SPATIAL AND TEMPORAL CHARACTERISTICS OF PAN EVAPORATION IN THE HUAIHE RIVER BASIN DURING 1951-2015

YANG, M.-Z.[1] – ZHONG, P. A.[1,2*] – LI, J.-Y.[1] – CHEN, J.[1] – WANG, W.-Z.[1] – ZHU, F.-L.[1] – WU, Y.-N.[1] – XU, B.[1] – YAN, K.[3] – LIU, W.-F.[1] – LI, Y.-H.[1]

[1]*College of Hydrology and Water Resources, Hohai University*
No.1, Xikang Road, Nanjing 210098, China

[2]*National Engineering Research Center of Water Resources Efficient Utilization and Engineering Safety, Hohai University, No.1, Xikang Road, Nanjing 210098, China*

[3]*Zhejiang Institute of Hydraulics & Estuary*
No.50, Fengqi East Road, Hangzhou 310020, China

**Corresponding author*
e-mail: zpa_hhu@163.com

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Abstract. The Huaihe River Basin (HRB) in China is located in the middle latitude zone with a land-tosea transitional characteristic, which is sensitive to climate change. Based on the daily pan evaporation (E_{pan}) data from 26 meteorological stations, we investigated the temporal and spatial characteristics of E_{pan} across the HRB from 1951 to 2015. Our results indicate that the annual average E_{pan} showed a single peak characteristic and mainly peaked in spring and summer, gradually increased from southeast to northwest, coastal area to inland, and humid area to semi-humid area. The annual average E_{pan} changed significantly both in 1966 and 1985, dividing the series into three periods, including: significant increasing period, significant declining period and slight increasing period. The E_{pan} of the majority of stations exhibited three obvious changing periods, of which the first two periods were consistent with the basin average, and the third one can be categorized into two types, i.e., the descending-to-ascending period and the steep decreasing period. The air temperature (T_a) and E_{pan} showed periodically contradictions. Specifically, they both presented increasing trends during 1951-1966 and 1986-2015, while during 1967-1985, there existed pan evaporation paradox. Therefore, T_a is not the dominant factor of E_{pan}.
Keywords: *climate change, evaporation paradox, variation, E601 pans, D20 pans, distribution*

Introduction

Evaporation is an indispensable variable in both of the surface heat balance equation and water balance equation. In fact, compared with the reference evapotranspiration and free water evaporation, the actual evapotranspiration is a direct participant in the process of water balance and has long been a major concern. However, it is difficult to measure actual evapotranspiration accurately by different kinds of instruments because the physical mechanism of actual evapotranspiration is too complex. In contrast, E_{pan} has a long history of observation and its data series can be easily obtained. As a result, people often calculate the actual evapotranspiration indirectly by E_{pan}, considering the close relationship between them (Brutsaert and Parlange, 1988; Lawrimore and Peterson, 2000; Golubev et al., 2001; Xu et al., 2006; Zuo et al., 2016). It will be of great significance to study the variation of E_{pan} since it can assist in sharpening our understanding about climate change and the mechanism of water cycle.

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In the recent century, T_a has risen remarkably (Rudd and Kay, 2016; Yang et al., 2017). It is widely acknowledged that global warming would make the atmosphere drier and accelerate evaporation from terrestrial open water bodies. However, Peterson et al. (1995) found that E_{pan} over most regions of the United States and the former Soviet Union has declined significantly since the 1950s. Therefore, the finding gave rise to a popular research topic called “pan evaporation paradox” or “evaporation paradox” (Roderick and Farquhar, 2002). Hydrologists and meteorologists around the world have already proved the existence of the evaporation paradox. Roderick and Farquhar (2004) found that the E_{pan} in Australia (Oceania) decreased at a rate of -4 mm/a from 1970 to 2002. Hoffman et al. (2011) found that in southern Africa (Africa), the E_{pan} had a -9.1 mm/a declining trend during the period from 1974 to 2005. Liu et al. (2004) divided China (East Asia) into eight climate zones and they discovered that from 1955 to 2000, the E_{pan} significantly decreased except for the northeast region. They also hold the view that the decreasing rate reached the highest in northwest and the lowest in southwest. In addition, UK (Europe) (Stanhill and Möller, 2008), Thailand (Southeast Asia) (Tebakari et al., 2005), India (South Asia subcontinent) (Chattopadhyay and Hulme, 1997; Jaswal et al., 2008; Jhajharia et al., 2009, 2012; Padmakumari et al., 2013) and other countries and regions have also been confirmed of having significant E_{pan} downward trends. During 1990-2000, in order to reveal the actual causes of E_{pan} decreasing and their impact on climate change and water resources, a group of scientists carried out a large amount of attribution recognition work (Morton, 1983; Stanhill and Cohen, 2001; Cohen et al., 2002; Xu et al., 2005; Rayner, 2007; Roderick et al., 2007; Zheng et al., 2009; Güldal and Tongal, 2008) as well as continuously confirming the significant decreasing trend of E_{pan} (Hobbins et al., 2001; Roderick and Farquhar, 2005; Yang et al., 2006, 2007; Li et al., 2013a; He et al., 2017).

At the beginning of this century, however, there has been a challenge to evaporation paradox in China. Cong et al. (2008, 2009) first discovered that E_{pan} has stopped decreasing and reversely turned upward. According to the daily E_{pan} observation data from 353 meteorological stations across China during 1956-2005, they found that the whole country’s E_{pan} (except for the south area) showed an upward trend from the middle of the 1980s and the evaporation paradox would no longer exist. Li et al. (2013b) believed that the continued declining trend of E_{pan} in arid areas of China stopped around 1993 and then increased at a rate of 10.7 mm/a. Liu et al. (2011) hold a point of view that the increasing rate of E_{pan} in China was 7.9 mm/a during 1992-2007.

There were a number of published papers concerning the change of E_{pan} and its attribution in the HRB from the end of twentieth century to the beginning of this century. Rong et al. (2011) found that E_{pan} in the basin showed a significant decreasing trend during 1960-2007 and it decreased rapidly in the northern and western parts. The decrease of E_{pan} was reported to be caused by the decrease of wind speed and sunshine duration along with the increase of relative humidity and precipitation. Guo and Ren (2005) believed that E_{pan} of the basin presented a downward trend from 1960s to 1990s. They speculated that the direct cause of E_{pan} decrease was the reduction of solar radiation. The decline of wind speed and diurnal temperature range may also play important roles. Ren and Guo (2006) found that the decreasing rate of E_{pan} in the basin was -54.6 mm/10a from 1956 to 2000, which was the largest among those around the country. Besides, the E_{pan} mainly decreased during 1956-1979, especially in summer,

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and the main attributing factors were wind speed, air temperature as well as sunshine duration.

Little attention has been paid to the E_{pan} of the HRB during the recent decade, especially to the analysis about whether the downward trend has stopped or presenting a reverse trend, while no related reports have been published yet. In view of this, we choose the HRB as the study area to conduct an analysis concerning the variation of E_{pan}. On the basis of previous results, we extend the data series for 10 to 20 more years so as to ensure that this study referred to the latest data series.

The paper is organized with two main objectives. The primary goal is to investigate the characteristics of the spatiotemporal variations of the E_{pan} of the HRB both in a basin scale and a single test station scale under the background of climatic change. Another one is to verify the infection years of E_{pan} and to find out whether the pan evaporation paradox exists in a particular transitional region such as the HRB.

Materials and methods

Study area

The HRB is located in the middle of China, between the east and north China plain climate regions (111°55’E-121°25’E and 30°55’N-36°36’N). The basin area is approximately 270,000 km^2. The west, southwest and northeast of the basin are mountainous and hilly areas, accounting for about 1/3 of the total basin area. The rest are vast plains (*Fig. 1*). Qinling Mountains-Huaihe River Line is an important geographical (landform, climate, soil) line in China. The north of this line is characterized by both the warm temperate continental climate and the semi-humid monsoon climate, while the south of it is humid subtropical monsoon climate zone. Therefore, the HRB has the obvious characteristics of north-to-south and land-to-sea transition because the east of the basin is close to the sea. The HRB has a unique topography and diverse climate characteristics, which is a suitable watershed for studying the hydrological cycle process and the evolution of hydrological factors.

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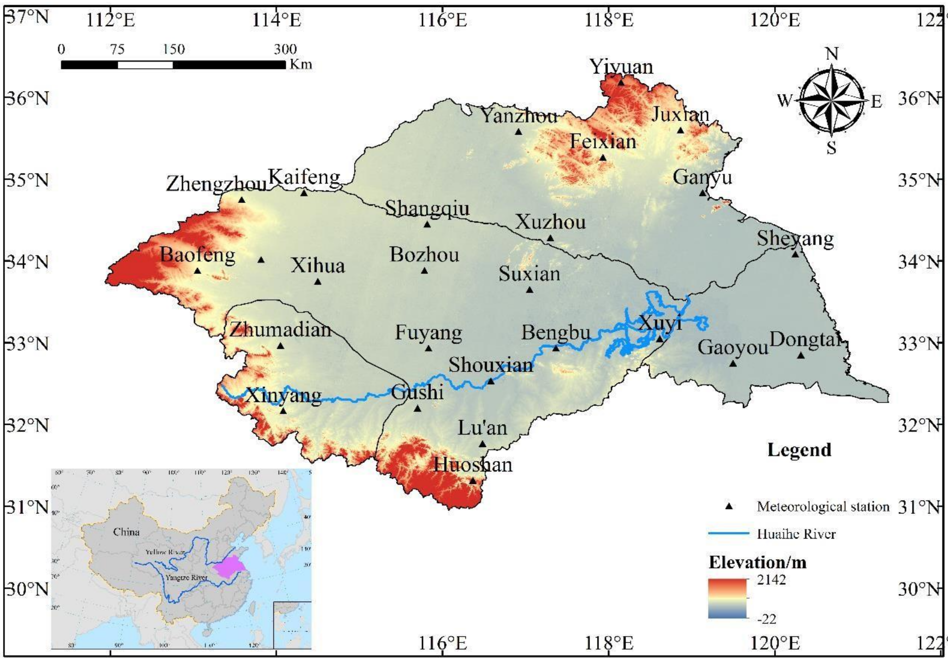

Figure 1. *Map of the Huaihe River Basin*

Data

Daily E_{pan} and T_a data of 26 evenly distributed meteorological stations in the HRB were selected for the study. *Table 1* shows the sites location and data series information. Data were downloaded from the China Meteorological Data Network (http://data.cma.cn/site/index.html) and have been subjected to strict homogenization quality control. Before 1990s, E_{pan} in China was measured by D20 pans, the pans are made of copper with a diameter of 20 cm and depth of 10 cm. They are installed 70 cm above the ground and have rims to prevent birds from drinking. The D20 pans are smaller and hold less water compared with Class A pans which are popular in the USA. After 2001, the evaporation pans are gradually changed into E601 pans. They consist of an evaporator, a water circle, an overflow barrel and a needle, and installed near the D20 pans. The pan area is 3000 cm^2 and the water circle is installed on the periphery of evaporator barrel, the inside and outside wall height is 13.7 cm and 15.0 cm respectively. Compared with the D20 pan, the E601 pan is more reasonable and scientific because of its instrument structure, installation height and surrounding environment, so the evaporation it measured is more representative to the condition of the natural water surface.

Table 1. *Characteristics of the meteorological stations selected for this study*

No.	Station	Longitude E/°	Latitude N/°	Elevation/m	Period	
					D20 pans	E601 pans
1	Yiyuan	118.15	36.18	304.5	1958-2001	1998-2015
2	Yanzhou	116.92	35.58	51.0	1952-2001	1998-2015
3	Feixian	117.93	35.27	109.8	1959-2001	1998-2015
4	Juxian	118.87	35.60	86.4	1952-2001	1988-2015
5	Zhengzhou	113.58	34.75	80.6	1951-2001	1985-2015
6	Xuchang	113.82	34.02	68.0	1952-2001	1998-2015

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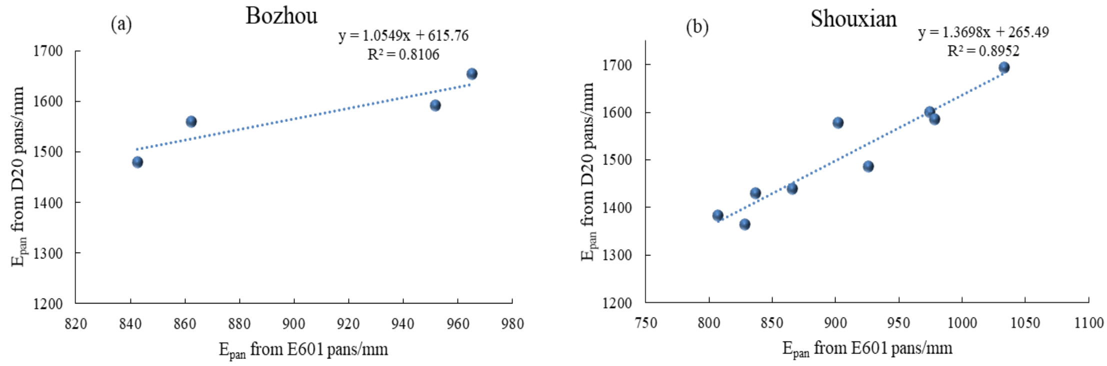
7	Kaifeng	114.33	34.83	75.0	1951-2001	1998-2015
8	Baofeng	113.05	33.88	135.1	1957-2001	1998-2015
9	Xihua	114.50	33.75	51.3	1953-2001	1999-2015
10	Zhuamadian	114.05	32.97	78.8	1958-2001	1998-2015
11	Xinyang	114.08	32.17	74.0	1951-2001	1985-2015
12	Shangqiu	115.82	34.45	50.1	1953-2001	1985-2015
13	Xuzhou	117.30	34.28	43.0	1960-2001	1984-2015
14	Ganyu	119.13	34.83	2.1	1957-2001	1998-2015
15	Bozhou	115.78	33.88	37.6	1953-2001	1998-2015
16	Suxian	117.05	33.65	28.0	1952-2001	1987-2015
17	Xuyi	118.62	33.05	13.4	1957-2001	1999-2015
18	Sheyang	120.25	34.08	1.6	1954-2001	1998-2015
19	Fuyang	115.83	32.93	33.3	1953-2001	1998-2015
20	Gushi	115.70	32.20	40.4	1952-2001	1998-2015
21	Shouxian	116.58	32.53	23.3	1955-2001	1993-2015
22	Bengbu	117.37	32.93	20.6	1952-2001	1998-2015
23	Gaoyou	119.50	32.75	6.4	1958-2001	1998-2015
24	Dongtai	120.32	32.85	5.8	1953-2001	1998-2015
25	Lu'an	116.48	31.77	39.5	1955-2001	1998-2015
26	Huoshan	116.37	31.32	91.9	1954-2001	1998-2015

Data processing

The E_{pan} series of each station during 1951-2015 were measured from two different types of evaporation pans, hence data processing is required. As shown by *Table 1*, for each site of the HRB, the length of data series from the D20 pans is longer than that from the E601 pans, while there also exist synchronous observations of the two types of pans. In order to eliminate the influence of data conversion on the following study, we converted data from the E601 pans into the D20 pans to get 65-year data series of all sites by building functions between the synchronous observation data of the two kinds of pans.

Figure 2 shows the correlations between the E_{pan} of two pans in three representative meteorological stations, which are Bozhou station (4-year synchronous observations), Shouxian station (9-year synchronous observations) and Suxian station (15-year synchronous observations). There exist linear correlations between the three different periods of synchronous data of two pans because each of the correlation coefficient is greater than 0.9.



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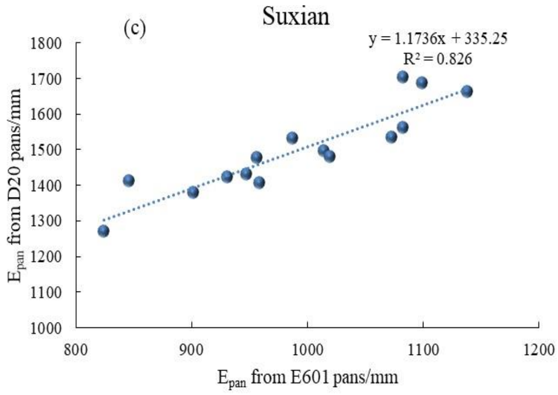

Figure 2. *Scatter plots between E_{pan} observed by the D20 pans and E601 pans in the three representative stations*

Relative error is calculated by *Equations 1* and *2:*

$$y_1 = ax_0 + b \quad \text{(Eq.1)}$$

$$\delta = \frac{|y_1 - y_0|}{y_0} \times 100\% \quad \text{(Eq.2)}$$

where x_0 is the E_{pan} observed from E601 pans, y_0 is the E_{pan} observed from D20 pans, y_1 is the converted D20 E_{pan}, and δ is the relative error.

Table 2 illustrates the conversion results of the two types of E_{pan}. As can be seen from the table, the average relative error of all sites is 2.2%, and the relative error of a single site is less than 5.4%. Overall, the correlations between the two types of E_{pan} suggest that the regression functions shown in *Table 2* can be used for data conversion after 2001. *Figure 3* presents the data conversion results of the three representative stations mentioned above.

Methods

In this study, we determined the spatial distribution of average annual E_{pan} and T_a of the HRB by using the inverse distance weighted (IDW) method. The variation trends of E_{pan} and T_a were analyzed by using linear regression approach, and the relationship between them was detected by examining the correlation coefficient.

Table 2. *Error analysis and conversion functions of the two types of E_{pan}.*

No.	Station	Conversion functions	Relative error (%)
1	Yiyuan	y = 0.4919x + 1097.4	0.44
2	Yanzhou	y = 1.8617x + 35.436	3.60
3	Feixian	y = 2.1671x - 525.43	0.32
4	Juxian	y = 1.1621x + 191.7	2.38
5	Zhengzhou	y = 0.2946x + 1416.5	2.18
6	Xuchang	y = 0.56x + 987.28	1.91

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7	Kaifeng	y = 0.9015x + 719.97	2.10
8	Baofeng	y = 1.4634x - 49.899	3.11
9	Xihua	y = 0.5584x + 796.09	2.62
10	Zhuamadian	y = 0.4501x + 1025.7	3.51
11	Xinyang	y = 0.9975x + 319.55	3.92
12	Shangqiu	y = 0.4664x + 954.75	5.36
13	Xuzhou	y = 1.076x + 563.96	3.64
14	Ganyu	y = 1.2154x + 254.41	1.55
15	Bozhou	y = 1.0549x + 615.76	1.72
16	Suxian	y = 1.1736x + 335.25	2.68
17	Xuyi	y = 1.7649x - 206.59	0.79
18	Sheyang	y = 1.6931x - 57.315	0.92
19	Fuyang	y = 1.3309x + 319.61	1.47
20	Gushi	y = 1.4358x - 84.341	3.24
21	Shouxian	y = 1.3698x + 265.49	1.75
22	Bengbu	y = 1.6586x + 64.702	1.98
23	Gaoyou	y = 1.2433x + 334.88	0.61
24	Dongtai	y = 1.3907x + 175.55	1.69
25	Lu’an	y = 1.5744x + 54.977	0.74
26	Huoshan	y = 0.9825x + 580.46	3.18

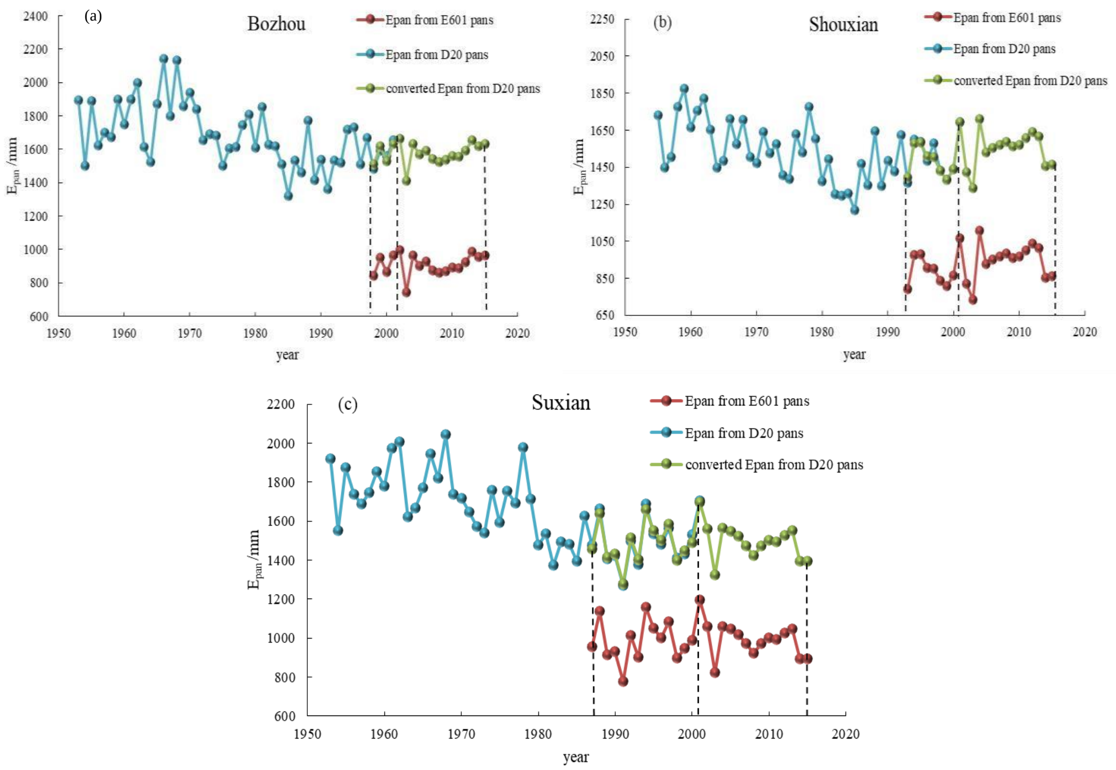

***Figure 3.** Data conversion results of the representative stations*

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Results

Spatial distribution of the average E_{pan} of the HRB

The average annual E_{pan} and T_a of 26 meteorological stations were calculated, and the spatial distributions of them are shown in *Figure 4*.

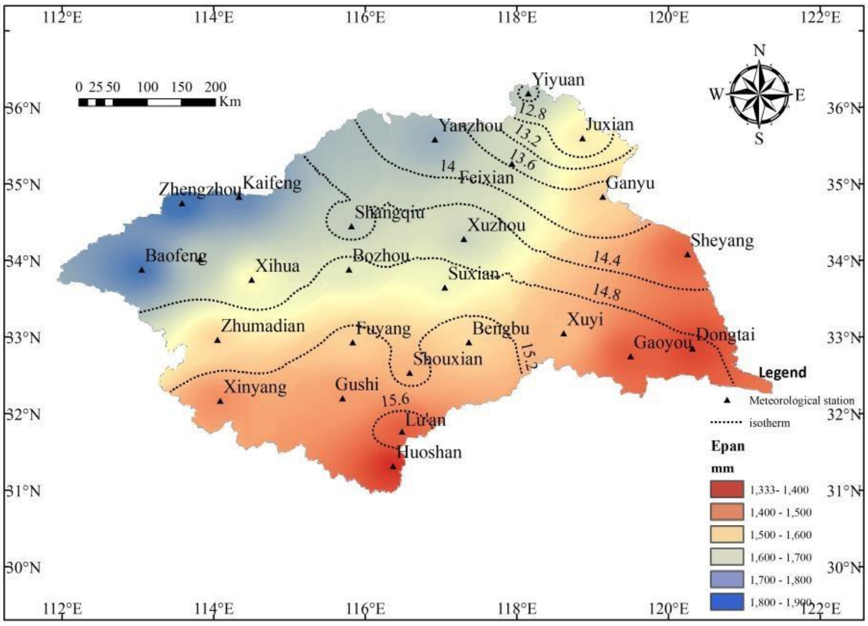

Figure 4. *Spatial distributions of E_{pan} and T_a in the HRB*

According to *Figure 4,* we can draw the following two conclusions:

(1) The average annual E_{pan} of the HRB features significant spatial variability, showing an obvious zoning characteristic and increasing gradually from southeast to northwest, from coastal area to inland, and from the humid area to semi-humid area. The maximum E_{pan} appears in the northwestern part of the HRB around Baofeng, Zhengzhou and Kaifeng, which is up to 1800 mm. The minimum appears in the eastern coast around Gaoyou, Dongtai and the southernmost Huoshan station of the basin, which is about 1400 mm.

(2) According to the isotherm (i.e., the dotted lines in *Figure 4*), it can be seen that the trend of T_a is not consistent with E_{pan}, and the T_a increases gradually from northeast to southwest, and the maximum value appears in Lu'an station. Around Xinyang, Gushi, Lu'an and Huoshan station, onthe right bank of the Huaihe River andin the southern part of the basin. T_a reaches the highest and E_{pan} reaches the lowest at the same time. The results show that the E_{pan} is not completely consistent with the T_a because it is affected by other factors besides the T_a.

Variation of the average E_{pan} of the HRB

Variation within the year

The average annual E_{pan} of the HRB is 1565 mm and portrays a single peak curve of the whole year. *Figure 5* presents the average monthly E_{pan} and T_a. It shows that the peak of the E_{pan} curve occurs in June with a value of 220.7 mm, accounting for 14.1% of the year. The E_{pan} of May and July follow after, accounting for 13.0% and 12.2%,

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respectively. The minimum appears in January with a value of 49.1 mm, accounting for merely 3.1%. Changes of T_a and E_{pan} within the year are similar but they are not completely synchronous. The peak of T_a occurs later than E_{pan}, and T_a peaks at 27.2 °C in July and bottoms out at 0.6 °C in January, indicating that T_a is not the unique climatic factor affecting E_{pan}.

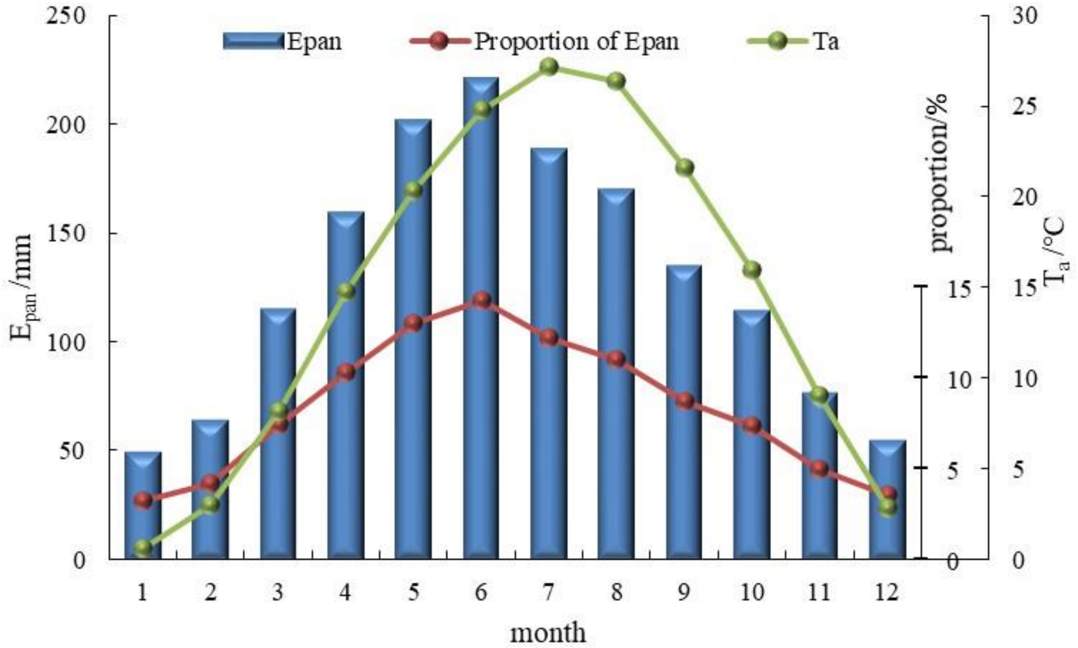

Figure 5. *The average monthly E_{pan} and T_a in the HRB*

It can be inferred that the reasons of the E_{pan} change are as following: in January, February and December, the T_a of the basin is relatively low and the surface is sometimes covered with snow and ice, which hinders evaporation from vegetation and soil (Ruosteenoja et al., 2017). From March to May, ice and snow start to melt as T_a slowly increases, resulting in a gradually increasing trend of E_{pan}. From June to August, the T_a reaches its maximum value of the year, creating the most favorable situation for evaporation with abundant sunshine and high wind speed, and E_{pan} reaches its peak in June. From September to November, the T_a decreases slowly and changes towards the unfavorable situation for evaporation and the E_{pan} of this period begins to decrease as a result.

Table 3 lists the average E_{pan} of four seasons and their proportions. It can be seen that the E_{pan} in summer is the largest, and the E_{pan} in spring and summer account for nearly 68.4% of the annual E_{pan} while the E_{pan} in winter is the smallest, which merely accounts for 10.8% of the annual value. Therefore, the E_{pan} in spring and summer play an important role in the water cycle.

Table 3. *Average seasonal E_{pan} and their proportions of the year*

Season	E_{pan}/mm	Proportion/%
Spring (March to May)	476	30.4
Summer (June to August)	594	38.0

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Autumn (September to November)	326	20.8
Winter (December to February)	169	10.8

Variation among years

Figure 6 shows the variations of average annual E_{pan} and T_a including the six-year moving average of E_{pan} of the HRB. It indicates that the annual E_{pan} fitting curve firstly increases then decreases and finally flattens, showing that the E_{pan} has a clear upward trend before the mid-1960s. After that period it decreases, and at last moves into a much smaller fluctuation state in the late 1980s. Therefore, we regarded the highest point (1966) and lowest point (1985) of the E_{pan} process as turning points, as well as analyzing the variation of the average annual E_{pan} of the HRB and drawing the following conclusions.

(1) The 65-year series from 1951 to 2015 can be divided into three periods. The 1951-1966 period shows a fluctuated increasing trend at a rate of about 257.3 mm per decade with a significance level of 0.05 and reaches its maximum in 1966. The 19671985 period presents a fluctuated downward trend at the rate of -195.2 mm/10a with a significance level of 0.01 and reaches its minimum in 1985. The 1986-2015 period portrays a non-significant increasing trend again but the rate is much smaller than that before 1966 (i.e., merely 12.8 mm/10a).

(2) From the variation of average T_a of the HRB, it can be found that during 19511966, the T_a fluctuates but has an increasing trend with the amplitude of 0.76 °C every decade with a significance level of 0.05. During 1967-1985, the rising of T_a slows down with a non-significant rate of 0.05 °C/10a. The warming trend in the HRB becomes significant again and the upward rate is 0.36 °C every 10 years with a significance level of 0.01 after 1985.

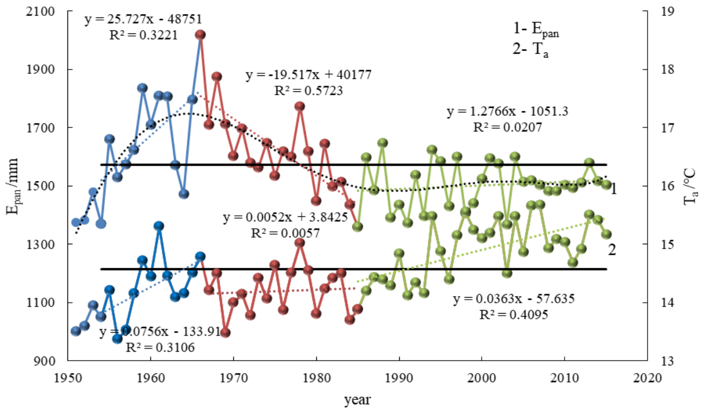

Figure 6. *Variations of the average annual E_{pan} and T_a in the HRB (the dotted curve is the sixyear moving average of $E_{pan,}$ the dotted lines represent the linear trends fitted to the corresponding periods)*

(3) *Figure 7* illustrates the relationships between variations of E_{pan} and T_a during different periods. The T_a and E_{pan} in the period of 1967-1985 vary inversely as the T_a increases while E_{pan} decreases, thus during this period there exists the so-called pan evaporation paradox. In the other two periods, the T_a and E_{pan} are positively correlated

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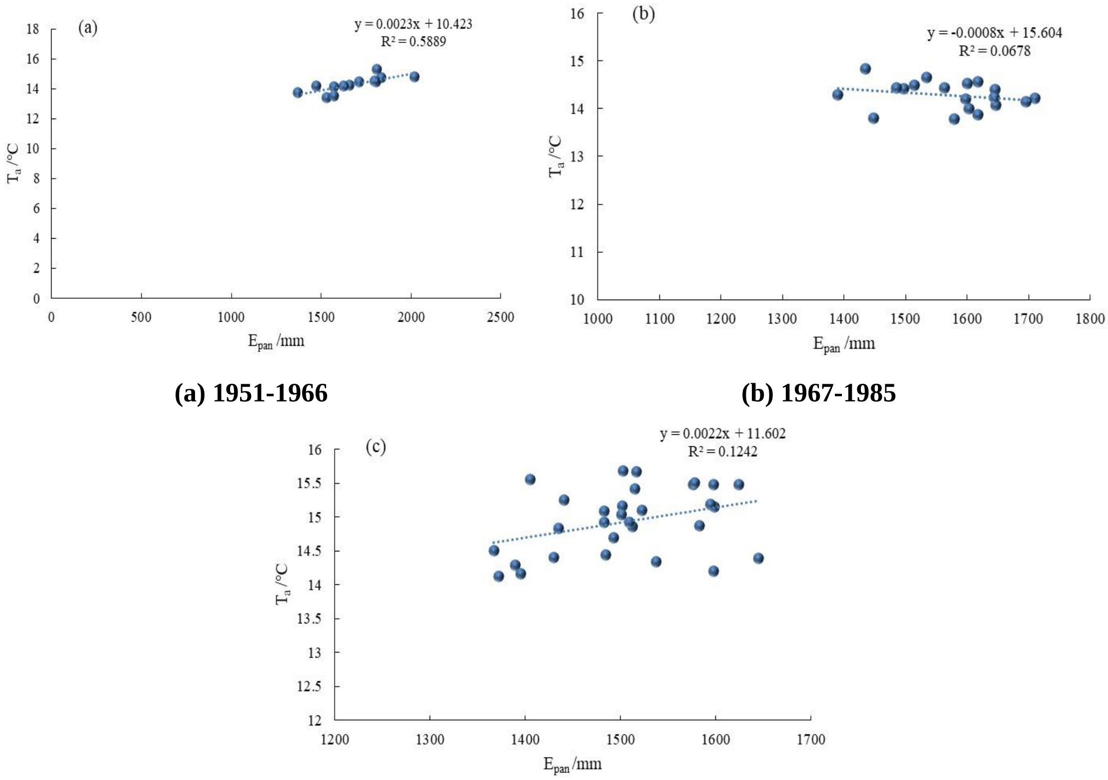
as they both show increasing trends. As a result, pan evaporation paradox does not exist. The trend of E_{pan} is not always consistent with that of T_a from 1951 to 2015, indicating that T_a is not the unique factor affecting E_{pan}. It deserves to be further studied on the attribution of E_{pan} change.



(a) 1951-1966 **(b) 1967-1985**

(c) 1986-2015

Figure 7. *Scatter plots between E_{pan} and T_a of the HRB during different periods*

Figure 8 shows the seasonal variations of E_{pan}. *Table 4* lists the change points, the evaporative rates and significance levels of average annual and seasonal E_{pan}. As can be seen, the variations of the four seasons and the whole year are basically the same. The first change points of the four seasons are around 1966, and the second are around 1985. Spring shows the largest increasing trend in the first period, which is 188.0 mm/10a, summer shows the largest decreasing trend for about -95.2 mm/10a in the second period. Trends of the third period are not obvious, with spring, summer and winter showing non-significant upward trends while autumn showing a slight downward trend. Therefore, the E_{pan} in spring and summer contributes the most to the significant increase and decrease period of annual E_{pan} separately, and the comprehensive effect of the four seasons results in a non-significant upward trend of annual E_{pan} after 1985.

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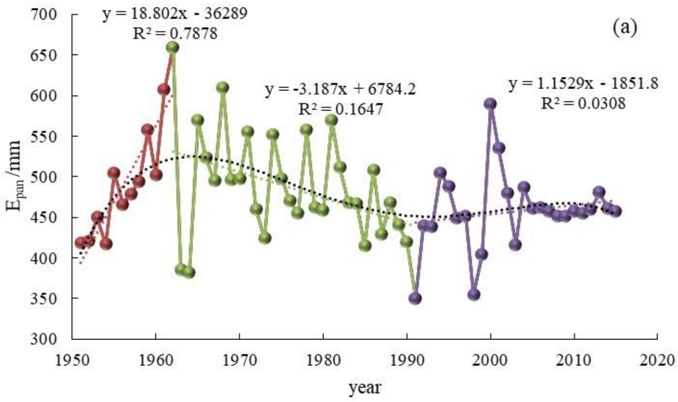
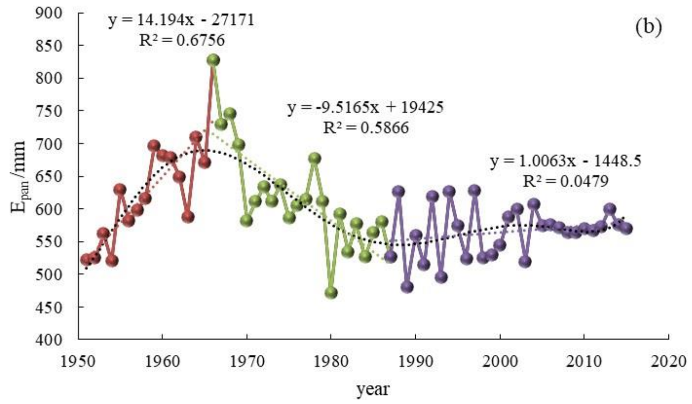
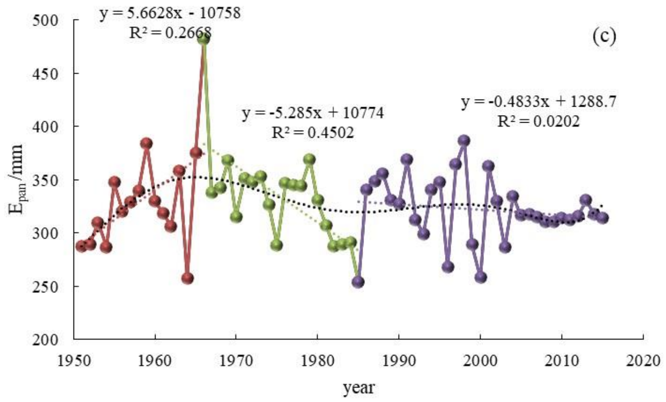


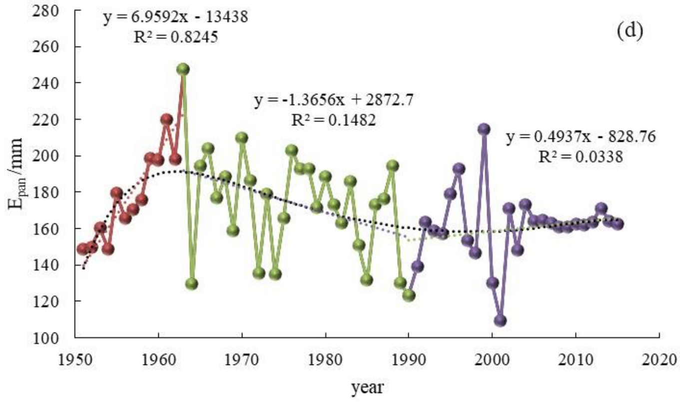
(a) Spring



(b) Summer



(c) Autumn



(d) Winter

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Figure 8. *Variations of the average E_{pan} of different seasons of the HRB*

Table 4. *Change points, evaporative rates and significance levels of average annual and seasonal E_{pan} of the HRB*

Period	1st change point	2nd change point	Evaporative rate (mm/10a)			Significance level		
			1st period	2nd period	3rd period	1st period	2nd period	3rd period
Spring	1962	1991	188.0	-31.9	11.5	0.01	0.05	/
Summer	1966	1987	141.9	-95.2	10.1	0.01	0.01	/
Autumn	1966	1985	56.6	-52.9	-4.8	0.05	0.01	/
Winter	1963	1990	69.6	-13.7	4.9	0.01	0.05	/
Annual	1966	1985	257.3	-195.2	12.8	0.05	0.01	/

"/" represents being non-significant at the significance level of 0.05

Variation of E_{pan} of a single site

The long-term changes of E_{pan} of the 26 meteorological stations were analyzed. The E_{pan} of a single station is not consistent with each other, but the clustering characteristics of them are obvious, which can be divided into two categories as below.

(1) The variations of E_{pan} of 24 sites are basically the same as that of the watershed average which has three obvious changing periods (*Fig. 9*). They all show increasing trends from 1951 to 1966 and significant decreasing trends from 1967 to 1985 except for Xuyi station. However, there are some differences in the E_{pan} changes during 19862015 (segmented analytical results are shown in *Tables 5–7*).

There are 12 stations showing non-significant increasing trends (the forms of their process are similar to Gushi station and Sheyang station shown in *Fig. 9*). Although 7 stations show decreasing trends, the slopes of them are much smaller (the forms are similar to Baofeng station and Yanzhou station shown in *Fig. 9*). The slopes of E_{pan} trends in Baofeng station and Yanzhou station decrease from -346 mm/10a and -274 mm/10a in 1967-1985 to -32 mm/10a and -31 mm/10a, decreasing by 91% and 89%. There are also 5 stations showing increasing trends with a significance level of 0.05 (the forms are similar to Shangqiu station and Fuyang station shown in *Fig. 9*).

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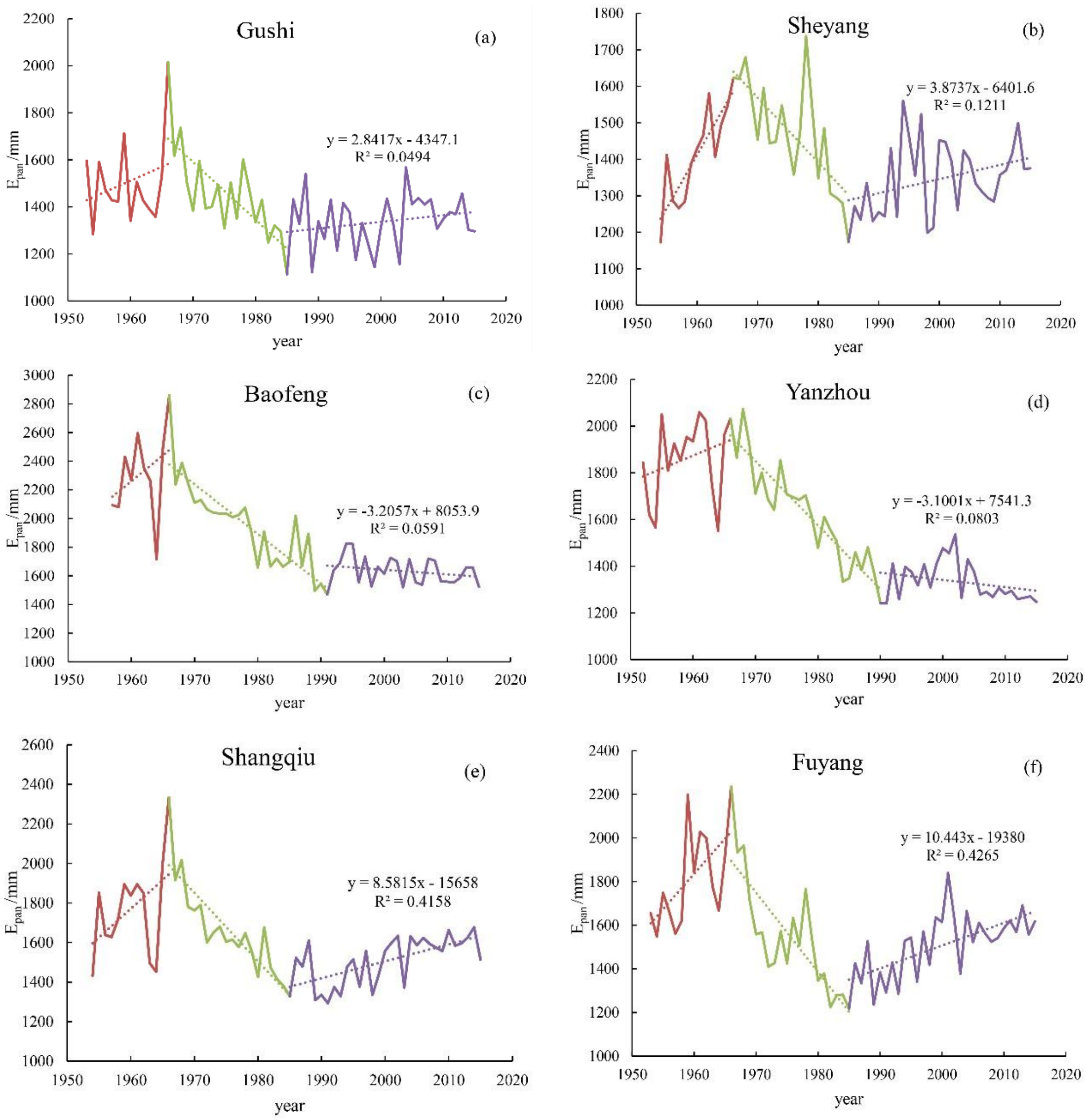

Figure 9. *Variations of the average annual E_{pan} of the first category (partly)*

Table 5. *Trend analysis of the average E_{pan} of the HRB during 1951-1966*

No.	Station	Correlation coefficient/R	Evaporative rate (mm/10a)	Significance level
1	Bengbu	0.65	346.8	0.01
2	Dongtai	0.55	152.3	0.05
3	Juxian	0.49	226.3	0.05
4	Feixian	0.52	165.4	0.05
5	Gushi	0.27	118.1	/
6	Sheyang	0.85	291.1	0.01
7	Xihua	0.31	200.6	/
8	Zhengzhou	0.49	353.1	0.05
9	Xinyang	0.68	198.1	0.01
10	Zhumadian	0.17	150.6	/

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11	Lu'an	0.06	21.7	/
12	Huoshan	0.67	234.7	0.01
13	Baofeng	0.35	361.2	/
14	Xuzhou	0.34	99.7	/
15	Yanzhou	0.29	111.3	/
16	Xuchang	0.59	428.8	0.05
17	Yiyuan	0.25	161.7	/
18	Ganyu	0.37	173.5	/
19	Xuyi	0.24	83.1	/
20	Bozhou	0.29	130.7	/
21	Kaifeng	0.31	269.2	/
22	Shangqiu	0.45	289.9	0.05
23	Fuyang	0.60	323.7	0.05
24	Suxian	0.15	48.2	/

Table 6. *Trend analysis of the average E_{pan} of the HRB during 1967-1985*

No.	Station	Correlation coefficient/R	Evaporative rate (mm/10a)	Significance level
1	Bengbu	-0.47	-166.9	0.05
2	Dongtai	-0.44	-113.8	0.10
3	Juxian	-0.72	-188.3	0.01
4	Feixian	-0.70	-367.1	0.01
5	Gushi	-0.74	-245.7	0.01
6	Sheyang	-0.72	-177.7	0.01
7	Xihua	-0.81	-263.6	0.01
8	Zhengzhou	-0.76	-334.3	0.01
9	Xinyang	-0.85	-464.1	0.01
10	Zhumadian	-0.63	-192.6	0.01
11	Lu'an	-0.69	-199	0.01
12	Huoshan	-0.63	-143.2	0.01
13	Baofeng	-0.86	-346.2	0.01
14	Xuzhou	-0.84	-368.9	0.01
15	Yanzhou	-0.92	-274.2	0.01
16	Xuchang	-0.83	-434.9	0.01
17	Yiyuan	-0.67	-188.3	0.01
18	Ganyu	-0.61	-122.1	0.01
19	Xuyi	-0.29	-57.5	/
20	Bozhou	-0.73	-247.4	0.01
21	Kaifeng	-0.80	-403.4	0.01
22	Shangqiu	-0.87	-346.3	0.01
23	Fuyang	-0.81	-363.9	0.01
24	Suxian	-0.70	-222.4	0.01

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Table 7. *Trend analysis of the average E_{pan} of the HRB during 1986-2015*

No.	Station	Correlation coefficient/R	Evaporative rate (mm/10a)	Significance level
1	Bengbu	0.23	25.7	/
2	Dongtai	0.24	23.2	/
3	Juxian	0.25	23.3	/
4	Feixian	0.34	42.1	/
5	Gushi	0.22	28.4	/
6	Sheyang	0.34	38.7	/
7	Xihua	0.07	7.9	/
8	Zhengzhou	0.02	2.6	/
9	Xinyang	0.16	20.9	/
10	Zhumadian	0.17	26	/
11	Lu'an	0.26	26.9	/
12	Huoshan	0.02	2.3	/
13	Baofeng	-0.34	-47.3	/
14	Xuzhou	-0.31	-34.5	/
15	Yanzhou	-0.28	-37.7	/
16	Xuchang	-0.35	-42.1	/
17	Yiyuan	-0.28	-30.6	/
18	Ganyu	-0.31	-45.7	/
19	Xuyi	-0.09	-10	/
20	Bozhou	0.38	44.3	0.05
21	Kaifeng	0.44	54.3	0.05
22	Shangqiu	0.65	85.8	0.05
23	Fuyang	0.65	104.4	0.05
24	Suxian	0.44	54	0.05

(2) The long-term changes of E_{pan} in Gaoyou station and Shouxian station are both divided into two obvious periods by the year of 1985 (*Fig. 10*). *Table 8* shows the trends of E_{pan} before and after 1985. As it shows, before 1985, the E_{pan} of both two stations decrease significantly at a level of 0.05 in Gaoyou station and 0.01 in Shouxian station. After 1985, the E_{pan} of Gaoyou station still shows a downward trend but the slope of it is smaller than before, decreasing from -50.2 mm/10a to -27.4 mm/10a, which is not statistically significant at a level of 0.05. However, the E_{pan} of Shouxian station shows a rising trend inversely with the evaporative rate turning from 115.6 mm/10a to 50.3 mm/10a and is statistically significant at a level of 0.05.

Table 8. *Comparison between the trends of the average annual E_{pan} of the second category before and after 1985*

Station	Correlation coefficient /R		Evaporative rate (mm/10a)		Significance level	
	Before 1985	After 1985	Before 1985	After 1985	Before 1985	After 1985
Gaoyou	-0.41	-0.27	-50.2	-27.4	0.05	/

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Shouxian	-0.62	0.39	-115.6	50.3	0.01	0.05

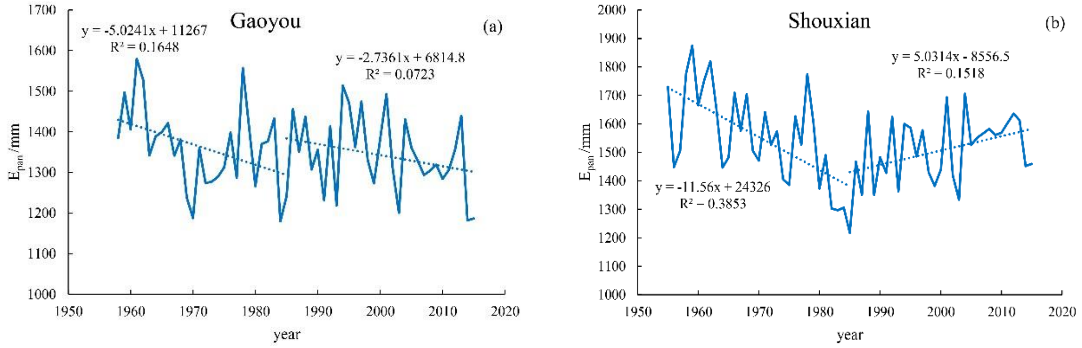

Figure 10. *Variations of the average annual E_{pan} of the second category*

For the whole basin, the continuous decreasing tendencies of E_{pan} in 26 sites in the HRB all stop in the middle of the 1980s, and the infection points divide the trends after 1985 into three categories, including 12 stations showing non-significant upward trends, 8 stations showing non-significant downward trends and 6 stations showing statistically significant upward trends. Because the sites showing upward trends are more than those presenting downward trends and the upward inclinations are greater than downward inclinations, the E_{pan} of the whole basin shows a non-significant upward trend.

Discussion

In the present study, we used the conversion functions to transfer E_{pan} observed by E601 pans into unified D20 data, and the E_{pan} of the HRB was analyzed. The annual scale adopted in this paper resulted in good simulation effects with the results consistent with the relationship between different evaporation pans (Fu et al., 2014), and the previous researches (Fu et al., 2014; Xu and Singh, 1998; Li et al., 2016) based on the monthly scale presented relatively small errors as well. Therefore, further studies are required to solve the issue of effects of different time scales on the simulation results.

We found that the E_{pan} of the HRB had three variation periods which is different from the nationwide findings (Cong et al., 2008, 2009; Li et al., 2013b; Liu et al., 2011). From 1951 to 1966, the E_{pan} increased at the rate of 257.3 mm/10a, and decreased at the rate of -195.2 mm/10a from 1967 to 1985, and the insignificant rate was 12.8 mm/10a during 1986 and 2015. The second mutation point of 1985 is consistent with the only mutation point considered in previous papers (Cong et al., 2009; Li et al., 2013b; Liu et al., 2011). Previous researches (Rong et al., 2011; Guo and Ren, 2005; Ren and Guo, 2006) on the existence of evaporation paradox in the HRB may result from the lengths of the selected E_{pan} series (mostly ended in 2000). On the one hand, the short series could lead to the misunderstanding of the variations of E_{pan}. On the other hand, those conclusions may also have close relationships with the analytical methods because the commonly used linear regression approach is only suitable for the trend analysis and is difficult to reflect the true changing characteristics.

The results of this paper may have an impact on the early analysis of attribution to the variation of E_{pan} of the HRB. In addition, the inconsistent rules of different sites may be

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related to the unique climate and geographical location of the HRB which deserves to be further studied.

Conclusion

Based on the E_{pan} data series from 1951 to 2015, the temporal and spatial variation characteristics of E_{pan} of the HRB were analyzed. The main conclusions are listed below.

(1) The average annual E_{pan} of the HRB was 1565 mm and the curve of the whole year exhibited a single peak characteristic which meant the seasonal changes were obvious. The average monthly E_{pan} mainly peaked in spring and summer, accounting for about 68.4% of the annual value and was not completely synchronized with the change of T_a. As for the spatial scale, the E_{pan} had an obvious zonation characteristic and increased gradually from southeast to northwest, from the coastal area to inland, and from humid basin to semi-humid area.

(2) The average annual E_{pan} of the HRB changed drastically in 1966 and 1985. The infection points divided the E_{pan} series into three periods: the significant increasing period, the significant decreasing period and the non-significant increasing period. Therefore, there existed pan evaporation paradox in the HRB from 1966 to 1985 and then the E_{pan} stopped declining and was reversed to weak upward trend again after 1985. The variations of E_{pan} in four seasons are similar to the year, and the E_{pan} in spring and summer contributes the most to the strong increasing and decreasing period, respectively.

(3) During 1951-1966, T_a in the HRB increased significantly, and was significantly and positively correlated with E_{pan}. During 1967-1985, E_{pan} decreased with the increase of T_a. After 1985, E_{pan} was reversed to a non-significant increasing trend with the gradually warming trend. It was showed that the T_a and E_{pan} had contradictory temporal dynamics before and after 1985. As a result, it was difficult to explain the complex mechanism of E_{pan} by a single factor and the T_a was not the important climatic factor affecting E_{pan}.

(4) Changes of E_{pan} in sites over the HRB were not entirely consistent with each other. The E_{pan} of most of the sites were similar to the basin average, having three obvious changing periods of which the first two were consistent with the average and the other was categorized into two types: the decreasing-to-increasing period and the steep decreasing period. There were only two sites having two obvious changing periods divided by the year 1985.

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