Reference evapotranspiration change and its sensitivity to climate variables in southwest China

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Abstract Reference evapotranspiration (ET_0) is the key factor for hydrologic water balance, irrigation scheduling, and water resources planning. Based on Food and Agriculture Organization (FAO) Penman–Monteith method and the climate variables of 57 meteorological stations from 1960 to 2010 in southwest China, the spatial and temporal distributions of ET_0 were analyzed by using Mann–Kendall test and Sen’s slope estimator. Sensitivity coefficient was used to analyze the sensitivities of ET_0 to four climate variables, and the key climate variables attributed to ET_0 change were determined. Result showed that there was a slight downward trend of ET_0 from 1960 to 2010 and spatially increasing trend from northeast to southwest in annual time scale. Results also showed that ET_0 had relatively higher sensitivity to wind speed and mean air temperature, and wind speed was the dominant variable for change of ET_0 in southwest China. The inverse relationship between increasing air temperature and decreasing evaporation, “evaporation paradox,” existed in southwest China, and the negative contribution of wind speed to the changes of ET_0 offset the positive contribution of air temperature.

1 Introduction

Evapotranspiration (ET) is one of the most important components of hydrologic cycle (Sabziparvar et al. 2010) and also is one of the key input factors for hydrological model. As ET is influenced by many factors including climate factors, crop factors, management, and environmental conditions, the estimation of actual ET over many regions where spatial and temporal variability exist in these factors is challenging (Tabari et al. 2012), reference ET (ET_0) under hypothetical crop and conditions is estimated as an alternative method for the study of hydrologic water balance, irrigation scheduling, and water resources planning (Dinpashoh 2006). ET_0 is influenced by the changes of climate variables such as air temperature, relative humidity, and wind speed, which has a nonlinear complex relationship with many of the parameters, and therefore the changes of the parameters on ET_0 is difficult to understand (Dinpashoh et al. 2011). The accurate estimation of reference evapotranspiration (ET_0) and its spatial and temporal analyses are significant for realizing the influences of climate change on hydrologic cycle.

Some researchers found there were decreasing trends in ET_0 or pan evaporation (ET_{pan}) in the different regions throughout the world including Canadian, the USA, Australia, and India (Gan 1998; Lawrimore and Peterson 2000; Roderick and Farquhar 2004; Bandyopadhyay et al. 2009; Jhajharia et al. 2011). On the other hand, ET_0 has increasing trends in some regions (Hess 1998; Talaei et al. 2014). For China, the general decreasing trends of ET_0 were reported, although the air temperature had increasing trends (Thomas 2000; Gao et al. 2006). The inverse relationship between increasing air temperature and decreasing evaporation has been known as the “evaporation paradox” (Roderick and Farquhar 2002). Cong et al. (2009) reported that “pan evaporation paradox” existed in China as a whole, but it was not spatially

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universal. Liu et al. (2010) reported that sunshine duration and maximum air temperature were the most important climate variables to influence the changes of ET_{pan} for the whole China.

The southwest region of China is an important grain-producing area for China and also is characterized by unique climate and complicated topography. The change of ET in this area has important influences on the water resources and agricultural production of the local area. Xu et al. (2006) found that the maximal annual ET_0 occurred in the southwest of the upper region for Yangtze River basin, which was mainly located in Sichuan. However, there was little intensive study on the spatial and temporal changes in the reference evapotranspiration in southwest China. In this paper, annual ET_0 were estimated for southwest China by using FAO-56 Penman–Monteith method, and annual ET_0 trends for 1960–2010 were analyzed by using the Mann–Kendall test and Sen's slope estimator. Moreover, the sensitivity of ET_0 to regular climate observation variables in climate station (mean air temperature, relative humidity, wind speed, and sunshine duration) and their contributions to the changes of annual ET_0 were investigated for southwest China.

2 Data and methods

2.1 Study area and data

In this paper, southwest China encompasses Sichuan Province, Guizhou Province, Yunnan Province, and Chongqing City, which has an area of $113.8 \times 10^4 \text{ km}^2$. It is approximately between 21.2° N – 34.4° N latitudes and 97.4° E – 110.2° E longitudes. The area is dominated by subtropical monsoon climate with the characteristics of dry winter and wet summer. The average annual precipitation is more than 900 mm, while its inter-annual and annual distributions are not even (Wang et al. 2010). There are mainly four typical landforms: plateau, mountain, hill, and plain.

Meteorological data from 57 national meteorological observatory stations provided by the National Meteorological Information Centre of China (NMIC) of the China Meteorological Administration (CMA) including monthly observations of maximum, minimum, and mean air temperature ($^\circ\text{C}$), relative humidity (%), wind speed at 10 m height (m/s), sunshine duration (h), and atmospheric pressure (kPa) for the period of 1960–2010 was used to calculate ET_0 of the study area. The location and distribution of these meteorological stations in the study area are showed in Table 1 and Fig. 1. The quality of meteorological data was examined, and no apparent error was found. Missing monthly data are about 0.47 % as an average for the 57 stations, and were supplemented by the median meteorological data from three neighboring stations (Wang et al. 2012).

2.2 Methods

The monthly reference evapotranspiration ET_0 was calculated by using Food and Agriculture Organization (FAO) Penman–Monteith method (Allen et al. 1998).

$$ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} \mu_2 (e_n - e_a)}{\Delta + \gamma (1 + 0.34 \mu_2)} \quad (1)$$

where G is the soil heat flux density ($\text{MJ}/(\text{m}^2 \text{ day})$), T is the mean air temperature at 2 m height ($^\circ\text{C}$), u_2 is the wind speed at 2 m height (m/s), e_n is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $e_n - e_a$ is the saturation vapor pressure deficit (kPa), Δ is the slope vapor pressure curve ($\text{kPa}/^\circ\text{C}$), γ is the psychrometric constant ($\text{kPa}/^\circ\text{C}$), R_n is the net radiation at the crop surface ($\text{MJ}/(\text{m}^2 \text{ day})$), which is the difference between net shortwave radiation (R_{ns}) and net longwave radiation (R_{nl}). R_{ns} is calculated as

$$R_{ns} = (1 - \lambda) R_s \quad (2)$$

where R_s is surface solar radiation ($\text{MJ}/(\text{m}^2 \text{ day})$) and λ ($=0.23$) is the albedo of the reference grassland. R_s can be calculated from sunshine duration (n):

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

where N is the maximum possible sunshine duration (h), n/N is the relative sunshine duration, R_a is the extraterrestrial radiation ($\text{MJ}/(\text{m}^2 \text{ day})$), and a_s and b_s are regression constants and are set to be 0.25 and 0.5 respectively. R_a is calculated as

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) \sin(\omega_s)] \quad (4)$$

where G_{sc} is the solar constant ($=0.0820 \text{ MJ}/(\text{m}^2 \text{ day})$), d_r is inverse relative distance Earth–Sun, ω_s is the sunset hour angle (rad), ϕ is the latitude (rad), δ is the solar declination (rad).

R_{nl} is calculated as

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

where σ is the Stefan–Boltzmann constant ($=4.903 \times 10^{-9} \text{ MJ}/(\text{K}^4 \text{ m}^2 \text{ day})$), $T_{\max, K}$ is the maximum absolute temperature

Table 1 Geospatial information of the meteorological stations in the study area

No.	Station	Latitude (°N)	Longitude (°E)	Elevation (m)	No.	Station	Latitude (°N)	Longitude (°E)	Elevation (m)
1	Anshun	26.25	105.93	1392.9	30	Lancang	22.57	99.93	1054.4
2	Baoshan	25.12	99.18	1653.5	31	Langzhong	31.58	105.97	385.4
3	Bazhong	31.87	106.78	417.7	32	Leibo	28.28	103.57	253.9
4	Bijie	27.3	105.29	1510.6	33	Leshan	29.57	103.75	422.1
5	Chuxiong	25.02	101.54	1772.0	34	Liangping	30.7	107.8	459.4
6	Dali	25.70	100.20	1990.5	35	Lijiang	26.87	100.22	2394.4
7	Daocheng	29.05	100.31	872.8	36	Lincang	23.95	100.22	1464.4
8	Daofu	30.98	101.13	2597.2	37	Luodian	25.43	106.77	441.5
9	Daxian	31.20	107.51	344.9	38	Luxi	24.53	103.77	1705.1
10	Dege	31.80	98.60	818.4	39	Maerkang	31.9	102.24	2665.9
11	Deqin	28.48	98.93	3319.0	40	Meitan	27.77	107.47	792.8
12	Duijiangyan	30.98	103.68	706.7	41	Mengla	21.48	101.57	633.2
13	Dushan	25.83	107.56	1013.3	42	Mengzi	23.38	103.39	1301.7
14	Emeishan	29.52	103.35	3047.4	43	Mianyang	31.47	104.69	472.3
15	Fengjie	31.05	109.51	607.3	44	Muli	27.93	101.27	2427.3
16	Ganzi	31.62	100.01	3393.5	45	Nanchong	30.78	106.11	309.7
17	Gongshan	27.75	98.68	1583.3	46	Neijiang	29.58	105.06	309.7
18	Guangyuan	32.43	105.87	492.4	47	Panxian	25.78	104.63	1515.2
19	Guiyang	26.58	106.73	1074.3	48	Pingbian	22.98	103.69	1412.1
20	Huaping	26.63	101.28	1242.0	49	Qianxi	27.03	106.02	1252.5
21	Huili	26.65	102.27	1788.6	50	Rongjiang	25.97	108.54	287.4
22	Huize	26.42	103.30	2113.4	51	Ruili	24.02	97.86	776.4
23	Jiangcheng	22.58	101.87	1120.8	52	Ruoergai	33.58	102.97	3441.1
24	Jingdong	24.47	100.88	1163.5	53	Sansui	26.97	108.67	611.0
25	Jinghong	22.00	100.82	553.6	54	Shapingba	29.58	106.47	259.1
26	Jiulong	29.00	101.52	2993.7	55	Simao	22.67	101.41	1302.9
27	Kaili	26.60	108.00	722.6	56	Sinan	27.95	108.26	417.7
28	Kangding	30.05	101.98	2615.5	57	Songpan	32.65	103.58	2852.1
29	Kunming	25.02	102.70	1896.8					

during the 24-h period ($K=^{\circ}\text{C}+273.16$), $T_{\min,K}$ is the minimum absolute temperature during the 24-h period ($K=^{\circ}\text{C}+273.16$), e_a is the actual vapor pressure (kPa), and R_{so} is the clear-sky radiation ($\text{MJ}/(\text{m}^2 \text{ day})$).

In this study, nonparametric statistical analyses, Mann–Kendall (Mann 1945; Kendall 1975) and Sen’s slope estimator (Sen 1968), β , were used to test the magnitude of the trend in ET_0 . Mann–Kendall method is a rank-based nonparametric method for assessing the significance of trends. As Mann–Kendall method does not need any distribution assumption for the data, it is recommended by World Meteorological Organization and has been widely used to assess the significance of trends in hydro-meteorological time series (Wang et al. 2012; Tabari et al. 2012). A statistic S is calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (6)$$

where n is the number of the observations, the x_j are the j th observation in the data set, and

$$\text{sgn}(\theta) = \begin{cases} 1 & (x_j - x_i) > 0 \\ 0 & (x_j - x_i) = 0 \\ -1 & (x_j - x_i) < 0 \end{cases} \quad (7)$$

Under the assumption that the data are independent and identically distributed, the mean and the variance of the S statistic are given as follows (Mann 1945; Kendall 1975):

$$E(S) = 0 \quad (8)$$

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18} \quad (9)$$

Fig. 1 Distribution of the meteorological stations in the study area

where t_i is the number of ties of extent m . The standardized test statistic Z is calculated as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & S < 0 \end{cases} \quad (10)$$

When $|Z| \geq Z_{1-\alpha/2}$, the hypothesis that there is no trend will be rejected at the significance level of α .

Sen's slope estimator is a slope-based method and closely related to Mann–Kendall test (Tabari et al. 2012). The Theil–Sen's estimator, β , is calculated as follows:

$$\beta = \text{Median} \left(\frac{x_j - x_l}{j - l} \right) \quad \forall 1 < l < j \quad (11)$$

where x_j and x_l are the time-series data. A positive β indicates an “increasing trend,” while a negative β indicates a “decreasing trend.”

Sensitive coefficient was defined as the ratio of change rate of ET_0 and change rate of climate variable (McCuen 1974; Liu et al. 2012)

$$S_x = \lim \left(\frac{\Delta ET_0 / ET_0}{\Delta x / x} \right) = \frac{\partial ET_0}{\partial x} \cdot \frac{x}{ET_0} \quad (12)$$

where ET_0 is the reference evapotranspiration (mm/day), x is the climate variable, S_x is the sensitivity coefficient of ET_0 which is related to x . A positive S_x for a climate variable indicates that ET_0 will increase with the increasing climate variable (Liu et al. 2012).

Fig. 2 Spatial distribution of annual ET_0 for Southwest China

The relative contribution of climate variables to the change of ET_0 at annual scale was estimated by using the approach of Yin et al. (2010).

$$C_x = S_x \cdot RC_x \quad (13)$$

$$RC_x = \frac{n \cdot \beta_x}{|av_x|} \times 100\% \quad (14)$$

where C_x is contribution rate of climate variable x to ET_0 , n is the number of observations, RC_x is the relative change of x to absolute average value ($|av_x|$) in observation period, β_x is the magnitude of the trend of climate variable x in observation period, expressed by Sen's slope estimator.

3 Results

3.1 Spatial distribution of annual ET_0

The spatial distribution of annual ET_0 for southwest China is showed in Fig. 2. The mean annual ET_0 in the whole study area, which was calculated by inverse distance weight interpolating (IDW), was 918.59 mm/year during the period from 1960 to 2010. It can be seen that the

mean annual ET_0 ranged from 560 to 1284 mm/year, and generally had an increasing trend from the northeast to southwest. In most of Sichuan, Guizhou, and Chongqing, the mean annual ET_0 were less than 900 mm/year. The largest value was found in Huaping station located in north region of Yunnan (1284.12 mm/year), while Emeishan station, which was in southeast of Sichuan, had the lowest one (558.66 mm/year).

Fig. 3 The time series of annual ET_0 for the whole study area from 1960 to 2010

Fig. 4 Trend slopes (β) and MK test statistics (Z at the 95% confidence level) of annual ET_0 from 1960 to 2010. Red upward and green downward open triangles with a point in center indicate increasing and

decreasing tendencies, respectively. Solid upward and downward triangles show significant increasing and decreasing significant trend at 95%, respectively

3.2 Trends of annual ET_0

The time series of annual ET_0 from 1960 to 2010 for the whole study area are showed in Fig. 3. Mann–Kendall test showed that ET_0 had a negative trend which was not significant at 95 % confidence level ($Z=-0.80$). Sen's slope estimator (β) was calculated to identify the slope of the trend line of annual ET_0 . For the whole study area, ET_0 had a downward trend with 0.22 mm/year.

Figure 4 shows the trend slopes (β) and MK test statistics (Z) of annual ET_0 from 1960 to 2010. Among 57 stations, there were 23 stations which had positive trends in annual ET_0 , while the other stations showed negative trends. In the stations showing positive trends, 12 stations had significant increasing trends at the 95 % confidence level, which mainly distributed in the southwest of Yunnan. Seventeen stations showed significant decreasing trends at the 95 % confidence level, which were mainly distributed in Guizhou and the northeast of Sichuan. In the

stations with positive trends, the annual ET_0 increased from 0 to 2.36 mm/year, in which Muli station of Sichuan had the largest positive trend ($\beta=2.354$ mm/year) and was statistically significant at 99 % confidence level ($Z=4.14$), and Ganzi station, which was in northwest of Sichuan, had the smallest positive trend ($\beta=0.023$ mm/year). For the stations with negative trends, the values of β changed among -2.627 to 0 mm/year. Huaping station in Yunnan presented the largest decreasing trend ($\beta=-2.627$ mm/year), which was also statistically significant at 99 % confidence level ($Z=-3.22$).

3.3 Spatial distribution of the sensitivity coefficients

For the whole study area, the sensitivity coefficient was the maximal for wind speed (0.293), followed by air temperature (0.205), relative humidity (-0.037), and sunshine duration (0.013). Figure 5 shows the spatial distribution of the sensitivity coefficients of annual ET_0 for climate

Fig. 5 Spatial distributions of sensitivity coefficient of ET_0 for climate variables. **a** wind speed at 2 m height (m/s) (wind); **b** mean air temperature at 2 m height ($^{\circ}\text{C}$) (T_a); **c** relative humidity (%) (RH); **d** sunshine duration (n)

variables. The coefficients for mean wind speed ranged from 0.120 to 0.426 (Fig. 5a), which were higher in the west of Sichuan and north of Yunnan, while lower in the southwest of Yunnan. In most part of Chongqing and Guizhou, the sensitivity of ET_0 to mean wind speed was relatively average. The sensitivity coefficients for mean air temperature had the widest range among all climate variables, which ranged from 0.022 to 0.541 (Fig. 5b). The low values were mainly distributed in the west part of

Sichuan Province, where the elevation was relatively higher, and the high values were mainly distributed in the southeast part of Yunnan Province. For relative humidity, sensitivity coefficients were negative for all study area, ranging from -0.191 to -0.003 (Fig. 5c). It means that ET_0 decreased with the increase of relative humidity. Moreover, the high value area was mainly distributed in the west part of Sichuan and north part of Yunnan, while the southwest part of Yunnan had the lower values. ET_0

Fig. 6 Contribution rates of climate variables to ET_0

generally had the higher sensitivity to sunshine duration in the northwest of Sichuan and southwest of Yunnan, while was relatively insensitive in Chongqing and Guizhou (Fig. 5d).

In this paper, the results showed that wind speed was the most sensitive factor in southwest China. The similar finding was reported in the other regions in China, such as Loess Plateau Region (Zhao et al. 2014). However, for China as a whole, relative humidity was found to be the most sensitive for ET_0 (Yin et al. 2010). Relative humidity was also the most sensitive variable in the Yellow River basin (Shan et al. 2015) and Wei River basin (Zuo et al. 2012). Ye et al. (2014) reported sunshine duration was the most sensitive factor in Poyang Lake catchment. It can be seen that

ET_0 has different responses to climate factors in different regions and climate conditions.

3.4 Contribution rates of climate variables

Contribution rates of five climate variables to ET_0 were calculated in annual scale (Fig. 6 and Table 2). The result showed that wind speed was the dominant climate factor influencing the trends of annual ET_0 . The contribution of wind speed to the changes in ET_0 was -4.12% for the whole study area. Among 57 stations, 48 of them were dominated by wind speed. Moreover, wind speed had negative contribution rate to the changes of ET_0 for 41 stations due to the decreasing trend of wind speed (Fig. 7a). The maximal positive and negative contribution rates

Table 2 Sensitivity coefficients of ET_0 for climate variables and their contributions

Climate variables	Sensitivity coefficient	Sen's slope estimator	Relative change (%)	Contribution rate to the changes in ET_0 (%)
Wind speed	0.293	-0.003	-12.94	-4.12
Air temperature	0.205	0.017	10.15	1.28
Sunshine duration	0.013	-0.010	-13.12	-0.15
Relative humidity	-0.037	-0.029	-1.94	0.11

occurred in Mianyang station of Sichuan (13.73 %) and Qianxi station of Guizhou (−25.67 %). This is same to the results from Yin et al. (2010), in which it was found that the decreasing trend of ET_0 was primarily attributed to wind speed due to its significant decreasing trend and high sensitivity for China. Air temperature was the secondary climate factor for the changes of ET_0 , and its contribution was 1.28 % for the whole study area. Mean air temperature was the dominated climate variable for nine stations, and had positive contribution for 51 stations due to their increasing trend in air temperature (Fig. 7b). The maximal positive and negative contribution rates of air temperature to ET_0 were obtained respectively by Deqin station of Yunnan (4.63 %) and Guiyang station of Guizhou (−0.83 %). The contribution rates of sunshine duration and relative humidity were less than 0.50 % for all stations. In the study of Yin et al. (2010), however, sunshine duration was the secondary climate factor influencing the trends of annual ET_0 , which had a negative contribution (−3.64 %) for China as a whole, while its contribution was only −0.15 % for southwest China in this study. As Table 2 shows, the sensitivity coefficient for sunshine duration was small for southwest China (0.013) compared with the whole China (0.31) (Yin et al. 2010). For southwest China, air temperature had more important influences than sunshine duration. For relative humidity, its contribution for southwest China (0.11 %) also was less than that for China (1.43 %). Therefore, in annual scale, wind speed was the dominant climate variable for the change of ET_0 in the study area, and the decreasing trends of annual wind speed for most stations were the main cause of the downward trend of

ET_0 . The positive contribution of air temperature to ET_0 was offset by the influences of wind speed.

4 Discussion

From Fig. 3, it can be seen that the annual ET_0 had an increasing trend after 1991, although it had a generally decreasing trend from 1960 to 2010 in southwest China. Cong et al. (2010) also reported that the increasing trend for ET_0 appeared over China from 1956 to 2005. Liu et al. (2012) reported that ET_0 had an increasing trend in China from 1993 to 2007. There were increasing trends for ET_0 in other regions in China in recent years. For example, a slight increasing trend in ET_0 was found over Yellow River basin in China from 1960 to 2007 (Liu et al. 2012). Liu and Zeng (2004) found, however, that pan evaporation had a decreasing trend over Yellow River basin from 1961 to 2000. The decreasing ET_0 trend also was found in the Beijing–Tianjin Sand Source Control Project Region in China from 1959 to 2011 (Shan et al. 2015). Liu et al. (2011) reported that pan evaporation decreased in China from 1960 to 1991 while increased from 1992 to 2007. Much longer series of observation data are required to analyze how the phenomenon of “evaporation paradox” will change in future (Liu et al. 2012).

In this paper, the uncertainties of the contribution of climate variables to the changes of ET_0 existed and came from the assumption where the climate variables were independent with each other (Liu et al. 2013). The interactions among the

Fig. 7 Trend slopes (β) of annual a wind speed and b air temperature from 1960 to 2010

climate variables were neglected when the Eqs. (12)–(14) were used to analyze the contribution of climate variables. However, the assumption might be inaccurate and thus result in errors.

5 Conclusions

Spatial and temporal analyses of ET_0 were conducted for the southwest region of China by using Mann–Kendall test, Sen's slope estimator, and sensitivity coefficient. The results showed that southwest China had a mean annual ET_0 of 918.59 mm/year, and a decreasing trend in annual ET_0 ($\beta = -0.22$ mm/year) from 1960–2010. In spatial distribution, southwest China had generally an increasing trend from northeast to southwest. Sensitivity analysis showed that relative humidity had negative influences on ET_0 , while the magnitude of its sensitivity coefficients was relatively lower. By contrast, ET_0 had relatively higher sensitivity to wind speed and air temperature, and wind speed was the dominant climate variable for the changes of ET_0 . In this study, it can be concluded that the phenomenon of “evaporation paradox” existed in southwest China. The negative contribution of wind speed to the changes of ET_0 offset the positive contribution of air temperature.

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