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Trend in pan evaporation and its attribution over the past 50 years in China

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Abstract: Trends in pan evaporation are widely relevant to the hydrological community as indicators of hydrological and climate change. Pan evaporation has been decreasing in the past few decades over many large areas with differing climates globally. This study analyzes pan evaporation data from 671 stations in China over the past 50 years in order to reveal the trends of it and the corresponding trend attribution. Mann-Kendall test shows a significant declining trend in pan evaporation for most stations, with an average decrease of 17.2 mm/10a in China as a whole, the rate of decline was the steepest in the humid region (29.7 mm/10a), and was 17.6 mm/10a and 5.5 mm/10a in the semi-humid/semi-arid region and arid region, respectively. Complete correlation coefficients of pan evaporation with 7 climate factors were computed, and decreases in diurnal temperature range (DTR), SD (sunshine duration) and wind speed were found to be the main attributing factors in the pan evaporation declines. Decrease in DTR and SD may relate to the increase of clouds and aerosol as well as the other pollutants, and decrease in wind speed to weakening of the Asian winter and summer monsoons under global climate warming.

Keywords: pan evaporation; Mann-Kendall test; diurnal temperature range; wind speed; compete correlation; China

1 Introduction

Evaporation is an important component of both hydrological and energy cycles. Change of pan evaporation has been recognized by most hydrologists as an integrative indicator of hydrological response to climate change. Therefore, study of pan evaporation trends has become a pertinent issue. It has been reported that pan evaporation has recently been in significant decline globally (Peterson *et al.*, 1995; Michael *et al.*, 2004; 2005; 2007), especially

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in the Northern Hemisphere (Chattopadhyay *et al.*, 1997; Brutsaert *et al.*, 1998; Cohen *et al.*, 2002; Zeng *et al.*, 2007). This phenomenon is in apparent contradiction with the expected increasing potential evaporation from global warming, e.g. the so called pan evaporation paradox (Michael *et al.*, 2002). This has given rise to many studies on pan evaporation trends and the attribution of their causes, as well as the relationship between pan evaporation and actual evaporation (Burn *et al.*, 2007; Sun, 2007).

China is located in the eastern part of the Eurasian Continent and has intricate topography and diverse climate types including continental monsoon climate. Therefore, the study of pan evaporation trends in China is of high importance not only regionally, but also globally as an indicator of response to climate change over diverse settings. Similar to elsewhere, pan evaporation in most of China has been shown to be trending downward. Qiu *et al.* (2003) found that pan evaporation was on a significant descending trend in the Yellow River Basin. Guo *et al.* (2005) reached a similar conclusion in the Huang-Huai-Hai Plain, and the attributing factors were thought to be wind speed and solar radiation. However, Liu *et al.* (2006) found close relationships between pan evaporation and diurnal temperature range (hereafter DTR) and wind speed. Zuo *et al.* (2005) found that pan evaporation had a good correlation with relative humidity based on the climate trend analysis for China as a whole.

The goal of this study is to analyze pan evaporation trends over the past half century in China on a regional basis and as a whole, and to investigate possible relationships with other climatic variables. Trend analysis was conducted using the Mann-Kendall non-parametric test method, and a regional mean pan evaporation (hereafter E_{pan}) changing pattern obtained by 5-point moving average. For trend attribution, we compared the complete correlations of pan evaporation with 7 climatic variables: precipitation, air temperature, relative humidity, wind speed, DTR, sunshine duration, and low clouds.

2 Methods and data

2.1 Methods

2.1.1 Mann-Kendall non-parametric test

The Mann-Kendall non-parametric test has been commonly used to assess the significance of trends in hydro-meteorological time series. The equation below is often used to estimate whether a series has a significant trend or not (Liu *et al.*, 2003):

$$M = \tau / \sigma_\tau \tag{1}$$

in which

$$\tau = \frac{4S}{N(N-1)} - 1 \tag{2}$$

$$\sigma_\tau^2 = \frac{2(2N+5)}{9N(N-1)} \tag{3}$$

where S is the number of the dual observed values (X_i,X_j, $i < j$, where $X_i < X_j$) in a series. N is the series length. For a fixed significance level $\alpha = 0.05$ in the present paper, if a series has a significant trend, $|M| > M_{\alpha/2} = 1.96$; a positive M indicates an ascending trend, and vice versa.

2.1.2 Complete correlation method

Many studies reported that E_{pan} is on a significant decreasing trend in China over the past 50 years. Therefore, a potential attributing factor to E_{pan} trend should show both a significant trend and a high correlation with E_{pan} during the corresponding period. Hence, the complete correlation coefficients calculation is proposed here,

$$R = r_e \cdot r_t \tag{4}$$

where R is the complete correlation coefficient, r_e is the correlation coefficient between the climate factor and E_{pan}, r_t is the correlation coefficient between the climate factor and the time series.

2.2 Data

Data for this study were provided by China Meteorological Administration from approximately 680 stations across China for the period of 1955–2001. After filtering data for missing observations, 671 were considered in this analysis. Observations include monthly E_{pan} measured by *Φ20cm* evaporator, air temperature, maximum and minimum air temperature, relative humidity, precipitation, wind speed, sunshine duration, and low cloud cover. DTR was calculated by the difference of maximum and minimum air temperature. The country was divided into three climate regions (humid region, semi-humid/semi-arid region, and arid region), according to the aridity index which was calculated by the ratio of annual mean E_{pan} and annual mean precipitation for the period of 1971–2000, which is the WMO (World Meteorological Organization) standard period for calculation of climatological normals (Figure 1). Boundaries approximately mirror 200 mm and 800 mm precipitation isohyets.

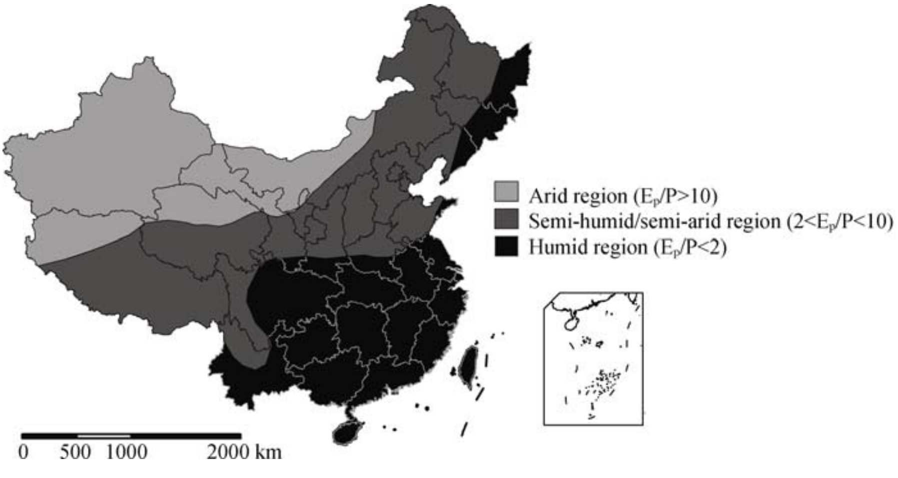

Figure 1 Climate zoning of China as classified by using arid index (E_{pan}/P)

3 Results

3.1 Spatial distribution of E_{pan} trends identified by Mann-Kendall test

Mann-Kendall test show that annual E_{pan} in most areas of China has been decreasing over the past 50 years (Figure 2), in accordance with previous studies. On a regional basis, the Middle-Lower Yangtze River Basin, South China, Yunnan and Guizhou provinces in the

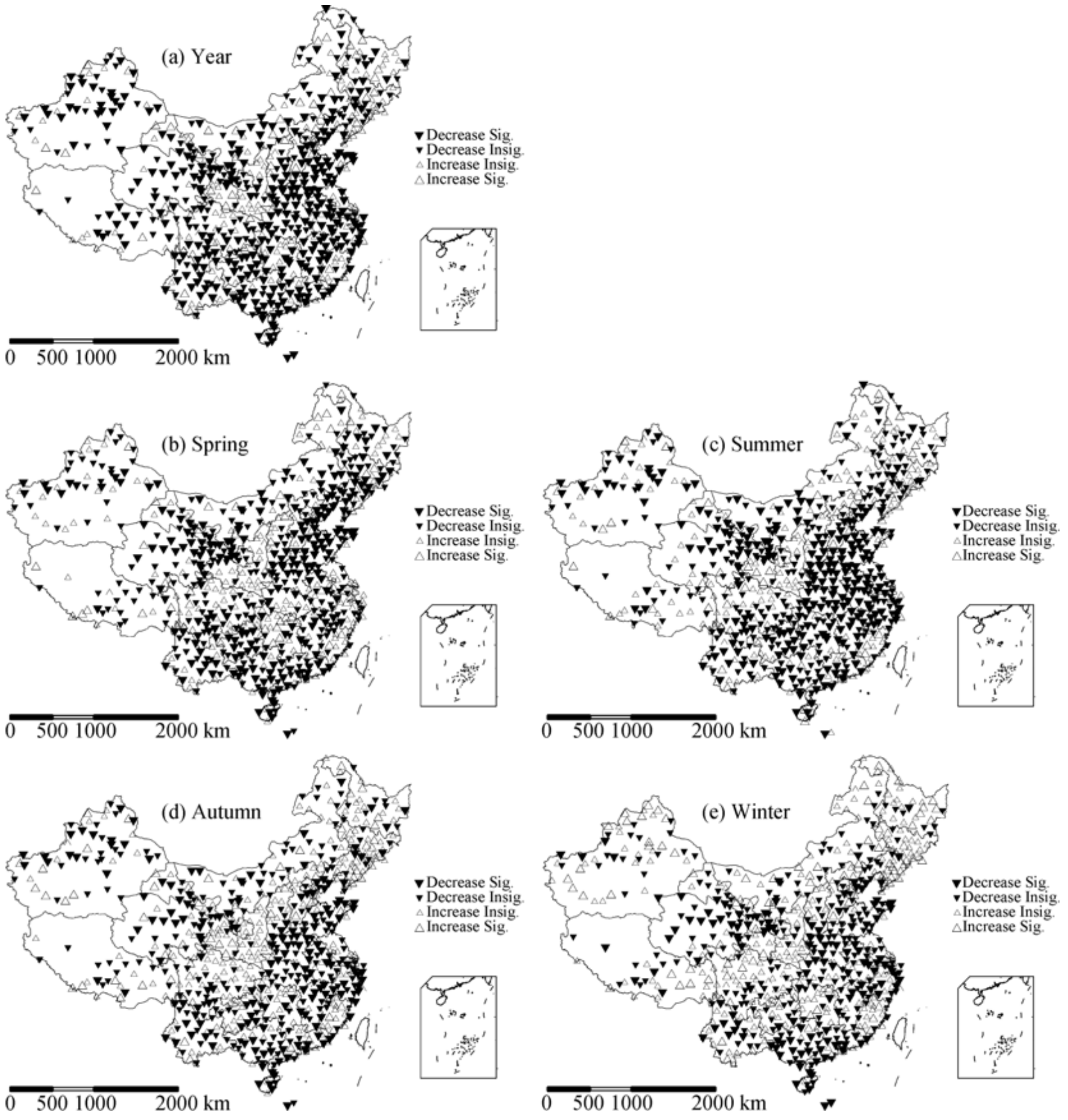

Figure 2 Spatial distribution of annual E_{pan} trends over past 50 years in China (Tested by Mann-Kendall at significance level 95%)

humid region, Huang-Huai-Hai Plain and eastern Tibet in the semi-humid/semi-arid region, and Xinjiang, central Gansu and Qinghai in the arid region have all experienced significant E_{pan} decreases. Wang *et al.* (2006) reached the conclusion that the decreasing trend in the Middle-Lower Yangtze River Basin was more significant than that in the upper reaches. Qiu *et al.* (2003) obtained the result of decreasing trend in E_{pan} in the upper and lower reaches of the Yellow River. And Su *et al.* (2003) found decreasing E_{pan} trend in Xinjiang. Table 1 lists the proportion of stations with different annual E_{pan} trends in China as a whole and its three climate regions. Stations with decreasing trends accounted for 60% or more of the totals in any case. The largest percentage was detected in the humid region (75%).

Seasonal E_{pan} trends were also tested with the Mann-Kendall method, which showed that they had decreasing tendencies in most areas of China, especially in summer and spring (Figure 2 and Table 2). Percentage of decreasing trends stations in summer, near to 70%, was the largest among four seasons. Stations with decreasing trend in autumn and winter were relatively less, however, still more than 50% of the total stations (Table 2). Stations with significant decreasing trends were distributed most widely in summer, mainly in South China and the Middle-Lower Yangtze River Basin in the humid region, Huang-Huai-Hai Plain in the semi-humid/semi-arid region, and parts of Xinjiang, Gansu and Qinghai provinces in the arid region (Figure 2c). Spring, with the second most widely distributed decreasing E_{pan} trend shows a similar pattern with that of summer except an insignificant decreasing trend in the Middle-Lower Yangtze River Basin (Figure 2b). Areas with significant decreasing trends in autumn and winter were relatively less (Figures 2d and 2e). This analysis suggests that decreasing trends in spring and summer contributed most to the decrease in annual E_{pan}. A small percentage of stations showed increasing E_{pan} trend. They were mainly distributed in Chuan-Shan-Jin (Sichuan-Shaanxi-Shanxi) Line and parts of Northeast China and Fujian Province. These stations showed increasing trends in almost all of the seasons.

Table 1 Proportions of stations with different trends in annual E_{pan} in China and its climate regions (unit: %)

Trends	China as a whole	Arid region	Semi-humid/semi-arid region	Humid region
Decrease sig.	46	50	37	53
Decrease insig.	25	24	28	22
Increase insig.	20	14	24	18
Increase sig.	9	12	11	7

Table 2 Proportions of stations with different trends in seasonal E_{pan} in China (unit: %)

Trends	Spring	Summer	Autumn	Winter
Decrease sig.	33	35	25	20
Decrease insig.	36	34	32	34
Increase insig.	24	24	32	31
Increase sig.	7	7	11	15

3.2 Regional based mean E_{pan} changing pattern

We calculated regional mean annual E_{pan}, and then used a 5-point moving average to illustrate its changing patterns in each climate region and for China as a whole. The declines were statistically significant at the 99% significance level. Annual E_{pan} has been on a decreasing trend since the 1960s, however it began to show a somewhat upward trend after the 1990s, except a fluctuation period from the 1960s to 1970s in the arid region (Figure 3). The decreasing rate of E_{pan} in the humid region was the steepest among the three climate regions, the second was in the semi-humid/semi-arid region; and for China as a whole, the rate of decreasing E_{pan} was slightly smaller than that in the semi-humid/semi-arid region (Table 3).

Similar to annual changes, seasonal E_{pan} for China as a whole has also shown a decreasing trend since the 1960s (Figure 4). The rate of decline was the largest in summer (16.2 mm/10a), accounting for 2.24% of summer mean; the second most significant decreasing rate was detected in spring; and the decreasing rates in autumn and winter were relatively

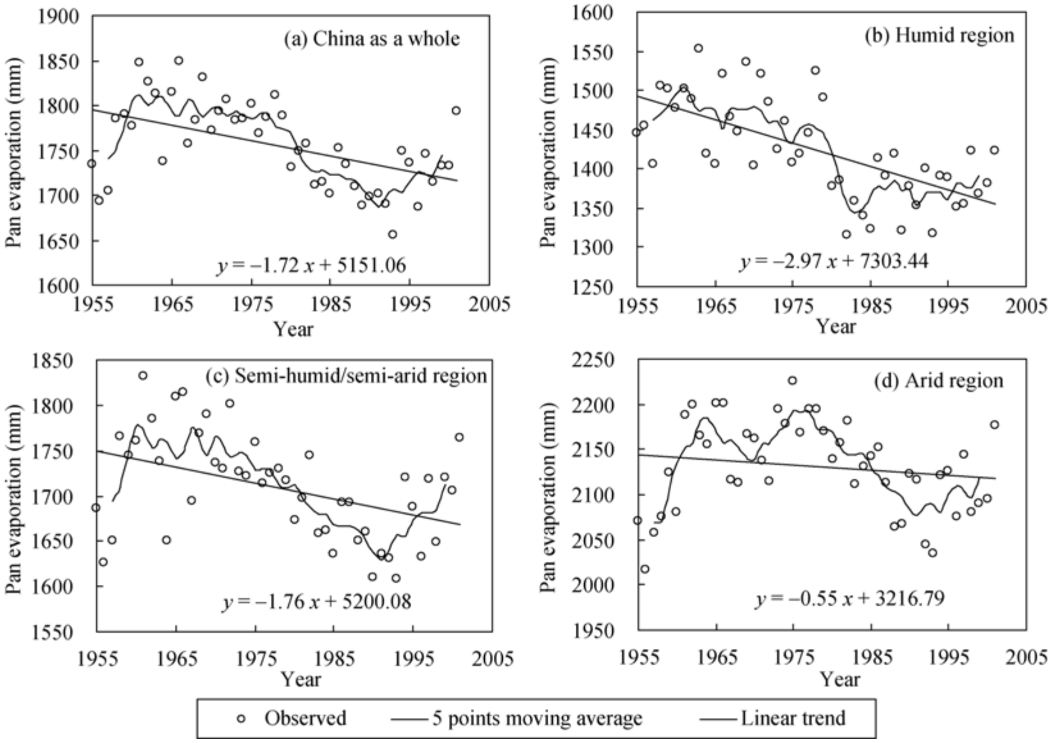

Figure 3 Temporal changes of annual E_{pan} in China and its three climate regions

smaller (Table 4). Upward tendencies before the 1960s and after the 1990s were also detected in both regional and seasonal E_{pan} changes. Sun (2007) found that the regional mean E_{pan} for China as a whole showed significant upward trending after around 1993. But more data are needed to ascertain the tendencies before the 1960s.

3.3 Complete correlation analysis and regression models

E_{pan} variability can be influenced by many factors, which can be mainly divided into three types: dynamic factors (wind speed), thermodynamic factors and water factors. To make a clear attribution of E_{pan} trends, we classified the 7 measured climate factors into the above 3 types, calculated the complete correlation coefficients of each factor to E_{pan} in different seasons and regions (Table 5), then chose the factors that had the highest complete correlation coefficients with E_{pan} in each attributing type, one factor at most for each type.

DTR, SD (short for 'sunshine duration') and wind speed had much higher complete cor-

Table 3 Regional based mean E_{pan} decreasing rates

	China overall	Humid region	Semi-humid /semi-arid region	Arid region
Decrease rate (mm/10a)	17.2	29.7	17.6	5.5
Regional mean E_{pan} (mm)	1756.0	1423.5	1709.1	2131.1
Percentage (%)*	0.98	2.09	1.03	0.26

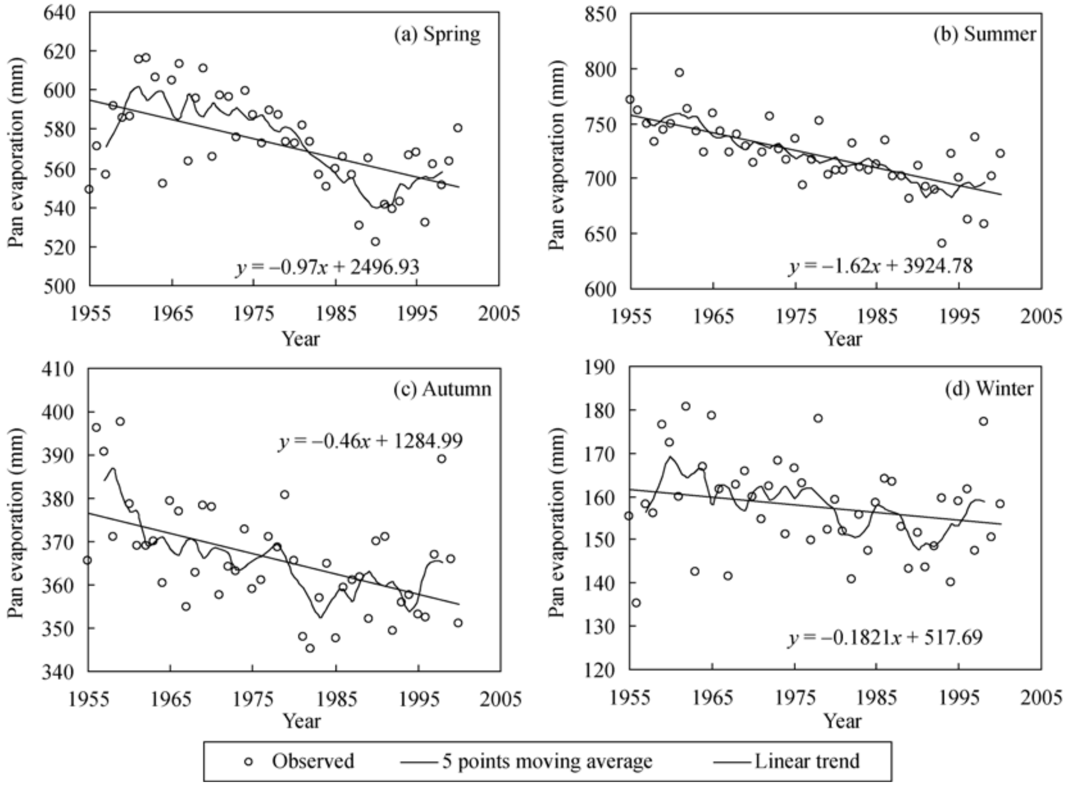

Figure 4 Seasonal E_{pan} changes for China as a whole

Table 4 Seasonal E_{pan} decreasing rates in China as a whole

	Spring	Summer	Autumn	Winter
Decrease rate (mm/10a)	9.7	16.2	4.6	1.8
regional mean E_{pan} (mm)	572.7	721.7	366.1	157.6
percentage (%)*	1.69	2.24	1.26	1.14

* 10-year decrease rate as a percent of E_{pan} (Tables 3 and 4).

relations with E_{pan} than the other factors in most temporal and spatial groups (Table 5). That is to say, they had higher correlation with E_{pan}, and at the same time, had experienced significant changing trend over the past 50 years. Therefore, we conclude that the E_{pan} trend in China related most to DTR/SD and wind speed. We compared spatial distributions of annual DTR, SD and wind speed trends in China during the investigated period, which were also identified by Mann-Kendall test, with that of E_{pan}, and drew the conclusion that annual DTR, SD and wind speed have also been on a significant decreasing trend in most parts of China. Furthermore, we found that E_{pan} trends were in accordance with that of DTR, SD and wind speed spatially to some degree. In humid region, stations with significant decreasing SD trend were distributed more widely than that of DTR, hence a larger complete correlation coefficients of SD with E_{pan} than that of DTR (Table 5). Among water factors, relative humidity had a higher complete correlation with E_{pan} than the other factors in summer. In the arid region, the coefficient between relative humidity and E_{pan} in summer was even larger

Table 5 Annual and seasonal complete correlation coefficients between E_{pan} and climate factors for China as a whole and each climate region*

		Water factors			Thermodynamic factors			Dynamic factor
		Lcl	P	RH	SD	Ta	DTR	WS
China as a whole	Ann.	0.05	0.02	0.02	0.41	0.10	**0.53**	**0.41**
	Spr.	0.02	0.04	0.18	0.09	0.00	**0.41**	**0.40**
	Sum.	0.02	0.04	0.27	**0.49**	0.01	0.33	**0.32**
	Aut.	0.01	0.03	0.16	0.34	0.01	**0.35**	**0.21**
	Win.	0.02	0.04	0.09	0.22	0.00	**0.24**	**0.29**
Humid region	Ann.	0.08	0.07	0.02	**0.66**	0.01	0.47	**0.56**
	Spr.	0.12	0.02	0.02	**0.38**	0.06	0.38	**0.52**
	Sum.	0.03	0.18	0.25	**0.63**	0.01	0.47	**0.40**
	Aut.	0.14	0.06	0.03	**0.43**	0.00	0.28	**0.17**
	Win.	0.10	0.12	0.05	**0.34**	0.06	0.32	**0.27**
Semi-humid /semi-arid region	Ann.	0.06	0.09	0.03	0.24	0.10	**0.56**	**0.34**
	Spr.	0.08	0.04	0.01	0.04	0.08	**0.58**	**0.42**
	Sum.	0.13	0.06	0.13	0.32	0.05	**0.36**	**0.23**
	Aut.	0.07	0.13	0.06	0.19	0.01	**0.41**	**0.21**
	Win.	—	—	—	—	—	—	—
Arid region	Ann.	0.01	0.15	0.03	0.14	0.08	**0.28**	**0.29**
	Spr.	0.08	0.14	0.11	0.07	0.00	**0.27**	**0.25**
	Sum.	0.08	0.02	**0.28**	**0.23**	0.07	0.09	**0.30**
	Aut.	0.02	0.05	0.07	0.14	0.07	**0.18**	**0.15**
	Win.	—	—	—	—	—	—	—

*Ann., Spr., Sum., and Win. represent annual, spring, summer, autumn and winter respectively; Lcl, P, RH, SD, Ta, DTR, and WS represent low cloud, precipitation, relative humidity, sunshine duration, air temperature, diurnal temperature and wind speed respectively. Bold-face represents the complete correlation coefficients which are far larger than that of the others (one factor at most in each type). We omit to analyze the complete correlation between E_{pan} and climate factors in winter in semi-humid/semi-arid region and arid region due to weak correlation.

than that of DTR and SD which showed a lower complete correlation with E_{pan}. Annually the coefficient between precipitation and E_{pan} in arid region were much larger than those of other water factors.

Based on the results above, multiple regression models of annual E_{pan} were derived with DTR (SD for humid region) and wind speed as independent variables. This provides a second statistical test of the relationship between these data, plus provides a new way to predict E_{pan}. For the arid region, we compared the model precision for cases of no precipitation and added precipitation because water factors also played an important role in the decrease in E_{pan} in this region (Shen *et al.*, 2010).

As Figure 5 illustrated, the models performed well at representing both the observed trends and E_{pan} values in most cases, and passed the F-test at a significant level of 99%. However in the arid region, with no precipitation added, the correlation coefficient between the modeled and the observed data was merely 0.62, and the root mean square error (RMSE) was 46.2 mm, showing a lower precision. When precipitation was added, precision was significantly improved, with a higher correlation coefficient (0.76) and RMSE (39.0 mm).

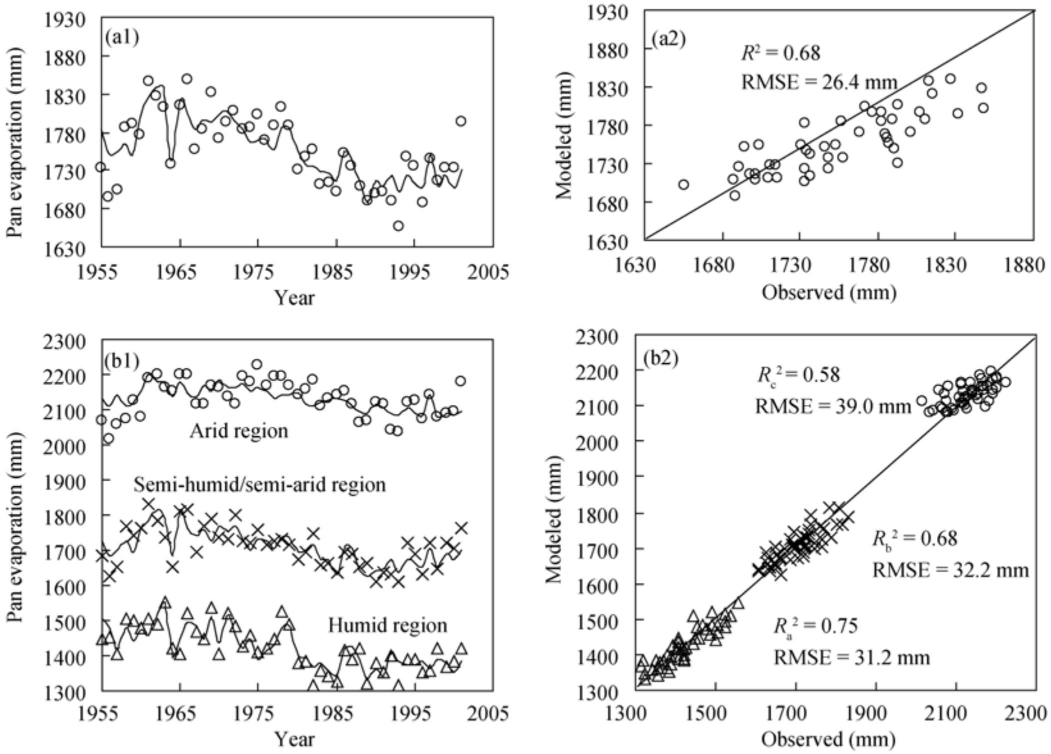

Figure 5 Precision tests of E_{pan} regression models for China as a whole and its three climate regions*
* In the humid region, the semi-humid/semi-arid region, and China as a whole, only DTR/SD (SD for humid region) and wind speed were considered independent variables. In the arid region, precipitation was also considered as an independent variable. (a1) and (b1) compare modeled and observed time series for China as a whole and its three climate regions, in which the scatter plots represent the observations and the line represents modeled. (a2) and (b2) show cross-plots of observed versus modeled; a, b and c in subscript of R^2 values represent the humid region, semi-humid/semi-arid region and arid region, respectively.

4 Discussion and conclusion

4.1 Attributing factors to descending trend in E_{pan}

E_{pan}, as an important index of potential evaporation, has an indicative meaning in measuring changes in climate and water cycling. Even though E_{pan} has been reported to have a decreasing trend in many regions, there are still many disputes on its attribution.

From the analysis in Section 3, it is concluded that the decrease in E_{pan} in China was most closely related to the decrease in DTR, SD and wind speed. While in the arid region, water factors, in addition to DTR and wind speed, also played an important role in the E_{pan} decreasing trend. Higher complete coefficients between humidity and E_{pan} in summer may explain this. Most of the stations in the arid region are distributed in oasis areas. Advanced irrigation solutions there lead to increased humidity, and this might also contribute to the decrease in potential evaporation. In addition, increases in both precipitation (Sun, 2007) and low cloud also result in decreased E_{pan} on the annual scale (Figure 6). Low cloud does so by reducing the incident sunlight.

Decrease in DTR was mainly caused by faster increase in minimum temperature com-

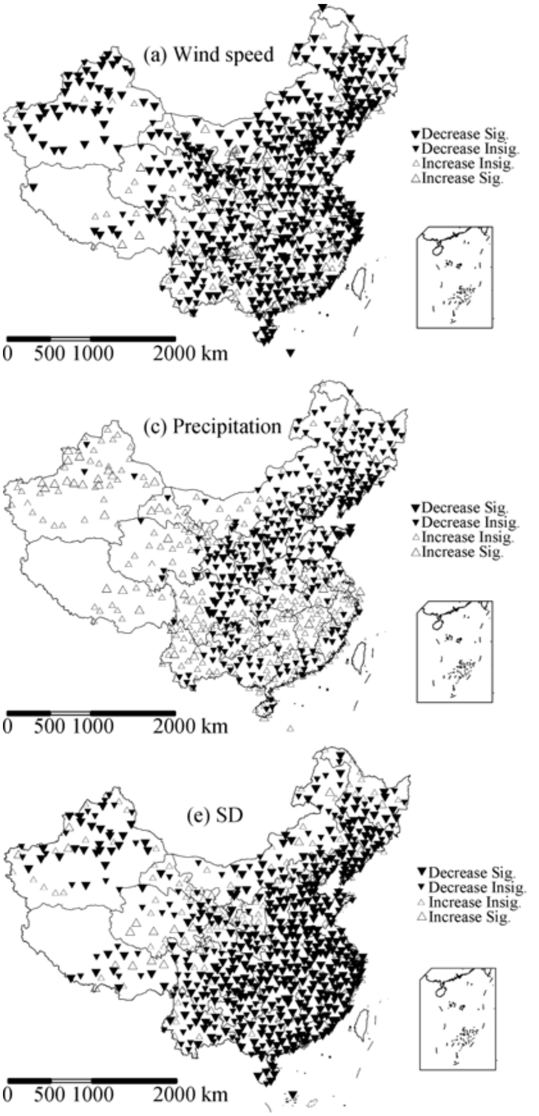

Figure 6 Spatial distribution of climate factors trends identified by Mann-Kendall test in China

pared to the maximum temperature. Roderick (2002) attributed decrease in DTR to increased clouds and/or aerosols, because increased clouds and/or aerosols dampen the diurnal cycle by reducing the incident sunlight and also by reducing the net loss of long-wave irradiance from the surface at night. And increased clouds and/or aerosols result in SD decrease as well. As Figure 6d illustrates, low clouds in South China, Yunnan Province and most part of Xinjiang were on increasing trends, which were in accordance with the increase in precipitation and decrease in SD and E_{pan}. Therefore, the decrease in E_{pan} in these areas may partly be attributed to the increase in low cloud/precipitation. However, low clouds and precipitation, in the Huang-Huai-Hai Plain showed a decreasing trend and these tendencies would suggest an increase in SD and E_{pan}, which was in contradiction with the result (Figures 2a and 6e). Then, the decrease in E_{pan} in the Huang-Huai-Hai Plain may mainly be attributed to the increase in aerosols and other pollutants, which would result in a decline in solar radiation. However, this still needs to be tested with additional aerosol data.

It is difficult to pinpoint the cause of the decreasing wind speed. Some authors have argued that changes in atmospheric circulation have resulted in a decrease in wind speed (Wang *et al.*, 2001; Wang *et al.*, 2004). Zonal circulation in Asia has been strengthened and the meridional circulation weakened over the past 50 years, possibly related to global warming trends. This has resulted in weakness of Asian winter and summer monsoons in China, which led to decrease in mean wind speed in China. However the urbanization procession which changed the circumstances around the weather stations may have also contributed to the reduction in measured wind speeds.

4.2 Conclusions

E_{pan} has been on a decreasing trend in most parts of China over the past 50 years. In the humid region, the Middle-Lower Yangtze River Basin, South China and Yunnan/Guizhou provinces have experienced significant decrease in E_{pan}. While in the semi-humid/semi-arid region, areas with significant decreasing trend in E_{pan} were mainly detected in the Huang-Huai-Hai Plain and eastern Tibet, and in the arid region, provinces of Xinjiang, Qinghai and central Gansu.

5-point moving average analysis showed that E_{pan} was on a steadily decreasing trend during the 1960s to 1990s. Among the three regions, E_{pan} in the humid region showed the largest decreasing rate (29.7 mm/10a); the second was in the semi-humid/semi-arid region (17.6 mm/10a); and the smallest decreasing rate was in the arid region (5.5 mm/10a). Among the four seasons, E_{pan} in summer experienced the most significant decreasing trend; the second was in spring; decreasing trends in autumn and winter were relatively moderate. Decreasing E_{pan} in summer and spring contributed most to annual decreasing E_{pan}.

Decrease in E_{pan} related most to the decreases in DTR, SD and wind speed in China over the past 50 years. In the arid region, water factors were also important. Decreasing trends in DTR and SD in Northwest China and areas south to the Middle-Lower Yangtze River Basin were mainly attributed to the increase in precipitation and low cloud, while in the Huang-Huai-Hai Plain, it may relate to the increase in aerosols and other pollutants. Increase in low cloud and aerosols leads to a decline in solar radiation, which in turn results in decreased E_{pan}. Decrease in wind speed relates more to the reduction of the Asian winter and summer monsoons because of global climate warming. However, detailed understanding of the decreasing DTR, SD and wind speed requires further investigation, and studies on this question should be strengthened.

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References

An Gaiyue, Li Yuanhua, 2005. Change of evaporation in recent 50 years in Hebei Region. *Journal of Arid Land Resources and Environment*, 19(4): 159–162. (in Chinese)

Brutsaert W, Parlange M B, 1998. Hydrologic cycle explains the evaporation paradox. *Nature*, 396: 30.

Burn D H, Hesch N M, 2007. Trends in evaporation for the Canadian prairies. *Journal of Hydrology*, 336: 61–73.

Chattopadhyay N, Hulme M, 1997. Evaporation and potential evapotranspiration in India under conditions on recent and future climate change. *Agric. Forest Meteorol.,* 87: 55–73.

Cohen S, Ianetz A, Stanhill G, 2002. Evaporative climate changes at Bet Dagan, Israel, 1964–1998. *Agric. For. Meteor.*, 111: 83–91.

Editorial Committee of Physical Geography of China CAS, 1984. Physical Geography of China: Climate. Beijing: Science Press, pp.161. (in Chinese)

Guo Jun, Ren Guoyu, 2005. Recent change of pan evaporation and possible climate factors over the Huang–Huai–Hai watershed, China. *Advances in Water Science,* 16(5): 666–672. (in Chinese)

Liu Bo, Ma Zhuguo, 2007. Area change of dry and wet region in China in the past 45 years. *Arid Land Geography*, 30(1): 7–15. (in Chinese)

Liu Bo. Ma Zhuguo, Ding Yuguo, 2006. Characteristics of the changes in pan evaporation over northern China during the past 45 years and the relations to environment factors. *Plateau Meteorology*, 25(5): 840–848. (in Chinese)

Liu Changming, Zheng Hongxing, 2003. Trend analysis of hydrological components in the Yellow River Basin. *Journal of Natural Resources*, 18(2): 129–135. (in Chinese)

Ohmura A, Wild M, 2002. Is the hydrological cycle accelerating? *Science*, 298: 1345–2004.

Peterson T C, Golubev V S, Groisman P Y, 1995. Evaporation losing its strength. *Nature*, 377: 687–688.

Qiu Xinfa, Liu Changming, Zeng Yan, 2003. Changes of pan evaporation in the recent 40 years over the Yellow River Basin. *Journal of Natural Resources*, 18(4): 437–442. (in Chinese)

Roderick M L, Rotstayn L D, Farquhar G D, 2007. On the attribution of changing pan evaporation. *Geophysical Research Letters*, 34, L17403.

Roderick M L, Farquhar G D, 2005. Changes in New Zealand pan evaporation since the1970s. *Int. J. Climatol.*, 25: 2031–2039.

Roderick M L, Farquhar G D, 2004. Changes in Australian pan evaporation from 1970 to 2002. *Int. J. Climatol.*, 24(9): 1077–1090.

Roderick M L, Farquhar G D, 2002. The cause of decreased pan evaporation over the past 50 years. *Science*, 298: 1410–1411.

Shanghai Normal University, Jilin Normal University, Beijing Normal University *et al*., 1979. Physical Geography of China. Beijing: People's Education Press, 148. (in Chinese)

Shen Yanjun, Liu Changming, Liu Min *et al*., 2010. Change in pan evaporation over past 50 years in the arid region of China. *Hydrological Processes*, 24: 225-231.

Sun Fubao, 2007. Study on watershed evapotranspiration based on the Budyko Hypothesis. PhD Dissertation, Tsinghua University. (in Chinese)

Su Hongchao, Wei Wenshou, Han Ping, 2003. Changes in air temperature and evaporation in Xinjiang during recent 50 years. *Journal of Glaciology and Geocryology*, 25(2): 174–178. (in Chinese)

Wang Yanjun, Jiang Tong, Xu Chongyu, 2006. Spatial-temporal change of 20cm pan evaporation over the Yangtze River Basin. *Advances in Water Science*, 17(6): 830–833. (in Chinese)

Wang Huijun, 2001. The weakening of the Asian monsoon circulation after the end of 1970's. *Adv. Atmos. Sci.*, 18: 376–38.

Wang Zunya, Ding Yihui, He Jinhai *et al*., 2004. An updating analysis of the climate change in China in recent 50 years. *Acta Meteorologica Sinica*, 62(2): 228–236. (in Chinese)

Yang Jianping, Ding Yongjian, Chen Rensheng *et al*., 2002. The interdecadal fluctuation of dry and wet climate boundaries in China in recent 50 years. *Acta Geographica Sinica*, 57(6): 655–661. (in Chinese)

Yue S, Pilon P, Phinney B *et al*., 2002. Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *J. Hydrology*, 259: 254–271.

Zeng Yan, Qiu Xinfa, Liu Changming *et al*., 2007. Changes of pan evaporation in China in 1960–2000. *Advances in Water Science*, 18(3): 311–318. (in Chinese)

Zuo Hongchao, Li Dongliang, Hu Yinjiao, 2005. Change trend of climate in China over the past 40 years and its relationship with the change of pan evaporation. *Chinese Science Bulletin*, 50(11): 1125–1130. (in Chinese)