The best alternative for estimating reference crop evapotranspiration in different sub-regions of mainland China

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Reference crop evapotranspiration (ET₀) is a critically important parameter for climatological, hydrological and agricultural management. The FAO56 Penman-Monteith (PM) equation has been recommended as the standardized ET₀ (ET₀,s) equation, but it has a high requirements of climatic data. There is a practical need for finding a best alternative method to estimate ET₀ in the regions where full climatic data are lacking. A comprehensive comparison for the spatiotemporal variations, relative errors, standard deviations and Nash-Sutcliffe efficacy coefficients of monthly or annual ET₀,s and ET₀,i (i = 1, 2, ..., 10) values estimated by 10 selected methods (i.e., Irmak et al., Makkink, Priestley-Taylor, Hargreaves-Samani, Droogers-Allen, Berti et al., Doorenbos-Pruitt, Wright and Valiantzas, respectively) using data at 552 sites over 1961–2013 in mainland China. The method proposed by Berti et al. (2014) was selected as the best alternative of FAO56-PM because it was simple in computation process, only utilized temperature data, had generally good accuracy in describing spatiotemporal characteristics of ET₀,s in different sub-regions and mainland China, and correlated linearly to the FAO56-PM method very well. The parameters of the linear correlations between ET₀ of the two methods are calibrated for each site with the smallest determination of coefficient being 0.87.

Atmospheric water demand has been described using potential evaporation (ETp), pan evaporation, and reference crop evapotranspiration (ET₀). ETp is the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height and with adequate soil water status in the profile1, 2. ETp has been applied as an important parameter for several decades in the field of hydrology, meteorology, agricultural engineering, etc. However, crop conditions in ETp estimation was assumed constant. To avoid ambiguities involved in the definition and interpretation of ETp, ET₀ was introduced by irrigation engineers and researchers in the late 1970s and early 1980s3, 4. ET₀ is evapotranspiration rate from a hypothetical grass reference crop with a height of 0.12 m, a fixed surface resistance of 70 sec m⁻¹ and an albedo of 0.23, actively growing, well-watered, and completely shading the ground5. ET₀ incorporates multi-climatic factors and expresses the evaporative demand of the atmosphere independent of crop type, crop development and management practices. Under the world-widely accepted global warming background6, ET₀ has become an important agrometeorological parameter for climatological and hydrological studies, as well as for irrigation planning and management7–9. ET₀ has also been incorporated in drought severity and evolution analysis10–12. The application of ET₀ was also related to water use of crops13. ET₀ has been widely used in different research fields with various objectives because it can be computed from meteorological data.

The methods for estimating ET₀ (ET₀) could be classified as empirical, temperature-based, radiation-based, pan, and combination types. In recent years, several simplified ET₀ equations were proposed and validated for their applicability14. Of these methods, the temperature-based equations, such as the Thornthwaite1, the Blaney-Criddle15, and the Hargreaves-Samani (1985a)16, 17, were extensively adopted because they mainly use easily-obtained temperature data. The radiation-based methods were also applied18. The pan evaporation methods were used when the observed pan data were available19–22. The physically-based combination methods

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explicitly incorporate physiological and aerodynamic parameters. The Penman-Monteith (PM) equation was selected as the standard ET₀ estimation method by the Food and Agriculture Organization (FAO) of the United Nations because it closely approximates ET₀ at the locations evaluated. Afterwards the FAO56-PM equation was world widely applied for the validation of the other equations in absence of experimental measurements.

In recent years, variations of FAO56-PM-based ET₀ (ET₀) has been extensively investigated since the FAO56-PM was recommended as a standard ET₀ estimation method. The ET₀ variations were also analyzed in partial or entire mainland China (EMC) concerning different application objectives. Meanwhile, the evaluation of the FAO56-PM method has also been widely conducted by comparing with different ET₀ estimation methods. The evaluation research mainly focused on answering which method could be an alternative for FAO56-PM either the input data were full, limited or missing. It is known that the FAO56-PM equation requires a large data input for estimating ET₀, including the geometrical variables such as elevation and latitude, and the meteorological variables such as minimum air temperature (T_min), average air temperature (T_avg), maximum temperature (T_max), wind speed, relative humidity (RH) and sunshine hour (h). The high data demand of the FAO56-PM method realized its overall high accuracy, but restricted its application in some data-lacking regions.

In the regions where the observed long-term meteorological data are difficult to obtain, the FAO56-PM method is not the best choice. To solve this problem, ET₀ estimation methods with a low data requirement and a simpler computation process are preferentially applied.

Although ET₀ and ETₚ are not equivalent terms, both provide estimates of atmospheric evaporative demand. In the previous studies, there are different understandings about the relationship between ET₀ and ETₚ. Several researchers differ the two items strictly. For instance, FAO56-PM ET₀ equation is considered a PM ETₚ equation for specific reference conditions. For strictly utilization of the items, Allen et al. strongly discourage the use of ET₀ for ETₚ estimation concerned about the ambiguities in their definitions. A few researchers consider ET₀ is a kind of ETₚ or it is reference values of ETₚ for a uniform grass reference surface. Noticeably, a lot of researchers look upon ET₀ and ETₚ as identical concepts and share similar equations for their estimations.

Usually, a climatologist or meteorologist and a hydrologist use the term “potential”, whereas an irrigation scientist uses the term “reference crop”, although the estimation equation could be same. Even some equation-proposers potentially identified the two items, such as Hargreaves and Samani adopted “potential” while Hargreaves and Samani used the term “reference crop”. Ambiguity between ET₀ and ETₚ was expected to be reduced by more extensive definition of ETₚ as potential crop evapotranspiration or by using one of the ET₀ definitions. Take Thorntwaite for another example, this method was originally proposed to estimate ET₀, but was also applied for estimating ETₚ in different cases. Therefore, although there are differences between ET₀ and ETₚ, there is close relationship between them and their estimations could be quantitively linked.

China has a total land area of 9,597,000 km² and is the third largest country in the world. It has a complicated geomorphology which contains different water bodies, glaciers, frozen soils, deserts, basins, mountains, farmland, and forests. The elevations are general lower and lower from the west to the east, shaping a so called “3-level-catena” landform. The weather stations in China distributed non-uniformly, there are more weather stations in the eastern China, but less in the western regions, especially less on Qinghai-Tibet Plateau. Neither is the distribution of the sites even, nor are the observed climatic elements same for different stations. The total sites available for air temperature and precipitation data are as large as 247,460, but when more climatic elements are needed, data from much less number of sites were available, estimated ET₀ values for 200 sites in China by Fan et al., while 552 sites are suitable for ET₀ analysis of this research. Not only in China, similar phenomena of difficulty in acquiring long-term and full weather data are also common in other developing countries because of some natural (geographical and climate) and humanity (economic power, knowledge and technology) reasons.

Under this condition, for the ET₀ estimation of China, to date to calibrate a suitable alternative equation which is simpler in computation process using less weather data and has a general good accuracy when compared to the FAO56-PM equation, are still very important for different sub-regions of China and EMC. Although performance of 16 different ET₀ equations were compared for Xiaotangshan, Changping, Beijing in North China Plain, a thorough and detail research for selecting a best alternative in EMC has not been conducted.

Based on the reasonable selection of 11 different ET₀ estimation methods for the calculation of monthly ET₀, this research aims to: (1) investigate the spatiotemporal variations and the trends of ET₀, using climatic data from the selected 552 sites in EMC; (2) compare the performance of the 10 selected ET₀ estimation methods with the standard FAO56-PM method in different sub-regions of China and EMC for the period 1961–2013; (3) select a best alternative of the FAO56-PM ET₀ equation, which would be simpler in ET₀ estimation and use less climatic variables; and (4) calibrate ET₀ using the alternative equation with the standard FAO56-PM equation.

**Data and Methodology**

**Data.** Geographical and weather data from 552 National Meteorological Observatory stations in EMC were collected from the China Meteorological Administration. The data contained both the daily and monthly timescales. The weather data included T_min, T_max, T_avg, U₁₀, wind speed at 10 m, RH, and h. The data duration was 1961–2013. The elevations of the selected sites covered a large range in EMC (Fig. 1a). To obtain more accurate ET₀ estimation, the 48 sites reported by Chen et al. were used as the radiation correction station. Meteorological station (marked with blue circle) and radiation calibration station (marked with red triangle) and they were set as the centers of the Thiessen polygons to find the other sites which would use same parameters with them for estimating radiation (Fig. 1b). The EMC is divided into seven sub-regions considering the differences in topography and climate (Fig. 1c). Including the temperate and warm-temperate desert of Northwest China (sub-region I, 61 sites), the temperate grassland of Inner Mongolia (sub-region II, 44 sites), the warm-temperate humid and sub-humid Northeast China (sub-region III, 72 sites), the warm-temperate humid and sub-humid North China (sub-region IV, 104 sites), the subtropical humid Central and South China (sub-region V, 165 sites), the Qinghai-Tibetan Plateau (sub-region VI, 49 sites), and the tropical humid South China (sub-region VII, 57 sites).
Estimation of \( ET_o \) using the FAO56-PM method. The FAO56-PM equation for estimating \( ET_o \) is written as bellow (Allen et al.)5:

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

(1)

where \( G \) is soil heat flux (MJ m\(^{-2}\) month\(^{-1}\)), \( T_m \) is mean air temperature at 2 m (°C), \( T_m = (T_{max} + T_{min})/2 \), and \( U_2 \) is wind speed at 2 m (m s\(^{-1}\)). \( e_s \) and \( e_a \) are saturation vapor pressure (kpa) and actual vapor pressure (kpa), \( e_s - e_a \) is saturation vapor pressure deficit (kpa), \( \Delta \) is slope of vapor pressure curve (kpa °C\(^{-1}\)), \( \gamma \) is psychrometric constant (kpa °C\(^{-1}\)), and \( R_n \) is net radiation (MJ m\(^{-2}\) month\(^{-1}\)). Monthly \( G \) is estimated by:

\[
G_K = 0.07(T_{K+1} - T_{K-1})
\]

(2)

where subscripts \( K + 1, K \) and \( K - 1 \) are order of month, respectively. Annual \( ET_o \) is cumulated from the values of 12 months.

\( R_n \) is calculated by:

\[
R_n = R_{ns} - R_{al}
\]

(3)

\[
R_{ns} = (1 - \alpha)R_s
\]

(4)

\[
R_s = a_s + b_s \left(\frac{N}{n}\right)R_a
\]

(5)

\[
R_{al} = \sigma \left(\frac{T_{max,k}^4 + T_{min,k}^4}{2}\right) \left(0.34 - 0.14\sqrt{\frac{T_m}{T_{max,k}}\left(1.35\frac{R_a}{R_{so}} - 0.35\right)}\right)
\]

(6)

where \( R_n \) is net shortwave radiation (MJ m\(^{-2}\) month\(^{-1}\)), \( R_{al} \) is net longwave radiation (MJ m\(^{-2}\) month\(^{-1}\)), \( n \) and \( N \) are actual and maximum possible sunshine duration, respectively, \( R_a \) is the extraterrestrial radiation (MJ m\(^{-2}\) month\(^{-1}\)), \( \sigma \) is the Stefan-Boltzmann constant (4.903 × 10\(^{-9}\) MJ K\(^{-4}\) m\(^{-2}\) d\(^{-1}\)), \( \alpha \) is albedo (\( \alpha = 0.23 \)), \( T_{max,k} \) and \( T_{min,k} \) are maximum and minimum absolute temperatures during 24-h, respectively, and \( R_{so} \) is clear sky solar radiation (MJ m\(^{-2}\) month\(^{-1}\)). The FAO56-PM recommended 0.25 for \( a_s \) and 0.50 for \( b_s \), respectively. For better accuracy, the calibrated values of \( a_s \) and \( b_s \) at 48 sites reported by Chen et al.\(^6\) were used here (marked with
red triangle) for determination of $a_i$ and $b_i$ values at nearby sites (marked with blue circle in Fig. 1b) using the Thiessen polygon method.

**Estimation of $ET_o$ using the other 10 selected methods.** A preliminary performance comparison of 16 $ET_o$ ($ET_a$) methods were conducted (Fig. S1). From the elementary results, $ET_o$ equations performed generally worse than $ET_a$ equations. Therefore, 10 $ET_o$ equations which performed generally well in different regions of the world, i.e., Irmak et al.55, Makkink56, Priestley-Taylor57, Hargreaves-Samani58, Droogers-Allen59, Berti et al.60, Doorenbos-Pruitt61, Wright62 and Valiantzas63, are selected to compare to the FAO56-PM equation. Of which, Valiantzas64 proposed two equations to simplify the FAO56-PM equation. The two Valiantzas equations and the Berti et al.60 equation were relatively new, but their performances have not been validated in China. Three Hargreaves-Samani-based equations (HS, MHS_1 and MHS_2) are adopted here because the FAO-56 manual recommended HS as the use of a less demanding method with only data on $T_{ave}$ and extraterrestrial radiation ($R_s$). The types, simplified method name, and main equations for estimating $ET_o$ of the selected 10 methods ($ET_{o,i}$) are given in Table 1. For the Droogers and Allen67 method (simplified as MHS_1), $S_o = 15.392d_i(\sin(\delta) \sin(\phi) + \cos(\phi) \cos(\delta) \sin(\omega))$ for the Berti et al.60 method (simplified as MHS_2), $P$ is precipitation. For the Valiantzas64 method (simplified as Val_1), $T_{ave} = [116.91 + 237.3 \ln(e_s)]/[16.78 - \ln(e_s)]$. For the Wright69 method (simplified as KPM), $a_o = 0.3 + 0.58 \exp[-(J - 170.7)/45]$, $b_o = 0.32 + 0.54 \exp[-(J - 228.6)/67]$, where $J$ is Julian day in the year between 1 (1 January) and 365 or 366 (31 December).

**Performance evaluation of the 10 selected methods.** Relative error ($RE$), standard deviation ($\theta$) and Nash-Sutcliffe efficacy coefficient ($NSE$)61 are used to assess the performances of monthly $ET_{o,i}$:

\[
RE = \frac{ET_{o,i} - ET_{o,d}}{ET_{o,d}}
\]

\[
\theta = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N - 1}}
\]

\[
NSE = 1 - \frac{\sum_{i=1}^{n} (ET_{o,i} - ET_{o,d})^2}{\sum_{i=1}^{n} (ET_{o,d} - ET_{o,d})^2}
\]

where $N = 1, 2, \ldots, 3636$ month. If $RE$ is close to 0, $ET_{o,i}$ is close to $ET_{o,d}$. The $NSE$ values ranged from $-\infty$ to 1. When $NSE$ is close to 1, the quality of the method for estimating $ET_{o,i}$ is good with high reliability. When $NSE$ is close to 0, $ET_{o,i}$ has an close mean value with $ET_{o,d}$, but the errors of the estimation processes are large; when $NSE$ is much less than 0, the estimation is not reliable.

**Trend test.** The modified nonparametric Mann-Kendall (MKK) test test, which takes into account the effects of auto-correlation in annual time series $ET_{o,i} (L = 1, 2, \ldots, n_t$, where $n_t = 53$ is total year number) based on the standardized Mann-Kendall (MK) method73,74, is used to test the trend of $ET_{o,i}$ if it is auto-correlated. The MK test statistic $(Z)$ follows the standard normal distribution with a mean of 0 and variance of 1 under the null hypothesis of no trend in $ET_{o,i}$. The null hypothesis is rejected if $|Z| > Z_{1.2}$ at a confidence level of $\beta$, where $Z_{1-\beta/2}$ is the $(1-\beta/2)$-quantile. If $Z$ is positive (or negative), $ET_{o,i}$ has an upward (or downward) trend. As $\beta = 0.05$, if $|Z| > 1.96$, the trend is significant. The MKM statistic $Z$ is computed by introducing a correction factor $n_1^2$ to $Z$ to estimate.
\[ Z^* = Z i \sqrt{n_1^2}, \]  
\[\begin{align*}
\text{where } n_1 &= 1 + \frac{2}{n_1} \sum_{j=1}^{n_1} (n_1 - 1) r_j \\
&\quad + \frac{1}{n_1} \sum_{j=1}^{n_1} (n_1 - 1)^2 
\end{align*}\]

where \( r_j \) is sample autocorrelation coefficient of \( ET_{o,L} \) at a lag \( jj \). For denoting significance of a trend, when \( jj = 0 \), \( Z^* \) equals to \( Z \); while as \( jj > 0 \), the MMK statistic \( Z^* \) is utilized.

**Variation coefficient.** The variability of series \( ET_{o,L} \) is quantified with a coefficient of variation (\( C_v \)), calculated with the following equation (Nielsen and Bouma)\(^7\):

\[ C_v = \frac{\theta}{ET_{o,L}} \quad \text{or} \quad C_v = \frac{\theta}{ET_{o,3}} \]  

where \( \theta \) and \( ET_{o,L} \) are standard deviation and multi-year mean \( ET_{o,L} \) series, respectively. Variability levels are classified by \( C_v \leq 0.1, 0.1 < C_v < 1.0 \) and \( C_v \geq 1.0 \) as weak, moderate or strong one, respectively.

Spatial distributions of the climatic variables, \( ET_{o,s}, ET_{o,i} \) and the other studied parameters are mapped by the Kriging interpolation method in ArcGIS 10.2 software.

**Results**

**Spatial distribution of climatic variables.** The spatial distribution of \( ET_o \) are closely related to that of the related meteorological elements. Figure 2 illustrates the distribution of multi-year mean \( T_{ave}, T_{min}, T_{max}, n, U_2 \) and \( RH \). The distribution of \( T_{min}, T_{max}, T_{ave} \) were generally similar, with high values in sub-regions V and VII but lower
values in sub-regions II, III and VI. Values of \( n \) were higher in sub-regions I, II, III and VI. \( U_2 \) values were large in north China especially in sub-regions II and III, and small in sub-region V, generally. Values of \( RH \) were higher in the southeast China for sub-regions V and VII. \( T_{ave}, T_{max}, n, U_2 \) and \( RH \) showed moderate variability, while \( T_{min} \) showed strong variability.

**Spatial distribution of \( ET_{oa,s} \) and its trend.** The equations and types of the FAO56-PM (for estimating \( ET_{oa,s} \)) and the other 10 methods (for estimating \( ET_{oa,i} \)) are shown in Table 1. Detail description of the equations is in the section “Data and methodology”.

Figure 3 shows the spatial distribution of multi-year mean monthly \( ET_{oa,s} \) and trend test results of annual \( ET_{oa,s} \) series for each site. The site number for different trends is presented in Table 2. In Fig. 3a, the \( ET_{oa,s} \) values were higher in the sub-regions I, II, VI and VII than the other 3 sub-regions, ranging from 49 to 108 mm. \( ET_{oa,s} \) had a moderate spatial variability with a coefficient of variation (Cv) being 0.15. In general, \( ET_{oa,s} \) in western China (high elevations) were larger than in eastern and middle China (low elevations). In Fig. 3b and Table 2, more sites (339) had decrease trends in \( ET_{oa,s} \) than increase trends (213 sites), and the trends at more sites were insignificant. The sites which had decrease and increase trends occupied 61.4% and 38.6% of the total, respectively. This indicated an overall decrease of \( ET_{oa,s} \) in China. The common occurrence of insignificance trends was induced by the removing of autocorrelation structures when using the modified nonparametric Mann-Kendall test (MKK) method. It's reasonable for the trend analysis. The sites with significant decrease (Sig. Dec) trends in \( ET_{oa,s} \) were mainly located in eastern China, while the sites with significant increase (Sig. Inc) trends in \( ET_{oa,s} \) were mainly located in middle China (i.e., sub-region VI).

**The Spatiotemporal variation of \( ET_{oa,i} \).** The spatial distribution of multi-year mean monthly \( ET_{oa,i} \) values during 1961–2013 showed remarkable differences between different sub-regions, their variation ranges and the spatial distributions of \( ET_{oa,i} \) also had different similarity with \( ET_{oa,s} \) (Fig. 4). All of the 10 methods had different ranges of \( ET_{oa,i} \), obtained lower \( ET_{oa,i} \) values in the northeastern China (sub-region III), and differed much in spatial distribution when compared with \( ET_{oa,s} \). The empirical method for estimating \( ET_{oa,i} \) only resembled \( ET_{oa,s} \) distribution in sub-region III very well, and its ranges were much smaller than \( ET_{oa,s} \) (radiation-based) distributed partly similar with \( ET_{oa,i} \). Among the temperature-based methods for estimating \( ET_{oa,i} \) (i.e., \( ET_{oa,4}, ET_{oa,5} \) and \( ET_{oa,6} \)), \( ET_{oa,6} \) resembled the spatial distribution and the value range of \( ET_{oa,s} \) more. The spatial distribution of \( ET_{oa,2} \) and \( ET_{oa,4} \) (combination type) were highly similar with that of \( ET_{oa,s}, ET_{oa,8} \) and \( ET_{oa,10} \) (simplified FAO56-PM) had high similarity in spatial distribution with \( ET_{oa,s} \), but with much smaller ranges than \( ET_{oa,s} \). \( ET_{oa,i} \) generally had moderate variability (Cv < 1.0), of which, \( C_o \) values of \( ET_{oa,i} \) and \( ET_{oa,10} \) were the first and the next largest, \( C_o \) values of \( ET_{oa,1} \) to \( ET_{oa,8} \) were small.
The temporal variations of multi-year mean monthly and annual \( ET_{o,i} \) in different sub-regions showed various similarity with that of \( ET_{o,s} \) (Figs 5 and 6). In Fig. 5, the variation patterns of monthly \( ET_{o,i} \) and \( ET_{o,s} \) were general with single peak (valley) around July (January or December), which were also the months that the largest (smallest) differences between \( ET_{o,i} \) and \( ET_{o,s} \) occurred. The differences between \( ET_{o,i} \) and \( ET_{o,s} \) curves was the largest for the sub-region I (northwestern China), and was the smallest for the sub-region VI (the Qinghai-Tibetan Plateau). The \( ET_{o,s} \) curves were generally in the upper of the 11 curves for different sub-regions. Of the ten curves, \( ET_{o,7} \), \( ET_{o,8} \), \( ET_{o,9} \) and \( ET_{o,10} \) deviated \( ET_{o,s} \) much and were not suitable for best alternative of \( ET_{o,s} \). \( ET_{o,7} \) estimated by the FAO24 method had the smallest differences in all of the 7 sub-regions and EMC, followed by \( ET_{o,8} \) estimated.
The other ET\textsubscript{o,\textit{i}} (i = 3, 4, 5, and 6) curves differed but had neither the largest nor the smallest deviations with ET\textsubscript{o,s} curves. ET\textsubscript{o,4} curves for sub-region I and ET\textsubscript{o,7} for sub-regions II to VII and EMC were closest to ET\textsubscript{o,s} curve. Except ET\textsubscript{o,7} which was a combination type estimated with a high data-requirement, ET\textsubscript{o,6} for sub-regions I, II, IV, VI and EMC were also very close to ET\textsubscript{o,s} curve. ET\textsubscript{o,6} was estimated by the modified Hargreaves-Samani (Berti et al.\textsuperscript{68}), which belonged to the temperature-based type, needed only temperature data, and was simple in computation. In general, both ET\textsubscript{o,i} and ET\textsubscript{o,s} curves were regional-, seasonal- and method-specific.

In Fig. 6, the annual variations of ET\textsubscript{o,i} or ET\textsubscript{o,s} generally had similar temporal variation patterns over 1961–2013 but their values differed a lot. For sub-region I, ET\textsubscript{o,i} curves ranked with a method order of MHS\textsubscript{1} > KPM > FAO56-PM > HS > FAO24 > MHS\textsubscript{2} > PT > Mak > Val\textsubscript{1} > IRA > Val\textsubscript{2} > i.e., ET\textsubscript{o,5} > ET\textsubscript{o,8} > ET\textsubscript{o,6} > ET\textsubscript{o,4} > ET\textsubscript{o,7} > ET\textsubscript{o,9} > ET\textsubscript{o,3} > ET\textsubscript{o,2} > ET\textsubscript{o,1} > ET\textsubscript{o,10} while the orders changed for the other sub-regions. Differences between annual ET\textsubscript{o,i} and ET\textsubscript{o,s} curves were generally large in sub-regions I and VII, but small in sub-regions III and VI. For sub-regions III, IV and EMC, annual ET\textsubscript{o,8} values were much close to ET\textsubscript{o,o}. For the other sub-regions, annual ET\textsubscript{o,7} was also similar to ET\textsubscript{o,o}. Annual ET\textsubscript{o,1} ET\textsubscript{o,2}, ET\textsubscript{o,9} and ET\textsubscript{o,10} values were much smaller at most sub-regions and EMC, which was similar to the results of monthly ET\textsubscript{o,1} ET\textsubscript{o,2}, ET\textsubscript{o,9} and ET\textsubscript{o,10}. Also, both annual ET\textsubscript{o,i} and ET\textsubscript{o,s} curves were regional-, seasonal- and method-specific.
Performance comparison of the selected 10 methods for estimating $ET_{o,i}$. Relative error. Because the estimated $ET_{o,i}$ values were regional-specific, the $RE$ values for $ET_{o,i}$ also showed differences in spatial distributions (Fig. 7). Ranges of $RE$ for $ET_{o,i}$ varied. The range of absolute $RE$ values for $ET_{o,9}$ was the largest, followed by $ET_{o,10}$. $RE$ for most of $ET_{o,i}$ covered both negative and positive values, but $RE$ range of $ET_{o,1}$, $ET_{o,9}$ and $ET_{o,10}$ covered only negative values. $ET_{o,7}$ had the smallest $RE$ range, which reflected that the FAO24 method was more accurate for estimating monthly $ET_{o}$ in EMC. The radiation-based Mak method had smaller $RE$ ranges when compared to the empirical, temperature-based methods and another radiation-based method PT, but it generally underestimated $ET_{o}$ in most of the months and sites and only had local adaptability in sub-region VI, therefore this method shouldn’t be the best alternative for $ET_{o,i}$ in different sub-regions and EMC. Considering the simpler temperature-based $ET_{o}$ type, the MHS_2 method had lower $RE$ than the other temperature-based methods. In general, the spatial distribution of $RE$ for different $ET_{o,i}$ differed at different locations. It revealed the differences in adaptability extents of the applied methods.

Generally consistent with the spatial distribution, the temporal variations of $RE$ for monthly $ET_{o,i}$ were also method and sub-region-specific (Fig. 8). The largest (smallest) $RE$ curves generally occurred for $ET_{o,9}$ ($ET_{o,7}$) in all of the 7 sub-regions and EMC. The largest negative $RE$ curves were $ET_{o,9}$, $ET_{o,8}$ and $ET_{o,10}$ in all of the 7 sub-regions and EMC, indicating worse performance of the methods IRA, Val_1 And Val_2. Although generally varied with the month, $RE$ values for $ET_{o,4}$, $ET_{o,6}$, $ET_{o,7}$, and $ET_{o,8}$ ranged between −0.2 to 0.2 in most time of the year for 3, 4,
7 and 7 sub-regions, respectively. The RE values were generally small for EMC when compared to any one of the sub-regions or the methods. In general, in the temperature-based methods, MHS_2 performed the best in most time of the year for most of the sub-regions.

The relative error (RE) values of the monthly and annual $ET_{o,i}$ using the selected 10 methods for EMC are presented in Table 3. Values of $ET_{o,1}$, $ET_{o,2}$, $ET_{o,9}$ and $ET_{o,10}$ underestimated $ET_{o,s}$ in all the 12 months and the whole year, of which, both monthly and annual $ET_{o,9}$ had the largest deviations, followed by $ET_{o,10}$. $ET_{o,8}$ underestimated $ET_{o,s}$ in 8 months (except June, July, August, September) and the whole year. $ET_{o,8}$ underestimated $ET_{o,s}$ in 6 months in January, February, March, April, November, December but slightly overestimated annual $ET_{o,s}$.

Figure 7. Spatial distribution of RE values for multi-year mean monthly $ET_{o,i}$ in EMC. (ArcGIS 10.2, http://map.baidu.com, Lingling Peng).
Moreover, the RE values were mostly month-free (i.e., overall larger or smaller than ET$_{o,s}$ in most months of the year) when comparing different estimation methods. However, ET$_{o,4}$, ET$_{o,5}$, ET$_{o,6}$, ET$_{o,7}$ and ET$_{o,8}$ overestimated ET$_{o,s}$ in 10, 8, 7, 7 and 6 months of the year, respectively, which resulted to overestimated annual ET$_{o}$. The RE values for annual ET$_{o,i}$ ranked in an order of ET$_{o,9}$ > ET$_{o,10}$ > ET$_{o,3}$ > ET$_{o,4}$ > ET$_{o,5}$ > ET$_{o,6}$ > ET$_{o,8}$ > ET$_{o,7}$, corresponding to the method order of Val$_1$ > Val$_2$ > IRA > Mak > HS > PT > MHS$_1$ > MHS$_2$ > KPM > FAO24. Each method overestimated or underestimated ET$_{o}$ in different months or the whole year when compared to FAO56-PM, but in the temperature type, the MHS$_2$ method was found to be the closest to FAO56-PM considering. Although the MHS$_2$ method underestimated the ET$_{o,s}$ by 24% in January, and 15% and 25% in November and December, but had a very low RE (2%) for the year when compared to the FAO56-PM method.

**Standard deviation.** The spatial distribution of multiyear mean monthly standard deviation ($\theta$) for ET$_{o,i}$ are illustrated in Fig. S2. All of the ten ET$_{o}$ estimation methods showed larger $\theta$ values in the northern China (sub-regions I, II and III), although with different ranges of $\theta$. There was a method order of ranges for $\theta$, i.e., IRA < Val$_1$ < Mak < PT < MHS$_2$ < HS < FAO24 < MHS$_1$ < Val$_2$ < KPM. In general, a larger ranges of ET$_{o,i}$ corresponded to a larger ranges of $\theta$, the IRA method had a smallest range of $\theta$ because it had a smaller range of ET$_{o}$. In fact, this method largely underestimated ET$_{o,i}$. The KPM method had a largest range of $\theta$, which indicated the variation

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**Figure 8.** The temporal variations of RE values for multi-year mean monthly ET$_{o,i}$ in different sub-regions and EMC.
the Val_2, Val_1, IRA, HS and Mak were excluded from the ten methods because their NSE values in each ET and 0.20, it performed well for most sub-regions except VI and VII. From climatic variable demand aspect, the ET method order of FAO24 for all of θ.

The spatial (temporal) distribution of multiyear mean monthly Nash-Sutcliffe efficiency coefficients (NSE) are illustrated in Figs S4 and S5. In Fig. S4, the ranges of NSE ranked in a method order of FAO24 < Mak < KPM < MHS_2 < PT < HS < MHS_1 < IRA < Val_2 < Val_1. The FAO24 and KPM, as analyzed above, were both combination based ET methods, although both had smaller NSE ranges, their equations had higher demand of climatic variables. The Mak method had a smaller range of NSE than MHS_2 (between −9.32 and 0.35), it performed better than MHS_2 in sub-regions IV and VI, but it needed addition shortwave radiation (or sunshine hour) when estimating ETo. The NSE of MHS_2 method ranged between −0.25 and 0.15 when θ in sub-region I, VI and VII, while the NSE of MHS_2 method ranged between 0.14 and 0.04 when θ in sub-region I, VI and VII. For EMC, the θ curves ranked in the method order of IRA < Val_1 < Val_2 < HS < Mak < PT < MHS_2 < FAO24 < KPM < MHS_1.

Table 3. Relative error (RE) values of the 10 selected methods for estimating ETo,i at the monthly and annual timescales for China.

| Month/Year | ETo,3 | ETo,4 | ETo,5 | ETo,6 | ETo,7 | ETo,8 | ETo,9 | ETo,10 |
|------------|-------|-------|-------|-------|-------|-------|-------|--------|
| Jan        | 0.84  | 2.15  | 0.93  | 2.46  | 3.23  | 2.17  | 1.69  | 1.49   | 0.79   | 1.07   | 2.19   |
| Feb        | 1.23  | 2.86  | 1.28  | 4.23  | 5.12  | 3.72  | 2.10  | 1.89   | 1.63   | 2.03   | 2.69   |
| Mar        | 1.32  | 3.55  | 2.59  | 4.68  | 6.13  | 4.13  | 3.28  | 3.05   | 2.54   | 2.84   | 3.94   |
| Apr        | 1.17  | 3.34  | 2.60  | 4.46  | 6.27  | 3.95  | 3.28  | 3.17   | 2.95   | 2.84   | 4.14   |
| May        | 1.13  | 3.26  | 2.99  | 3.91  | 6.99  | 3.49  | 4.06  | 4.48   | 2.80   | 3.57   | 4.94   |
| Jun        | 1.24  | 3.57  | 3.74  | 3.48  | 6.63  | 5.11  | 4.23  | 4.18   | 2.49   | 2.81   | 4.75   |
| Jul        | 1.53  | 4.16  | 4.75  | 3.16  | 6.40  | 2.82  | 4.52  | 5.50   | 2.40   | 2.50   | 4.65   |
| Aug        | 1.50  | 4.12  | 4.50  | 3.11  | 5.83  | 2.77  | 4.31  | 5.36   | 2.33   | 2.45   | 4.48   |
| Sep        | 0.98  | 2.78  | 2.46  | 2.85  | 5.18  | 2.54  | 2.70  | 3.37   | 2.11   | 1.74   | 3.04   |
| Oct        | 0.89  | 2.96  | 1.72  | 2.90  | 5.02  | 2.59  | 2.20  | 2.42   | 2.17   | 1.45   | 2.65   |
| Nov        | 0.98  | 2.57  | 1.12  | 2.82  | 4.06  | 2.50  | 1.80  | 1.75   | 1.50   | 1.44   | 2.42   |
| Dec        | 0.91  | 2.19  | 0.92  | 2.36  | 3.17  | 2.09  | 1.57  | 1.41   | 0.84   | 1.05   | 2.09   |
| Year       | 1.27  | 14.8  | 14.0  | 17.3  | 25.2  | 15.3  | 17.9  | 21.1   | 15.9   | 12.9   | 20.3   |

Table 4. Standard deviation values of ETo,i (i = 1 to 10) and ETo,10 at the monthly timescale.
0 months fell into the ranges of 0 and 1 for NSE values of \(ET_{o,1}\), \(ET_{o,2}\), \(ET_{o,3}\), \(ET_{o,4}\), \(ET_{o,5}\), \(ET_{o,6}\), \(ET_{o,7}\), \(ET_{o,8}\), \(ET_{o,9}\) and \(ET_{o,10}\) respectively. This indicated a better performance of the MHS_2 method estimated by Berti et al. in the non-combination type. For the whole year, only NSEs of the FAO24 and MHS_2 methods were larger than 0.68 in the

| Table 5. Nash-Sutcliffe efficiency coefficients of \(ET_{o,i}\) in different sub-regions and EMC. |

| Month/Year | \(ET_{o,1}\) | \(ET_{o,2}\) | \(ET_{o,3}\) | \(ET_{o,4}\) | \(ET_{o,5}\) | \(ET_{o,6}\) | \(ET_{o,7}\) | \(ET_{o,8}\) | \(ET_{o,9}\) | \(ET_{o,10}\) |
|------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Jan        | 4.39        | 9.27        | -7.18       | 0.10        | -0.93       | -2.87       | 0.76         | -0.62       | -96.0       | -55.7       |
| Feb        | -2.08       | -3.73       | -4.20       | -1.49       | -0.54       | 0.13         | 0.87         | -0.06       | -80.9       | -39.0       |
| Mar        | -10.2       | -4.50       | -2.78       | -6.47       | -3.40       | 0.44         | 0.93         | 0.21        | -92.2       | -35.4       |
| Apr        | -52.1       | -14.0       | -4.26       | -16.7       | -10.5       | -0.34        | 0.81         | 0.31        | -136.0      | -57.7       |
| May        | -88.5       | -20.9       | -0.73       | -23.0       | -10.3       | -1.12        | 0.83         | -0.09       | -146.0      | -84.8       |
| Jun        | -103        | -22.4       | 0.46        | -37.0       | -6.88       | -4.11        | 0.95         | -10.5       | -162.0      | -119.0      |
| Jul        | -113        | -21.4       | -4.76       | -33.5       | -0.26       | -2.03        | 0.80         | -16.3       | -207.0      | -164.0      |
| Aug        | -104        | -20.5       | -5.52       | -21.0       | 0.07        | 0.20         | 0.74         | -11.8       | -209.0      | -171.0      |
| Sep        | -124        | -35.9       | -0.81       | -16.9       | -2.49       | 0.66         | 0.86         | -10.1       | -280.0      | -222.0      |
| Oct        | -72.3       | -31.7       | -1.97       | -2.45       | -0.37       | -2.21        | 0.86         | -0.01       | -233.0      | -160.0      |
| Nov        | -25.0       | -19.2       | -6.60       | 0.21        | -1.10       | -5.08        | 0.71         | 0.44        | -151.0      | -94.8       |
| Dec        | -12.9       | -16.8       | -9.07       | -0.61       | -2.50       | -6.55        | 0.66         | -0.74       | -124.0      | -78.9       |
| Year       | -245        | -76.8       | -0.55       | -52.4       | -7.39       | 0.12         | 0.91         | -5.83       | -678.0      | -439.0      |

Scatter plots of monthly \(ET_{o,i}\) vs. \(ET_{o,s}\). Although the spatiotemporal distribution of multi-year mean \(ET_{o,i}\) were analyzed and the performances of all the methods were compared for each sub-region, direct comparison between monthly \(ET_{o,i}\) and \(ET_{o,s}\) are still necessary, in order that if the required full climatic data for estimating \(ET_{o,s}\) are lacking, an relatively accurate alternative method could be selected out from the 10 candidate methods using less weather data. The scatter plots of monthly \(ET_{o,i}\) with \(ET_{o,s}\) for different sub-regions and EMC are illustrated in Fig. 9. In general, \(ET_{o,i}\) deviated more with \(ET_{o,s}\) in July, but less for December and January. In all of 7 sub-regions and EMC, \(ET_{o,1}\), \(ET_{o,2}\), \(ET_{o,3}\) and \(ET_{o,10}\) were smaller but \(ET_{o,4}\) and \(ET_{o,5}\) were larger than \(ET_{o,s}\). \(ET_{o,5}\), \(ET_{o,6}\) and \(ET_{o,7}\) were not consistently larger or smaller than \(ET_{o,s}\) in different sub-regions. \(ET_{o,6}\) and \(ET_{o,7}\) were close to \(ET_{o,s}\) of which, data points of \(ET_{o,7}\) concentrated to the 1:1 lines the most. Of the 10 \(ET_{o,i}\), \(ET_{o,5}\) deviated the greatest from \(ET_{o,s}\), followed by \(ET_{o,10}\) which showed large scattered distances with the 1:1 lines. From visual comparison, \(ET_{o,2}\), \(ET_{o,3}\), \(ET_{o,4}\), \(ET_{o,5}\), \(ET_{o,6}\), \(ET_{o,7}\) and \(ET_{o,8}\) tended to concentrated to a striating in spite of their deviations from 1:1 line and had good linear correlations with \(ET_{o,s}\) in all 7 sub-regions and EMC.

By comprehensive comparisons using \(R^2\), standard deviations, NSE and scatter plots, although the two equations proposed by Valiantzas are relatively new, both had worse performance than the other methods in different sub-regions and EMC. The two combination type equations Doorenbos-Pruitt and Wright performed generally well, but had high weather data requirements. The equations proposed by Irmak et al. (2003), Makkink, Priestley-Taylor, Hargreaves-Samani and Droogers-Allen were all simple equations with less data requirements but didn’t perform very well. The Berti et al. (2008) equation (MHS_2) was a newly proposed temperature-based equation based on modified Hargreaves-Samani. The MHS_2 equation met the least data demand and had general best performance in either the empirical-based, radiation-based, temperature-based or the simplified FAO56-PM equations.

Validation of a best alternative equation for \(ET_{o,s}\). For most sub-regions and EMC, there were good linear correlations between monthly \(ET_{o,i}\) and \(ET_{o,s}\). The linear equation is written as:

\[
ET_{o,i} = aET_{o,s} + b \quad \text{or} \quad ET_{o,s} = \frac{ET_{o,i} - b}{a}
\]

where \(a\) and \(b\) are fitted coefficients.

Values of \(a\), \(b\) and coefficient of determination \((R^2)\) for various \(ET_{o,i}\) and 7 different sub-regions as well as EMC are given in Table 6. \(R^2\) values for \(ET_{o,i}\), \(ET_{o,2}\), \(ET_{o,3}\), \(ET_{o,4}\), \(ET_{o,5}\), \(ET_{o,6}\), \(ET_{o,7}\), \(ET_{o,8}\), \(ET_{o,9}\) and \(ET_{o,10}\) were larger than 0.85 for each sub-region and EMC. Of these, the estimation of \(ET_{o,i}\), \(ET_{o,2}\), \(ET_{o,3}\), \(ET_{o,4}\), \(ET_{o,5}\), \(ET_{o,6}\) and \(ET_{o,8}\) and \(ET_{o,10}\) utilized 5, 4, 5, 6, 6, 4 and 4 climatic variables among \(T_{min}, T_{max}, RH, U, n\) and \(P\), respectively; whereas \(ET_{o,8}\) and \(ET_{o,9}\) used only 3 (i.e., \(T_{min}, T_{ave}\) and \(T_{max}\)) with much simpler computation procedures.

Because temperature data are easier with less cost to observe, and \(ET_{o,s}\) estimated by the MHS_2 method was not only simpler, highly correlated with \(ET_{o,s}\) in each month and most sub-regions, but also had generally good similarity in spatiotemporal distribution with \(ET_{o,s}\). Considering both good performance and the correlation with
The MHS_2 method was generally good for substituting ETso. Therefore, ET6 was finally selected as the best alternative for estimating ETso in EMC. The calibrated \(a\) values were 0.93, 1.00, 1.19, 1.17, 1.15, 1.09, 0.93 and 1.12, and \(b\) values were -4.73, -11.1, -11.0, -12.2, 0.28, -16.2, 10.4 and -8.04 for sub-regions I, II, III, IV, V, VI, VII and EMC, respectively.

The best alternative MHS_2 could then be widely applied in China for ETo estimation when only temperature data are available. Because there were still deviations in the MHS_2 method, the linear equation correlated for ET6 and ETso using Equation 12 could be rewritten as follows:

![Figure 9. Comparisons of ETi and ETo in each month and sub-region.](image)
The fitted $a$, $b$ and $R^2$ values for correlating $ET_{a,i}$ with $ET_{o,s}$ in different sub-regions using Equation 12.

$$ET_{a,i} = A ET_{o,s} + B$$

where $A$ and $B$ are numerically equal to $1/a$ and $-b/a$, respectively. Equation 13 is also a calibration between $ET_{o,s}$ and $ET_{a,i}$.

For easier application of Eq. 13, values $A$ and $B$ for the 552 sites in China were validated. Figure 10 indicates the spatial distribution of $A$, $B$, and correlation coefficient ($R$). Values of $A$ decreased from 1.32 to 0.67 from northwest to southwest and eastern China. $B$ values were the largest in sub-region VI, followed by sub-regions II, III, IV, I, V, and VII, respectively. Values of $R$ ranged between 0.87 and 0.99, were larger than 0.95 in most of China, especially in north China. The general high $R$ values confirmed the applicability of the best alternative MHS-2 method in China after accurate calibration.

### Discussion

Under the global climate change, decreasing trends in $ET_r$ have been observed in different parts of the world$^{32,76,77}$, including China$^{78}$ and most parts of China, e.g., the Haihe River basin$^{79}$, the Huang-Huai-Hai Plain$^{80}$, the north-west China including Xinjiang Uywer Autonomos Region$^{81}$, southeast China, the Yangtze river basin$^{82}$, etc. The increasing trends were found at most sites of the Qinghai-Tibetan Plateau$^{83}$. The trends were also bi-directional in China. This study revealed that annual $ET_{a,i}$ for 61.4% of the study sites had decreasing trends, of them, 9% of the trends were significant. Our research agreed with the former research in the general decreasing trends of $ET_{a,i}$ in China. This study revealed that annual $ET_{a,i}$ decreased from 1.32 to 0.67 from northwest to southwest and eastern China. $B$ values were the largest in sub-region VI, followed by sub-regions II, III, IV, I, V, and VII, respectively. Values of $R$ ranged between 0.87 and 0.99, were larger than 0.95 in most of China, especially in north China. The general high $R$ values confirmed the applicability of the best alternative MHS-2 method in China after accurate calibration.

### Table 6

| Sub-region/ Parameter | $ET_{o,1}$ | $ET_{o,2}$ | $ET_{o,3}$ | $ET_{o,4}$ | $ET_{o,5}$ | $ET_{o,6}$ | $ET_{o,7}$ | $ET_{o,8}$ | $ET_{o,9}$ | $ET_{o,10}$ |
|-----------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| I                     | a 0.49     | 0.71       | 0.87       | 1.06       | 1.17       | 0.93       | 1.15       | 1.09       | 1.26       | 0.89       |
| b 10.5 4.18           | -6.56      | -5.35      | -7.32      | -4.73      | -1.07      | -9.02      | -12.2      | -8.19      | -12.2      |
| $R^2$ 0.97            | 0.99       | 0.99       | 0.99       | 0.98       | 0.99       | 0.98       | 0.98       | 0.98       | 0.98       |
| II                    | a 0.47     | 0.78       | 0.97       | 1.14       | 1.19       | 1.00       | 1.16       | 1.04       | 1.19       | 0.96       |
| b 6.33 -0.57          | -10.9      | -12.7      | -13.6      | -11.1      | -1.50      | -8.46      | -13.8      | -10.7      |
| $R^2$ 0.96            | 0.98       | 0.98       | 0.99       | 0.98       | 0.99       | 0.98       | 0.98       | 0.98       | 0.98       |
| III                   | a 0.58     | 0.85       | 1.08       | 1.36       | 1.31       | 1.19       | 1.02       | 1.16       | 0.54       | 0.62       |
| b 4.31 -2.87          | -9.79      | -12.6      | -11.7      | -11.0      | -1.91      | -5.81      | -9.72      | -7.47      |
| $R^2$ 0.96            | 0.98       | 0.98       | 0.98       | 0.98       | 0.99       | 0.98       | 0.96       | 0.95       |
| IV                    | a 0.53     | 0.83       | 1.13       | 1.34       | 1.26       | 1.17       | 1.02       | 1.19       | 0.62       | 0.60       |
| b 8.32 -2.81          | -16.0      | -13.9      | -11.6      | -12.2      | -2.84      | -11.4      | -14.8      | -4.06      |
| $R^2$ 0.95            | 0.98       | 0.98       | 0.96       | 0.97       | 0.98       | 0.99       | 0.98       | 0.95       |
| V                     | a 0.51     | 0.86       | 1.23       | 1.32       | 0.98       | 1.15       | 1.03       | 1.20       | 0.51       | 0.46       |
| b 16.1 -4.51          | -10.5      | 0.37       | 8.55       | 0.28       | -0.50      | -1.95      | -2.88      | 4.37       |
| $R^2$ 0.97            | 0.98       | 0.99       | 0.93       | 0.90       | 0.93       | 0.99       | 0.99       | 0.95       |
| VI                    | a 0.54     | 0.90       | 1.25       | 1.24       | 1.23       | 1.09       | 1.07       | 1.23       | 0.53       | 0.71       |
| b 7.00 -2.32          | -15.0      | -18.6      | -15.3      | -16.2      | -2.44      | -11.2      | -18.3      | -10.8      |
| $R^2$ 0.98            | 0.99       | 0.98       | 0.98       | 0.99       | 0.98       | 0.99       | 0.99       | 0.95       |
| VII                   | a 0.50     | 0.88       | 1.34       | 1.08       | 0.59       | 0.93       | 1.06       | 1.27       | 0.37       | 0.38       |
| b 16.3 -6.65          | -22.3      | 11.7       | 45.2       | 10.4       | -3.68      | -18.9      | 7.49       | 10.4       |
| $R^2$ 0.94            | 0.97       | 0.97       | 0.85       | 0.31       | 0.85       | 0.99       | 0.98       | 0.89       |
| EMZ                   | a 0.52     | 0.83       | 1.13       | 1.28       | 1.12       | 1.12       | 1.02       | 1.20       | 0.55       | 0.58       |
| b 10.2 -2.02          | -11.7      | -9.17      | -4.26      | -8.04      | -1.50      | -10.5      | -9.81      | -3.69      |
| $R^2$ 0.98            | 0.99       | 0.98       | 0.98       | 0.99       | 0.99       | 0.98       | 0.98       | 0.96       |
the MHS_2 method as the best alternative of ET_o,s for different sub-regions and EMC, which were very useful for researchers to apply the calibrated MHS_2 method in China.

The MHS_2 method overestimated ET_o in the sub-regions V and VII in the high temperature section of EMC (Fig. 7f). RE reached 20% especially in March, April, May and June (Figs 8e,g and 9). Both sub-regions are humid and sub-humid climatic zones of EMC. This reflected the disadvantages of MHS_2 which only applied temperature data for estimating ET_o. When temperature is high, ET_o,6 obtained with the MHS_2 method could be high but ET_o,s may not be as high as it considering also wind speed, relative humidity and sunshine hour. Under the overestimation conditions, the relationship between ET_o,6 and ET_o,s should be re-calibrated for March, April, May and June. The re-calibrated parameters A, B and R^2 in March, April, May and June for the two sub-regions are presented in Table 7.

Conclusions

Based on monthly climatic data collected from 552 stations during 1961–2013 across different sub-regions of China, a comprehensive comparison between ET_o,i (estimated by the IRA, Mak, PT, HS, MHS_1, MHS_2, FAO24, KPM, Val_1 and Val_2 methods) and ET_o,s estimated by the FAO56- PM method has been conducted in 7 sub-regions and EMC. 339 and 213 sites had decrease and increase trends in annual ET_o,s, indicating a general decrease trend in annual ET_o,s. For the spatial distribution, values of multi-year mean monthly ET_o,s in western China (high elevations) were larger than in eastern China (low elevations). The step by step comparison of spatiotemporal distribution, RE, standard deviations, NSE and scatter plots between ET_o,i and ET_o,s either for monthly and annual timescales or different sub-regions and ECM consistently showed the general high accuracy of ET_o,6 estimated by the MHS_2 method proposed by Berti et al. The MHS_2 method utilized only temperature data, was simple in computation procedure when compared to the other 9 ET_o estimation methods, and was highly correlated with ET_o,s. It was a best alternative for ET_o,s when climatic data were lacking. After accurate validation for the MHS_2 method using equation 13, the calibrated parameters of A and B for each site, sub-region and EMC were obtained. This research is an important contribution to ET_o estimation method in China when the high requirements of climatic data could not be met.
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Author Contributions
Peng L.L. did the calculation, analyzed the data and wrote the paper; Li Y. designed the research and revised the paper; Feng H. revised the paper.

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