Changes of pan evaporation and its influencing factors in different climate zones of China

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Abstract Changing trends of observed pan evaporation are detected and its key influencing meteorological factors, which result in new changes in pan evaporation, are identified for different climate zones in China. The Mann-Kendall method is used to detect the variation trends of E601 pan evaporation over China from 1960 to 2006. The results show that during the last 50 years, temperature has presented a significantly increasing trend while E601 pan evaporation shows a decreasing trend for most climate zones of China before the late 1990s. After the late 1990s, pan evaporation has shown insignificant but increasing trends for some regions. The cause for the changing trend in pan evaporation and the reason for recent shifts in pan evaporation rates are analysed by considering thermal and turbulent conditions and the changing trends of the main influencing climate factors. The results show that daily temperature range, sunshine duration and average wind speed correlated well with the E601 pan evaporation, and the significantly decreasing trends of these influential factors are the main reason explaining the decreasing rates of E601 pan evaporation before the late of 1990s. Recent changes of these meteorological factors, together with a continuously increasing temperature trend can explain the changes in pan evaporation after the late 1990s.

Key words pan evaporation; climate zones; changing trend; influencing factors; China

1 INTRODUCTION

Evaporation is an important part of the hydrological cycle and a main loss component of surface water. In total, two-thirds of the precipitation over land is consumed in evapotranspiration in one year (Chahine, 1992; Brutsaert, 2005; Oki & Kanae, 2006). Changes in evaporation will affect agricultural irrigation, water resources utilization, as well as the ecological environment.

Global warming has become an indisputable fact. Research on the influence of climate change on evaporation started in late 1970s (Wang, 2006). It was generally considered that the temperature is an important influencing factor for evaporation. The atmospheric near-surface humidity would become dry, and land and water evaporation would increase with global warming. When evaporation increases, the amount of water resources decreases, and global warming would therefore enforce the situation of water shortage (Cong, 2008). However, Peterson *et al*. (1995) found that observed pan evaporation (E_{pan}) continued to decrease in the last 50 years (1946–1995) in the USA and the former Soviet Union. Since then, many scholars have focused on evaporation changes, and extensive data analysis and research have been conducted at global and regional scales. It was found that E_{pan} shows decreasing trends in most of the world (Chattoopadhyay & Hulme, 1997; Golubev *et al*., 2001; Moonen *et al*., 2002; Roderick & Farquhar, 2004; Shen *et al*., 2009). This contrast between expectation and observation is called the pan evaporation paradox (Michael *et al*., 2002). There is still a hot academic debate about how does climate warming impact the hydrological cycle, whether from the angle of the water balance or the energy balance. Therefore, it is essential to carefully study E_{pan} and its responses to climate change. Better understanding of this mechanism will provide scientific support for improvement of hydrological simulation technology, planning of regional water resources and accurate prediction of water for agriculture irrigation.

2 DATA AND METHODOLOGY

2.1 Study region and data

The study region is the Chinese mainland. According to China's special geographical conditions and following the national climate division (National Bureau of Technical Supervision, 1998), this study divides the country into eight climate zones: Northeast (NE), North China (NC), East China (EC), Central China (CC), South China (SC), Southwest (SE), Northwest Zone 1 (excepting Xinjiang province) (NWI) and the Xinjiang area (NWII (Fig. 1).

There are 754 standard meteorological stations with daily data from 1961 or after 1961 to 2006 including 10 meteorological elements: mean temperature (TA), maximum temperature (TH), minimum temperature (TL), average relative humidity (RH), average low cloud cover (CS), average wind speed (WS), sunshine duration (S), precipitation (P), pan evaporation measured by the E601 pan (VG) and pan evaporation measured by the Φ20 pan (VS). These stations are maintained according to the standard methods of the National Meteorological Administration of China. Monthly data are used for analysis in this paper. For this purpose, daily data are converted to monthly data. In the case of a continuous lack of measurements for up to 10 days, missing daily data are estimated using linear interpolation. If there is a continuous lack of measurement for less than 3 days, a stepwise regression method referring to neighbouring stations is used to fill the data gap. Otherwise, we note that monthly data is missing. The missing monthly data is estimated using a linear interpolation method if the continuous lack of measurement period is less than 2 years. Those stations with data not complying to the conditions mentioned above were abandoned for this analysis. In total, 571 stations with high-quality data were used for analysis (Fig. 1). The two types of E_{pan} data (VG and VS) were converted into VG data (E601) in order to ensure the consistency of the data series (Ren, 2002).

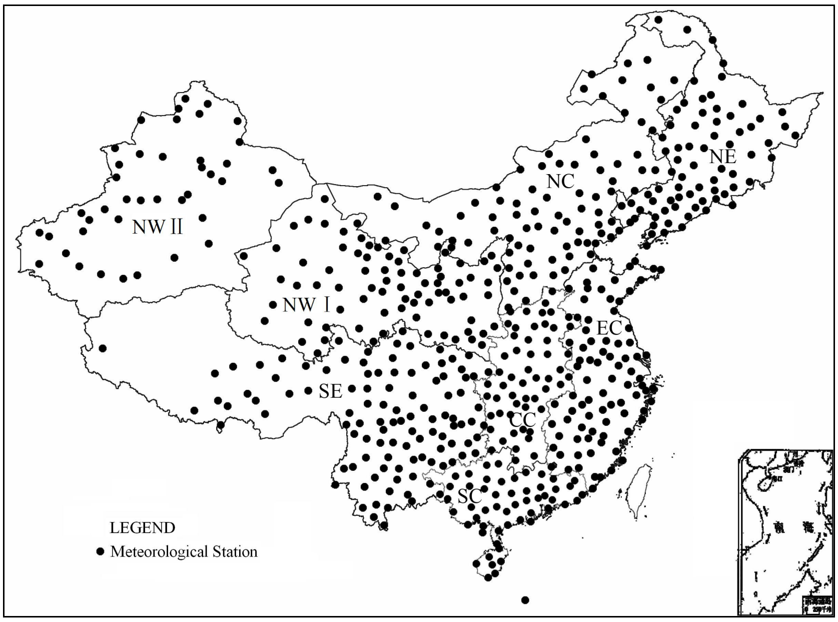

Fig. 1 The distribution of meteorological stations and climate zones in China.

2.2 The relationship between meteorological factors and pan evaporation

In order to analyse the different changing characters of E_{pan} in different periods, we should first clarify the relationship between meteorological factors and E_{pan}. Theoretically, E_{pan} would increase as temperature is rising, daily temperature range increasing, sunshine duration increasing, wind speed increasing, cloud cover decreasing, relative humidity decreasing and precipitation decreasing (Fig. 2).

2.3 Mann-Kendall test

Mann-Kendall rank correlation testing is a nonparametric testing method. Nonparametric testing is also called distribution-free testing. Its advantage is that the sample does not require a certain data distribution and it tolerates a few outliers. It is generally more suitable for categorical variables and order variables (Zhao, 2004).

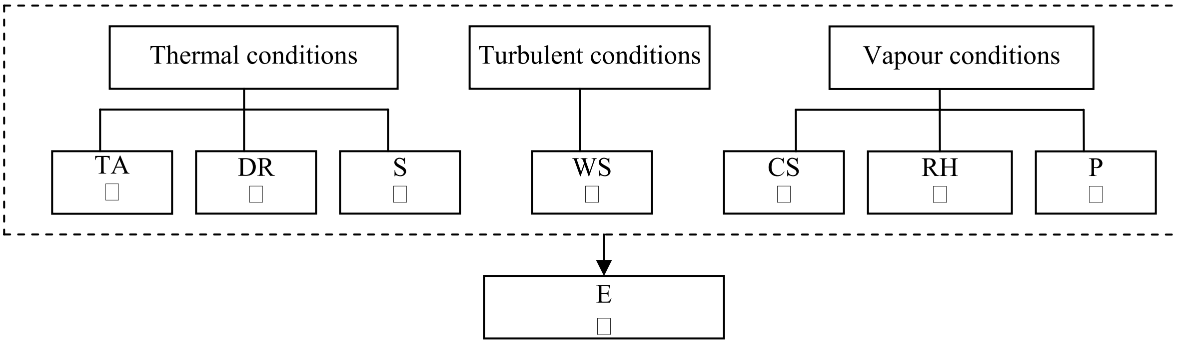

Fig. 2 The relationship between E_{pan} and meteorological factors.

2.4 Partial correlation analysis

When a variable is affected by multiple variables, the relationship between multiple independent variables and a dependent variable can be reflected by multiple linear regression. The partial regression coefficients are the partial correlation coefficients if the variables are standardized. Partial correlation coefficient indicates the degree of dependency between two variables as other variables are kept constant (Xie, 2009). Using partial correlation coefficients to describe the linear relationship between two variables would be more reasonable and more reliable for practical application. Partial correlation coefficient can relatively truly reflect the degree of dependency between E_{pan} and meteorological factors by deducting all other affecting variables.

3 RESULT

3.1 Trend of pan evaporation

Firstly, time series of E_{pan} are analysed according to the Mann-Kendall test in eight climate zones from 1961 to 2006; the results are shown in Table 1.

The MK test shows rapidly decreasing trends for annual E_{pan} in China and all climate zones. The MK value of annual E_{pan} in China is –0.44 and symbolizes a statistically significantly decreasing trend. Annual E_{pan} shows decreasing trends in all climate zones, and the trends are statistically significant except for NE and NWI. For 383 of 571 stations (about two-thirds) decreasing trends of E_{pan} are found in China, and 61% of the stations show significant decreasing trends. In EC, CC, SC and NWII, more than 70% of the stations show a decreasing trend and more than 60% of the decreasing stations show significant decreasing trends. However, in NE only 50% of the stations show a decreasing trend and only 37% of the decreasing stations show significant decreasing trends.

The changes of decadal departure of annual E_{pan} were analysed (Table 2). Annual E_{pan} showed continuously decreasing trends before 2000, whereas annual E_{pan} increases after 2000 in China and all climate zones. Even though the decadal departure of 2000–2006 is less than in 1961–1969 and the 1970s, E_{pan} increases in 2000–2006 compared to the 1980s and 1990s in China.

Table 1 Mann-Kendall (MK) test statistics values for annual E_{pan} in different climate zones. Total number of stations and number of stations with negative E_{pan} trends are also shown.

Items	China	NE	NC	EC	CC	SC	SW	NWI	NWII
Annual MK value	–0.438***	–0.101	–0.291**	–0.341***	–0.424***	–0.366***	–0.310**	–0.179	–0.424***
Number of stations	571	72	82	83	53	55	106	78	42
Stations w. neg. trend	383	38	56	63	44	39	69	43	31
Stations w. neg. trend (%)	60.8	36.8	53.6	66.7	61.4	69.2	62.3	62.8	74.2

Note: * symbolizes 5% significance level, ** symbolizes 1% significance level and *** symbolizes 0.1% significance level.

Table 2 Decadal departure of annual E_{pan} in different climate zones.

Decades	China	NE	NC	EC	CC	SC	SW	NWI	NWII
1961–1969	45.7	12.4	40.2	72.6	77.9	51.1	29.7	39.5	64.2
1970–1979	15.7	11.9	21	13.7	21.8	22.4	6.4	18	18.7
1980–1989	–22.1	–15.9	–17.3	–35	–33.5	–22	–5.9	–44.3	–1.7
1990–1999	–33.5	–20.6	–39.6	–37.9	–34.6	–40.8	–22.1	–29.7	–59.9
2000–2006	–1.8	19.2	–0.3	–8.8	–33.9	–8.1	–7.4	29.4	–21.3

Note: Decadal departure (mm) refers to the departure of the average value of different decades to the average value of the whole period (1961–2006).

Table 3 MK test statistics values of the influencing factors in different climate zones.

Factors	China	NE	NC	EC	CC	SC	SW	NWI	NWII
TA	0.55***	0.48***	0.52***	0.39***	0.31**	0.41***	0.41***	0.55***	0.44***
DR	–0.532***	–0.540***	–0.532***	–0.295**	–0.225*	–0.268**	–0.472***	–0.181	–0.660***
S	–0.583***	–0.426***	–0.515***	–0.546***	–0.503***	–0.443***	–0.455***	–0.132	–0.403***
CS	–0.252*	–0.422***	–0.281**	–0.225*	–0.335**	–0.246*	–0.347***	–0.138	0.239*
RH	–0.144	–0.270**	–0.254*	–0.146	–0.057	–0.358*	0.042	–0.125	0.328**
P	–0.008	–0.103	–0.144	0.111	0.001	0.038	–0.105	–0.127	0.360*
WS	–0.735***	–0.753***	–0.729***	–0.832***	–0.693***	–0.643***	–0.324**	–0.472***	–0.662***

Note: * symbolizes 5% significance level,** symbolizes 1% significance level and *** symbolizes 0.1% significance level.

3.2 Trends of other climate variables

E_{pan} is comprehensively influenced by thermal factors and turbulent factors including TA, DR, S, CS, RH, P and WS. The changing trends of all seven influencing factors are analysed using the MK test (Table 3).

The results show that TA has significantly increasing trends in China and in all climate zones in the last 50 years (p = 5%), and the significance level in most climate zones reached 0.1% (only CC 1%); The DR and CS show significantly decreasing trends in China and in most climate zones in China except NWI (p = 5%), and the significance levels of DR in NWII, NE, NC, SW and of CS in NE, SW reach 0.1%. The S shows significantly decreasing trends in China and in most climate zones except NWI (0.1%). RH shows decreasing trends in most climate zones except NWII; however, the changing trends of RH are not significant for most climate zones. The P shows no clear changing trends in China, except for region NWII. The WS shows significantly decreasing trends in China and in all climate zones during the last 50 years, and all the trends are significant (p = 0.1%).

3.3 Partial correlation analysis of pan evaporation

All seven influencing factors for E_{pan} were analysed using partial correlation analysis (Table 4). The partial correlation coefficient reflects the correlation degree between E_{pan} and meteorological factors. The correlation degree is higher when the partial correlation coefficient is larger. It is seen that E_{pan} has good correlations with TA, DR, S and RH in China and in most climate zones. E_{pan} significantly correlates with TA, DR (in most climate zones p = 1%) indicating that these two factors are very important influencing factors for E_{pan}.

3.4 Integrated analysis of pan evaporation

The decadal departure and the changing rate (equal to the decadal departure divided by the average value of the whole period (1961–2006)) of annual E_{pan} and meteorological factors in different climate zones are shown in Table 5. Annual E_{pan} has a decreasing trend in China from 1961 to 2006. However, E_{pan} increases after 2000 compared to the 1980s and 1990s. The changing trends of the influencing factors from 1961 to 2006 are: TA is increasing, DR is decreasing, and S, RH and WS show generally decreasing trends.

Table 4 Partial correlation coefficient of the influencing factors on E_{pan} in different climate zones.

Factors	China	NE	NC	EC	CC	SC	SW	NWI	NWII
TA	0.520**	0.532**	0.545**	0.823**	0.492**	0.245	0.389*	0.364*	0.368*
DR	0.692**	0.356*	0.446**	0.516**	0.439**	0.344*	0.562**	0.685**	0.272
S	0.392*	0.206	0.357*	0.359*	0.598**	0.465**	0.054	0.397*	0.112
CS	0.383*	0.307*	0.26	0.133	0.388*	0.450**	0.243	0.749**	0.255
RH	–0.500**	–0.508**	–0.279	–0.684**	–0.308*	–0.477**	–0.147	–0.032	–0.551**
P	–0.151	–0.393*	–0.443**	–0.420**	–0.532**	–0.257	–0.364*	–0.505**	–0.216
WS	0.309*	0.109	0.418**	0.679**	0.151	0.280	0.161	0.160	0.490**

Note: * symbolizes 5% significance level and ** symbolizes 1% significance level.

Table 5 Decadal departure and the changing rate of annual E_{pan} and meteorological factors in climate zones.

Factors		1961–1969	1970–1979	1980–1989	1990–1999	2000–2006
E	Departure (mm)	45.7	15.7	–22.1	–33.5	–1.8
	Changing rate (%)	4.50	1.55	–2.17	–3.30	–0.17
TA	Departure(℃)	–0.33	–0.31	–0.20	0.34	0.66
	Changing rate (%)	–2.95	–2.77	–1.79	3.04	5.90
DR	Departure(℃)	0.40	0.15	–0.17	–0.18	–0.20
	Changing rate (%)	3.66	1.37	–1.56	–1.65	–1.83
S	Departure(h)	101.5	49.0	–26.7	–69.7	–62.8
	Changing rate (%)	4.42	2.13	–1.16	–3.03	–2.73
CS	Departure (10%)	0.08	0.09	–0.02	–0.19	0.06
	Changing rate (%)	1.38	1.55	–0.35	–3.28	1.04
RH	Departure (%)	0.17	0.27	–0.06	0.31	–0.95
	Changing rate (%)	0.26	0.41	–0.09	0.47	–1.44
P	Departure(mm)	–5.5	–0.2	–4.1	17.5	–11.8
	Changing rate (%)	–0.67	–0.03	–0.50	2.15	–1.45
WS	Departure(m/s)	0.16	0.22	–0.03	–0.18	–0.21
	Changing rate (%)	6.75	9.28	–1.27	–7.59	–8.86

The results of partial correlation analysis showed that TA, DR, S, and RH have great influence on E_{pan}, and that CS and P have relatively less influence (Table 4). TA shows a significant increasing trend, while DR, S and WS show significant decreasing trends. Also, CS shows decreasing trend, RH decreases a little, and P changes relatively little (Table 3).

The results of the integrated analysis are:

(a) From 1961 to the late 1990s, although TA shows a significant increasing trend, DR, S and WS show significant decreasing trends (Table 3), and these three factors also have a good relationship with E_{pan} (Table 4), so the significant decreasing trends of DR, S and WS are the main reason for the significant decreasing trends of evaporation in this period.

(b) After the late 1990s, the decadal changing rate of TA continues to increase (Table 5).The decreasing rate of DR continues to decrease, and S and WS are also still decreasing in 2000–2006, but these three meteorological factors change little compared to the changing rate in the 1990s. RH and P are decreasing in 2000–2006, and RH shows relatively obvious negative relationship with E_{pan} (Table 4). Even though CS is increasing in 2000–2006, the CS shows a weak positive relationship with E_{pan} (Table 4). The continuously increasing trend of TA together with the decreasing trend of RH could be responsible for increasing rates of observed E_{pan} in 2000–2006 compared to the 1980s and 1990s.

4 CONCLUSIONS

(a) The MK test was used to detect the changing trends of E_{pan} in China as a whole and in eight climate zones from 1960 to 2006. The results show that there have been significantly decreasing trends for annual E_{pan} in China and decreasing trends in all climate zones. The results from analysing the changes of decadal departure of annual E_{pan} show that annual E_{pan} shows decreasing trends before 2000, but shows increasing trends after 2000 in China and all climate zones.

(b) E_{pan} shows good correlation with TA, DR, S and RH in most climate zones according to the results of partial correlation analysis.

(c) The significantly decreasing trends of DR, S and WS are the main reason for the significant decreasing trends of E_{pan} from 1961 to the late 1990s. The recent changing rates of these meteorological factors together with continuously increasing trend of temperature are the reasons for the recent changes in E_{pan} after the late of 1990s.

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