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Spatiotemporal variation of reference evapotranspiration during 1954–2013 in Southwest China

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ABSTRACT

Analysis of temporal trend and spatial variation of reference evapotranspiration (ET_0) is important in Southwest China, where water resources are vulnerable under the impacts of climate changes and human activities. The main objective of this study was to analyze temporal and spatial variation of ET_0 computed by FAO-56 Penman-Monteith model for 119 stations in Southwest China during the period of 1954–2013. Mann-Kendall test, linear trend, Morlet wavelet analysis and inverse distance weighting interpolation methods were applied for the analysis. The results showed that during the past 60 years, annual sunshine hours, relative humidity, wind speed and precipitation decreased while temperature increased. ET_0 decreased at a rate of −1.5 mm per decade, or −0.4, −0.7, −0.3, and −0.1 mm per decade in spring, summer, autumn, and winter, respectively. There existed significant periods of 26, 12 and 5a in annual ET_0 series based on the Morlet wavelet analysis. Lower and higher ET_0 values were found in the northeast and southwest regions both for annual and spring series. These findings will be useful for sustainable planning of water resources under the impacts of climate changes and human activities.

1. Introduction

As reported by the Intergovernmental Panel on Climate Change (IPCC, 2007), surface air temperature has risen by an average of 0.74 °C in recent 100 years (1906–2005) and global temperature may rise by 1.1–6.4 °C in the next hundred of years. As a connection between energy balance and water balance, evapotranspiration (ET) is an important indicator for the activity of climate change and water cycle. (Wang et al., 2012; Xu and Singh, 2005). Evapotranspiration not only plays a key role in the energy budget of the earth-atmospheric system, but also is an essential component of water balance (Zhang et al., 2007; Wang et al., 2007). Reference evapotranspiration (ET_0) is defined as the rate of ET from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s/m and an albedo of 0.23, where the reference surface closely resembled an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water (Allen et al., 1998). It is an important component of hydrological cycles in agricultural ecosystems, which is often used to derive actual evapotranspiration (Fan et al., 2016). A better understanding of spatiotemporal trends in ET_0 is of great significance for regional cropping system management and regional hydrological and ecological research (Wang et al., 2014; Fan et al., 2016).

The increase of surface temperature is expected to accelerate the hydrological cycle and increase ET_0 as studies around the world indicate (Jiang et al., 2011; Fu et al., 2013; Li et al., 2015). However, relevant literature showed that ET_0 and pan evaporation, had decreased over the past decades in many areas of the world, such as the United States (Irmak et al., 2012), Australia (Rayner, 2007), and Thailand (Tebakari et al., 2005), which is known as "evaporation paradox" (Peterson et al., 1995; Roderick and Farquhar, 2002). The same phenomena of ET_0 decreasing have also been found in China (Wang et al., 2007; Zhang et al., 2007, 2010; Huo et al., 2013; Feng et al., 2014a), which revealed the existence of "evaporation paradox" in China. Wang et al. (2011) analyzed the spatial and temporal patterns of ET_0 at 34 meteorological stations (between

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1957 and 2007) in the Haihe River basin of China, using the Mann-Kendall (M-K) test and the Sen's method, they found the Haihe River basin was dominated by a significant decreasing trend in annual ET_0 at > 95% confidence level. Liu and Zhang (2013) examined trends of ET_0 at 80 meteorological stations during 1960–2010 in the driest region of China (Northwest China), they found that there was a change point for ET_0 series around the year 1993 based on the Pettitt's test, ET_0 decreased from 1960 to 1993 by while began to increase since 1994. Zhang et al. (2015) applied M-K method, wavelet transform and simple linear regression to investigate the temporal trends and spatial distributions of ET_0 in the Yellow River Basin of China, from 1961 to 2012, the results showed that the annual mean ET_0 had a significant declining trend at the rate of 1.29 mm per year. However, Li et al. (2012) found ET_0 increased significantly due to the downward trend in relative humidity and upward trend in temperature on the Loess Plateau during 1961–2009.

Recently a severe drought occurred in Southwest China during the period from the autumn of 2009 to the spring of 2010, which affected more than 60 million people (Yan et al., 2013). The Ministry of Civil Affairs of China revealed that the direct economic loss exceeded 23.66 billion CNY (Feng et al., 2014b). Water resources in Southwest China are vulnerable under the impacts of climate change and human activities. It is necessary to analyze the variation of ET_0 in this region, which can provide reasonable water regulation and management-options to maintain the eco-hydrological system (Zhang et al., 2015). Fan and Thomas (2013) found annual and seasonal ET_0 rates declined, with most remarkable decreases during pre-monsoon (−1.5 mm per decade, Mar–May) and monsoon (−0.6 mm per decade, Jun–Aug) seasons over Yunnan Province of Southwest China. Yin et al. (2010) found the declining ET_0 trend was attributed to decreased sunshine duration in Southwest China. However, quantitative analyses on annual and seasonal changes of ET_0 are still limited in Southwest China.

The main objectives of this study are: (1) to analyze annual and seasonal patterns of ET_0 series in Southwest China from 1954 to 2013; (2) to quantify the annual and seasonal trends of ET_0 series, and present spatial structure of the trends (3) to analyze periods of ET_0 series under the conditions of climate changes; and (4) to discuss the “evaporation paradox” in Southwest China.

2. Materials and methodologies

2.1. Study area and dataset

Southwest China includes Sichuan, Yunnan and Guizhou Provinces, Guangxi Autonomous Region and Chongqing Municipality of China. It covers 1.4 million km^2 and has a population of 0.2 billion. In this study, Southwest China was divided into four regions based on topography conditions: (I) western-Sichuan Plateau (WSP), (II) Sichuan Basin (SB), (III) Yunnan-Guizhou Plateau (YGP), and (IV) Guangxi (GX) (Fig. 1).

There are 141 national meteorological stations in Southwest China, the stations were selected by the following criteria: the time series had to be long enough to obtain statistically significant results in trend analyses, and the missing data of one station is no more than 0.1%, thus 119 stations were selected (Fig. 1). Six daily meteorological variables between 1954 and 2013 were recorded, including minimum air temperature (T_{min}, ^{0}C), maximum air temperature (T_{max}, ^{0}C), mean relative humidity (RH, %), wind speed at 10 m (U_{10}, m/s), sunshine hours (n, h/d), and precipitation (P_r, mm/d). Mean daily air temperature was calculated as the average of the maximum and minimum air temperatures. Missing daily data which account for about 0.92% of the 119 stations were reconstructed by averaging the meteorological data from the neighboring stations.

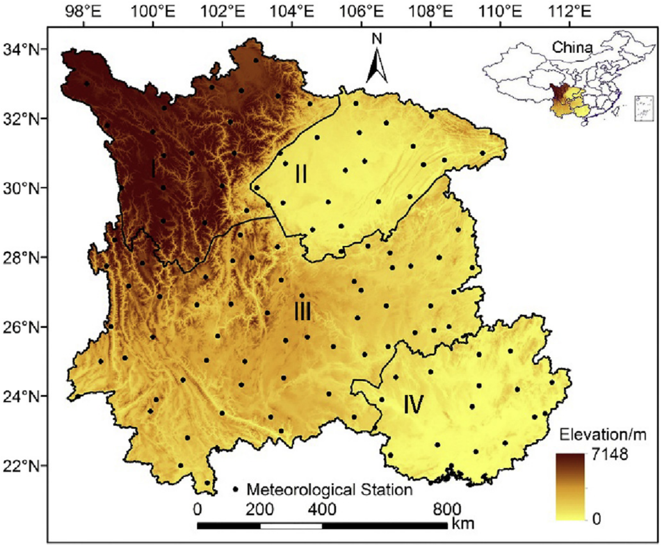

Fig. 1. Study area and locations of meteorological stations.

2.2. Calculation of reference evapotranspiration and wetness index

Measured ET_0 data were not available in the study area, thus the FAO-56 Penman-Monteith (P-M) model was applied to calculate ET_0, which is an accepted and very common practice when ET_0 measurements are not directly available, as recommended by FAO (Allen et al., 1998; Kisi, 2016; Feng et al., 2016, 2017). FAO recommended the P-M model as the sole standard method to estimate ET_0, which was proved well for various climates and time step calculations without any local calibration (Lopez-Urrea et al., 2006; Valiantzas, 2013; Feng et al., 2014a). The P-M model is expressed as the follows

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{mean}+273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{1}$$

Where ET_0 is reference evapotranspiration (mm d^{-1}); R_n is net radiation (MJ m^{-2} d^{-1}); G is soil heat flux density (MJ m^{-2} d^{-1}); T_{mean} is mean air temperature (°C); e_s is saturation vapor pressure, (kPa); e_a is actual vapor pressure, (kPa); Δ is slope of the saturation vapor pressure function (kPa °C $^{-1}$); γ is psychrometric constant (kPa °C $^{-1}$); U_2 is wind speed at 2 m height (m s^{-1}).

Due to the lack of U_2 data, this variable was estimated from U_{10} data by using the logarithmic vertical wind speed profile, as 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 ground surface (m), U_z is measured wind speed at z m above ground surface (m s^{-1}), U_2 is the wind speed at a 2 m height (m s^{-1}).

The calculation of all data required in estimating ET_0 followed the method and procedure given in Chapter 3 of FAO-56 (Allen et al., 1998). Monthly, seasonal and annual values of ET_0 were calculated by the daily ET_0 data. Meanwhile, a season is defined in the standard climatological way: spring is defined as occurring from March to May, summer from June to August, autumn from September to November, and winter from December to February (Wang et al., 2011).

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