



# Article Spatial and Temporal Variations of Potential Evapotranspiration in the Loess Plateau of China During 1960–2017

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**Abstract:** Potential evapotranspiration  $(ET_0)$  is an integral component of the hydrological cycle and the global energy balance, and its long-term variation is of much concern in climate change studies. The Loess Plateau is an important area of agricultural civilization and water resources research. This study analyzed the spatial and temporal evolution processes and influential parameters of  $ET_0$  at 70 stations in different topographical areas of the Chinese Loess Plateau (CLP). Using the Mann–Kendall trend, Cross wavelet transform, and the ArcGIS platform, the  $ET_0$  of each station was quantified using the Penman–Monteith equation, and the effects of climatic factors on  $ET_0$ were assessed by analyzing the correlation coefficients and contribution rates of the climatic factors. The results showed that: (1) the overall trend of the  $ET_0$  in different terrains of the Loess Plateau is consistent, however, the  $ET_0$  values differ; the hill region (HR) has the highest  $ET_0$ , followed by the valley region (VR), and the mountain region (MR) has the lowest, and  $ET_0$  changes differ between seasons. (2) Spatial distribution characteristics of multiyear mean ET<sub>0</sub> in the study are as follows: the ET<sub>0</sub> values in mountain and hilly areas are decreasing from west to east, and the higher mean annual  $ET_0$  value in the VR is mainly concentrated in the eastern CLP. (3) In the past 58 years, the annual mean and the seasonal  $ET_0$  of the region showed increasing trends, however, differences in different terrains were obvious. (4) ET<sub>0</sub> has significant correlations with El Niño–Southern Oscillation (ENSO), Pacific–North American teleconnection (PNA), and Atlantic Multidecadal Oscillation (AMO). The resonance period of  $ET_0$  and ENSO was 3–6 a, mainly in 1976–1985. The mean coherence phase angle was close to  $360^{\circ}$ , indicating that ET<sub>0</sub> lags behind PNA by approximately 2–6 a; ET<sub>0</sub> has a very strong positive correlation with AMO. (5) Relative humidity (RH) is the main influencing factor of  $ET_0$  change in the Loess Plateau. Temperature (T) variation has the highest contribution rate (42%) to the regional  $ET_0$  variation in the entire CLP. We should pay more attention to the variation of evaporation under future climate change, especially temperature change.

**Keywords:** potential evapotranspiration; Penman–Monteith model; temporal–spatial distribution; controlling parameters; Loess Plateau

# 1. Introduction

Potential evapotranspiration ( $ET_0$ ) is an important parameter of hydrological processes and is closely related to regional precipitation and energy spatial distribution [1,2]. With the changing global climate, rising temperatures will further result in increasing rates of water circulation which further change regional climate patterns [3–5]. The global temperature has a significant increasing trend over the past decade. Rising temperature has proven to have a remarkable influence on the regional  $ET_0$  variation, which caused the frequency of global heat waves and agricultural drought to increase, and the chance of a damaging hot spell for food production also increased significantly [6,7]. Besides, disordered human activities had a serious impact on regional evapotranspiration variation and further reduced plant cover and agricultural production [8,9]. Assessment of regional  $ET_0$  is not only essential for understanding the energy balance in the earth–atmospheric system but also has a key role in understanding hydrological processes and climate change. Previous research has provided numerous useful methods to evaluate the variation of the regional  $ET_0$ , including the Penman–Monteith (PM) method [10], the Hargreaves method [11], the Priestley–Taylor method [12], and other empirical methods [13]. Due to the accessibility of input data and wide applicability, the PM method is recommended by the Food and Agriculture Organization (FAO) and is widely used for assessing spatial–temporal  $ET_0$  variations during various climate scenarios and the response to variations in environmental factors [14,15].

Several researchers [16–18] have reported on case studies of regional  $\text{ET}_0$  variations throughout the world. For example, the regional  $\text{ET}_0$  of eastern Europe has been proven to have had a significant increasing trend during 1961–2012 [19]. In Australia, obvious variability can be observed in the regional  $\text{ET}_0$  during 1995–2004, during which time the regional  $\text{ET}_0$  ranged from 699 mm to 2634 mm [20]. Similar research has been carried out in various regions [21,22]. These studies indicated that the regional  $\text{ET}_0$  has had significant changes over recent decades. Besides, an increasing number of studies have indicated close relationships between the variations of regional  $\text{ET}_0$  and environmental factors (e.g., meteorological parameters, circulation parameters, and terrain parameters) [23–25]. According to previous reports, meteorological parameters have been considered as important controlling factors. Based on an investigation of 500 Chinese meteorological stations between 1956 and 2000, Gao et al. [26] highlighted the importance of temperature, sunshine duration, wind speed, and relative humidity on the evapotranspiration. Liu et al. [23] indicated that wind speed variation is the main controlling factor for  $\text{ET}_0$  variations in Gansu. In the Hengduan Mountains, research has found that the  $\text{ET}_0$  variation was related to variations in regional temperature, wind speed, and sunshine duration [24].

Nowadays, an increasing amount of research has indicated that circulation parameters are related to variations in regional climate patterns [25,27,28]. Gong et al. [29] found that regional temperature fluctuation is significantly associated with variation of the North Atlantic Oscillation (NAO), the North Pacific Oscillation (NPO), and the Southern Oscillation (SO). Li et al. [30] reported that the Arctic Oscillation (AO) has a remarkable influence on the precipitation structure in some typical catchments, and results in regional  $ET_0$  variations. Besides, some studies pointed out that the regional  $ET_0$  of China, with different topographic conditions, usually appeared with obvious spatial variability. For example, Yao et al. [31] found that the  $ET_0$  in the arid and subtropical regions of northwest China is higher, while the values of the  $ET_0$  in the northeast and the Qinghai–Tibet Plateau are relatively low. Li et al. [30] concluded that the areas with higher  $ET_0$  values are mainly in the Tibetan Plateau, Hengduan Mountains, and Yunnan Plateau, whereas the  $ET_0$  values in the Guizhou Plateau and Sichuan Basin are lower (a significant evaporation paradox [28] can be observed).

In China, temporal and spatial variations of regional  $ET_0$  of some typical regions were also systematically evaluated. For example, Wang et al. [32] calculated  $ET_0$  values and estimated the temporal and spatial variation of the Hexi region in northwestern China. Zhou et al. [33] analyzed the variation of  $ET_0$  in southwestern China and found that the  $ET_0$  values during recent decades showed a significant increasing trend. These studies provide important information for assessing the influence of regional climate change and understanding regional hydrological processes. However, few studies have focused on evaluating  $ET_0$  variations in the Chinese Loess Plateau (CLP). Some studies focus on the  $ET_0$  under different geomorphic types and the relationships with the main controlling factors remain unclear. The CLP is an important geomorphic region in Asia, and the thick, sedimentary loess is a useful material for reconstruction of paleoclimate and studying climate change. As an important place of origin of world agricultural civilization, the fragile ecological environment in the CLP is very sensitive to climate change. Therefore, it is necessary to improve our understanding of the temporal and spatial characteristics of regional  $ET_0$  in the CLP. In this study, data from 70 weather stations with three topography types in the CLP during 1960–2017 were used to analyze spatial and temporal  $ET_0$  variations. The main objectives of this study were to: (1) analyze the temporal and spatial variation characteristics of regional  $ET_0$  with different topographies in the CLP; (2) determine the main controlling factors of the variations of regional  $ET_0$  with different topographies in the CLP; and (3) determine the relationship between regional  $ET_0$  of the CLP and larger-scale circulation parameters. The results of this study will be of great significance to improve our understanding of regional hydrological processes and regional water resource management.

# 2. Methods

# 2.1. Study Area

In the current study, the CLP was defined as the area between  $33^{\circ}43'-41^{\circ}16'$  N and  $100^{\circ}54'-114^{\circ}33'$ E [36] and has three geomorphic units: the mountain region (MR, including Qin Ling Mountains in the southern CLP, Wu Shao Ling Mountains in the western CLP, and Taihang Mountains and Luliang Mountains in the eastern CLP), the valley region (VR, including Hetao Basin in the northern CLP, Weihe Basin in the southern CLP, Yinchuan Basin in the western CLP, and Fenhe Basin in the eastern CLP), and the hill region (HR, mainly concentrated in the inner part of the CLP) (Figure 1). The area is approximately  $64 \times 10^4 \text{ km}^2$ , which is approximately 6.67% of the total area of China. The terrain of the CLP is high in the southwest region and low in the southeast. Based on long-term observation data from 70 national meteorological observatory stations in and around the CLP, we found the mean annual temperatures ranging from 3.6 to 14.3 °C and annual precipitation ranging from 150 to 750 mm. The soil type is mainly brown soil and cinnamon soil. Vegetation types are diverse and are mainly grassland, woodland (the categories of trees in the CLP mainly include Chinese catalpa, cypress, and Chinese prickly ash), and arable land [37]. The CLP has a long history of agricultural cultivation and its main types of crop producation are wheat and millet [38].



**Figure 1.** Topography and meteorological stations distribution map of the Loess Plateau; (**a**) meteorogical stations location information, (**b**) topography information, (**c**) soil map.

# 2.2. Data

This study used continuous daily series data from 1960 to 2017 at 70 national meteorological observatory stations in and around the CLP (Table 1). Data included wind speed (WS) (m/s), sunshine duration (SD) (h), daily mean temperature (T) (°C), daily maximum temperature (Tmax) (°C), daily minimum temperature (Tmin) (°C), and relative humidity (RH) (%). Data were provided by the China Meteorological Administration (http://data.cma.cn/site/index.html). Large-scale circulation parameters data were downloaded from the National Oceanic and Atmospheric Administration (http://www.esrl.noaa.gov/psd/data/climateindices). Four seasons were divided in this study as: spring (March to May), summer (June to August), autumn (September to November), and winter (December to February).

Table 1. Basic information of meteorological stations used in this study.

Study Areas	Altitude (m)	T (°C)	RH (%)	SD	WS (m/s)	ET <sub>0</sub> (mm)
CLP	1224	8.76	58	7.12	2.99	1074.06
MR region	1970	5.88	61	6.98	2.67	936.86
VR region	891	9.99	58	7.04	2.16	1085.92
HR region	1098	9.33	56	7.32	2.46	1069.19

# 2.3. Methods

### 2.3.1. ET<sub>0</sub> Calculation Method

In this study, the FAO Penman–Monteith method [13] was used to estimate  $ET_0$  variations. The FAO–PM equation to calculate  $ET_0$  (mm.day<sup>-1</sup>) is given as:

$$\mathrm{ET}_{0} = \frac{0.408\Delta(R_{n} - G) + \gamma \frac{900}{T + 273}u_{2}(e_{s} - e_{a})}{\Delta + \gamma(1 + 0.34u_{2})} \tag{1}$$

where  $\text{ET}_0$  is the daily potential evapotranspiration rate,  $\text{mm}\cdot\text{d}^{-1}$ ;  $\Delta$  is the slope of the saturation vapor pressure curve,  $\text{K}P_a\cdot^{\circ}\text{C}^{-1}$ ; Rn is the net radiation,  $\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ; *G* is the soil heat flux density,  $\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ;  $\gamma$  is the psychometric constant,  $\text{K}P_a\cdot^{\circ}\text{C}^{-1}$ ;  $u_2$  is the wind speed at the height of 2 m,  $\text{m}\cdot\text{s}^{-1}$ ; *T* is the temperature at the height of 2 m,  $^{\circ}\text{C}$ ;  $e_s$  is the saturated water vapor pressure;  $e_a$  is the actual water vapor pressure, and  $(e_s - e_a)$  is the saturated water vapor pressure differential value,  $\text{K}P_a$ .

#### 2.3.2. Mann-Kendall Trend Test

The Mann–Kendall (MK) test was used to detect regional  $ET_0$  trends and hydrological imbalances [39,40]. For a given data series, the statistical value S and the standardized test statistics  $Z_{MK}$  were calculated as follows [41]:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(X_j - X_i)$$
(2)

$$\operatorname{sgn}(X_j - X_i) = \begin{cases} +1 & if(X_j - X_i) > 0\\ 0 & if(X_j - X_i) = 0\\ -1 & if(X_j - X_i) < 0 \end{cases}$$
(3)

$$\operatorname{Var}(S) = \frac{1}{18} \left[ n(n-1)(2n+5) - \sum_{p=1}^{q} t_p (t_p - 1)(2t_p + 5) \right]$$
(4)

and

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if \ S > 0\\ 0 & if \ S = 0\\ \frac{S-1}{\sqrt{Var(S)}} & if \ S < 0 \end{cases}$$
(5)

where  $X_i$  and  $X_j$  are the values of the year i and j of the time series, n is the length of the time series data,  $t_p$  is the binding value corresponding to the pth number, and  $Z_{MK}$  is the variation trend of the time series data. If  $Z_{MK} > 0$ , the time series data have an increasing trend over time; if the contrary, the data have a decreasing trend. If  $|Z_{MK}| > Z_{(1-a/2)}$ , then the null hypothesis that there is a significant trend in the time series data was rejected. The  $Z_{(1-a/2)}$  values can be found in the standard normal distribution chart. When taking a = 5% as the significance level, the corresponding value of  $Z_{(1-a/2)}$  is 1.96; when taking a = 1% as the significance level, the corresponding value of  $Z_{(1-a/2)}$  is 2.58.

# 2.3.3. Wavelet Transform Coherence and Contribution Rate Analysis

Wavelet transform coherence is a new signal analysis technology combining wavelet transform and cross-spectrum analysis. It can study the correlation between two time series in the time–frequency domain from multiple time scales [42]. Wavelet transform coherence was introduced by Hudgins et al. [43] among others. In hydrology, it has been used in rainfall–runoff cross-analysis [44].

$$R_n^2(s) = \frac{\left|S\left(s^{-1}W_n^{XY}(s)\right)\right|^2}{S\left(s^{-1}\left|W_n^X(s)\right|^2\right) \cdot S\left(s^{-1}\left|W_n^Y(s)\right|^2\right)}$$
(6)

$$S_{time}(w)\Big|_{x} = W_{n}(s) \times c_{1}^{\frac{-t^{2}}{2s^{2}}}\Big|_{s}$$

$$\tag{7}$$

$$S_{time}(w)\big|_{x} = \left(W_{n}(s) \times c_{2} \prod(0.6s)\right)\big|_{n}$$
(8)

Here,  $|W_n^{XY}(s)|$  indicates the cross wavelet power spectrum, S is the smoothing function,  $c_1$ ,  $c_2$  are the normalized constants, and  $\prod (0.6s)$  indicates a rectangular function. In the formula, Y is the standardized value of the ET<sub>0</sub>,  $X_1$ ,  $X_2 \cdots X_n$  are standardized values of the meteorological parameters,  $a_1$ ,  $a_2 \cdots a_n$  are regression coefficients after sequence normalization,  $g_1$  is the relative contribution rate of  $X_n$  variation to Y variation.

$$Y = a_1 X_1 + a_2 X_2 + a_3 X_3 + \dots + a_n X_n \tag{9}$$

$$g_1 = \frac{|a_1|}{|a_1| + |a_2| + |a_3| + \dots + |a_n|}$$
(10)

#### 3. Results

# 3.1. Changes in the Annual and Seasonal ET<sub>0</sub> of Different Topographic Regions

Figure 2 shows the seasonal and annual mean  $ET_0$  over the entire CLP and the three topographic regions from 1960 to 2017. The annual mean  $ET_0$  was 1074 mm during 1960–2017 in the CLP, and the maximum and minimum values were 1181 mm and 987 mm, respectively. Comparing the  $ET_0$  values of the three topographic regions (MR, HR, and VR), the mean annual  $ET_0$  value of the HR (1078 mm) was larger than that of the MR (933 mm) and the VR (1021 mm). Over recent decades, the mean annual  $ET_0$  value of the CLP displayed an upward trend of 7.7 mm/10a. There was a decreasing trend during the 1960s and 1970s. During this period, the  $ET_0$  value exhibited a decreasing trend of fluctuations from the 1960s (1074 mm) to the 1970s (1052 mm), and then, a relatively stable trend of regional  $ET_0$ 

variation occurred in the period of the 1970s to the 1990s. A step increase was observed in 1997. During 2005–2017, the annual  $ET_0$  of the CLP showed a decreasing trend.



**Figure 2.** Annual and seasonal variation of ET<sub>0</sub> during 1960–2017 in the Loess Plateau (mm); (a) annual (a1 CLP; a2 MR; a3 VR; a4 HR); (b) spring (b1 CLP; b2 MR; b3 VR; b4 HR); (c) summer (c1 CLP; c2 MR; c3 VR; c4 HR); (d) autumn (d1 CLP; d2 MR; d3 VR; d4 HR); (e) winter (e1 CLP; e2 MR; e3 VR; e4 HR).

During the study period, the mean  $\text{ET}_0$  values in spring, summer, autumn, and winter were 250, 445, 247, and 97mm, respectively. Comparing the four seasons, the mean  $\text{ET}_0$  value for summer during 1960–2017 was higher than that for winter. A larger temporal variation can be observed in the mean  $\text{ET}_0$  values for the spring and autumn. For spring (Figure 2b), the  $\text{ET}_0$  exhibited a relatively consistent value from 1960 to 1990, after which time a remarkable increase can be seen since the 1990s. A similar variation appeared in the mean  $\text{ET}_0$  for the summer and autumn. A slightly decreasing trend was displayed in the mean  $\text{ET}_0$  values for the summer and autumn during the period of the 1960s to the mid-1980s. From the mid-1980s, the mean  $\text{ET}_0$  for the summer and autumn showed increasing trends. The temporal variation of the mean  $\text{ET}_0$  in winter showed a similar trend to that in the spring. Regarding the three topographic regions (MR, HR, and VR), the mean  $\text{ET}_0$  values for the three regions exhibited similar temporal variations in all seasons except for the summer. In summer, the mean  $\text{ET}_0$  of the MR showed a slightly increasing trend (Figure 2c).

# 3.2. Spatial Distribution of Et<sub>0</sub> in Different Terrain Regions and Seasons

Figure 3 shows the spatial patterns of the seasonal and annual  $ET_0$  values mean from 1960 to 2017. During 1960–2017, the annual mean  $ET_0$  of the CLP was 1044 mm, ranging from 495 to 1467 mm.

The highest value of  $ET_0$  was at the Xiangning station (1467 mm), and the lowest value was at the Wutaishan station (495 mm). The  $ET_0$  values in the southern and eastern areas of the CLP were always higher than those in the western part of the CLP (Figure 3), which may be related to the different spatial distributions of the climatic conditions (e.g., T, WS, RH, and SD) and the complicated topography in the CLP. In spring, the maximum mean  $ET_0$  value occurred at the Xiangning station (388 mm) and the minimum mean  $ET_0$  value was observed at the Wutaishan station (100 mm). The mean ET0 values of the VR were higher than those of the MR and HR. In summer, the Xiangning station (578 mm) displayed the maximum average  $ET_0$  value, and the Wutaishan station (219 mm) displayed the minimum average  $ET_0$  value. The average  $ET_0$  values of the VR were higher than those of the HR and MR. As for the autumn, there was a minimum average  $ET_0$  value observed at the Wutaishan station (133 mm), and a maximum average  $ET_0$  value occurred at the Xiangning station (347 mm). In winter, the Xiangning station (155 mm), located in the southeastern part of the Loess Plateau, displayed the maximum average  $ET_0$  value, and a minimum average  $ET_0$  value occurred at the Wutaishan station (44 mm). The average  $ET_0$  values of the MR were lower than those of the HR and VR.



Figure 3. Spatial distribution of variation for annual and seasonal ET<sub>0</sub> during 1960–2017.

In addition, the  $ET_0$  of the VR had higher values throughout the entire year, especially in spring and summer. The VR region is an important food-growing area for the CLP, and the higher  $ET_0$  values in summer and autumn may result in the regional water shortages being more serious. Therefore, water management should pay more attention to the higher  $ET_0$  values of the VR during the spring and summer.

# 3.3. Spatial Variation of the Trends of Annual and Seasonal Et<sub>0</sub> Series—MK Tests

Nonparametric Mann–Kendall tests were performed for 70 meteorological stations to analyze trends of annual and seasonal  $ET_0$  series in the CLP during 1960–2017 at the 5% significance level (Figure 4). The annual mean  $ET_0$  series of the majority of stations displayed an increasing trend during 1960–2017. Approximately 93% of stations exhibited a statistically significant increasing trend in the annual mean  $ET_0$  series. The annual  $ET_0$  of the HR regions had a stronger significant increasing trend appeared than that of the VR and MR regions. In the HR region, the most significant increasing trend appeared at the Wuzhong station (6.47 mm/a), and the slightly increasing trend of the annual mean  $ET_0$  was observed at the Xintai (1.91 mm/a) and Tongxin (1.61 mm/a) stations. In the VR region, the most significant increasing trend of the Mengjin station (1.46 mm/a) was not obvious. In the MR region, the annual mean  $ET_0$  series had overall significant increasing trends, except for Wushaoling station. However, the increase trend of the Wushaoling station (0.13 mm/a) was not obvious.



Figure 4. Spatial distribution of variation trends for annual and seasonal ET<sub>0</sub> during 1960–2017.

In spring, the majority of stations showed statistically significant increasing trends, with the largest increase at the Xiangning station (6.57 mm/a), and regional magnitudes declined from the VR regions to the MR regions. In summer, 59 stations showed increasing trends, while decreasing trends occurred in the majority of stations in the MR and HR. In autumn, more than 90% of the total stations showed an increasing trend during 1960–2017, and only six stations (WuQiaoLing, SanMenXia, MengJin, XiangNing, YongJi, YuLin) had statistically significant decreases. In winter, the ET<sub>0</sub> exhibited increasing trends at 69 stations, mostly in the MR and HR regions. A decreasing trend was observed at Hequ station, which was located on the eastern edge of the Loess Plateau.

Overall, on a temporal scale, an increasing trend existed in the CLP throughout almost the entire year, especially in spring. On a spatial scale, the seasonal  $ET_0$  in the majority of the CLP exhibited increasing trends, and decreasing trends mainly occurred in the HR and VR regions.

# 3.4. Wavelet Transform Coherence of Et<sub>0</sub> and the Large-Scale Circulation Patterns

Figure 5 shows the wavelet transform coherence (WTC) results for the ET<sub>0</sub> and the large-scale circulation patterns (for example, NAO, Atlantic Multidecadal Oscillation (AMO), Pacific-North American teleconnection (PNA), etc.). For ET0 (Figure 5a), the WTC with NAO had very good negative correlations in the periods of 1980–2000 and 2003–2009, which indicated it to have large interannual covariance at scales of 12–16 and 3–5 a, respectively. In the resonance period of 3–5 a, its coherence phase angle was 160°, and its coherence phase angle was 210° in the resonance period of 12–16 a. The resonance period of  $ET_0$  and AO in the high-energy region was mainly distributed in the resonance period of approximately 3–6 a in around 2008, and in the resonance period of 10–20 a in 1980–2000 (Figure 5b). Figure 5c shows that in the cone of influence (COI) region, the resonance period of  $ET_0$ and El Niño-Southern Oscillation (ENSO) passing the 95% red noise test was 3-6 a; there was a significant resonance relationship at this frequency band, and the oscillation cohesion was the strongest. The coherence phase angle between ET0 and ENSO was  $-60^{\circ}$ , showing the ENSO lags behind the ET<sub>0</sub> by around 0.5–1 year band between 1978 and 1984. This phase change was relatively stable. There was significant coherence power and a consistent phase angle for the period 1983–1993 associated with signals in the 2–6 years band, and in this period the phase angle was  $360^\circ$ , which indicated the ET<sub>0</sub> lags about 2–6 a behind PNA (Figure 5d). Similar to the PNA, a significant coherence power and consistent phase appeared in the period 1985–1994 associated with signals in the 2–5 years band and the coherence phase angle of  $ET_0$  and AMO was  $-45^\circ$ , which means that AMO lags behind  $ET_0$  by around 0.25–0.63 a. The ET0 and WPI showed significant resonance relationships between 6 and 8 years in 1968–1976, reflecting that the  $ET_0$  was ahead of WPI; another significant resonance relationship was 7–10 a, and the coherence phase angle of ET0 and WPI was  $10^{\circ}$ , indicating that ET<sub>0</sub> lags behind WPI by around 0.19–0.28 a (Figure 5f).



**Figure 5.** Wavelet transform coherence for  $ET_0$  and the large-scale circulation patterns. Thick contours denote 5% significance levels against red noise. Pale regions denote the Cone of Influence (COI) where edge effects might distort the results. Small arrows denote the relative phase relationship (in-phase, arrows point right; anti-phase, arrows point left).

# 4. Discussion

#### 4.1. Relationships between Regional Et0 and Climatic Factors

Table 2 shows the correlation coefficients between the  $ET_0$  and the meteorological parameters. In the CLP, the regional RH variation had a significant association with the variation of the  $ET_0$  (i.e., the correlation coefficient is 0.76). In addition, there is an obvious correlation between the variation of regional  $ET_0$  and Tmax/T. Regarding the three geomorphic regions, higher correlation coefficients between the regional  $ET_0$  variation and Tmax variation were observed at the MR (0.77) and VR (0.84) regions. For the HR region, the regional  $ET_0$  displayed the most remarkable (i.e., passed the 0.1 level test) association with the variation of RH, followed by the variations of Tmax and T. According to the results in Table 2, the main meteorological controlling parameters for the regional variation of  $ET_0$  in the CLP were RH, T, and Tmax, which indicated that regional  $ET_0$  is more sensitive to the variations in regional relative humidity and air temperature.

However, the influences of meteorological controlling parameters on regional  $ET_0$  variations have spatial variation among the three topographic regions. There is a remarkable correlation relationship between the variation of regional T and the regional  $ET_0$ , and variations in regional RH and T may cause regional  $ET_0$  variability. Besides, the WS plays an important role in regional  $ET_0$  variation, whereas the SD has no significant association with the variation of regional  $ET_0$ .

	WS	Т	Tmax	Tmin	SD	RH
CLP	-0.363 **	0.605 **	0.717 **	0.416 **	0.303 *	0.757 **
MR	-0.31 *	0.69 **	0.773 **	0.603 **	0.175	-0.69 **
VR	-0.326 *	0.749 **	0.84 **	0.579 **	0.08	-0.709 **
HR	-0.489 **	0.61 **	0.703 **	0.442 **	0.137	-0.713 **

Table 2. The correlation coefficient between potential evapotranspiration and climatic factors.

\* Significantly correlated at the 0.05 level; \*\* Significantly correlated at the 0.1 level.

To assess the contributions of the main meteorological controlling parameters to the regional  $ET_0$  variation in the entire CLP, the contribution rates were analyzed using the method contribution rate analysis. The results (Table 3) show the T variation had the highest contribution rate (42%). The variations of RH, WS, and SD made smaller contributions to the  $ET_0$  in the CLP. As for the MR region, the largest contribution rate for the regional  $ET_0$  variation was T variation (40%), followed by variations of Tmax (26%), Tmin (26%), SD (4%), RH (4%), and WS (1%). As for the VR region, the contribution rate pattern had a similar order to that of the MR region. As for the  $ET_0$  variation in the HR region, the variation of Tmax displayed the highest contribution rate (39%). The contribution rates of the regional  $ET_0$  in the CLP was mainly controlled by regional air temperature variations, while the influences of the regional WS, SD, and RH on regional  $ET_0$  variation were relatively weak.

**Table 3.** The contribution rate of climatic parameters to the variation of the  $\text{ET}_0$  (%).

	WS	Т	Tmax	Tmin	SD	RH
CLP	7	42	13	23	7	8
MR	1	40	26	26	4	4
VR	7	39	10	28	1	15
HR	1	11	39	17	4	28

#### 4.2. Comparison with Other Study Areas

Recently, some researchers have paid increasing attention to assessing regional  $ET_0$  variations. Due to the different environments in various regions, temporal and spatial variations of the  $ET_0$  in different regions have been proven to have significant differences (Table 4). In a study of the  $ET_0$  for the whole of China, researchers found that the overall  $ET_0$  variations in China showed a downward trend [45]. This same variation was also found in the northwestern part of China [28]. However, in the southwestern part of China [46], the Wei River basin [47], and the Yangtze River [48], the  $ET_0$  had increasing trends. The trend of the CLP is the opposite to the trend of the whole of China. Comparing the  $ET_0$  trend in the three topographic regions (MR, HR, and VR), the trend of the  $ET_0$  in the VR (1.49 mm/a) was larger than in the MR (1.28 mm/a) and HR (1.09 mm/a).

**Table 4.** The information of the  $ET_0$  in other parts of China and the whole of China during the past decades.

Study Area	Time Period	Trends	Abrupt Change	Sources
Northwest China	1958-2008	decrease	1978	[32]
Southwest China	1961-2009	increase	1985	[46]
Wei River Basin, China	1959-2008	increase	1993	[47]
Yangtze River, China	1960-2011	increase	2000	[48,49]
Whole of China	1960-2013	decrease	1993	[45]
CLP, China	1960-2017	increase	1997	This study

#### 5. Conclusions

During the period of 1960–2017, the mean annual  $ET_0$  of the CLP was 1074 mm, and the maximum and minimum values were 1181 mm and 987 mm, respectively. The trends of  $ET_0$  in three different topographies were generally the same, however, the  $ET_0$  values differed. The  $ET_0$  in the HR was the highest of the three regions, followed by the VR, and the  $ET_0$  in the MR was the lowest. The magnitude of the  $ET_0$  varied in different seasons; in spring, summer, and autumn, the magnitudes of the  $ET_0$  were consistent with the annual  $ET_0$  variation, which was the largest in the HR, the second-largest in the VR, and the smallest in the MR. In winter, the  $ET_0$  values of the HR and MR were very similar, while the  $ET_0$  of the VR was the smallest.

The spatial distribution of the annual  $ET_0$  in the study area varied in different topographies. The  $ET_0$  value in the MR decreased from west to east, and the distribution of the  $ET_0$  in the HR was consistent with the MR. The larger  $ET_0$  values in the VR were mainly concentrated in the eastern CLP, and the rest were mostly distributed in Inner Mongolia. In the four seasons of comparative analysis, the larger values of the MR were distributed in the western region, and the  $ET_0$  distributions in the HR and VR differed. The annual mean  $ET_0$  series of the majority of stations displayed increasing trends during 1960–2017. Approximately 93% of stations exhibited a statistically significant increasing trend for the annual mean  $ET_0$  series. The annual  $ET_0$  of the HR regions had a stronger significant increasing trend than that of the VR and MR regions.

The wavelet transform coherence results of  $ET_0$  and large-scale circulation factors showed that  $ET_0$  had significant correlation with ENSO, PNA, and AMO. The resonance period of  $ET_0$  and ENSO was 3–6 a, mainly in 1976–1985. The resonance period of  $ET_0$  and PNA was mainly in 1983–1993; the average coherence phase angle was close to 360°, indicating that the  $ET_0$  lags behind the PNA by about 2–6 a;  $ET_0$  had a very good positive correlation with AMO, and its significant resonance period was 2–5 a.

The RH, T, and Tmax are important meteorological parameters for the variation of control of regional ET<sub>0</sub>. In the CLP, RH is the main influencing parameter of the ET<sub>0</sub> variation; however, in the MR and VR, the correlation coefficients of Tmax were the largest (0.77 and 0.84, respectively). The correlation coefficient of the RH in the HR was 0.71, which is the main controlling parameter. The temperature variation had the highest contribution rate (42%) for the regional ET<sub>0</sub> variation in the entire CLP. As an important controlling factor for the regional energy balance, temporal–spatial variation of evaporation usually resulted in the regional water cycle rate increasing and further affected the regional water–heat balance and ecological security. We should pay more attention to the variation of evaporation under climate change, especially temperature change.

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