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Does evaporation paradox exist in China?

Z. T. Cong and D. W. Yang

State Key Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China

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Correspondence to: Z. T. Cong (congzht@tsinghua.edu.cn)

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Abstract

One expected consequence of global warming is the increase in evaporation. However, lots of observations show that the rate of evaporation from open pans of water has been steadily decreasing all over the world in the past 50 years. The contrast between expectation and observation is called the evaporation paradox. Based on data from 317 weather stations in China from 1956 to 2005, the trends of pan evaporation and air temperature were obtained and evaporation paradox was analyzed. The following conclusions were made: (1) From 1956 to 2005, pan evaporation paradox exists in China as a whole with decreasing in pan evaporation and the warming though it does not exist in Northeast and Southeast; (2) From 1956 to 1985, pan evaporation paradox exists narrowly as a whole with unobvious warming though it does not exist in Northeast (3) From 1986 to 2005, in the past 50 years, the precipitation and the pan evaporation exhibit contrary trend in most areas. Furthermore, pan evaporation paradox does not exist as a whole with increasing in pan evaporation though it exists in South. Furthermore, the trend of other weather factors including sunlight time, windspeed, humidity and vapor pressure deficit and their relation with pan evaporation are discussed. It can be concluded that pan evaporation decreasing is caused by the decreasing in radiation and wind speed before 1985 and pan evaporation increasing is caused by the deceasing in vapor pressure deficit due to strong warming after 1986.

1 Introduction

Terrestrial evapotranspiration contributes to 2/3 of annual precipitation, or an equivalent amount of water twice of total surface runoff (Chahine, 1992; Brutsaert, 2005; Taikan, 2006).At the same time, evapotranspiration plays an important role in the global energy budget. Therefore, the change of evapotranspiration has great impacts on the global hydrologic cycle and energy budget.

Global warming has become one popular topic for governments and public. It was

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reported that the surface temperature of the Earth has been increasing by about 0.13° per decade over the past 50 years (IPCC, 2007). One expects that global warming tends to make the air near the Earth surface drier and results in an increase in the rate of evaporation from terrestrial open water bodies. The increase would increase the scarcity of water resources, as predicted by some studies of climate change (Yao et al., 1997; Chattopadhyay et al., 1997; Brutsaert et al., 1998).

However, lots of observations show that the rate of pan evaporation has been consistently decreasing around the world over the past 50 years. This phenomenon was firstly reported by Peterson et al. (1995). It was then found that similar trends widely present in India (Chattopadhyay et al., 1997), Venezuela (Quintana-Gomez et al., 1998), China (Thomas, 2000; Liu, 2004), Italy (Moonen et al., 2002), Australia (Roderick et al., 2004), Japan (Asanuma et al., 2004), Thailand (Tebakari et al., 2005), New Zealand (Roderick et al., 2005), and Canada (Burn et al., 2006). The contrast between expected and observed trends of the pan evaporation rate is called the pan evaporation paradox or evaporation paradox (Roderick, 2002). Besides, a falling trend of the reference evapotranspiration was also noticed by Chattopadhyay et al. (1997) and Roderick et al. (2004).

What did cause the decreases in the pan evaporation rate and reference evapotranspiration? The cause may be: (1) decreasing sunlight due to increases in cloud coverage (Peterson et al., 1995; Roderick et al., 2002) and aerosol concentration (Stanhill et al., 2001); (2) decreasing vapor pressure deficit due to increasing air humidity (Chattopadhyay et al., 1997); and, (3) decreasing wind speed due to monsoon change (Cohen et al., 2002). The decreasing solar radiation or sunlight, referred as to global dimming, could be the primary cause but this trend changed reversed in 1980s (Wild et al., 2005; Pinker et al., 2005).

It is debatable if a decreasing pan or reference evaporation rate indicates decrease of actual evapotranspiration. A proportional relation between the pan evaporation and actual evaporation rates is generally assumed in hydrological models, especially in models for crop evapotranspiration, such as FAO-56, in which a crop coefficient is introduced for the conversion from pan evaporation rates to actual evaporation rates (Allen et al., 1998). Peterson (1995) also concluded that a decreasing pan evaporation rate indicates decrease in actual evaporation. Supporting evidence for this opinion includes that increasing runoff coefficients over the past 20 years were observed in the former Soviet Union and the United States. However, Bouchet et al. (1963) found that there is a complementary relation between the potential evaporation and actual evaporation, then Morton (1976, 1983) proposed CRAE (Complementary Relationship Areal Evapotranspiration) model. The complementary relationship was validated in some basins (Brown et al., 2001; Yue et al., 2003). Brutsaert et al. (1998) concluded that decrease in pan evaporation indicates an increase in actual evaporation from the surrounding non-humid environment, which indicates that the actual evaporation and pan evaporation exhibit a complementary relationship rather than a proportional behavior. Based on Budyko hypothesis (Budyko, 1963, 1974), Yang et al. (2006, 2007) presented a generalized description that there is complementary relationship when water control and complementary relationship when energy control.

Variation of pan evaporation and reference evapotranspiration in China has been studied by some researchers. Thomas (2002) analyzed the time series (1954–1993) of Penman-Monteith evapotranspiration estimates from 65 stations. Liu (2004) analyzed records of 85 stations from 1955 to 2000. Ren (2006) analyzed records of 600 stations from 1956 to 2000. Wu (2006) analyzed records of 616 stations from 1971 to 2000. These studies suggest the existence of the evaporation paradox in China as decreasing rates of the pan evaporation and reference evapotranspiration were observed together with an increasing trend of the air temperature.

In the present study, 317 stations in China with complete data from 1956 to 2005 were selected from 751 stations. Trend analyses were conducted for observations of pan evaporation, air temperature, sunlight time, wind speed, humidity and vapor pressure deficit in different period. The purposes of this study are to investigate the evaporation paradox in China and further understanding of the variation of the pan evaporation.

2 Data and methodology

2.1 Data

Available data for the present study include pan evaporation rates recorded at 709 stations from 1956 to 2005 obtained from Climatic Data Center, National Meteorological Information Center, China Meteorological Administration, and other weather data from 751 stations released by China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/). Complete records from 317 stations for the period of 1956 to 2005 were selected for trend analysis. It was assumed that the selected stations are sufficient to characterize the climate over the whole country.

2.2 Methodology

The arithmetic means over the 317 selected stations were taken in the analyses.

Linear regression was used to identify trends of climatic variables including pan evaporation, air temperature and windspeed. The nonparametric Mann-Kendall's test was applied for trend detection (Maidment et al, 1993) with a significance level (α) of 5%.

The following equations were used to obtain vapor pressure deficit (Allen et al., 1998):

$$e_s - e_a = e_s(1 - \mathrm{RH}) \tag{1}$$

$$e_s = 6.11 \exp\left(\frac{17.27 T_{\mathrm{mean}}}{T_{\mathrm{mean}} + 237.3}\right) \tag{2}$$

Where, e_s=saturated vapor pressure in mbar; e_a=actual vapor pressure in mbar; T_{mean}=daily mean air temperature in $^{\circ}$; and RH=relative humidity (%).

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3 Result and discussion

3.1 Trends

The arithmetic means of annual pan evaporation rates and annual mean air temperature based on the data from the 317 stations are shown in Fig. 1. The pan evaporation presents a decreasing trend from 1956 to 1985 while the daily temperature was increasing; but they appear increasing after 1986. Therefore, the 50 year period from 1956 to 2005 could be divided into two sections: a 30 year period from 1956 to 1985 and a 20 year period from 1986 to 2005. Trends of analyzed climate variables are listed in Table 1.

3.2 Evaporation paradox

Over the past 50 years from 1956 to 2005, the warming is obvious in China. The daily mean air temperature had been increasing at a rate of 0.23° per decade. Records of 306 stations out of the 317 selected stations show the increasing trend, and 84.3% of them satisfy the nonparametric Mann-Kendall's test (Fig. 2a). Over the same period, the pan evaporation was on a decreasing trend. The annual pan evaporation has been decreasing at 19.3 mm per decade. The decreasing trend was noticed at 195 stations (about 2/3 stations of the selected stations) and 65.6% of them satisfy the nonparametric Mann-Kendall's test (Fig. 2b). At the same time, there are 186 out of the 195 stations where the air temperature has been increasing. Accordingly, it could be concluded that the evaporation paradox does exist in China in general.

Over the 30 years before 1985, the warming appears relatively weak. The annual mean air temperature had been increasing at 0.04° per decade. Only 167 stations present the increasing trend, and 12.6% of them satisfy the nonparametric Mann-Kendall's test (Fig. 3a). Over the same period, the annual pan evaporation appeared decreasing at 35.7 mm per decade. 226 stations show the decreasing trend but only 46.9% of them satisfy the nonparametric Mann-Kendall's test (Fig. 3b). During this period, there are only 99 stations whose records support the evaporation paradox. Therefore, it might be debatable to conclude the existence of the evaporation paradox in China over the 30 years before 1985.

Over the 20 years after 1986, the warming is obvious. The daily mean air temperature had been increasing at 0.44° per decade. Records of 304 out of the selected 317 stations indicate the increasing trend, and 71.7% of them satisfy the nonparametric Mann-Kendall's test (Fig. 4a). For the same period, the pan evaporation had been increasing at 46.5 mm per decade. The increasing trend presents at about 2/3 of the selected stations (199 out of 317) and 55.3% of them satisfy the nonparametric Mann-Kendall's test (Fig. 4b). Accordingly, it may be concluded that the evaporation paradox does not exist in China for the past 20 years after 1986 because pan evaporation increased.

In space, it can be found the universal for the evaporation paradox. In the 50 years from 1956 to 2005, the evaporation paradox does exist as a whole but does not exist in Northeast and Southwest where the pan evaporation increased with the warming (showing in Fig. 2). In the 30 years before 1985, the evaporation paradox does exist as a whole but does not exist in Northeast where the pan evaporation increased with the warming and in Southwest where the air temperature decreased with the decreasing in pan evaporation (showing in Fig. 3). In the 20 years after 1986, the evaporation paradox does not exist for the whole but does exist in South China where pan evaporation decreased with the warming (showing in Fig. 4).

In summary, it can be concluded that the pan evaporation paradox exists in China as a whole (showing in Fig. 1) but it is not universal in time and space.

3.3 Relation between evaporation and other weather factors

3.3.1 General

Evaporation, including pan evaporation, potential evaporation and actual evapotranspiration, can be influenced by solar radiation, air temperature, wind speed, vapor pressure deficit, etc. Variations of some weather factors are shown in Fig. 5 and the relations between trends of pan evaporation and those of other weather factors are presented in Table 2.

Reference evapotranspiration was calculated using the standard Penman-Monteith function presented by Allen (1998):

$$ET_0 = \frac{0.408\Delta(R_n - G)}{\Delta + \gamma(1 + 0.34U_2)} + \frac{\frac{900}{T+273}\gamma U_2(e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)} \tag{3}$$

Where, ET_0 = reference evapotranspiration rate in mm/day; R_n = net radiation at the crop surface in $\text{MJm}^{-2}\text{day}^{-1}$; G= soil heat flux density in $\text{MJm}^{-2}\,\text{day}^{-1}$; T = air temperature at 2 m above... in °; U_2 = wind speed at 2 m height in ms^{-1}; e_s = saturation vapor pressure in Kpa; e_a = actual vapor pressure in Kpa; $e_s - e_a$ = saturation vapor pressure deficit in Kpa; Δ = slope of saturation vapor pressure curve in $\text{kPa}\,^\circ\text{C}^{-1}$; and, γ = psychrometric constant in $\text{kPa}\,^\circ\text{C}^{-1}$.

As solar radiation observations were not available for this study, the radiation was estimated based on sunlight time according to Allen (1998).

A correlation analysis was conducted between pan evaporation and other weather factors. The correlation coefficients based on the 50 years records from the 317 stations are shown in Table 3. These correlations are further discussed below.

3.3.2 Sunlight time

A positive correlation between the pan evaporation and sunlight time was obtained, which is reasonable as the radiation is the energy source for evaporation. As shown in Table 3, the coefficient is 0.37 on average and about 2/3 stations have a coefficient larger than 0.3.

From 1956 to 2005, the sunlight time was overall on a decreasing trend. The decreasing trend was presented at more than half of the 317 stations for both pan evaporation and sunlight time. The decreasing sunlight time may be caused by more cloudy cover and increasing aerosol concentration. However, when the pan evaporation became increasing after 1986, the sunlight time was still on the decreasing trend even though this trend became weaken (Tables 1 and 2).

3.3.3 Wind speed

The evaporation decreases with decrease of wind speed, which can be represented with a positive correlation relation as shown in Table 3. The average coefficient is 0.27. From 1956 to 2005, the wind speed was on a decreasing trend overall. The decreasing wind speed may be a result of the monsoon weakening (Xu et al., 2006) or urbanization over the past 50 years. The wind speed kept decreasing after 1986.

3.3.4 Humidity and vapor pressure deficit

According to Eq. (2), saturated vapor pressure would increase for given humidity when air temperature increases. As a result, vapor pressure deficit would increase. Over the past 50 years in China, changes in humidity were minor, while increase of vapor pressure deficit was observed (Table 1). According to Eq. (3), increasing vapor pressure deficit would result in increase of pan evaporation. However, the pan evaporation over the past 50 years did not increase consistently with the increase of vapor pressure deficit, which may suggest that effects of increasing vapor pressure deficit on pan evaporation weigh less than effects of decrease in radiation and wind speed. After 1986, the vapor pressure deficit increased obviously due to the strong warming, and its effects on pan evaporation could become more significant than the influence of decreasing in radiation and wind speed, which contributed to the increase of pan evaporation.

3.3.5 Summary

Before 1985, pan evaporation reduced with radiation decreasing, windspeed decreasing and vapor pressure deficit increasing, so the energy condition controls evaporation mainly. After 1986, pan evaporation increased with radiation decreasing, windspeed

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decreasing and vapor pressure deficit increasing, so the water condition controls evaporation mainly. For the past 50 years as a whole, pan evaporation reduced with radiation decreasing, windspeed decreasing and vapor pressure deficit increasing.

4 Conclusion

Based on the weather data at 317 stations from 1956 to 2005 in China and the trend analysis, the conclusions include:

1. Pan evaporation paradox exists in China as a whole with the warming and decreasing in pan evaporation in the past 50 years. But pan evaporation paradox does not exist in Northeast and Southwest where the pan evaporation increased with the warming in the same period.

2. From 1956 to 1985, the warming is not obvious while pan evaporation decreased, so pan evaporation paradox exists narrowly as a whole. In the same period, the paradox does not exist in Northeast where the pan evaporation increased with the warming and in Southwest where the air temperature decreased with the decreasing in pan evaporation.

3. From 1986 to 2005, the warming is obvious but pan evaporation increased, so pan evaporation paradox does not exist in China as a whole for the past 20 years. In the same period, pan evaporation paradox does exist in South China where pan evaporation decreased with the warming.

4. Before 1985, pan evaporation decreasing caused by radiation decreasing and windspeed decreasing in despite of vapor pressure deficit increasing, so the energy condition controlled evaporation mainly. After 1986, pan evaporation increasing caused by vapor pressure deficit increasing in despite of radiation decreasing and windspeed decreasing, so the water condition controls evaporation mainly.

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Table 1. Trend of weather factors in China from 1956 to 2005.

Item	Period	Average	Unit	Trend	Unit	Increasing Number	Decreasing Number	Kendall test in increasing	Kendall test in decreasing
Annual pan evaporation	1956–2005	1662	mm/a	−19.3	mm/a/10a	122	195	44.3%	65.6%
	1956–1985	1682	mm/a	−35.7	mm/a/10a	91	226	35.2%	46.9%
	1986–2005	1632	mm/a	46.5	mm/a/10a	199	118	55.3%	33.1%
Daily maximum air temperature	1956-2005	18.6	°	0.15	°/10a	293	24	62.8%	12.5%
	1956–1985	18.4	°	−0.08	°/10a	98	219	35.7%	26.5%
	1986–2005	18.9	°	0.46	°/10a	308	9	60.1%	0.0%
Annual mean air temperature	1956-2005	12.8	°	0.23	°/10a	306	11	84.3%	18.2%
	1956–1985	12.6	°	0.04	°/10a	167	150	12.6%	12.0%
	1986–2005	13.2	°	0.44	°/10a	304	13	71.7%	15.4%
Daily minimum air temperature	1956–2005	8.3	°	0.31	°/10a	308	9	89.0%	55.6%
	1956–1985	8.0	°	0.12	°/10a	219	98	36.1%	10.2%
	1986–2005	8.8	°	0.49	°/10a	295	22	71.9%	9.1%
Annual sunlight time	1956–2005	2225	h/a	−49.4	h/10a	46	271	19.6%	76.0%
	1956–1985	2276	h/a	−60.6	h/10a	61	256	18.0%	57.4%
	1986–2005	2150	h/a	−18.1	h/10a	133	184	24.8%	28.8%
Annual mean wind speed	1956–2005	2.3	m/s	−0.11	m/s/10a	67	250	35.8%	84.0%
	1956–1985	2.5	m/s	−0.07	m/s/10a	115	202	29.6%	61.9%
	1986–2005	2.1	m/s	−0.06	m/s/10a	134	183	43.3%	45.9%
Annual mean RH	1956–2005	67.4	%	−0.20	%/10a	108	209	37.0%	49.8%
	1956–1985	67.6	%	0.00	%/10a	173	144	24.9%	27.8%
	1986–2005	67.2	%	−0.91	%/10a	83	234	9.6%	35.9%
Annual mean vapor pressure deficit	1956–2005	4.5	hpa	0.10	hpa/10a	254	63	66.5%	28.6%
	1956–1985	4.4	hpa	−0.01	hpa/10a	157	160	28.7%	29.4%
	1986–2005	4.7	hpa	0.29	hpa/10a	276	41	52.9%	9.8%

Table 2. Relations between trends of pan evaporation and that of other weather factors.

Weather factors	Period	Decreasing in pan evaporation with its decreasing		Decreasing in pan evaporation with its increasing		Increasing in pan evaporation with its decreasing		Increasing in pan evaporation with its increasing	
Sunlight time	1956–2005	170	54%	25	8%	101	32%	21	7%
	1956–1985	190	60%	36	11%	66	21%	25	8%
	1986–2005	73	23%	45	14%	111	35%	88	28%
Wind speed	1956–2005	163	51%	32	10%	87	27%	35	11%
	1956–1985	157	50%	69	22%	45	14%	46	15%
	1986–2005	76	24%	42	13%	107	34%	92	29%
Vapor pressure deficit	1956–2005	51	16%	144	45%	12	4%	110	35%
	1956–1985	139	44%	87	27%	21	7%	70	22%
	1986–2005	25	8%	93	29%	16	5%	183	58%
Humidity	1956–2005	109	34%	86	27%	100	32%	22	7%
	1956–1985	81	26%	145	46%	63	20%	28	9%
	1986–2005	76	24%	42	13%	158	50%	41	13%

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Table 3. Correlation coefficients between pan evaporation and other weather factors.

Weather factors	Coefficient of average	Average coefficient	Number of stations with coefficient more than 0.3	Number of stations with coefficient less than 0.3
Sunlight time	0.75	0.37	189	1
Wind speed	0.53	0.27	152	8
Vapor pressure deficit	0.19	0.47	247	2
Humidity	−0.36	−0.49	0	261
Air temperature	−0.02	0.24	139	14
Precipitation	−0.33	−0.36	0	212

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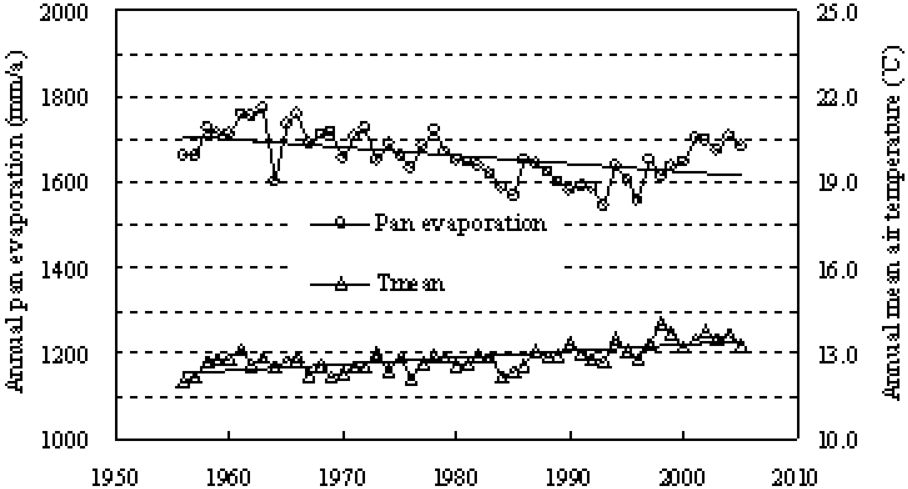
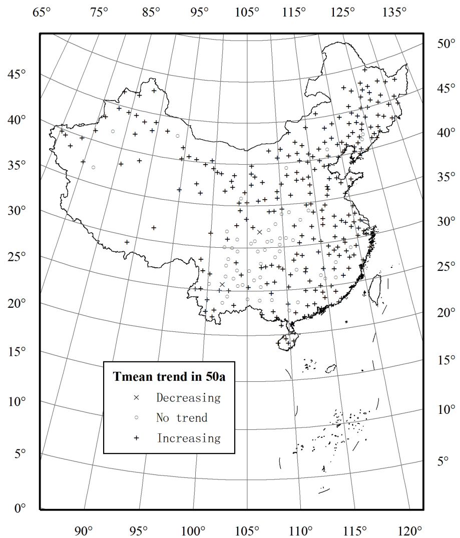
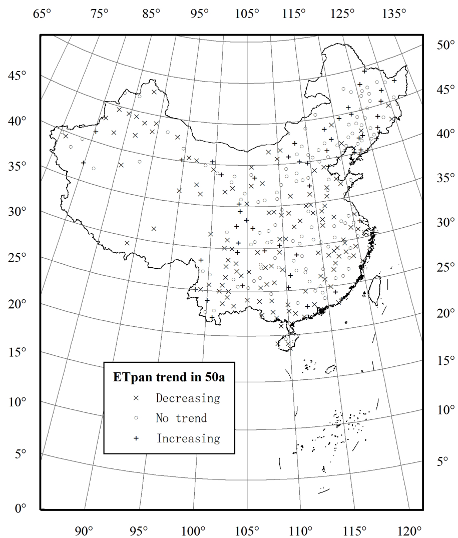


Fig. 1. Annual pan evaporation and annual mean air temperature from 1956 to 2005.

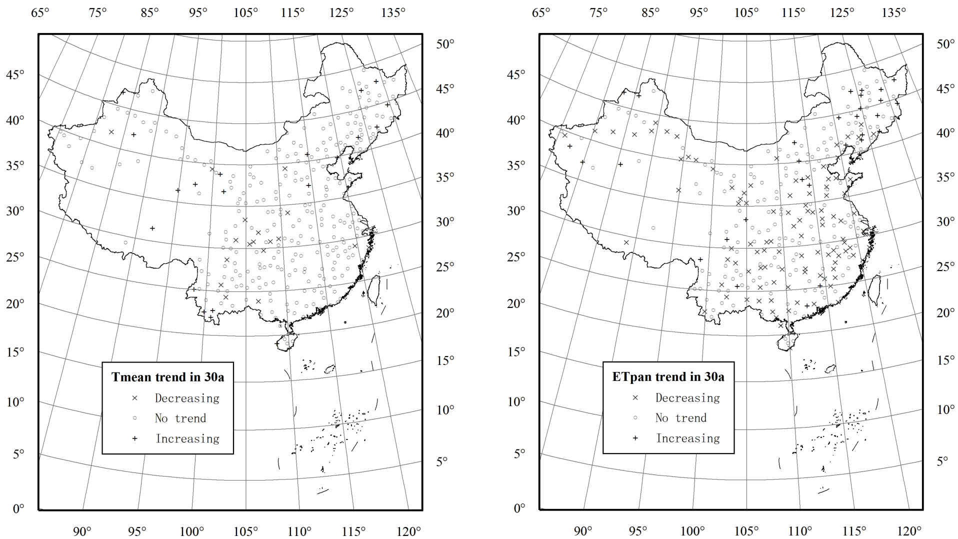


(a) Trend of annual mean air temperature



(b) Trend of annual pan evaporation

Fig. 2. Trends in the past 50 years from 1956 to 2005.



(a) Trend of annual mean air temperature **(b)** Trend of annual pan evaporation

Fig. 3. Trends in the 30 years before 1985.

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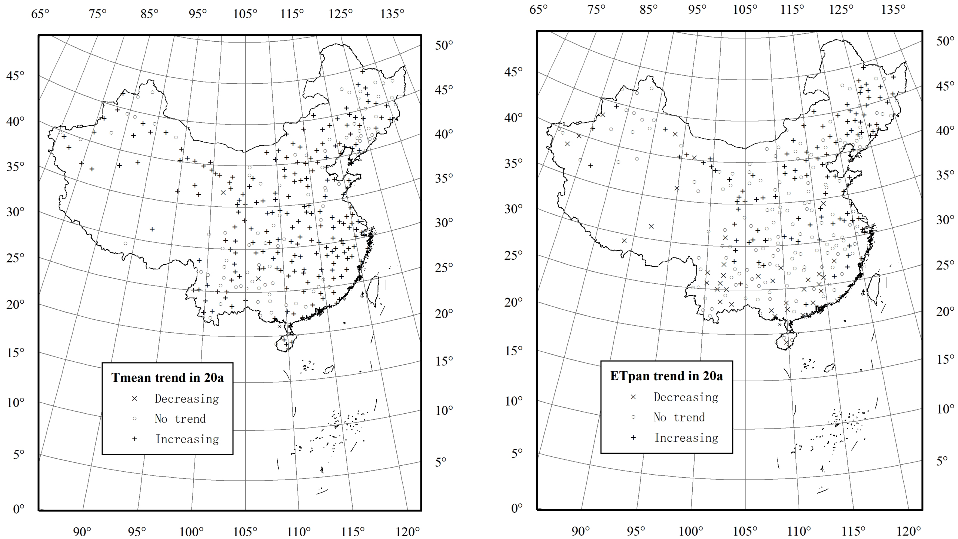

(a) Trend of annual mean air temperature **(b)** Trend of annual pan evaporation

Fig. 4. Trends in the 20 years after 1986.

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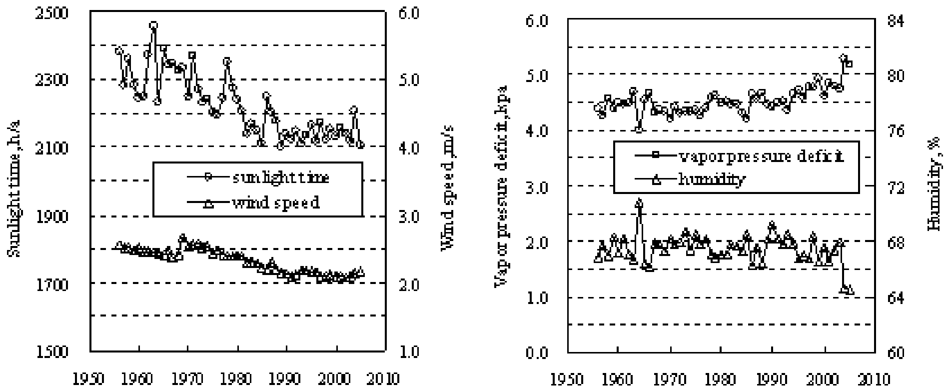

(a) Sunlight and wind speed

(b) Humidity and vapor pressure deficit

Fig. 5. Weather factors in the past 50 years.