

Trends in reference evapotranspiration and its attribution over the past 50 years in the Loess Plateau, China: implications for ecological projects and agricultural production

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Abstract In the water-limited Loess Plateau, reference evapotranspiration (ET_o) is an important hydrological factor affecting the implementation of ecological projects, agricultural production, and water resource management, and its long-term variation is of great interest in climate change studies. Based on daily data from 57 meteorological stations, temporal and spatial patterns in ET_o and related driving factors were evaluated for the period 1958–2011. In addition, the influences of agricultural cultivation and urbanization on ET_o trends were also analyzed. The results indicated both decreasing and increasing trends in annual and seasonal ET_o series in this area. The area-average ET_o series experienced a weak decreasing annual trend. However, more ET_o series were found with increasing trends. More decreasing trends were found in summer, winter, and the growing season, but more increasing trends were seen in spring and autumn. Analysis of the contributions of meteorological variables on trends in ET_o showed that wind speed was the most dominant factor affecting ET_o .

variation at most stations. In addition, cultivation and urbanization also affected ET_o trends. The impact on ET_o trend was more obvious for the urbanization than cultivation. A warmer and drier trend would affect the implementation of ecological projects, the occurrence of dried soil layers, desertification, and agricultural production of the area.

Keywords Reference evapotranspiration · Trend · Attribution · Mann–Kendall · Land use · Loess plateau

1 Introduction

Over the past century, the near-surface global mean air temperature has increased by 0.74 °C (IPCC 2007). Climate change has emerged as an important environmental science issue, and it significantly influences hydrological cycles including evapotranspiration, precipitation, and runoff. Evapotranspiration, which comprises evaporation and plant transpiration, is a key process in the hydrological cycle and energy balance, revealing the climate change and temporal-spatial patterns of parameters influencing the eco-hydrological processes and controlling the evolution of the surface ecosystem. As the only connecting term between the hydrological balance and energy balance (Xu and Singh 2005), Evapotranspiration is the important indicator of climate change and the hydrological cycle. Estimation of ET is necessary for improving the planning, management, and efficient use of water resources (Gavilan and Castillo-Llanque 2009). Moreover, assessment of climate change impacts on ET variability can help in determining appropriate strategies for mitigating the probable damage from these impacts.

Reference evapotranspiration (ET_o) has been widely used in water resource research and management. As one

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of the important parameters of hydrological cycles, ET_o reflects atmosphere evaporation capacity and vegetation water requirement and plays a key role in calculating and predicting crop evapotranspiration, water management, irrigation planning, and other practices of agricultural production and vegetation restoration. Therefore, it is clear that any changes in ET_o would affect agricultural production, vegetation restoration, and water resource planning (Allen et al. 1998).

Reference evapotranspiration is expected to increase due to temperature increases. However, the decrease of observed ET_o and pan evaporation has been widely detected over recent decades in many areas (Yin et al. 2010; Limjirakan and Limsakul 2012; Darshana et al. 2013). This phenomenon of a discrepancy between expected and observed trends in evaporation is known as the “evaporation paradox”. In addition, a trend of increasing ET_o was also detected in areas such as Shiyang River (Su et al. 2015), Romania (Croitoru et al. 2013), Iran (Tabari et al. 2011), and the Mississippi River basin (Qian et al. 2007).

Many studies have attempted to identify the reasons causing ET_o changes (Zheng and Wang 2015). In general, ET_o change is mainly due to decreases in sunshine duration and wind speed. Global dimming could explain the decrease of ET_o in many regions (Yin et al. 2010; Bandyopadhyay et al. 2009). Changes in wind speed and relative humidity have also been reported as driving forces affecting ET_o over recent decades at different regions (Bandyopadhyay et al. 2009; Yin et al. 2010). Thus, an analysis of the contribution of meteorological variables to ET_o change is essential, and will help us discern the main driving forces causing changes in ET_o .

However, the effect of human activities such as cultivation and urbanization on ET_o was often neglected. Rapid changes in cultivation and urbanization could impact regional-scale climate to a certain extent and further induce changes in evapotranspiration (Han et al. 2012). Some studies have focused on the impacts of large-scale land use change on climatic variables and ET_o (Han et al. 2012; Rim 2009). The effect of human activities on ET_o trend should be evaluated to determine the driving mechanisms of land use changes.

The Loess Plateau is currently experiencing severe water shortages. In past decades, the regional climate showed a warmer and drier trend (Li et al. 2010), further the runoff decreased (Zhao et al. 2015). At the same time, many conservation projects, e.g., grain for green, afforestation, and reforestation, have been performed to control soil erosion, and this substantially alters the land use patterns and hydrological cycles. In addition, many farmlands are distributed in the region, e.g., on the Weihe–Fenhe plain, Hetao plain, and Yinchuan plain, and these

support a large population. All of these factors may affect the regional evapotranspiration. In the context of climate and land use/vegetation changes, it is very necessary to understand ET_o change and its influencing factors to provide valuable information for vegetation restoration, agricultural production, and water management on the Loess Plateau.

The aims of this study were to (1) analyze the spatial and temporal variation of ET_o series in the Loess Plateau from 1958 to 2011, (2) to investigate the trends in ET_o using the Mann–Kendall (MK) nonparametric test and Sen’s slope estimator, (3) to quantify the contribution of key meteorological variables to ET_o trend, and (4) to determine the influence of human activities, such as cultivation and urbanization, on ET_o variation.

2 Data and methods

2.1 Study area

The Loess Plateau, supporting a population of 108 million, is located in Northern China (34°–41°N, 100°–114°E), covers approximately 6.24×10^5 km², and includes the middle and northern regions of Shan’xi Province, most of Shanxi province, the middle and eastern regions of Gansu province, Ningxia, the northeast of Qinghai Province, the southwest of Inner Mongolia, and a small portion of Henan Province (Fig. 1). The area is a transition zone from a semi-humid to an arid environment and has a temperate continental climate that is characterized by hot, wet summers and cold, dry winters. Vegetation types include forest (I), forest–grassland (II), typical grassland (III), desert–grassland (IV), and desert (V) (Fig. 1) and are cropland in the Weihe–Fenhe plain, Hetao plain, and Yinchuan plain. Most areas are covered by grassland, forest, and cropland, which account for 49.4, 10.3, and 36.5 % of this plateau, respectively. In the past 60 years, several eco-environmental problems have become prominent and serious due to the combined impacts of climate change and intensified human activity.

2.2 Data sources

Daily data from 1958 to 2011 were obtained from 57 meteorological stations of the China Meteorological Administration. Meteorological variables were included: (1) mean air temperature (T_a , °C), (2) mean maximum air temperature (T_{max} , °C), (3) mean minimum air temperature (T_{min} , °C), (4) mean relative humidity (RH, %), (5) mean wind speed measured at 10 m height (u , m/s), (6) bright sunshine duration (n , h/d), and (7) precipitation (P , mm).

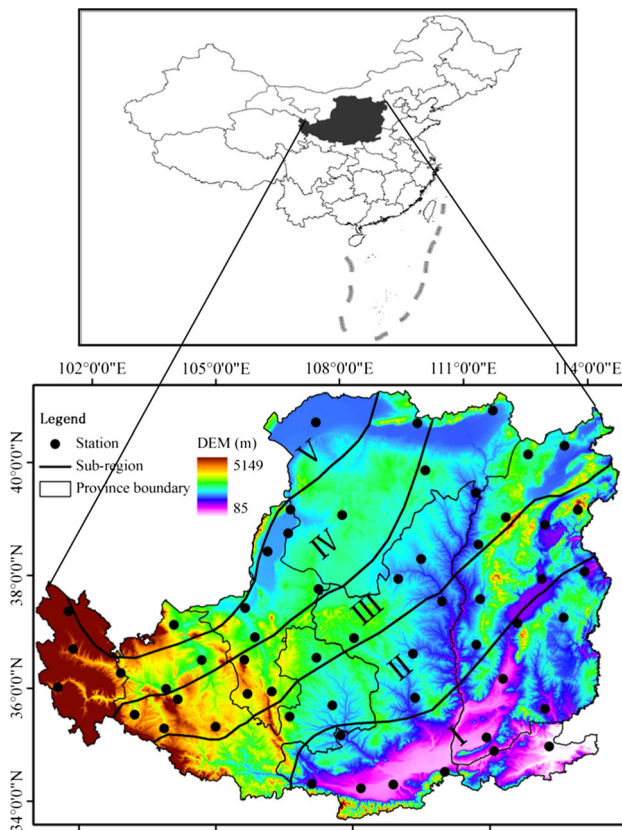


Fig. 1 Location of the study area and meteorological stations. I Forest sub-region; II forest–grassland sub-region; III typical grassland sub-region; IV desert–grassland sub-region; V desert sub-region

Land use data with 1 km resolution (Ran et al. 2012) was used to identify the agricultural, natural, or urban stations. Each grid was attributed to cropland, forest, grassland, urban land. In this paper, cultivated land was included with cropland, and natural vegetation was included with forest, grassland, and waterbody. The average ratios of cultivated land, natural land, and urban land within a 1–10 km radius of each station were calculated. According to the correlation between the ET_o trend magnitudes and the cultivated land percentage, a land-use with a 3-km radius was used in this study. The stations were classified into four categories: (1) agricultural stations where the ratio of cultivated land was larger than 50 %, (2) urban stations with a ratio of urban land larger than 50 %, (3) natural stations with a ratio of natural vegetation larger than 50 %, and (4) combined stations with similar ratios of agricultural, natural, and urban land uses.

2.3 ET_o estimation

In this study, the daily ET_o was calculated by the FAO-56 Penman–Monteith method (Allen et al. 1998),

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma(900/(T_a + 273))u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_o is the daily reference evapotranspiration rate (mm/d), R_n is the net radiation at the land surface ($MJ\ m^{-2}\ d^{-1}$), G is the soil heat flux density ($MJ\ m^{-2}\ d^{-1}$), T_a is the mean daily air temperature at 2 m height ($^{\circ}C$), u_2 is the wind speed at 2 m height (m/s), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $e_s - e_a$ is the saturation vapor pressure deficit (kPa), Δ is the slope of the vapor pressure curve ($kPa\ ^{\circ}C^{-1}$), and γ is the psychrometric constant ($kPa\ ^{\circ}C^{-1}$). Because soil heat flux is small compared with R_n , particularly when the surface is covered by vegetation, and because time steps were 24 h or longer, the estimation of G is ignored in the ET_o estimation (Allen et al. 1998).

To calculate ET_o , wind speed measured at 2 m height is required. Adjustment of wind speed from 10 to 2 m height is recommended by Allen et al. (1998),

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \tag{2}$$

where z is the height of measurement above the ground surface (m), u_z is the wind speed at the height z m, and u_2 is the wind speed at 2 m height.

Due to lack of actual solar radiation data, R_s is often estimated from sunshine data by the Angstrom formula:

$$R_s = \left(a_s + b_s \frac{n}{N} \right) R_a \tag{3}$$

where R_s is the solar radiation ($MJ\ m^{-2}\ d^{-1}$), R_a is the extraterrestrial radiation ($MJ\ m^{-2}\ d^{-1}$), n is daily bright sunshine duration (h), N is maximum possible duration of sunshine in daylight hours (h), n/N is relative sunshine duration, and a_s and b_s are regression coefficients. This study used the recommended values of $a_s = 0.25$ and $b_s = 0.5$.

The missing data were reconstructed for ET_o , but trends in the other variables were analyzed from measured data only. Missing values of daily temperature and relative humidity were filled using neighboring stations and the linear regressive method. All the correlation coefficients, r^2 , were greater than 0.85.

When sunshine duration data were missing, solar radiation (R_s) was estimated from T_{max} and T_{min} by the Hargreaves radiation equation (Hargreaves and Samani 1982):

$$R_s = k_{RS} \cdot \sqrt{(T_{max} - T_{min})} \cdot R_a \tag{4}$$

where the empirically adjusted coefficient k_{RS} is usually 0.16 for inland regions (Hargreaves and Samani 1982; Allen et al. 1998). Due to high variation in wind speed, the missing data were filled with a monthly average value calculated for each station.

In this model, the net radiation is calculated by an empirical formula (Allen et al. 1998):

$$R_n = (1 - \alpha)R_s - \sigma \left(\frac{T_{max,K}^4 + T_{min,K}^4}{2} \right) (0.34 - 0.14\sqrt{e_a}) \times \left(1.35 \frac{R_s}{R_{so}} - 0.35 \right) \quad (5)$$

where α is albedo or canopy reflection coefficient for the reference crop, and the value is 0.23; σ is Stefan–Boltzmann constant [$4.903 \times 10^{-9} \text{ MJ K}^{-4} \text{ m}^{-2} \text{ d}^{-1}$]; $T_{max,K}$ is maximum absolute temperature (K); $T_{min,K}$ is minimum absolute temperature (K); R_{so} is clear-sky solar radiation [$\text{MJ m}^{-2} \text{ d}^{-1}$]; R_a is solar radiation of the atmosphere [$\text{MJ m}^{-2} \text{ d}^{-1}$].

$$R_{so} = (0.75 + 2 \times 10^{-5}z)R_a \quad (6)$$

where z is the station elevation above sea level (m). And R_a can be estimated as:

$$R_a = \frac{24 \times 60}{\pi} G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)] \quad (7)$$

where G_{sc} is solar constant ($0.0820 \text{ MJ m}^{-2} \text{ min}^{-1}$), φ is expressed in radians, and other parameters were calculated by the following equations:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365}J\right) \quad (8)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365}J - 1.39\right) \quad (9)$$

$$\omega_s = \arccos[-\tan(\varphi) \tan(\delta)] \quad (10)$$

$$N = \frac{24}{\pi} \omega_s \quad (11)$$

where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December).

After the daily ET_o values were calculated, they were transformed into ET_o at monthly, seasonal, and annual scales. The seasons were divided into spring (March–May), summer (June–August), autumn (September–November), and the growing season (April–October). Regional ET_o in the plateau was computed by averaging all station values.

2.4 Trend detection

To analyze trends and changes in the long-term time series of ET_o and climatic variables, the nonparametric MK test (Mann 1945; Kendall 1975) was applied. At the same time, the Sen's method was used to estimate the magnitude in the trends (Sen 1968). The MK test has been used widely for

analyzing trends in hydrological and meteorological data (Yin et al. 2010; Tabari et al. 2011, 2015; Huang et al. 2015). Before applying the MK test, a trend-free pre-whitening approach was used to remove the influence of serial correlation on the MK test (Yue and Wang 2002).

2.5 Contribution analysis of meteorological variables to ET_o trend

To determine the relative contributions of meteorological variables to ET_o trends, stepwise linear regression was performed with ET_o as the dependent variable and meteorological variables as the independent variables. The meteorological data series were firstly standardized by dividing them by the standard deviation. A certain factor was entered into the model if its regression coefficient was significant at the 0.05 level. The final model yielded, via regression, a useful set of predictors, which can be regarded as the dominant meteorological variables in the change and variability of ET_o . Stepwise linear regression has been widely employed in other studies (Chun et al. 2012; Li et al. 2014b).

3 Results

3.1 Seasonality and spatial distribution of ET_o

The mean annual ET_o over the study area was 1110 mm during 1958–2011 and varied from 741 mm at Wutaishan station to 1378 mm at Tongxin station. The annual ET_o showed a strong spatial difference with lower values in the southwestern region and higher values in the northwestern and southeastern regions of the study area (Fig. 2). Mean annual ET_o in the growing season ranged from 533 mm at Wutaishan station to 1020 mm at Tongxin station, with an area-average value of 816 mm. The spatial distribution of ET_o , which accounted for 73.5 % of the annual value, generally agreed with the distribution of annual ET_o . The average ET_o in spring, summer, autumn, and winter were 351, 449, 205, and 104 mm, respectively, accounting for 31.6, 40.5, 18.5, and 9.4 % of annual ET_o , respectively. The values were higher in the summer half-year than in the winter half-year. The highest ET_o , 154 mm, occurred in July, and the lowest value, 31 mm, occurred in January.

3.2 Temporal and spatial trends in ET_o

As a whole, the ET_o series at the annual and growing season scales experienced decreases of 1.24 and 1.26 mm/decade during 1958–2011, respectively. An increasing trend was found from the 1960s to early 1970s, followed by a decrease until 1989, an increase in the 1990s, and then a

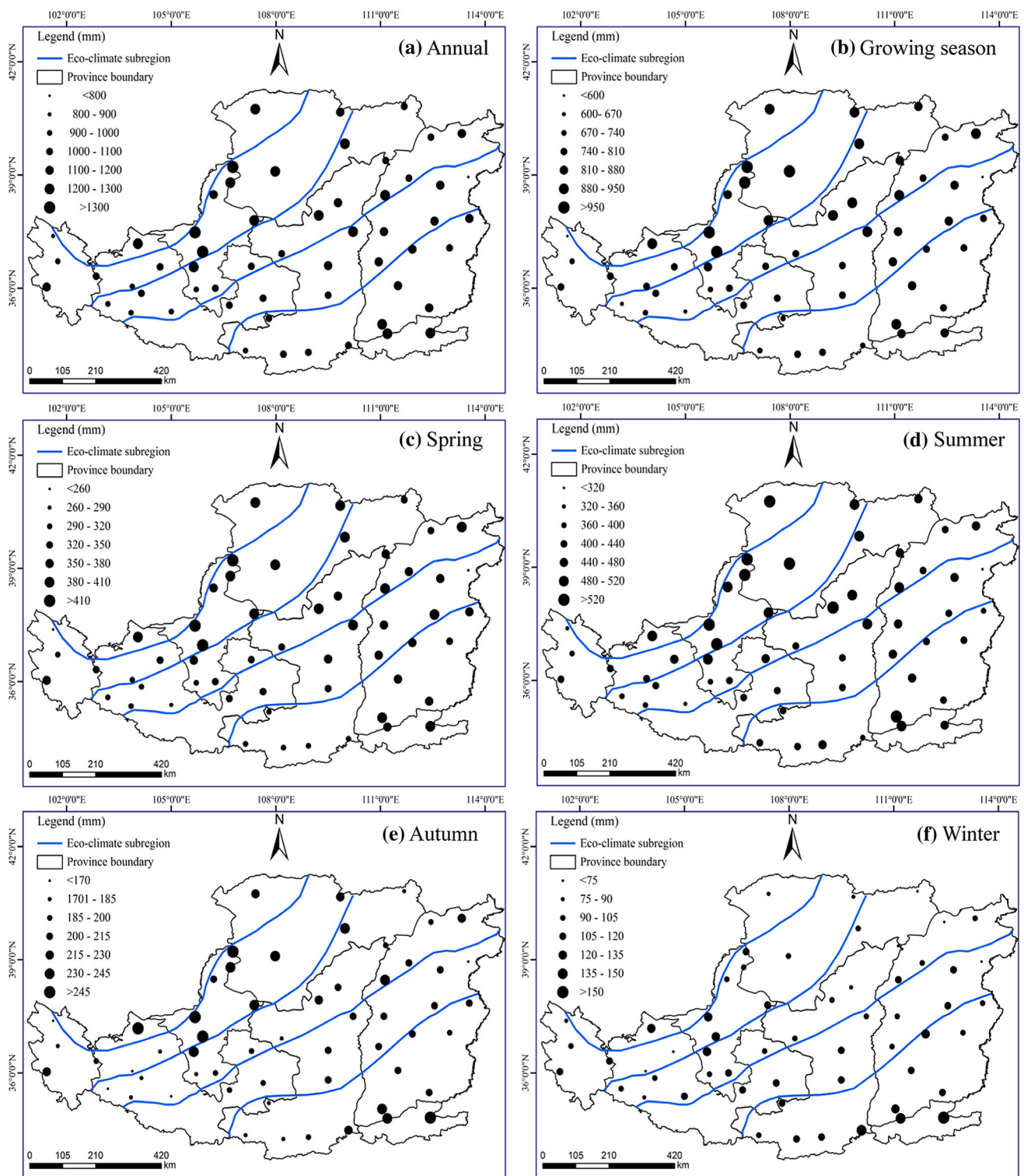


Fig. 2 Spatio-temporal distribution of potential evapotranspiration in the Loess Plateau

decrease until 2011 (Fig. 3). The median of annual ET₀ trend for all stations was 1.02 mm/decade (Fig. 4). For the stations with a significant trend, the significant decreasing trend rates ranged from 5.11 mm/decade at Menyuan

station to 23.51 mm/decade at Wugong station; while the significant increasing trend rates ranged from 8.35 mm/decade at Guyuan station to 15.51 mm/decade at Hohhot station. In the growing season, the median of ET₀ trend

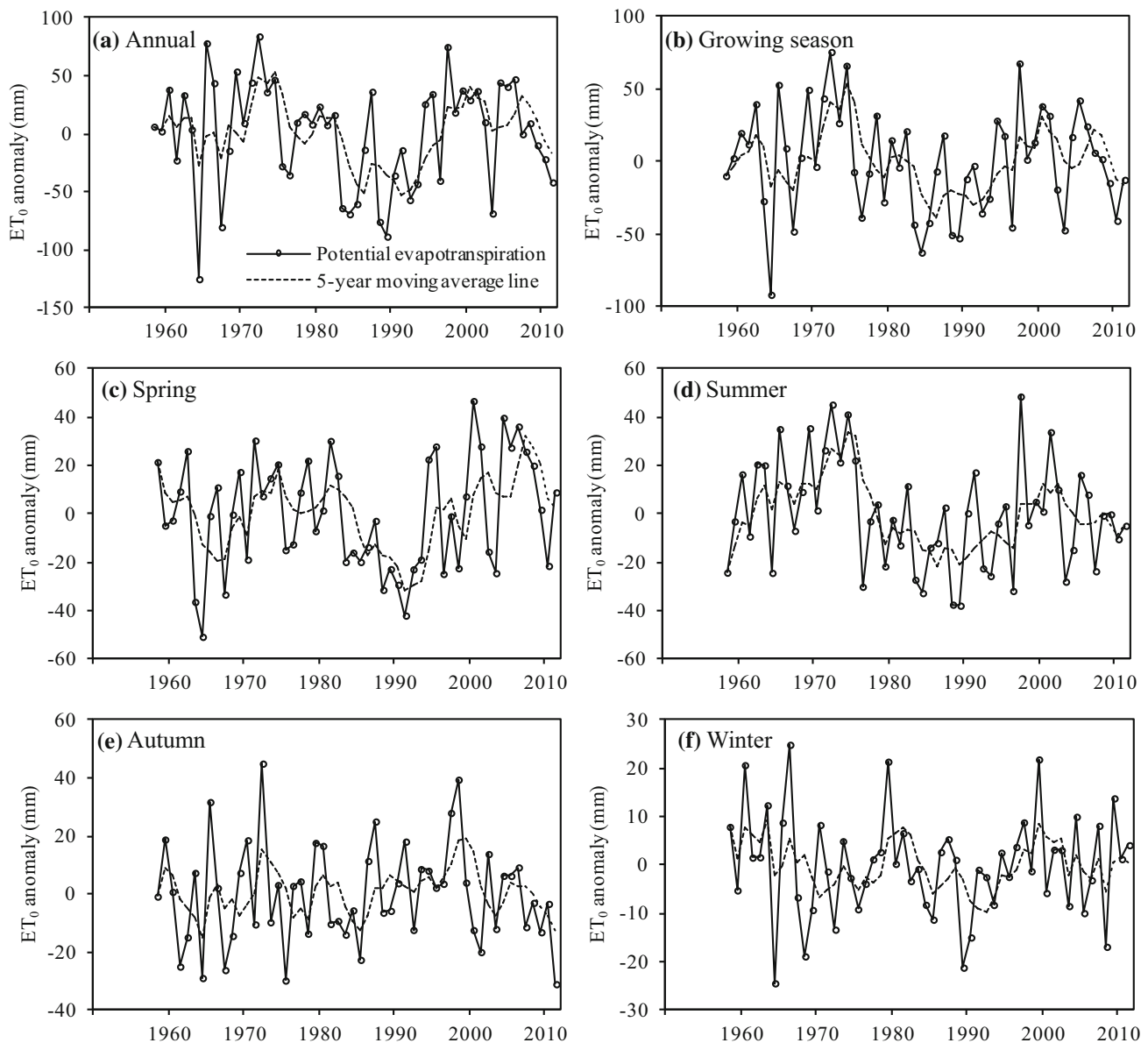


Fig. 3 Annual and seasonal variation of ET_0 during 1958–2011

magnitudes for all stations was 0.40 mm/decade (Fig. 4) and the significant downward trend rates ranged from 19.56 mm/decade at Sanmenxia station to 8.03 mm/decade at Xining station, while the significant upward trend rates ranged from 6.25 mm/decade at Lintao station to 11.03 mm/decade at Hohhot station.

The area-average magnitudes (mm/decade) of ET_0 trend were +1.58, -2.26, +0.65, and +0.25 for spring, summer, autumn, and winter, respectively (Table 1). However, these trends were not significant, which reflects the seasonal differences in ET_0 trend. Spring ET_0 slowly increased from the 1960s to early 1980s, decreased rapidly until the early 1990s, increased rapidly until early 2000s, and then again decreased rapidly. Summer ET_0 exhibited an increasing

trend in the 1960s and first-half of the 1970s, decreased significantly during 1974–1989, increased again until 2001, and then decreased again during 2001–2011. Autumn ET_0 had an increasing trend before 1998, and then decreased significantly. Winter ET_0 showed a very weak decreasing trend before 1990, followed by an increasing trend (Fig. 3).

In 49.1 % of the annual ET_0 series, a decreasing trend was detected during 1958–2011, but only 19.3 % of the series showed a significant declining level at the 90 % confidence level. The stations with a significant decreasing trend were mainly distributed in the southeastern, northwestern, and western regions of the plateau, whereas a significant increasing trend, accounting for 21.1 % of all stations, was seen in the southwestern and northeastern

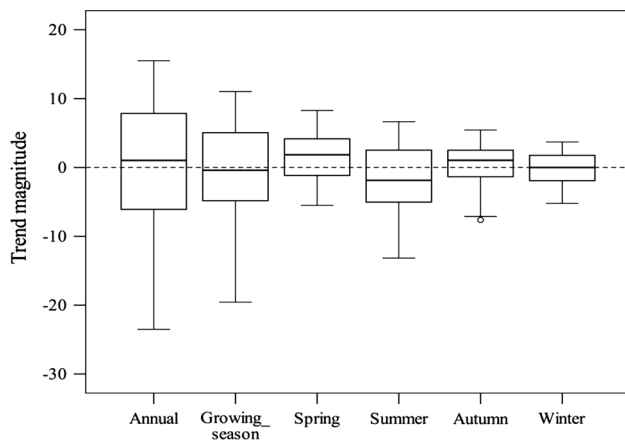


Fig. 4 Box and whisker plot of ET_0 trend magnitude

regions of the study area (Fig. 5a). In the growing season, 50.9 % of stations showed a decreasing trend, and the regional ET_0 as a whole decreased by 1.26 mm/decade. The trends showed statistically significant increases at 17.5 % of stations and decrease at 14.0 % of stations (Fig. 5b). The spatial pattern was similar to that of the annual ET_0 trend.

About 66.7 % of the spring ET_0 series displayed an increasing trend and statistical significance was found at 24.6 % of stations, distributed mainly in the middle and southern regions of the study area. A statistically significant decreasing trend was observed in the northwestern and western regions of the area, accounting for only 7.0 % of total stations (Fig. 5c). In 64.9 % of summer ET_0 series, a decreasing trend was observed but only 26.3 % tested significantly at the 0.1 significance level; these were mainly centered in the southeastern and eastern regions but were also dispersed in the northern and western regions of the area (Fig. 5d). In autumn, the numbers of stations with increase trends (31 stations) was greater than that with decreasing trends (26 stations), but there were more stations with significant decreasing trends (11 stations) than with increasing trends (9 stations) (Fig. 5e). In winter, 50.9 % of the ET_0 series exhibited a decreasing trend, but only 19.3 % of the series showed a significantly declining level at the 90 % confidence level (Fig. 5f). The ET_0 with significant trends in autumn and winter exhibited a dispersed spatial distribution.

3.3 Changes in meteorological variables

Annual T_{max} and T_{min} fluctuated as they rose before the mid-1980s, and then increased significantly until the early 2000s. Annual RH fluctuated slightly in the fall before the early 1990s, and then decreased significantly. Precipitation has decreased continuously since 1958. Wind speed

(WS) decreased significantly during 1958–2011; however, blips occurred in the late-1960s and early-1990s. SD decreased significantly during the period 1958–2011 but an increase occurred in the 1990s (Fig. 6).

The MK tests showed significant increasing trends for the annual T_{max} and T_{min} at most of stations, respectively (Fig. 6). As a whole, T_{max} and T_{min} increased by 0.28 and 0.33 °C/decade. All seasonal T_{max} and T_{min} values exhibited a significant increasing trend, but the magnitudes at most stations were lower for T_{max} than for T_{min} (Table 1). Most of stations showed a downward trend in RH in most seasons except winter (Table 1). The area-averaged annual RH decreased by 0.44 %/decade. About 94.7 % of stations showed a decreasing trend in precipitation, but only 21.1 % were found to be statistically significant (Table 1; Fig. 6). The decreasing trends in precipitation were found in most seasons except the winter. The area-averaged annual precipitation decreased by 15.1 mm/decade (Table 1). About 66.7 % of stations were found the significant decreasing trends in annual WS. However, 12.3 % were also found to have significant increasing trends (Table 1; Fig. 6). The MK tests also showed significant decreasing trends in WS at most of stations in all seasons. The area-averaged WS decreased by 0.098 m/s/decade over the past 54 years in annual (Table 1). The annual SD series saw decreasing trends at most of stations, and 57.9 % were found to be statistically significant (Table 1). In seasonal timescales, most of SD series showed decreasing trend. The area-averaged SD decreased significantly by 0.107 h/d/decade annually (Table 1).

3.4 Contribution from meteorological factors

Across the whole Loess Plateau, annual ET_0 variation was mainly dominated by increasing T_{max} (0.28 °C/decade) and decreasing WS (0.098 m/s/decade) during 1958–2011, which accounted for 27.5 and 26.0 % of the variation, respectively. In addition, the decreases in precipitation and RH also contributed 15.7 and 13.4 % of the variation, respectively. In the growing season (29.3 and 28.4 %) and summer (26.9 % and 25.5 %), T_{max} and WS, respectively, contributed to greater ET_0 variations. In spring, autumn, and winter, the most important contributors were T_{max} and RH, which caused an increase in ET_0 . In general, the variation of ET_0 was mainly dominated by T_{max} and WS at the annual, growing season, and summer scales, and by T_{max} and RH in spring, autumn, and winter.

Figure 7 shows the contributing ratios of meteorological variables and the dominant factors that affected the variation of ET_0 for the 57 stations at different timescales. Annually, WS was the most important dominant factor, affecting ET_0 variation at 48 of the 57 stations. The T_{max} also dominated ET_0 variations at a further 5 stations. In the

Table 1 Statistic of annual and seasonal trend of ET_o (mm/decade), T_{max} (°C/decade), T_{min} (°C/decade), RH (%/decade), VPD (/decade), WS (m/s/decade), SD (h/d/decade) and P (mm/decade) for 57 meteorological stations in the Loess Plateau

Season	Variable	Magnitude of trend	Decreasing	Increasing	Season	Variable	Magnitude of trend	Decreasing	Increasing
Annual	ET _o	-1.24	28 (49.1 % , <i>19.3 %</i>)	29 (50.9 % , <i>21.1 %</i>)	Summer	ET _o	-2.26	37 (64.9 % , <i>26.3 %</i>)	20 (35.1 % , <i>12.3 %</i>)
	T _{max}	0.28	0 (0.0 % , <i>0.0 %</i>)	57 (100.0 % , <i>94.7 %</i>)		T _{max}	0.19	9 (15.8 % , <i>1.8 %</i>)	48 (84.2 % , <i>50.9 %</i>)
	T _{min}	0.33	2 (3.5 % , <i>1.8 %</i>)	55 (96.5 % , <i>89.5 %</i>)		T _{min}	0.25	3 (5.3 % , <i>3.5 %</i>)	54 (94.7 % , <i>71.9 %</i>)
	RH	-0.44	41 (71.9 % , <i>36.8 %</i>)	16 (28.1 % , <i>3.5 %</i>)		RH	-0.45	43 (75.4 % , <i>28.1 %</i>)	14 (24.6 % , <i>7.0 %</i>)
	VPD	0.019	3 (5.3 % , <i>1.8 %</i>)	54 (94.7 % , <i>80.7 %</i>)		VPD	0.025	9 (15.8 % , <i>5.3 %</i>)	48 (84.2 % , <i>47.4 %</i>)
	WS	-0.098	46 (80.7 % , <i>66.7 %</i>)	11 (19.3 % , <i>12.3 %</i>)		WS	-0.071	41 (71.9 % , <i>52.6 %</i>)	14 (24.6 % , <i>12.3 %</i>)
	SD	-0.107	44 (77.2 % , <i>57.9 %</i>)	13 (22.8 % , <i>5.3 %</i>)		SD	-0.154	48 (84.2 % , <i>56.1 %</i>)	9 (15.8 % , <i>1.8 %</i>)
Growing season	P	-15.11	54 (94.7 % , <i>21.1 %</i>)	3 (5.3 % , <i>0.0 %</i>)	Autumn	P	-8.27	50 (87.7 % , <i>7.0 %</i>)	7 (12.3 % , <i>0.0 %</i>)
	ET _o	-1.26	29 (50.9 % , <i>14.0 %</i>)	28 (49.1 % , <i>17.5 %</i>)		ET _o	0.65	26 (45.6 % , <i>19.3 %</i>)	31 (54.4 % , <i>15.8 %</i>)
	T _{max}	0.24	1 (1.8 % , <i>0 %</i>)	56 (98.2 % , <i>82.5 %</i>)		T _{max}	0.32	0 (0.0 % , <i>0.0 %</i>)	57 (100.0 % , <i>93.0 %</i>)
	T _{min}	0.29	3 (5.3 % , <i>1.8 %</i>)	54 (94.7 % , <i>86.0 %</i>)		T _{min}	0.27	5 (8.8 % , <i>1.8 %</i>)	52 (91.2 % , <i>77.2 %</i>)
	RH	-0.64	46 (80.7 % , <i>42.1 %</i>)	10 (17.5 % , <i>1.8 %</i>)		RH	-0.42	40 (70.2 % , <i>26.3 %</i>)	17 (29.8 % , <i>3.5 %</i>)
	VPD	0.028	4 (7.0 % , <i>0.0 %</i>)	53 (93.0 % , <i>71.9 %</i>)		VPD	0.013	9 (15.8 % , <i>1.8 %</i>)	47 (82.5 % , <i>50.9 %</i>)
	WS	-0.086	44 (77.2 % , <i>57.9 %</i>)	13 (22.8 % , <i>12.3 %</i>)		WS	-0.085	45 (78.9 % , <i>54.4 %</i>)	12 (21.1 % , <i>10.5 %</i>)
Spring	SD	-0.101	44 (77.2 % , <i>49.1 %</i>)	13 (22.8 % , <i>1.8 %</i>)	Winter	SD	-0.096	41 (71.9 % , <i>47.4 %</i>)	15 (26.3 % , <i>0.0 %</i>)
	P	-12.43	53 (93.0 % , <i>17.5 %</i>)	4 (7.0 % , <i>1.8 %</i>)		P	-4.5	45 (78.9 % , <i>10.5 %</i>)	12 (21.1 % , <i>0.0 %</i>)
	ET _o	1.58	19 (33.3 % , <i>7.0 %</i>)	38 (66.7 % , <i>24.6 %</i>)		ET _o	0.25	29 (50.9 % , <i>19.3 %</i>)	28 (49.1 % , <i>21.1 %</i>)
	T _{max}	0.28	0 (0.0 % , <i>0.0 %</i>)	57 (100.0 % , <i>70.2 %</i>)		T _{max}	0.34	0 (0.0 % , <i>0.0 %</i>)	57 (100.0 % , <i>75.4 %</i>)
	T _{min}	0.29	4 (7.0 % , <i>1.8 %</i>)	53 (93.0 % , <i>77.2 %</i>)		T _{min}	0.49	1 (1.8 % , <i>1.8 %</i>)	56 (98.2 % , <i>87.7 %</i>)
	RH	-1.17	55 (96.5 % , <i>42.1 %</i>)	2 (3.5 % , <i>0.0 %</i>)		RH	0.21	18 (31.6 % , <i>3.5 %</i>)	39 (68.4 % , <i>12.3 %</i>)
	VPD	0.03	1 (1.8 % , <i>0.0 %</i>)	56 (98.2 % , <i>73.7 %</i>)		VPD	0.005	7 (12.3 % , <i>1.8 %</i>)	50 (87.7 % , <i>31.6 %</i>)
Winter	WS	-0.114	49 (86.0 % , <i>64.9 %</i>)	8 (14.0 % , <i>10.5 %</i>)	WS	-0.116	46 (80.7 % , <i>63.2 %</i>)	11 (19.3 % , <i>10.5 %</i>)	
	SD	0.027	30 (52.6 % , <i>19.3 %</i>)	27 (47.4 % , <i>21.1 %</i>)	SD	-0.167	52 (91.2 % , <i>61.4 %</i>)	5 (8.8 % , <i>0.0 %</i>)	
	P	-2.61	40 (70.2 % , <i>10.5 %</i>)	17 (29.8 % , <i>0.0 %</i>)	P	0.25	10 (17.5 % , <i>3.5 %</i>)	47 (82.5 % , <i>10.5 %</i>)	

Percentage of stations (bold) and Percentage of stations shown significant ($p < 0.1$) trends (Italics) are indicated in parenthesis, for both decreasing and increasing trends

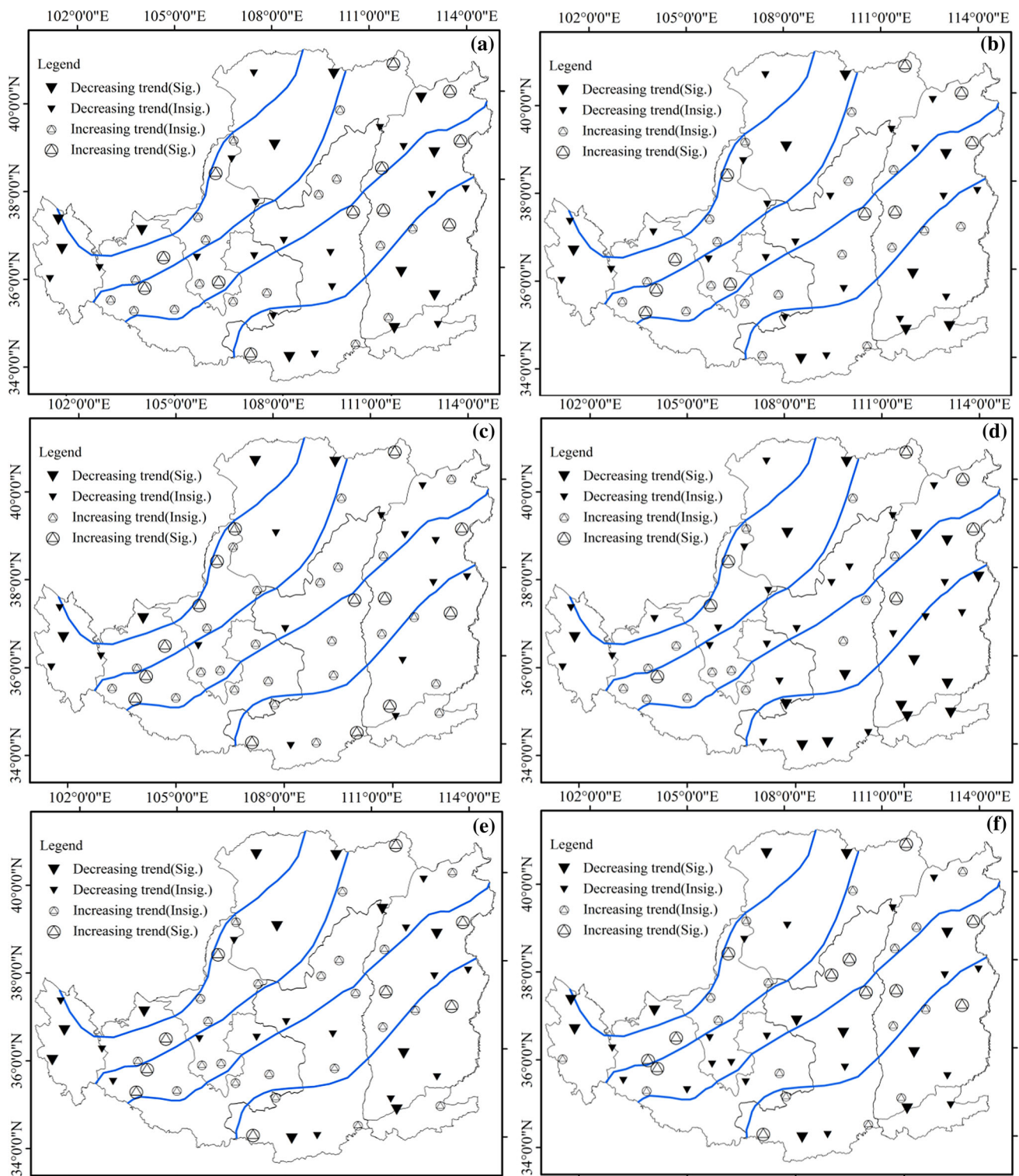
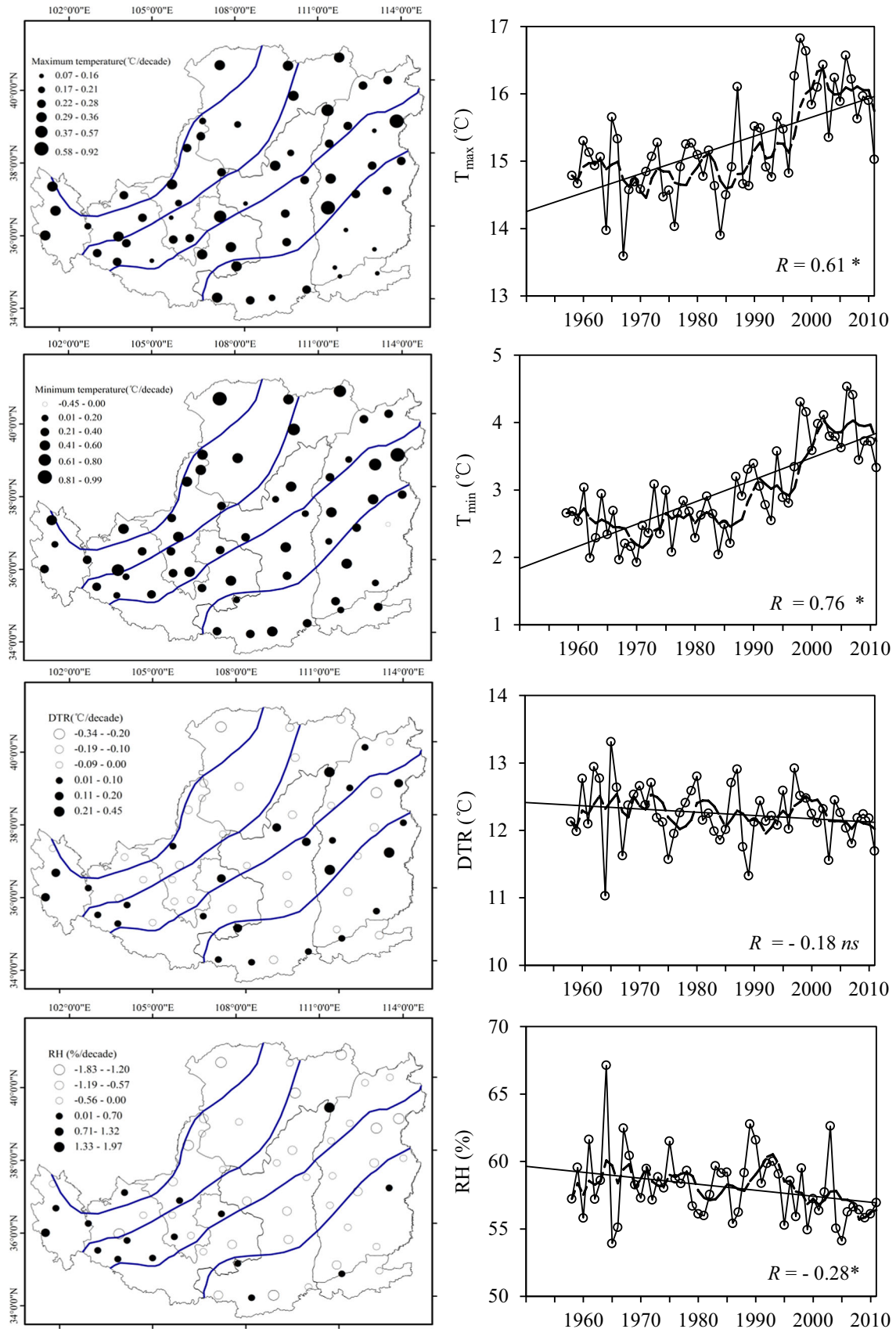


Fig. 5 Trends of annual and seasonal ET_0 during 1958–2011. **a–f** Is annual, growing season, spring, summer, autumn and winter, respectively

growing season, WS was also one of the most important factors, dominating the ET_0 variation at 38 stations. The RH and SD also dominated ET_0 variations at 8 stations, respectively. There were 35, 30, 39, and 29 stations

dominated by WS in spring, summer, autumn, and winter, respectively. In addition, RH was the other important contributing variable to spring ET_0 variation at 13 stations. In summer, SD was another important factor, dominating



◀ **Fig. 6** Spatial pattern of Sen's slope per decade and area-average curve of annual T_{\max} , T_{\min} , RH, P, WS and SD in the Loess Plateau during 1958–2011

ET_o variation at 17 stations. In autumn, T_{\max} and RH dominated the ET_o change at 8 and 9 stations, respectively. In winter, T_{\max} also dominated the ET_o change at 22 stations.

3.5 Influences of human activities on ET_o trend

Figure 8 indicates a statistically significant negative correlation between the trend magnitude of ET_o and the percentage of cultivated land ($r = -0.410$, $p < 0.05$) for agricultural stations in the growing season. Significant correlation for agricultural stations was also observed in annual ($r = -0.371$, $p < 0.05$), spring ($r = -0.365$, $p < 0.05$), summer ($r = -0.365$, $p < 0.05$), and autumn ($r = -0.373$, $p < 0.05$). For the urban stations, the significant correlation between the trend magnitude and the ratio of cultivated land was non-significant at all timescales. In addition, no significant correlations were found for the natural and combined stations at different timescales. There were no significant positive correlations between the ET_o trend magnitude and ratio of urban land for the agricultural and urban stations at all timescales (Fig. 8).

The average values of ET_o trend magnitudes are compared in Table 2 for the agricultural, natural, and urban stations at different timescales. Increasing trends were seen for the natural stations, but decreasing trends were observed for urban and agricultural stations. Furthermore, the decreasing trend for urban stations was more obvious than for agricultural stations.

4 Discussion

4.1 ET_o trend and its driving factors

Based on the FAO-56 Penman–Monteith method, annual ET_o showed both increasing and decreasing trends in the Loess Plateau. At other timescales, similar trends were also found. Trends in ET_o are often considered as an important indicator of climate change, and are influenced by many climatic factors (Li et al. 2014a).

In the Loess Plateau, the decreases in ET_o were mainly due to the decreases in WS at almost all timescales. This is similar to many studies in China (Li et al. 2014b). Decreases in WS have also been found in other regions (Hoffman et al. 2011). Decreases in WS may be related to changes in large-scale atmospheric circulation associated

with global warming. Usually, weak atmospheric circulation is suggested as the reason for WS decrease (Zhang et al. 2009). A weakened Siberian High (Tubi and Dayan 2013), a declining temperature gradient between the polar and tropical regions, and weakening of the East Asian Monsoon (Xu et al. 2006) commonly reduce the strength of atmospheric circulation and WS (McVicar et al. 2012). In addition, an increase in land surface roughness due to grain-for-green, afforestation, reforestation, and urbanization near the meteorological stations may be the cause of WS decreases. However, wind speeds at some meteorological stations also showed significant increasing trends, which further induced an increase in ET_o . Due to its complexity, the reasons for decreasing or increasing WS in the Loess Plateau need to be further studied.

T_{\max} was one of the dominant factors in ET_o change for the plateau as a whole, which was similar to some other studies (Tabari et al. 2011). Most stations showed significant increasing trends in T_{\max} and T_{\min} at all timescales. The warming trend in this study area is consistent with global warming from other studies (Tabari and Hosseinzadeh Talaei 2011; Najafi et al. 2015). However, in the present study, the increasing trends with T_{\max} and T_{\min} of 0.28 and 0.33 °C/decade, respectively, are generally higher than the increases reported for other parts of the world (IPCC 2007). The most common asymmetry of air temperature was associated with the general decreasing tendency detected for the diurnal temperature range. The increasing trends in air temperature were due to several factors such as increasing emissions of anthropogenic greenhouse gases and aerosols (Najafi et al. 2015; Xu et al. 2015), increased cloud cover, and urbanization (Ji and Zhou 2011).

Some studies have found that a decrease in solar radiation is also one of the reasons for decreasing ET_o (Yin et al. 2010). Solar radiation was considered as an important influencing factor inducing the change in ET_o at the Loess Plateau, especially in summer and the growing season. Decreasing trends in SD were also observed at most stations, which is similar to other regions (Li et al. 2014a, b; Fan and Thomas 2013). However, increasing trends were found in the middle and western regions of the plateau. The radiation change remains subject to debate. Increasing cloud cover and aerosol abundance may be the major factors responsible for radiation decrease. Regional cloud cover increase has induced global dimming (Dai et al. 2006). However, the hypothesis of increased cloud cover as the cause of radiation reduction at the Loess Plateau does not seem plausible because of the evidence for widespread decreasing trends in precipitation. Aggregated aerosols and pollution have also been considered as primary dimming factors (Streets et al. 2008). Increased atmospheric humidity and pollution from energy consumption due to human activities have also contributed to radiation

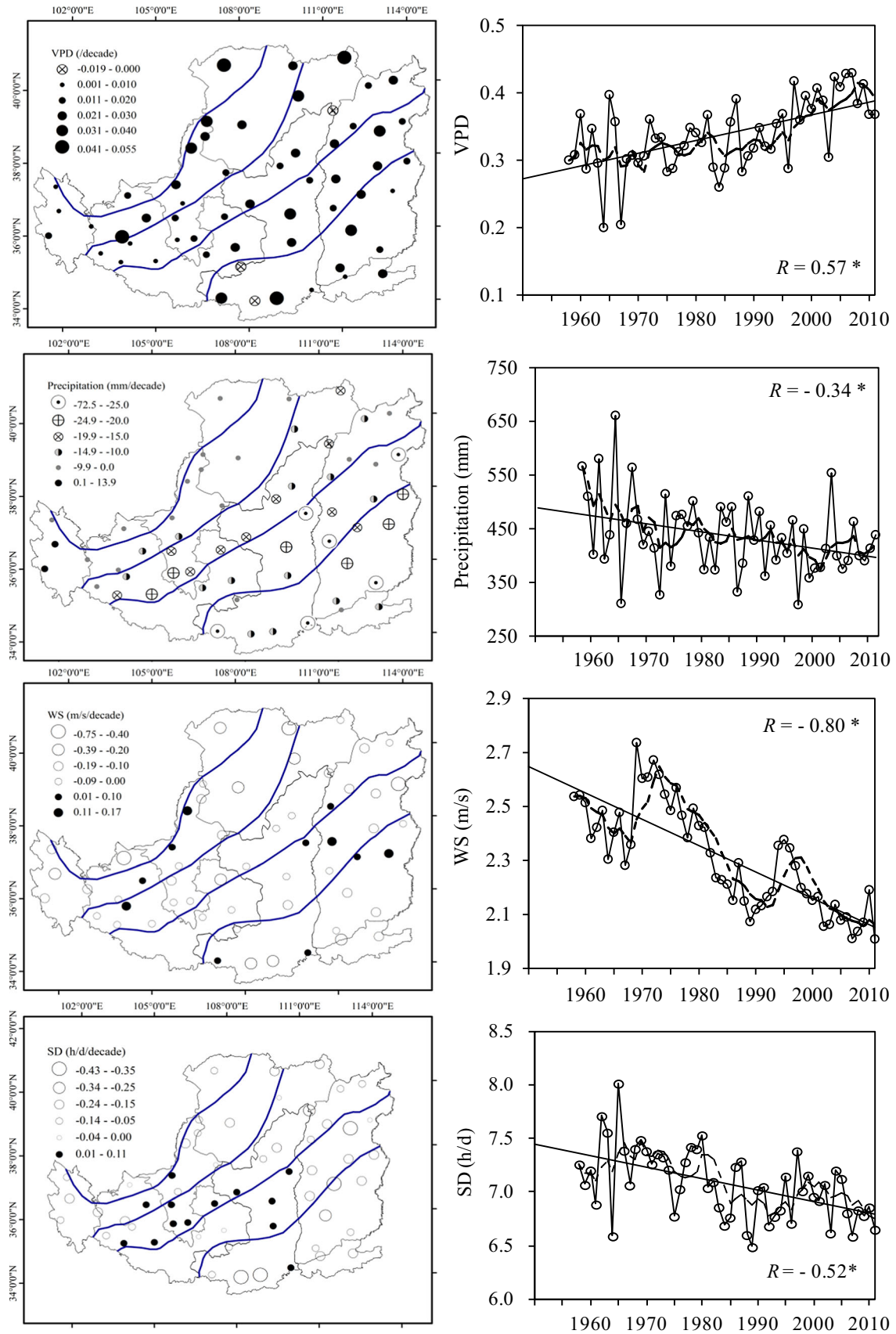


Fig. 6 continued

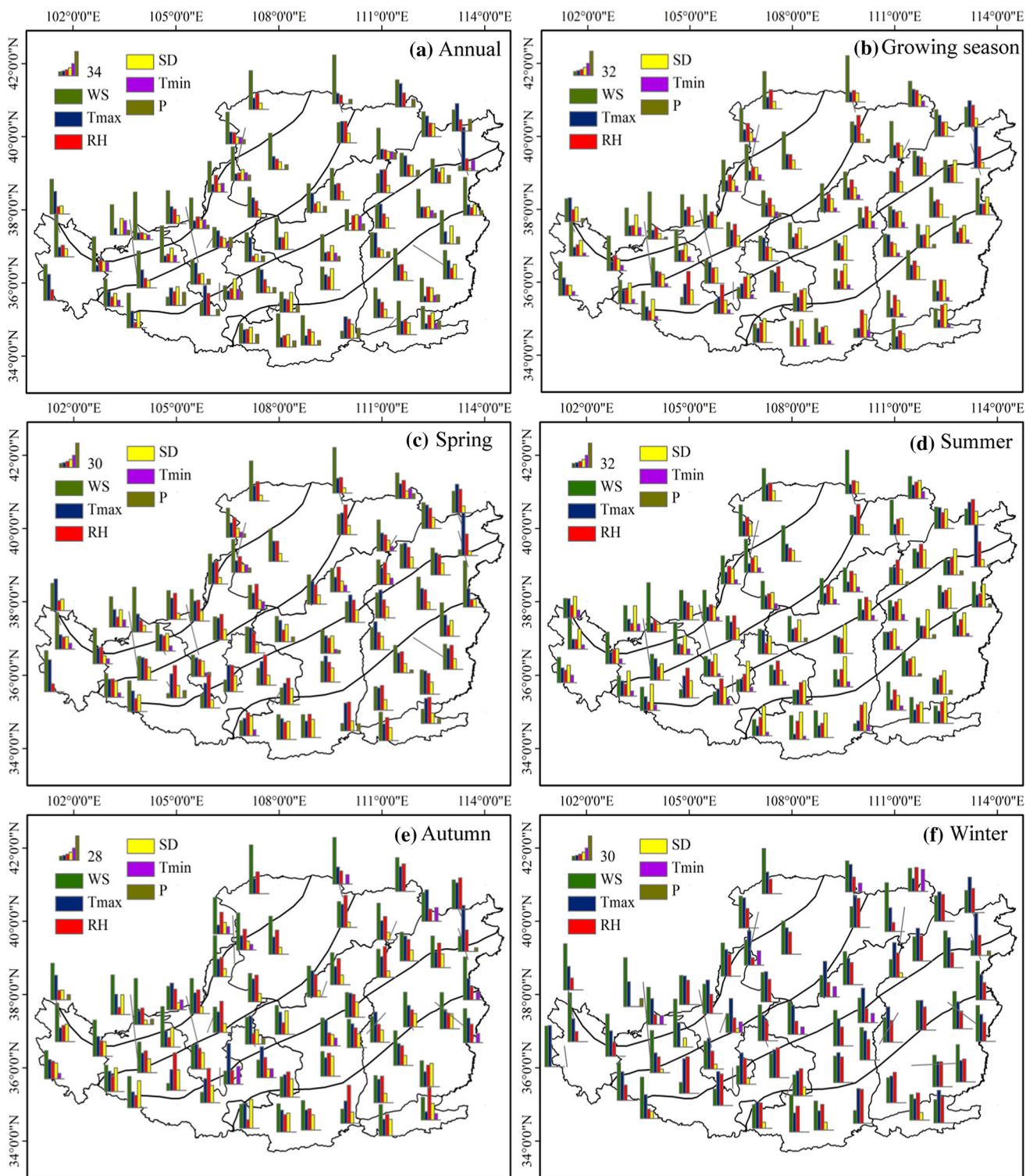


Fig. 7 Contribution ratios of different meteorological variables to ET_0 trend

dimming (Xie and Wang 2007). Slower WS have weakened the diffusion of aerosols and other pollutants, thereby reducing SD (Yang et al. 2009). The increase of radiation in the middle and western regions of the plateau may be

induced by the decrease in precipitation and lower emissions of industrial aerosols. In addition, the reduction of dust aerosols originating from the desert (Huang et al. 2014) in spring may also help to increase solar radiation.

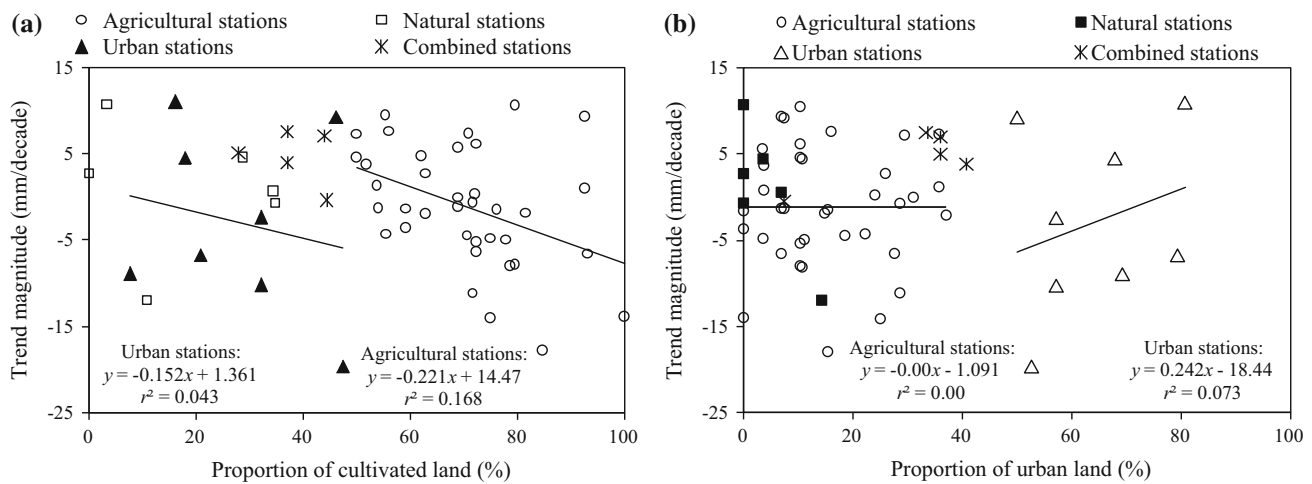


Fig. 8 Plots of trend in growing season ET_0 against the proportion of cultivated land and urban land with a 3-km radius of each stations in the growing season

Table 2 ET_0 trend magnitudes of different land use during 1958–2011

Type	Stations	Percentage of land use (%)			Average trend magnitude (mm/decade)					
		Natural vegetation	Cropland	Urban land	Annual	Growing season	Spring	Summer	Autumn	Winter
Agricultural stations	38	14.6	70.1	15.3	-0.94	-1.09	1.47	-2.02	0.10	-0.19
Urban stations	8	8.2	27.5	64.2	-3.18	-2.84	-0.46	-3.06	-0.67	-0.92
Natural stations	6	77.2	18.7	4.1	1.37	1.05	2.31	-1.32	1.21	0.43
Combined stations	5	30.4	38.8	30.7	6.04	4.63	3.88	0.66	1.94	0.76
All stations	57	21.7	55.9	22.3	-1.24	-1.26	1.58	-2.26	0.65	0.25

Precipitation for the Loess Plateau showed decreasing trends at most stations and timescales, which may have also indirectly influenced the changes in RH, solar radiation, and vapor pressure deficit, and, further, the trend in ET_0 . The RH was observed with decreasing trends at most of timescales, which affected the variation in ET_0 . However, the increasing trend in RH was consistent with the increasing precipitation in winter. The RH was also one of the dominant factors affecting ET_0 trend in spring, autumn, and winter.

Variation in ET_0 may be affected by the coupling between the surface and atmospheric boundary layers at the landscape scale (Shuttleworth et al. 2009). Agricultural activities and urban growth are important artificial processes that contribute to interactions between the land surface and atmosphere (Han et al. 2012, 2014; Rim 2009). Some research has focused on the impacts of large-scale land use change on climatic variables and ET_0 (Han et al. 2012; Rim 2009). In the Loess Plateau, more significant decreasing trends were observed at urban and agricultural stations than at natural stations, which may be mainly due to local climatic effects induced by agricultural activities

and urbanization. More attention should be focused on quantifying the impact of agricultural activities and urbanization on ET_0 to improve our understanding of its implications for eco-hydrology, water resources, regional ecology, and agricultural production in the context of climate change.

4.2 Influence on ecological projects and vegetation restorations

To control the serious soil erosion in the Loess Plateau, many ecological projects, including grain for green, afforestation, reforestation, and small watershed managements, have been performed. Soil water shortage is the main limiting factors for these projects. The change in ET_0 may have been a substantial impact on these ecological projects. We found that regional annual ET_0 had a weak decreasing trend with a magnitude of 1.24 mm/decade, suggesting a weak decrease in water demand by vegetation. However, annual precipitation was observed with a significant decreasing trend with a magnitude of 15.11 mm/decade, which indicates that stronger drought would occur

frequently. Increasing drought occurrence may restrict the performance of regional vegetation restoration and ecological projects, and may even induce vegetation degradation. However, there was spatial differentiation for drought trends in this study. Greater decreasing trends in ET_o than in precipitation were found in the western and northwestern regions of the plateau, which suggests that more soil moisture could be supplied to the vegetation. This is likely beneficial to the implementation of ecological projects. Moreover, it may also reduce the occurrence of desertification in the northwest of the plateau. In the central region of the Loess Plateau, increasing drought would impede the growth of vegetation and the implementation of projects. In this region, frequent drought may lead to vegetation degradation, conversely enhancing soil erosion.

A dried soil layer, with soil water content lower than the stable field capacity, was found to be widespread in the Loess Plateau. This was developed by the climatic conditions of low rainfall and high evapotranspiration (Chen et al. 2009). The occurrence of a dried soil layer can impede or reduce soil moisture exchange between the surface and deep soil, leading to a lowering of soil moisture storage, and increased vegetation degradation or death (Wang et al. 2011). An increasing drought trend may enhance the development of dried soil layers which may seriously affect vegetation restoration and implementation of ecological projects. To better implement such projects in the future, more drought-resistant species should be utilized in these projects.

In the Kubuqi desert and Mu Us sand land located in the northwest of the plateau, dust storms occur frequently in spring, and this is dominated by strong wind, low vegetation cover, and low soil moisture (Tan et al. 2012). We found increasing precipitation, and decreasing ET_o and WS, in spring and winter in the dust storm source regions, and this may result in the increased soil moisture. The increasing soil moisture and decreasing WS commonly impeded the occurrence of dust storm events in spring. A study also showed that dust storm days had a significant decreasing trend from 1958 to 2007 in our study area, decreasing in the mid-1960s through the end of the 1990s, and slightly increasing thereafter (Wang et al. 2010); this was related to the changes in precipitation, ET_o , and WS in spring and winter. It also suggested that the decreasing ET_o in this region may help reduce the occurrence of dust storms and desertification.

4.3 Influence on agricultural production and hydrological cycle

As an important agricultural region of China, crops are mainly developed by irrigation in the Weihe–Fenhe, Hetao, and Yinchuan plains and were rainfed in the gully regions

of the Loess Plateau. The variation in ET_o would affect regional agricultural production and food security. In the growing season, a greater decreasing trend for precipitation than for ET_o may not be beneficial to crop production in rainfed agricultural regions. The decreasing ET_o represents a decline in evaporative demand in the Weihe–Fenhe and Hetao plains. However, the increasing ET_o may cause increasing water demand by various crops in the Yinchuan plain. In autumn, decreasing precipitation and weak increasing ET_o in autumn may be harmful to newly-sown winter wheat; whereas the significantly increasing snow and decreasing ET_o in winter would help improve soil moisture in rainfed agricultural regions and promote the crop growth in spring. However, the larger decreasing trend for precipitation than for ET_o in spring may increase the frequency of drought events, further inducing a more serious water deficit for crops and leading to a requirement for more irrigation in the plains. In our study, summer ET_o showed a decreasing trend, suggesting a decreasing crop water demand; however, the magnitudes of decreasing precipitation were greater, indicating that more irrigated water will be required to maintain crop production. Therefore, considering the temporal and spatial distributions of ET_o and precipitation, reasonable management of water resources might be the focus of agricultural management in the context of climate change.

In the context of climate change, the terrestrial hydrological cycle will also become altered. In the past several decades, runoff was also observed to exhibit declining trends in many rivers (Guo et al. 2014; Zhang et al. 2011). In addition, the increasing drought in most regions of the study area would decrease soil moisture, and further decrease runoff. The increasing of crop water demand in the Yinchuan plain will require more irrigated water from the Yellow River, further inducing a reduction in runoff. Thus, it can be concluded that the main hydrological components, i.e., precipitation, runoff, and evapotranspiration, experienced decreasing trends, suggesting weaker hydrological cycles in the Loess Plateau.

5 Conclusions

Both decreasing and increasing trends were detected in annual and seasonal ET_o series at different stations during 1958–2011. The MK tests also showed significant increasing trends in T_{max} and T_{min} but significant decreasing trends in RH, precipitation, WS, and SD. The WS appeared to be the most important factor responsible for the decreasing and increasing trends in ET_o at most stations at all timescales. However, the secondary dominant factor was found to be SD in summer, RH in spring and autumn, and T_{max} in winter. We also found that

agricultural cultivation and urbanization significantly affected the change in ET_o trends. In comparing the ET_o trend magnitudes across the different land uses, the human activities, such as cultivation and urbanization, promoted the decrease in ET_o trend. Furthermore, the impact on ET_o trend was more obvious for the urbanization than cultivation.

Due to the greater decreasing trends for precipitation than for ET_o at different regions in the Loess Plateau, droughts were observed with an increasing trend, which would affect the implementation of many ecological projects, the occurrence of dried soil layers, dust storms, desertification, and agricultural production of the study area. The more accurate evaluation of ET_o in response to changes in meteorological variables may be beneficial to the design and operation of agricultural systems, and to revegetation planning for ecological restoration and agricultural production in the future. The ET_o variations due to meteorological variables and human activities should receive more attention in order to understand the hydrological cycle and water management in the Loess Plateau under conditions of global change.

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