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Spatiotemporal analysis of potential evapotranspiration in the Changwu tableland from 1957 to 2012

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ABSTRACT: The Changwu tableland is located in the semi-humid to semi-arid transition area of the Loess Plateau, China. In the present study, the daily potential evapotranspiration (ET_0) of the Changwu tableland was calculated using the FAO Penman–Monteith (FPM) equation for the years 1957–2012, and the temporal variation and frequency distribution characteristics were analysed. The results indicate that the annual average ET_0 of the Changwu tableland was 949.3 mm, varying from 789.2 to 1093.3 mm; a slight downward trend with a rate of −0.48 mm year^{-1} was found. An abrupt increase occurred in 1994. The ET_0 values that correspond to frequencies of 5, 10, 25, 50, 75, 90 and 95% were 1076.8, 1047.6, 999.7, 947.8, 897.3, 853.0 and 827.0 mm, respectively. The recurrence intervals of maximum and minimum ET_0 were both more than 50 years. The contributions of T_{max}, T_{min}, vapour pressure, wind speed and sunshine hours to changes in ET_0 were 0.74, 0.07, −0.51, −0.57 and −0.23, respectively. The change in ET_0 and the meteorological factors in the Changwu tableland are worthy of attention; measures to reduce the negative impacts of climate change are necessary.

KEY WORDS Changwu tableland; potential evapotranspiration; FAO Penman–Monteith equation; Mann–Kendall test; frequency analysis

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1. Introduction

Potential evapotranspiration (ET_0) is the largest possible evaporation under the condition of a sufficient underground water supply. ET_0 measures the atmospheric evaporation capacity, which is an essential parameter for scientific research on hydrology, meteorology, geography, ecology and agriculture (Allen *et al.,* 1998); ET_0 is also widely used to estimate crop water requirement (Abdelhadi *et al.,* 2000; Xu and Singh, 2005), to analyse dry and wet climate conditions (Bordi *et al.,* 2004; Nastos *et al.,* 2013; Some'e *et al.,* 2013), and ecological process model analysis (Xu and Chen, 2005).

Many studies have focused on the comparison and applicability of different models for calculating ET_0. Lu *et al.* (2005) found that the results of six models of ET_0 in the southeastern United States were significantly different from each other, and there were greater differences among temperature-based methods than among radiation-based methods. Trajkovic and Kolakovic (2009) compared the FAO Penman–Monteith (FPM) equation and five other equations to calculate ET_0 in humid regions, and the results showed that the FPM equation was the most accurate; however, when weather data were insufficient for the FPM equation, the Turc equation (Turc, 1961) was an appropriate choice. Liu and Li (1989) posited that without the influence of horizontal flow, the revised Penman–Monteith equation would be suitable for the Changwu tableland.

Although the temperature has increased by nearly 1 °C over the past 50 years, pan evaporation has continued to decrease. This pattern is known as the 'evaporation paradox' (Brutsaert and Parlange, 1998) and has been confirmed by many researchers (Arora, 2002; Ohmura and Wild, 2002; Roderick and Farquhar, 2002, 2004). Researchers have conducted extensive studies on pan evaporation and ET_0 at various scales in China, including the national scale (Liu *et al.,* 2004; Gao *et al.,* 2007; Yin *et al.,* 2010; Han *et al.,* 2012), within the Yangtze River Basin (Gong *et al.,* 2006; Xu *et al.,* 2006), within the Yellow River Basin (Zhang *et al.,* 2011; Wang *et al.,* 2012), on the Loess Plateau (Li *et al.,* 2012) and on the Tibetan Plateau (Zhang *et al.,* 2009; Liu *et al.,* 2011). Most of these studies have found decreasing trends in pan evaporation and ET_0.

The Changwu tableland is located in the southern Loess Plateau, China, which is a transition area between semi-arid and semi-humid regions and an area in which water scarcity is the main constraint on agricultural production and ecological construction. Regional water balance studies suggest that ET_0 predominantly controls water demand. The temporal variations in ET_0 are important for a variety of analyses, including the study of eco-hydrological processes on the Loess Plateau. Based on daily meteorological data for the Changwu tableland from 1957 to 2012, characteristics of ET_0 and its influencing factors were studied in order to provide a basis for regional agricultural production, vegetation restoration and relevant scientific research including the adaptability of countermeasures for climate change.

2. Materials and methods

2.1. Data sources

The study area is located in Changwu County, Shaanxi Province, China (107.7° E, 35.2° N; 1207 m a.s.l.). The daily average, maximum and minimum temperatures (T_{mean}, T_{max} and T_{min}, respectively; °C); actual vapour pressure (e_a; kPa); 2 m wind

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Table 1. Monthly average ET_0 and their proportion of the year.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Monthly average (mm)	29.4	38.8	68.9	99.9	123.6	138.5	136.6	110.2	76.9	55.0	36.3	27.7
Proportion (%)	3.1	4.1	7.3	10.5	13.0	14.6	14.4	11.6	8.1	5.8	3.8	2.9

ET_0, potential evapotranspiration.

speed (u_2; m s^{-1}); sunshine hours (SH; h) and precipitation (P; mm) were obtained from the national meteorological stations, which are maintained by the Chinese Meteorological Administration (CMA) (http://cdc.cma.gov.cn). The investigated seasons were categorized as spring (March to May), summer (June to August), autumn (September to November) and winter (December to February of the following year).

2.2. ET_0 calculation

ET_0 was calculated using the FPM equation (Allen *et al.,* 1998), which is applicable to various regions of the world such as America (Tsanis *et al.,* 2002; Exner-Kittridge and Rains, 2010), Europe (Fermor *et al.,* 2001; Gavin and Agnew, 2004), Africa (Schumacher *et al.,* 2009; Farg *et al.,* 2012), Asia (Mallikarjuna *et al.,* 2014; Valipour, 2014) and Oceania (Chiew *et al.,* 1995; Ortega-Farias *et al.,* 2006). The FPM specifies hypothetical reference values for plant height (0.12 m), fixed surface resistance (70 s m^{-1}) and albedo (0.23):

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma\frac{900}{T+273}u_2\left(e_s - e_a\right)}{\Delta + \gamma\cdot\left(1 + 0.34u_2\right)} \quad (1)$$

where ET_0 is potential evapotranspiration (mm day^{-1}), Δ is the slope of the saturation vapour pressure curve (kPa °C^{-1}), R_n is the surface net radiation (MJ m^{-2} day^{-1}), G is the soil heat flux (MJ m^{-2} day^{-1}), γ is the psychrometer constant (kPa °C^{-1}), T is the mean temperature (°C), u_2 is the 2 m wind speed (m s^{-1}) and e_s and e_a are the saturation vapour pressure and water vapour pressure (kPa), respectively.

2.3. Contribution of meteorological factors

According to Equation (1), ET_0 is a function of several meteorological factors, that is, $ET_0 = f(T_{max}, T_{min}, e_a, u_2, \text{SH})$. The contributions of various meteorological factors to temporal change in ET_0 were calculated according to the following total derivative equation:

$$\frac{dET_0}{dt} = \frac{\partial ET_0}{\partial T_{max}}\cdot\frac{dT_{max}}{dt} + \frac{\partial ET_0}{\partial T_{min}}\cdot\frac{dT_{min}}{dt} + \frac{\partial ET_0}{\partial e_a}\cdot\frac{de_a}{dt} + \frac{\partial ET_0}{\partial u_2}\cdot\frac{du_2}{dt} + \frac{\partial ET_0}{\partial \text{SH}}\cdot\frac{d\text{SH}}{dt} \quad (2)$$

The variables on the right side of the equation represent the contributions of these meteorological factors. Factors that cause ET_0 to increase are considered to be positive, whereas factors that caused ET_0 to decrease are considered to be negative. The factor with the strongest influence on ET_0 was determined by comparing the absolute values of each contribution.

2.4. Abrupt change test

The Mann–Kendall (M-K) test is used widely as an abrupt change test (Parkinson *et al.,* 1999; Alley *et al.,* 2003); the test

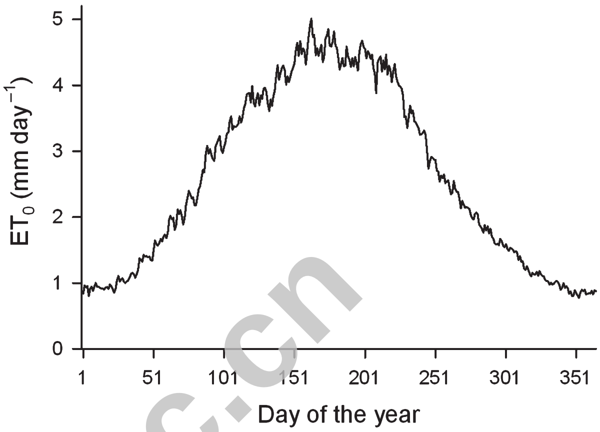

Figure 1. The variations in daily average potential evapotranspiration (ET_0) from 1957 to 2012.

was first proposed by Mann in 1945 to detect trends in weather data. The method is continuously being improved, and is used widely because of its wide detection range and high degree of quantification. In the present study, the M-K test was used (with 95% confidence intervals) to quantify trends in ET_0 in the Changwu tableland region.

2.5. Frequency analysis

Hydrological frequency analysis is based on the statistical properties of hydrological phenomena. The analysis uses existing hydrological data to analyse the quantitative relationship between the designated values and frequency of occurrence (or return period) of hydrological variables. In the present study, ET_0 values were calculated annually and for spring, summer, autumn and winter for the 56 studied years. These values were used to conduct a frequency analysis, and a fitting method was used to obtain a Pearson type III frequency curve (Ippolitov *et al.,* 2002; Zhou and Adeli, 2003; Mi *et al.,* 2005; Zhai *et al.,* 2005).

3. Results

3.1. Inner-annual variations in ET_0

The maximum monthly mean ET_0 in Changwu tableland occurred in June (Table 1) and the minimum ET_0 occurred in December. The ET_0 from May to August accounted for 53.6% of the annual ET_0, because this period experienced substantial water and heat exchange.

The ET_0 values in summer, spring, autumn and winter were 385.3, 292.4, 168.2 and 95.8 mm, respectively, and accounted for 40.9, 31.1, 17.9 and 10.2% of the annual ET_0, respectively. The magnitude of the ET_0 change was smallest in winter and largest in summer. Moreover, as a result of the continental monsoon climate, the change was more significant in spring than that in autumn.

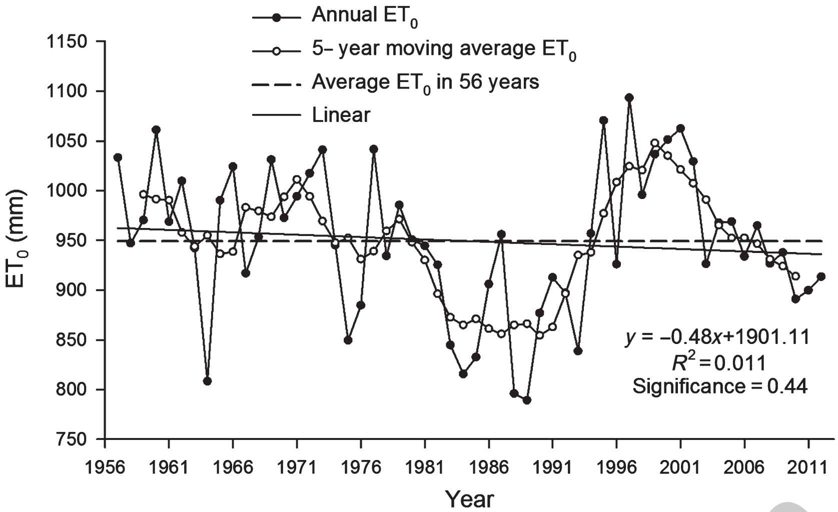

Figure 2. The variation trend in the annual potential evapotranspiration (ET_0) and 5 year moving average ET_0 during the studied 56 year period (the linear trend is for the annual ET_0).

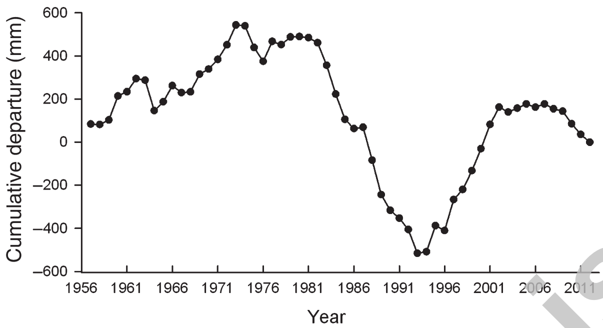

Figure 3. Cumulative departure curve of the annual potential evapotranspiration (ET_0) during the past 56 years.

The daily ET_0 for the Changwu tableland is shown in Figure 1. The values continuously increased to a maximum in summer (5.0 mm day^{-1}) and thereafter declined gradually to a minimum value (0.8 mm day^{-1}). Because ET_0 is based on calculations related to a series of meteorological elements, there were fluctuations during certain periods, especially during the months of high rainfall from June to August.

3.2. Inter-annual variations in ET_0

The average ET_0 of the Changwu tableland for the period 1957–2012 was 949.3 mm. The minimum ET_0 (789.2 mm) occurred in 1989, while the maximum ET_0 (1093.3 mm) occurred in 1997 (Figure 2). During the 56 years, the annual ET_0 exhibited several decreasing and increasing trends, and fluctuated near the historical average line. A linear-regression analysis indicated that the annual ET_0 exhibited a slight downward trend with a rate of −0.48 mm year^{-1}, which suggests that despite its substantial inter-annual difference, the overall change in magnitude was small. The cumulative departure curve (Figure 3) suggests that the general trend in the annual ET_0 can be roughly divided into four stages. From 1957 to 1980, the annual ET_0 exhibited an increasing trend. Beginning in 1981, the annual ET_0 decreased to its minimum cumulative departure in 1993. Beginning in 1994, the annual ET_0 increased substantially before decreasing again from 2002 to 2012. Therefore, 1994 was the turning point in the overall ET_0 trends during the period 1957–2012.

The ratio of the extreme values may reflect the magnitude of inter-annual variability, whereas the co-efficient of variation (C_v) is an indicator of relative variation, which can reflect the degree of dispersion in the overall series. The two indexes were calculated to determine the general inter-annual variability in ET_0 (Table 2). The multiple regression analysis for annual ET_0 and the meteorological factors shows that T_{max}, T_{min} and actual vapour pressure had a rising trend, with rates of 0.03 °C year^{-1}, 0.005 °C year^{-1} and 0.001 kPa year^{-1}, respectively, while the wind speed and sunshine hours exhibited decreasing trends, with rates of −0.007 m s^{-1} year^{-1} and −0.004 h year^{-1}, respectively. Contributions of T_{max}, T_{min}, vapour pressure, wind speed and sunshine hour to change in ET_0 are shown in Table 2.

3.3. Results of the Mann–Kendall test

An abrupt change test for ET_0 using the M-K method showed that the two curves intersected in 1994, 2008 and 2011 (Figure 4). In 1994, only one point was outside the confidence interval, and the point could not be confirmed as representing an abrupt change point. However, after comparing the M-K test of T_{mean} and the cumulative departure curve, we found that both curves displayed an abrupt change in 1994. Thus, 1994 appears to have been the point of abrupt change in the ET_0 rate in the Changwu tableland.

3.4. Frequency analysis of ET_0

Pearson III frequency curves were drawn to determine the probability and recurrence interval of the annual and seasonal ET. Figure 5 shows that during the 56 year study, the dispersion of the annual ET_0 was small ($C_v = 0.08$ and $C_s = 0.12$), which also indicates that the frequency corresponding to the mean value (949.3 mm) was <50%. The ET_0 values that correspond to frequencies of 5, 10, 25, 50, 75, 90 and 95% were 1076.8, 1047.6, 999.7, 947.8, 897.3, 853.0 and 827.0 mm, respectively. The recurrence intervals of the maximum (1093.3 mm) and the minimum (789.2 mm) ET_0 values were both exceeded in 50 years.

For the ET_0 values in winter, spring, summer and autumn, the recurrence intervals of extreme values were similar; however, the

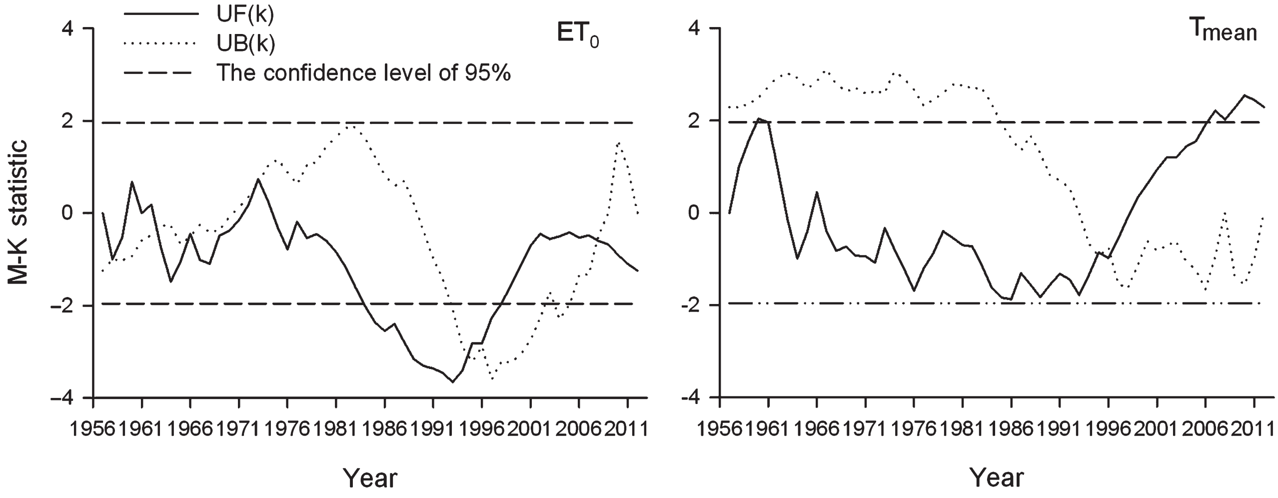

Figure 4. Abrupt change in the annual potential evapotranspiration (ET_0) and T_{mean} for the Changwu tableland during the period 1957–2012.

Table 2. Inter-annual variability of ET_0 and contributions of the meteorological elements.

	ET_0 (mm)	T_{max} (°C)	T_{min} (°C)	e_a (kPa)	u_2 (m s^{-1})	SH (h)
Mean	949.31	15.24	4.23	0.94	2.23	5.82
Max.	1093.30	16.89	5.19	1.05	2.73	7.10
Min.	789.24	13.29	3.46	0.85	1.73	4.16
Ratio	1.39	1.27	1.50	1.24	1.58	1.71
STDEV	73.76	0.89	0.39	0.05	0.32	0.70
C_v	0.08	0.06	0.09	0.05	0.14	0.12
Slope	−0.48	0.027	0.0053	0.0011	−0.0067	−0.005
Contribution		0.74	0.07	−0.51	−0.57	−0.23

ET_0, potential evapotranspiration.

values of the deviation co-efficient (C_s) and variable co-efficient (C_v) showed that the dispersion degree by time of year was larger than the annual ET_0 and that the variability in the annual distribution was greater than during specific times.

4. Discussion

ET_0 is the result of a combination of meteorological factors; however, the main influencing factor varies across different regions. The main factors that affected ET_0 in the Tibetan region over the 40 years were wind speed and relative humidity (Chen *et al.,* 2006). Li *et al.* (2012) studied the spatial and temporal variations in ET_0 on the Loess Plateau from 1961 to 2009 using data from 48 stations and found that temperature and humidity were the main influencing factors; the study area was also in the Loess Plateau region, and ET_0 was most affected by temperature, followed by wind speed and vapour pressure.

While the average annual temperature of the Changwu tableland increased by 0.6 °C over the past 56 years, ET_0 decreased by 26.9 mm; this pattern is an example of the

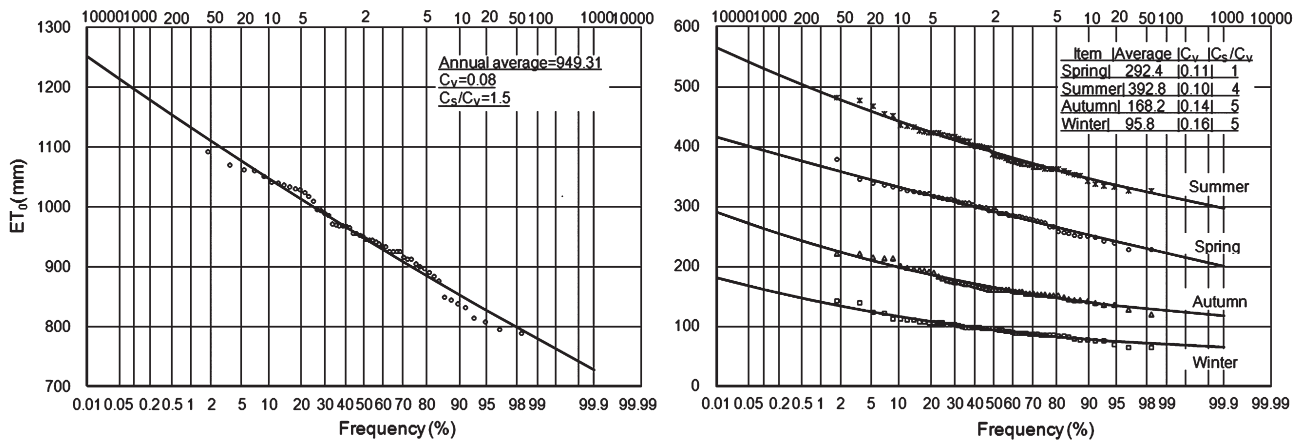

Figure 5. Frequency distribution curves for the annual and seasonal average ET_0.

'evaporation paradox'. The precipitation also decreased by 24.5 mm, changes in ET_0 and decreasing precipitation over the Changwu tableland are noteworthy, because these changes may accelerate soil desiccation and alter the rules for crop water consumption, which can affect water usage, management and crop production in the region. Therefore, measures that reduce the negative impacts of climate change are necessary.

5. Conclusions

The annual average potential evapotranspiration (ET_0) of the Changwu tableland during the period 1957–2012 was 949.3 mm. The minimum occurred in 1989, whereas the maximum occurred in 1997. The maximum monthly and daily ET_0 both occurred in June and the minimum occurred in December. From May to August, ET_0 accounted for 53.6% of the annual ET_0 because there was a substantial amount of water and heat exchange.

The results of the frequency analysis showed that during the 56 years of study period, the dispersion of the annual ET_0 was small ($C_v = 0.08$ and $C_s = 0.12$), which indicates that the frequency corresponding to the mean value (949.3 mm) was <50%. The recurrence intervals of the maximum (1093.3 mm) and the minimum (789.2 mm) ET_0 were both 50 years. The frequency distributions in winter, spring, summer and autumn were similar to that of the annual ET_0. However, the dispersion degree was larger and the variability of the annual distribution was greater. Thus, the distribution of crop water requirements in different months should be assessed.

During the period 1957–2012, there was an overall decreasing trend in ET_0 at a rate of −0.48 mm year^{-1}. Moreover, there was an abrupt change in 1994. The contributions of T_{max}, T_{min}, vapour pressure, wind speed and sunshine hours to changes in ET_0 were 0.74, 0.07, −0.51, −0.57 and −0.23, respectively; T_{max} was the main factor that resulted in changes to ET_0.

Regional climatic dry and wet conditions have been of great interest in academic research on drought processes. Increasing attention has been given to these topics due to the current increased concern of climate change. Understanding the ET_0 characteristics and its influencing factors in the Changwu tableland region is very important for regional agricultural production, vegetation restoration and relevant scientific research.

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