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Abstract

Evaporation is an important component both in surface energy balance and terrestrial water cycle, and it is also a key factor determining weather and climate conditions. It plays a significant role in the studies of water and energy balance within a certain area and estimations of water resources. In this study, based on pan evaporation data and their variation trends from 499 stations in China, the correlations between evaporation and various influence factors, including the amount of precipitation, temperature, wind speed, sunshine duration and relative humidity, were studied in depth by means of correlation analysis and set pair analysis methods. The analysis results indicated that there was a decline of pan evaporation in both of the whole China and its seven major river basins, and it has decreased significantly since mid-1970s, mainly due to the decreasing sunshine duration and wind speed. In addition, increased precipitation and relative humidity may inhibit the reduction to a certain degree. In most regions of China, temperature change presented a contrary trend compared with the variation of evaporation, as described in 'evaporation paradox'; however, the correlation between them was not very striking, which implied that the variation of water surface evaporation was slightly affected by temperature.

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Changes of Pan Evaporation and Its Influence Factors in China

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ABSTRACT

Evaporation is an important component both in surface energy balance and terrestrial water cycle, and it is also a key factor determining weather and climate conditions. It plays a significant role in the studies of water and energy balance within a certain area and estimations of water resources. In this study, based on pan evaporation data and their variation trends from 499 stations in China, the correlations between evaporation and various influence factors, including the amount of precipitation, temperature, wind speed, sunshine duration and relative humidity, were studied in depth by means of correlation analysis and set pair analysis methods. The analysis results indicated that there was a decline of pan evaporation in both of the whole China and its seven major river basins, and it has decreased significantly since mid-1970s, mainly due to the decreasing sunshine duration and wind speed. In addition, increased precipitation and relative humidity may inhibit the reduction to a certain degree. In most regions of China, temperature change presented a contrary trend compared with the variation of evaporation, as described in 'evaporation paradox'; however, the correlation between them was not very striking, which implied that the variation of water surface evaporation was slightly affected by temperature.

INTRODUCTION

Climate change alters the current situation of hydrologic cycle, which gives rise to a redistribution of water resources in space-time, and moreover, poses direct impacts on various factors, such as precipitation, evaporation, runoff, soil humidity, etc. As an important component, both in surface energy balance and terrestrial water cycle, evaporation also determines weather and climatic conditions significantly, occupying vital roles in the studies on water and energy balance within a certain area and estimation of water resources. Accordingly, researches on evaporation capacity have attracted a great deal of attention by the domestic and foreign scholars, and now have been one of the focus issues in the fields of geoscience and biology (Qiu et al. 2003).

Climate warming has become a popular topic for governments and the general public. 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 (Cong et al. 2009). In 1995, Peterson et al. (1995) have pointed out that pan evaporation decreased steadily during the past five decades, and moreover the land evaporation induced by water cycle decreased as well. The contrast between expectation and observation is called 'Evaporation Paradox' (Michael et al. 2002), which has been proved in many other countries, such as India, Venezuela, China, etc. (Chattopadhyay & Hulme 1997, Michael & Graham 2004, 2005, Cong et al. 2009).

Do the declines of pan evaporation and potential evaporation capacity mean the decrease of land evaporation? No consistent conclusions have been gained yet. With regard to the reasons accounting for the decline of pan evaporation, a large number of investigations have been performed by many scholars from different perspectives. Michael and Graham (2005) have found that pan evaporation and other evaporations, all decreased under warm and moist conditions, and proposed that the reduction of sunshine radiation, caused by the increases of cloud cover and aerosols, were responsible for the decline of evaporation. This could account for the decline in pan evaporation theoretically. In the studies performed by Chattopadhyay & Hulme (1997), the increased moisture in air generated the reduction of vapour pressure and finally lead to the decline of evaporation. Besides, some scholars have proposed that the decreased wind speed in land caused by the variations

of summer monsoon, gave rise to the decline of pan evaporation (Cohen et al. 2002).

Generally, the influence factors on pan evaporation can be classified into two categories: meteorological factors and water factors, in which the meteorological conditions are the determining factors, mainly including solar radiation, temperature, humidity, wind speed, etc. In acid regions, the water factors should be taken into account owing to their significance, in which the amount of precipitation is of most correlation with water surface evaporation. In the study, trend analyses were conducted based on observations of pan evaporation from 499 stations using linear regression and Mann-Kendall's test. In addition, the relationships between water surface evaporation and various influence factors, including solar radiation, relative humidity, temperature, wind speed and the amount of precipitation, were studied by means of correlation analysis and set pair analysis methods. The purpose of this study is to explore the primary meteorological factors affecting the pan evaporation in China and its seven major river basins under the climate-change background, and to investigate their variation mechanisms.

DATA AND METHODOLOGY

Data: Aiming at revealing the main reasons for the variation of water surface evaporation in China and the related seven major river basins, we have studied the relationship between pan evaporation and meteorological factors. The adopted meteorological data were taken from *Data Sets of Monthly Ground Climate in China*, provided by China Meteorological Data Sharing Service System. The data sets consisted of the monthly climatic data which were collected from the total 752 basic meteorological stations and automatic stations from 1951 to 2007, including the amount of precipitation, temperature, wind speed, sunshine duration and relative humidity, etc.

In accordance with the measured evaporation data by small-caliber dishes with 20cm and E601 evaporators, the data from 499 nationwide meteorological stations were selected as shown in Fig. 1, in which the length of same evaporation data sequences from two evaporators were not less than 5 years, and moreover the length of evaporation data sequence from small-caliber dish were not less than 30 years. The meteorological stations in Songhuajiang River basin (SHJ), Liaohe River basin (LH), Haihe River basin (HaiH), Yellow River basin, Huaihe River basin (HuaiH), Yangtze River basin and Pearl River basin amounted to 56, 37, 31, 47, 36, 106 and 65, respectively. The observations on evaporation using E601 evaporators started relatively late, and sometimes had to stop measuring on account of the freezes in winter in most areas of northern China. The measurements of evaporation capacity by small-caliber dishes with 20 cm were of a long history in a majority of stations. The correlations between the measurements by two types of evaporators in different regions were studied by many domestic scholars, with the purpose to acquire long-sequence pan evaporation data more close to the actual conditions. In this study, the long-sequence evaporation capacity measured by the small-caliber dishes with 20 cm

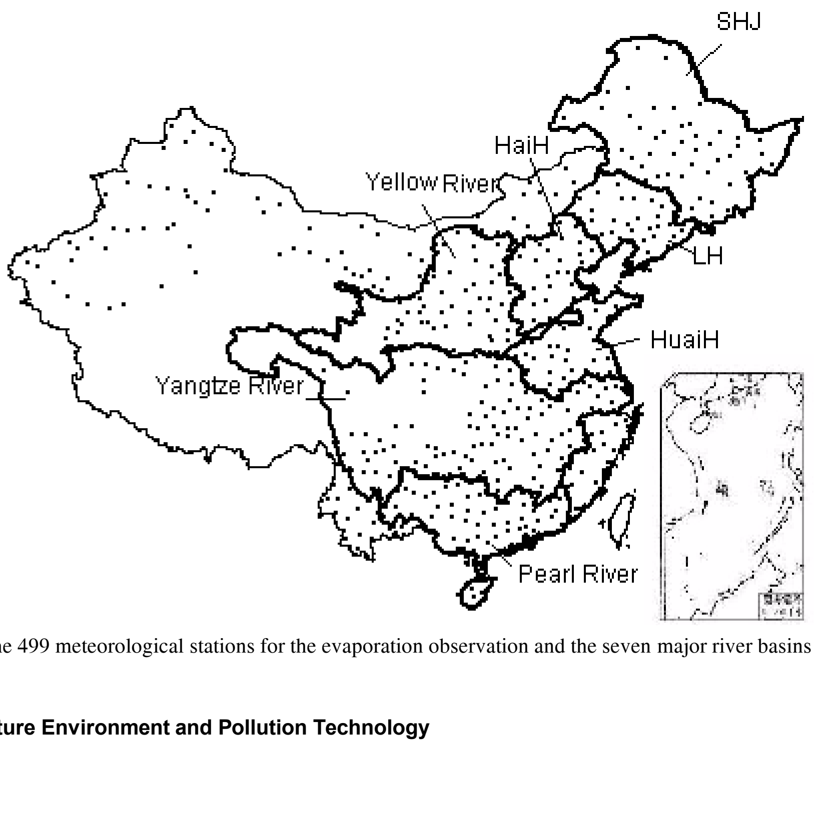

Fig 1: The 499 meteorological stations for the evaporation observation and the seven major river basins in China.

were translated to the capacity by E601 evaporators, with the adoption of monthly conversion coefficient, by which the variation tendency of pan evaporation and the related influence factors were investigated.

Methodology: The arithmetic average of the stations is taken to get the averages of the studied regions. The linear regression and the non-parametric Mann-Kendall's test were used to identify trends of climatic variables (Meng et al. 2013). The non-parametric Mann-Kendall's test was applied both for trend detection and abrupt change analysis with a significance level of 5% (Tabari & Marofi 2011, Wei 2007). The Mann-Kendall's test used as a method of mutation detection can determine the starting time of a mutation and indicate the mutation region. Then the correlation analysis and set pair analysis methods were used to reveal the relationship between pan evaporation and meteorological factors, including precipitation, temperature, wind speed, solar duration and relative humidity.

Set pair analysis (SPA) method (Wang et al. 2006, 2009) is a systemic analysis method to deal with uncertainties. The core technology of SPA is to view certainties and uncertainties as a certain-uncertain system, in which the certainties and uncertainties are of correlation, interaction and mutual restriction, and can be converted to each other under given conditions. Generally, the connection degree is used to describe these certainties and uncertainties. For two given sets, A and B, the connection degree can be expressed as:

$$\mu_{A\text{-}B} = a + bi + cj \quad ...(1)$$

Where, $a = S/N$ denotes the identity degree, $b = F/N$ denotes the discrepancy degree, $c = P/N$ denotes the opposite, and N is the total amount of elements in the set. Following certain standards, set A and set B can be classified into three grades, i.e., large, medium and small; and S, P and F are the numbers of the identical terms, contradictory terms and opposite terms of characteristic in the two sets, respectively. The standardized data adopted in the present work were divided into three levels, according to the three ranges ($-\infty$, Ex-0.5s), (Ex-0.5s, Ex+0.5s) and (Ex+0.5s,$+\infty$), respectively, in which 'Ex' and 's' were the mean value and standard deviation of the elements in the set. 'i' is the uncertainty coefficient of discrepancy, which has different values in [-1, 1] in different conditions or sometimes may be considered as a marker of discrepancy only; while 'j' is the uncertainty coefficient of contradictory degree, and predetermined to be -1.

With regard to the connection degree, 'a' and 'c' are supposed to be representative of positive and negative correlations, respectively; and 'b' denotes the correlation which is neither positive nor negative. The characteristics of correlation can be estimated in accordance with the values of a, b and c, suggesting a positive correlation, a negative correlation and an uncertain correlation, respectively. The connection degree can illuminate the correlation behaviors between two sets from a microscopic aspect, which can be employed as supplements and improvements on the overall correlation between two sets from a macroscopic perspective.

Table1: The MK trend test values for the annual evaporation and other meteorological factors in China and its major basins during 1961-2006.

	SHJ	LH	HaiH	Yellow	HuaiH	Yangtze	Pearl	China
PE	-0.95	-1.1	-3.65	-1.68	-3.92	-3.65	-2.96	-4.39
P	-0.32	-1.31	-1.53	-1.7	-0.61	-0.04	0.17	0.25
T	4.6	4.35	4.91	4.83	3.72	3.65	3.86	4.96
U	-6.89	-7.66	-6.06	-4.47	-6.86	-6.79	-5.77	-7.69
US	-2.75	-3.79	-5.83	-2.56	-4.79	-5.23	-4.53	-5.55
UH	-2.84	-1.57	-1.74	-1.59	-0.91	-1.7	-3.28	-1.75

RESULTS AND DISCUSSION

Trends of PE and its influence factors during 1961-2006: From 1961 to 2006, the annual mean pan evaporation in China amounted to 1012.6 mm, far exceeding the amount of precipitation which is about 834mm during the corresponding period. Fig. 2 displays the annual variations of water surface evaporation in China during 1961 to 2006, from which we can observe that pan evaporation presented an obvious decrease during the past 46 years, with a linear change rate of 17.6 mm/10a. Calculated by MK abrupt change analysis, the year of 1973 was the remarkable mutational point and water surface evaporation decreased significantly since the mid-1970s.

In the study, water surface evaporation (mm), the amount of precipitation (mm), temperature (°C), wind speed (m/s), sunshine duration (h) and relative humidity (%) were denoted by PE, P, T, U, RS and RH, respectively. MK trend test values for the annual evaporation in China and its major basins from 1961 to 2006 with various factors are listed in

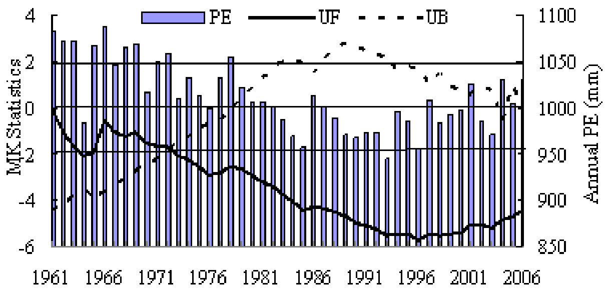

Fig. 2: The annual variations of pan evaporation and its MK abrupt change statistics from 1961 to 2006.

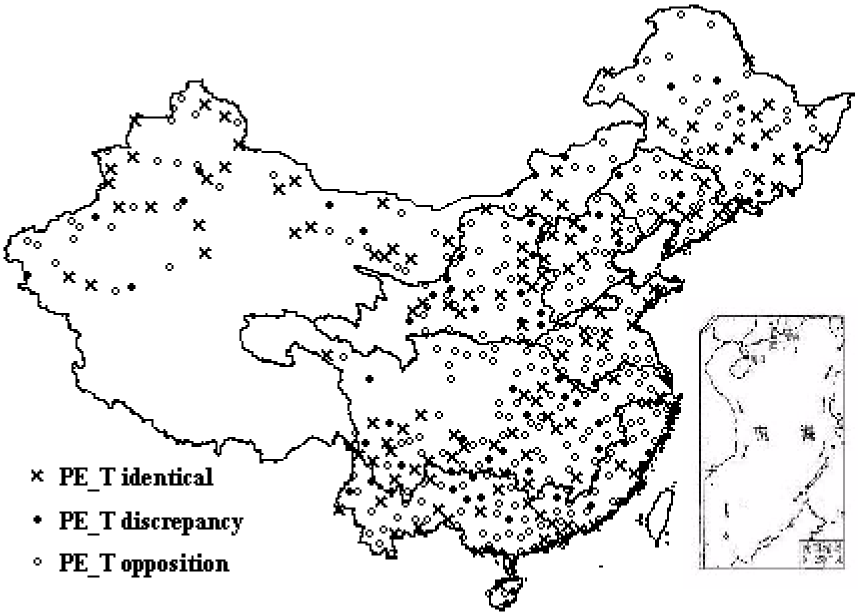

Fig. 3: The spatial distribution of the correlation between pan evaporation and temperature change during 1961-2006.

Table 1. For a convenience of identification, the zero-value range in MK trend tests is listed meanwhile. To be specific, the variable was supposed to be changeless during the past 46 years when $|MK| < 0.5$ while presented a significant variation when $|MK| > 1.96$ (at the 95% confidence level). The variable exhibited a decrease trend when $-1.96 < MK < -0.5$ while exhibited a rising when $0.5 < MK < 1.96$. As given in Table 1, from 1961 to 2006, pan evaporation in Chinese major river basins all decreased, especially for the river basins except SHJ River, LH River and Yellow River. Similar tendencies could be observed for wind speed, sunshine duration and relative humidity, and moreover the decreasing trends were more striking for wind speed and sunshine duration. Conversely, the air temperature increased significantly.

'Evaporation paradox' is a kind of natural phenomenon existed universally in many countries and regions all over the world. To obtain a further proof that 'Evaporation paradox' exists in China, the nonparametric MK trend tests were performed, in which the variations of water surface evaporation and temperature over time were separated into three levels, $(-\infty, -0.5)$, $(-0.5, 0.5)$ and $(0.5, +\infty)$, respectively. If the test values of the two factors were at the same level, their variations were defined to be identical. If the two variables presented exactly the opposite changes, their variations were opposition, otherwise they were assumed to be discrepancy. Fig. 3 presents the spatial distribution of the correlation between pan evaporation and temperature changes from 1961 to 2006, from which we can conclude that 'evaporation paradox' was ubiquitous in China. On a nationwide scale, there were 360 out of the 499 stations with pan evaporation and temperature being in different trends and about 58% of the meteorological stations displayed the opposite variation trends. For the meteorological stations in Haihe and Yellow river basins, the phenomenon was more prominent and more than 80% stations exhibited opposite variations. The same tendencies can also be observed in 60% of the stations in Yangzi and Pearl River basins.

Correlation analysis: Correlation analyses were carried out on the annual pan evaporation and the related meteorological factors, with the results for the whole country and its seven major river basins from 1961 to 2006 shown in Table 2. Take the country as a whole, we can find that the positive correlation coefficient of annual pan evaporation with wind speed and sunshine duration were comparative large, suggesting significant correlations at the 99% confidence test. And there was a negative correlation coefficient of annual pan evaporation with the amount of precipitation at the 95% confidence test.

The evaporation in the seven river basins all presented remarkable negative correlations with the amount of precipitation and relative humidity, while remarkable positive correlation with sunshine duration, significant at the 99% confidence level. Except SHJ and LH river basins, remarkable positive correlations can also be observed between the annual pan evaporation and wind speed, significant at the 99% confidence level. In SHJ, HaiH and Pearl River basins, pan evaporation was negatively correlated with temperature;

Table 2: The correlation coefficients between the annual pan evaporation and the related meteorological factors for the whole China and its seven major river basins.

	SHJ	LH	HaiH	Yellow	HuaiH	Yangtze	Pearl	China
P	-0.708[b]	-0.669[b]	-0.508[b]	-0.608[b]	-0.509[b]	-0.508[b]	-0.640[b]	-0.331[a]
T	-0.021	0.209	-0.068	0.158	0.03	0.053	-0.022	-0.229
U	0.284	0.218	0.599[b]	0.595[b]	0.612[b]	0.586[b]	0.530[b]	0.661[b]
US	0.666[b]	0.687[b]	0.779[b]	0.803[b]	0.857[b]	0.898[b]	0.888[b]	0.843[b]
UH	-0.503[b]	-0.658[b]	-0.515[b]	-0.632[b]	-0.550[b]	-0.405[b]	-0.440[b]	-0.259

[a] significant at the 95% confidence level; [b] significant at the 99% confidence level

Table 3: Set pair analyses of pan evaporation and meteorological factors for the whole China and its seven river basins.

SHJ	$\mu_{PE-P}=0.26+0.28i+0.46j$ $\mu_{PE-T}=0.33+0.46i+0.22j$ $\mu_{PE-U}=0.35+0.59i+0.07j$ $\mu_{PE-RS}=0.63+0.37i+0.00j$ $\mu_{PE-RH}=0.17+0.46i+0.37j$	LH	$\mu_{PE-P}=0.13+0.46i+0.41j$ $\mu_{PE-T}=0.35+0.52i+0.13j$ $\mu_{PE-U}=0.41+0.39i+0.20j$ $\mu_{PE-RS}=0.57+0.41i+0.02j$ $\mu_{PE-RH}=0.26+0.35i+0.39j$
Haij	$\mu_{PE-P}=0.24+0.46i+0.30j$ $\mu_{PE-T}=0.28+0.50i+0.22j$ $\mu_{PE-U}=0.54+0.41i+0.04j$ $\mu_{PE-RS}=0.61+0.39i+0.00j$ $\mu_{PE-RH}=0.39+0.33i+0.28j$	Yellow River	$\mu_{PE-P}=0.28+0.35i+0.37j$ $\mu_{PE-T}=0.48+0.37i+0.15j$ $\mu_{PE-U}=0.50+0.39i+0.11j$ $\mu_{PE-RS}=0.59+0.39i+0.02j$ $\mu_{PE-RH}=0.22+0.48i+0.30j$
Huaih	$\mu_{PE-P}=0.20+0.50i+0.30j$ $\mu_{PE-T}=0.35+0.50i+0.15j$ $\mu_{PE-U}=0.59+0.37i+0.04j$ $\mu_{PE-RS}=0.67+0.33i+0.00j$ $\mu_{PE-RH}=0.31+0.41i+0.28j$	Yangtze	$\mu_{PE-P}=0.24+0.43i+0.33j$ $\mu_{PE-T}=0.35+0.50i+0.15j$ $\mu_{PE-U}=0.50+0.56i+0.04j$ $\mu_{PE-RS}=0.78+0.22i+0.00j$ $\mu_{PE-RH}=0.17+0.52i+0.30j$
Pearl River	$\mu_{PE-P}=0.26+0.37i+0.37j$ $\mu_{PE-T}=0.39+0.41i+0.20j$ $\mu_{PE-U}=0.48+0.48i+0.04j$ $\mu_{PE-RS}=0.74+0.26i+0.00j$ $\mu_{PE-RH}=0.13+0.61i+0.26j$	China	$\mu_{PE-P}=0.28+0.41i+0.30j$ $\mu_{PE-T}=0.20+0.48i+0.33j$ $\mu_{PE-U}=0.61+0.35i+0.04j$ $\mu_{PE-RS}=0.65+0.35i+0.00j$ $\mu_{PE-RH}=0.26+0.50i+0.24j$

however, it was positively correlated in the other basins. The correlations were unremarkable and below the 95% confidence level.

Set pair analysis: In order to further explore the relationship between pan evaporation and the related meteorological factors, set pair analyses were performed and the calculated connection degrees are listed in Table 3. Nationally, the relationships of pan evaporation with the amount of precipitation and relative humidity exhibited the largest discrepancy degrees, while almost the same identical degrees and opposite degrees, indicating uncertain correlations. The discrepancy degree between the evaporation and temperature was the largest, but the opposite between them was larger than the identity degree, which implied that the uncertainties dominated in the correlation and still a weak negative correlation existed. The identical degrees of evaporation with wind speed and sunshine duration were quite considerable, exceeding the opposite and discrepancy degrees, which implied that pan evaporation was positively correlated with wind speed and sunshine duration. By set

pair analyses, the probabilities of identity, opposite and discrepancy degrees between two variables can be reflected, exhibiting a more detailed correlation between two factors compared with analyses by linear correlation. Slight differences appeared between two analysis results, partly due to the fact that the correlation analysis results were affected by several extreme values. Overall, the strong positive relationships can be observed between pan evaporation and wind speed/sunshine duration, suggesting that the decline of pan evaporation was mainly induced by the decreasing wind speed and sunshine duration.

Similarly, it can be concluded from Table 3 that the decline of pan evaporation was mainly on account of the reduction of sunshine duration, and secondly the decreasing wind speed in the seven river basins. It should also be noted that pan evaporation was inhibited by the increasing of precipitation and relative humidity to a certain degree.

CONCLUSIONS

As a whole, the annual pan evaporation in China from 1961 to 2006 decreased gradually, and its decline was more significant since 1973, which was the point of abrupt change. Analyses were performed on the correlations between evaporation and various meteorological factors, and the results indicated that the decline of pan evaporation presented positive correlations with sunshine duration and wind speed, while negative correlations with precipitation and relative humidity. These implied that both sunshine duration and wind speed were the primary meteorological factors leading to the decline of pan evaporation, and contrarily the precipitation and relative humidity posed certain inhibitory effects. In most regions of China, the variation of temperature presented a contrary trend compared with the variation of evaporation, as described in 'evaporation paradox'; however, the correlation between them was not very striking, which implied that the variation of pan evaporation was slightly affected by temperature.

In recent years, the decline of pan evaporation in China was mainly induced by the decreasing sunshine duration, which was consistent with Michael's view (Michael et al. 2004). The reduction of sunshine duration was indicative of a decline of solar radiation. It should also be mentioned that the required energy for pan evaporation mainly originated from solar radiation. The decline of sunshine duration probably resulted from the increasing cloud cover, and also probably caused by the rising aerosol contents artificially. The increases of aerosol contents and smoky days were likely to be responsible for the declines of sunshine duration and solar radiation. Additionally, the decline of pan evaporation was partly affected by the decreasing wind speed, with the effects on the ground mainly achieved by turbulence exchange interactions. The increase of aerosol contents and smoky days were significantly affected by the decline of average wind speed, which would pose indirect impacts on pan evaporation by solar radiation.

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