indicating that the adjustment has little effect on the distribution of the estimated PET value throughout the year (Figure 3).

### Parameter adjustment feature

The parameter adjustment values using different methods are listed in Table 7. In addition to the Hamon method

| MBTMT | BC | BC-ap | Linacre | Linacre-ap | Kharrufa | Kharrufa-ap |
|-------|----|-------|---------|------------|----------|-------------|
| PE    | 631.14 | 883.94 | 1355.10 | 885.08    | 631.67   | 884.59      |
| Hamon | 288.75 | 884.17 | 934.27 | 885.49    | 491.03   | 886.08      |
| P-T   | 841.00 | 885.44 | 683.90 | 885.38    | 1187.01  | 885.11      |
| Door  | 996.98 | 885.46 | 989.94 | 885.44    | 1018.18  | 885.90      |

MBTMT and MBR are the same in Table 3; PE: PET (mm); -ap: methods calibrated.
variation, the parameter range is >200%, whereas the values from other methods are within 100%, indicating that the Hamon method is not suitable. The Rohwer and P-T methods are within 10%, and the Harg and Jensen methods are between 10 and 20%. The Mak and Abtew methods are between 20 and 30%. The adjustment range of these six methods is relatively small, indicating that the high applicability of these six methods; other methods are even more applicable.

**Different AHRs**

**Correlation analysis**

The correlation coefficients of the different methods calculated by the PET and P-M methods for different AHRs are shown in Figure 4. The monthly correlation coefficient between the Linacre and Kharrufa methods and the FAO P-M method was higher in the arid regions than in the humid regions, and it was smallest in the humid and arid boundary areas. Other temperature and mass-transfer-based methods showed a significant increase in humidity with the FAO P-M method. The monthly correlation decreased, and therefore, the correlation between the temperature and mass-transfer-based
methods showed that these methods are more suitable in the arid areas than in the humid areas. Among the methods, the six methods based on radiation showed a little change in each AHR, without conspicuous low. The monthly correlation coefficients between these six methods and the FAO P-M method are greater than 0.94, indicating well the applicability of these six methods in different AHRs.

Figure 3 | Seasonal distribution of PET using different methods.

Table 7 | Adjustment value of parameters using different methods

| Method | Parameter | BC | Linacre | Kharrufa | Hamon | Rohwer | Penman |
|--------|-----------|----|---------|----------|-------|--------|--------|
| MBTMT  | AV        | 41.92 | -64.37 | 63.78    | 223.91| 1.22   | 90.06  |
| MBR    | P-T       | 6.87  | 24.03   | -25.71  | -10.02| 98.86  | 15.53  |

Unit: %; AV: Average variation.
Annual mean values

With an increase in humidity, the annual mean changes in evapotranspiration calculated using BC, Linacre, Kharrufa, Hamon, Rohwer, P-T, Mak, and Door methods decrease gradually, which indicates that the range of PET values to be adjusted by these methods in wetter areas is less. This also indicates that these methods are more applicable in the humid areas. However, the Penman is more suitable for the application in the arid areas. The annual mean change in evapotranspiration calculated by the Abtew method first increases and then decreases, indicating that it is more suitable for the arid or humid areas. In contrast, the Harg method is applicable for boundaries between the arid and humid areas (Figure 5).

Seasonal spatial distribution

The distribution of the P-M method increased with the increase in wetness throughout the year, and the proportion of PET decreased in summer and increased significantly in winter, especially in the humid zone (5-HR). The PET in winter accounted for approximately 13%. In the different AHRs (Figure 6, 1-EAR), the mass-transfer-based methods are significantly better than the temperature-based methods, and the seasonal distribution of the calculated values is similar to that of the FAO P-M method, especially in the extreme arid region (1-EAR) and the arid region (2-AR) (Figure 6). The seasonal distribution of temperature-based methods is better in humid regions than in arid regions, which is most clearly demonstrated by the Kharrufa method (Figure 6). The seasonal distribution of mass-transfer-based methods performs lower than that in arid regions. However, it performs more effectively than the temperature-based method, indicating that the seasonal distribution of mass-transfer-based methods is more applicable in arid regions versus in humid regions and is better performing than the temperature-based methods in all AHRs. Among the six methods, the Rohwer method has the greatest applicability in AHRs,
and the Kharrufa method is undoubtedly the least suitable method, particularly in arid regions (1-EAR, 2-AR, and 3-SAR). The PET value is approximately zero in winter, even at multiple sites (Hailar, Nenjiang, Keshan, Bayinbulak, Wudaoliang, Maduo, and Heihe). However, in humid regions, the method performs well, especially in the humid zone (5-HR). The distribution in summer and winter is reasonable, and the applicability is significantly better than that in the arid region.

In the AHRs (Figure 6, 1-EAR), the radiation-based methods can be divided into three types based on the performance throughout the year. (1) As wetness increases, the seasonal distribution improves; this means when applying the Abtew method, the seasonal distribution of these methods is from the beginning of the winter to a large proportion and the summer to a small proportion to a more reasonable distribution within the year. This is similar to the seasonal distribution of the FAO P-M method in the humid region (5-HR). (2) With an increase in humidity, the seasonal distribution of some methods increasingly worsens (P-T, Mak, Harg, and Door). The seasonal distribution of these four methods is essentially consistent with the FAO P-M method in the extremely dry area (1-EAR), and subsequently, in the summer season, the proportion progressively increases and decreases with an increase in humidity in the winter. (3) The seasonal distribution of

Figure 5 | Annual average of PET in different AHRs using different methods.
Figure 6 | Seasonal distribution of PET calculated by different methods in different AHRs. (Continued.)
some methods is very poor in all humid climate regions, such as the Jensen method. The value calculated with the method accounts for a very large proportion in summer, especially in the subhumid area (4-SHR). The values calculated by the Jensen method after the adjustment accounts for more than 85% in summer, close to the total proportion of the spring, summer, and autumn seasons of the FAO P-M method. In winter, the proportion of the Jensen method has a negative value in all regions. After adjusting the parameters, the seasonal distribution of the Door and Jensen methods perform worse, and other methods remain relatively unchanged before and after the adjustment.

Figure 6(a) and 6(b) show that the seasonal distribution of various methods is essentially unchanged before and after the adjustment. The methods with the highest consistency in the distribution of the FAO P-M method in different AHRs are shown in Table 10.

Parameter adjustment feature

The adjustment values of the parameters using different methods based on temperature and mass-transfer in different AHRs are shown in Table 8. The standard deviation of the BC method parameters needs to be adjusted in different arid or humid regions. The standard deviation is only 3.36%; therefore, the parameter adjustment range of the BC method does not change with the changes in humidity. The parameter ranges, which need to be adjusted, in Linacre, Kharrufa, P-T, Rohwer, Door, and Mak methods, decrease with increasing humidity. The six methods are more suitable in humid regions; the Penman method exhibits the contrary. As the humidity increases, the range of parameter adjustment is gradually increased; therefore, the applicability of the method is more effective in arid regions.

For the adjustment value of parameters using different methods based on radiation in different AHRs (Table 9), the Abtew method gradually increases the range of parameters from AHRs to the arid and humid boundary region, thereby representing a mountain peak shape. However, the range of the Harg method parameter adjustment decreases between the AHRs and the arid and humid boundary region, presenting the shape of a valley. These lows are almost identical to the distribution of the PET variation shown in Figure 5.

**Table 8** Adjustment value of parameters using different methods based on temperature and mass-transfer in different AHRs

| Methods   | TZ       | BC       | Linacre  | Kharrufa | Hamon    | Rohwer   | Penman   | RMSE (%) |
|-----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 1-EAR     | 44.05    | −106.57  | 76.17    | 211.89   | −32.09   | 34.26    | 97.94    |
| 2-AR      | 39.63    | −88.12   | 61.75    | 194.16   | −27.26   | 47.80    | 86.81    |
| 3-SAR     | 40.96    | −74.77   | 135.49   | 251.13   | −9.50    | 85.18    | 104.43   |
| 4-SHR     | 35.51    | −59.00   | 81.38    | 219.66   | −3.04    | 90.29    | 87.30    |
| 5-HR      | 44.89    | −54.73   | 35.74    | 223.93   | 14.16    | 104.43   | 86.52    |
| RMSE (%)  | 3.36     | 18.99    | 32.77    | 18.54    | 16.77    | 26.72    |

Unit: %.
Different TZs

Correlation analysis

Because some of the sites were in the plateau areas (1–3), the law of monthly correlation between the various methods and the FAO P-M method cannot be fully reflected; therefore, the monthly correlation of the Linacre method suddenly drops in the 2–3 region. As shown in Figure 7(a), in the regions with lower and higher temperatures, the monthly correlation coefficients between the various methods and the FAO P-M method are not high, and the monthly correlation is greater when temperatures are optimal. Therefore, the temperature-based and mass-transfer-based methods are more suitable

Table 9 | Adjustment value of parameters using different methods based on radiation in different AHRs

| Methods | TZ        | P-T      | Mak      | Abtew    | Harg    | Door     | Jensen   | RMSE (%) |
|---------|-----------|----------|----------|----------|---------|----------|----------|----------|
| 1-EAR   | 43.30     | 42.81    | −15.42   | 9.68     | 151.74  | 21.04    | 52.96    |
| 2-AR    | 39.78     | 42.14    | −18.75   | 7.40     | 119.42  | 16.46    | 43.19    |
| 3-SAR   | 20.42     | 28.75    | −31.89   | 4.12     | 144.90  | 142.72   | 67.98    |
| 4-SHR   | 10.39     | 26.00    | −29.37   | −7.81    | 92.79   | 28.01    | 38.08    |
| 5-HR    | −7.52     | 17.00    | −24.84   | −19.70   | 79.17   | −24.62   | 36.88    |
| RMSE (%)| 18.84     | 9.89     | 6.21     | 11.01    | 28.31   | .09      |

Unit: %.

Figure 7 | Correlation coefficients of different methods using PET and the P-M method in different TZs.
for these TZs. In Figure 7(b), the monthly correlation coefficients between the various radiation-based methods and the FAO P-M method are mostly above 0.94, and the variation in different TZs is small, indicating that these methods have better applicability in each TZ.

**Annual mean values**

The annual mean of PET in different TZs using different methods is shown in Figure 8. With increasing temperature, the annual mean variation values calculated using the Kharrufa and Abtew methods gradually decrease; that is, the magnitude of the PET that needs to be adjusted gradually decreases, indicating the excellent application of the two methods in higher TZs. However, the Harg method performs well at lower temperatures. The annual mean variation value of PET calculated by BC, Hamon, and Penman is independent of temperature, and the applicability of these methods is the same in each TZ. The applicability of the Door method in the plateau zones (TZ1-3) is poor and is better in other zones (TZ4-9).

**Seasonal spatial distribution**

The FAO P-M method had the same regularity in the TZs (1–3) in the plateau region and the TZs (4–9). As the temperature increased, the proportion of the calculated value in summer declined, with proportional rising in winter, even in the marginal tropics (9-MT), and the proportion in summer was almost the same as that in spring (Figure 9). Among the temperature-based methods in different TZs, the BC method had a constant distribution throughout the year as the temperature changed. The Kharrufa and Hamon methods improved as the temperature increased in both regions, and the seasonal distribution of the Kharrufa method was similar to that of the FAO P-M method in the
marginal tropical TZ (9-MT). The Linacre method performed worse in the plateau region (TZ1-3) as the temperature increased, and the overall performance differed greatly from the FAO P-M method during the year. In other regions, as the temperature increased, the change was minimal; however, the seasonal distribution was somewhat similar to that of the FAO P-M method. Although the seasonal distribution of mass-transfer Rohwer and Penman methods did not change.
with temperature, these methods performed significantly better in temperature regions other than the plateau.

The radiation-based methods (b) of different TZs, such as P-T, Abtew, Harg, and Jensen methods, perform better in the plateau and other regions separately with increasing temperature, among which the seasonal distribution of the Harg method is similar to that of the FAO P-M method in the northern subtropical TZ (6-NST) and is almost the
same in the marginal tropics (9-MT). Furthermore, the Abtew method still performs the worst among all methods compared with the FAO P-M method in the marginal tropics (9-MT). The Jensen method accounts for a large proportion of the summer in the plateau subfrigid zone (1-PSF), the plateau subtemperate zone (2-PST), and the middle temperate zone (4-MT), especially in the plateau subfrigid zone (1-PSF). Furthermore, the PET is negative in winter; however, as the temperature rises, the seasonal distribution is almost the same as that of the FAO P-M method in the TZs of 7-MST, 8-SST, and 9-MT. The seasonal distribution of the Mak and Door methods is highly consistent with that of the FAO P-M method and does not vary with temperature in all TZs.

Figure 9(a) and 9(b) show that the seasonal distribution of various methods is almost unchanged before and after the adjustment. The methods providing the best seasonal distribution in different TZs and AHRs are shown in Table 10.

Parameter adjustment feature

The adjustment values of the parameters using different methods based on temperature, mass-transfer, and radiation in different TZs are presented in Tables 11 and 12. The Kharrufa and Abtew methods gradually decrease in the range of parameter adjustment as the temperature increases, indicating that the two methods are more suitable for higher TZs. The Harg method exhibits the contrary, with better applicability in the lower TZs; however, because the plateau subfrigid zone (1-PSF) has fewer sites, larger values are observed. The applicability of the Door method is poor in the plateau regions (TZ1-3) because of its large parameter adjustment range, the applicability of which is better in other regions (TZ4-9). The parameter adjustment range of the Jensen method is very large in the plateau subfrigid zone (1-PSF); therefore, outliers are likely to appear. The above rule is almost identical to the distribution law of the PET variation demonstrated in Figure 8.

CONCLUSIONS

Many methods exist for estimating PET, and this study examined four temperature-based methods, two mass-transfer-based methods, and six radiation-based methods, while...
using the FAO P-M formula as the standard, and then analyzes the applicability of the 12 PET methods to draw the following conclusions:

1. The radiation-based methods have the best monthly correlation with the FAO P-M method, followed by the temperature-based methods, and the mass-transfer-based methods perform the worst. Among these, the P-T method is the best, and the Hamon method is the least applicable. After performing parameter adjustments, all methods can achieve comparable values to the FAO P-M method. The parameter adjustment range of the Hamon method is relatively large in China, which indicates that its applicability is low.

2. The annual PET value estimated by the FAO P-M method decreases with an increase in humidity and rises with an increase in temperature in plateau, temperate, and tropical regions. The BC, Linacre, Kharrufa, Hamon, Rohwer, P-T, Mak, and Door methods are suitable in humid regions, whereas the Penman methods are suitable in arid regions. The Kharrufa and Abtew methods have better applicability in higher TZs, whereas the contrary is true for the Harg method, and the BC, Hamon, and Penman methods have similar applicability in different TZs.

| Table 11 | Adjustment value of parameters using different methods based on temperature and mass-transfer in different TZs |
|---|---|---|---|---|---|---|---|
| TZ | BC | Linacre | Kharrufa | Hamon | Rohwer | Penman | RMSE (%) |
| 1-PSF | 66.14 | −77.89 | 4.16 | 434.05 | 29.83 | 151.87 | 201.47 |
| 2-PST | 60.54 | −75.79 | 230.51 | 469.44 | 12.65 | 118.64 | 176.15 |
| 3-PT | 43.30 | −100.04 | 104.64 | 326.95 | −14.16 | 53.87 | 131.77 |
| 4-MT | 38.20 | −68.66 | 74.05 | 212.20 | −13.95 | 74.87 | 87.34 |
| 5-WT | 32.61 | −72.46 | 42.43 | 191.82 | −13.55 | 67.85 | 81.02 |
| 6-NST | 40.68 | −55.42 | 31.36 | 205.50 | 9.95 | 104.84 | 81.76 |
| 7-MST | 54.67 | −57.14 | 28.07 | 220.18 | 15.05 | 100.35 | 85.71 |
| 8-SST | 43.37 | −57.45 | 17.60 | 218.55 | 13.16 | 94.78 | 85.89 |
| 9-MT | 27.28 | −45.22 | −0.85 | 175.85 | 31.80 | 129.99 | 76.02 |
| RMSE (%) | 12.11 | 15.32 | 139.02 | 104.07 | 16.94 | 29.40 |

| Table 12 | Adjustment value of parameters using different methods based on radiation in different TZs |
|---|---|---|---|---|---|---|---|
| TZ | P-T | Mak | Abtew | Harg | Door | Jensen | RMSE (%) |
| 1-PSF | -3.43 | 8.05 | -46.22 | 11.55 | 229.48 | 644.83 | 242.22 |
| 2-PST | -1.29 | 12.95 | -37.71 | 0.43 | 186.44 | 51.49 | 72.45 |
| 3-PT | 8.32 | 15.42 | -26.53 | -2.04 | 327.50 | 7.45 | 122.59 |
| 4-MT | 27.19 | 35.08 | -27.58 | 2.74 | 99.01 | 23.21 | 38.37 |
| 5-WT | 16.66 | 30.17 | -23.45 | -8.36 | 96.58 | -9.01 | 39.71 |
| 6-NST | -8.73 | 14.57 | -27.11 | -20.68 | 106.93 | -26.73 | 47.18 |
| 7-MST | -8.91 | 18.85 | -22.28 | -21.01 | 44.42 | -30.67 | 26.53 |
| 8-SST | -8.09 | 17.19 | -19.66 | -21.62 | 80.09 | -32.80 | 38.01 |
| 9-MT | -12.76 | 12.50 | -20.18 | -25.85 | 101.54 | -38.23 | 46.76 |
| RMSE (%) | 12.80 | 8.26 | 8.26 | 12. | 84.44 | 206.75 |
3. The seasonal distribution of radiation-based methods (excluding the Jensen method) in different AHRs and TZs is superior to the temperature-based and mass-transfer-based methods. The annual distribution of the PET value of the Rohwer method is the best among all AHRs, and the Abtew method performs the best in arid regions. The P-T, Mak, Harg, and Door methods are most applicable in humid regions, whereas the Jensen and Kharrufa methods perform the worst in all AHRs.

4. Overall, the application of the radiation method in China performs the best. When the study area is humid, the temperature-based and mass-transfer-based methods are selected. When the study area is arid, the Penman and Abtew methods are preferred.

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**DATA AVAILABILITY STATEMENT**

All relevant data are available from an online repository or repositories. This study uses conventional observation data from 228 weather stations from the China Meteorological Data Network (http://data.cma.cn/) from 1960 to 2013.

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