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Evaporation paradox and its mechanism in coastal wetlands of northern China

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सार – पिछली कुछ शताब्दियों में, भूमंडलीय उष्णन एक निर्विवाद विषय बन गया है, जबकि कई शोधों में पाया गया कि दुनिया भर में वाष्पोत्सर्जन की मात्रा पिछले 50 वर्षों से लगातार कम हो रहा है, और इस घटना को "वाष्पीकरण विरोधाभास" कहा जाता है। इस अध्ययन में, हमने पुष्टि की है कि यह उत्तरी चीन के तटीय आर्द्रभूमि में मौजूद था और तंत्र को समझने की कोशिश की। इस निष्कर्ष में शामिल हैं: (*i*) उत्तरी चीन के तटीय आर्द्रभूमि के तापमान में काफी कमी आई है, जो वाष्पोत्सर्जन की प्रवृति को काफी बढ़ाता है, और "वाष्पीकरण विरोधाभास" वास्तव में अध्ययन क्षेत्र में मौजूद है; (*ii*) जलवायु कारकों की संवेदनशीलता यह थी कि तापमान (T), अधिकतम तापमान (Tmax), न्यूनतम तापमान (Tmin), सापेक्षिक आर्द्रता (RH), पवन (W) और धूप (S) में 10% की वृद्धि हुई जिसके परिणामस्वरूप वाष्पीकरण की मात्रा (E_o) में क्रमश: 2.169% (2.169% की वृद्धि), 2.440%, 0.640%, -4.310% (4.310% की कमी) कमी हुई (*iii*) 6 जलवायु कारकों में वाष्पोत्सर्जन की मात्रा को प्रभावित करने वाले कारक धूप की अवधि (41.65%), पवन (25.23%), हवा का तापमान (18.04%) सापेक्षिक आर्द्रता (12.51%) थे और उत्तरी चीन के तटीय आर्द्रभूमि में वाष्पीकरण विरोधाभास की परिघटना हवा की गति और धूप की अवधि में कमी के कारण हुई।

ABSTRACT. Over the past few centuries, global warming has become an indisputable fact, while many researches found that the potential evapotranspiration throughout the world showed a consistently decreasing over the past 50 years, and called this phenomenon as “evaporation paradox”. In this study, we validated that it did exist in coastal wetlands of northern China and tried to understand the mechanism. The conclusions include: (*i*) The temperature of in coastal wetlands of northern China shows a significantly decreased trend while potential evapotranspiration is significantly increased, and suggests “evaporation paradox” actually exists in study area; (*ii*) The sensitivities of climate factors were that a 10% increase in T, T_{max}, T_{min}, RH, W and S would result in a 2.169% (increase 2.169%), 2.440%, 0.640%, -4.310% (decrease 4.310%), 1.413% and 4.416% in potential evapotranspiration (E_o), respectively; (*iii*) among the 6 climatic factors, the contribution rate of the effects on potential evapotranspiration were sunshine duration (41.65%) > wind (25.23%) > air temperature (18.04%) > relative humidity (12.51%). And the phenomenon of evaporation paradox in coastal wetlands of northern China was caused by the decrease of wind speed and sunshine duration.

Key words – Evaporation paradox, Climatic factors, Mechanism, Coastal wetlands, Northern China.

1. Introduction

Global warming caused by anthropogenic-driven emissions of greenhouse gases has become a serious issue worldwide in recent years and the evapotranspiration would be expected to increase in both capacity and amount in view of the rise in temperature, however, the evapotranspiration showed a trend of decrease in various part of the world, including China. Observations have shown that the temperature throughout China has risen by (0.09±0.017) °C/10a in the past 50 years (Liu *et al.*, 2017), but the trend of the rate of the Pan evaporation in China has been consistently decreasing in the past 50 years. The phenomenon of the decreasing of evapotranspiration under rising temperature is called evaporation paradox.

However, there is no clear conclusion about the mechanism of evaporation paradox yet (Liu *et al.*, 2017) and the existing researches mainly concentrated on the qualitative analysis and lacking the studies of how the other climate factors affect the evapotranspiration and the contributions other climate factors made to affect it. Potential Evapotranspiration plays an important role in water cycle and energy cycle in a watershed and shows a specific characteristic under certain climate and landscape

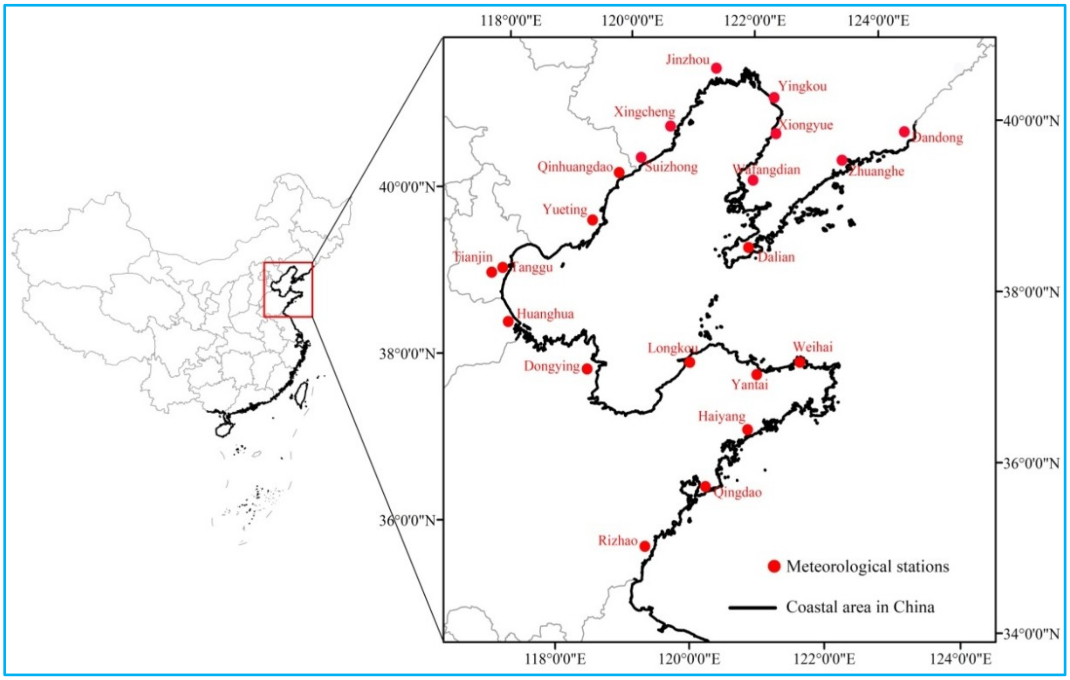


Fig. 1. The location of the study area and meteorological stations

conditions (Lin *et al.*, 2018, Luo *et al.*, 2017). It is affected by characteristics of meteorological variables, vegetation cover rate and management methods (Pandey *et al.*, 2016). The reasons for the decline of pan evaporation can be summed up as follows: the increase in atmospheric cloudiness, resulting in a decline of solar radiation (Roderick and Farquhar, 2002). The decrease of solar radiation results from the increase of atmospheric aerosols and other pollutants, as the air humidity increases, the difference of the vapor pressure decreases (Huang *et al.*, 2015). According to the present research, global radiation decline caused by cloud cover or aerosol increase is the main reason of pan evaporation and potential evapotranspiration decrease, while it differs in different regions.

Schaake and Waggoner (1990) first proposed the concept of climate elasticity. Many previous researches estimated climate elasticity towards understanding the effects of climate change and most of them were studying the hydrologic (streamflow) response (Xu *et al.*, 2013; Ma *et al.*, 2010; Zheng *et al.*, 2009; Sun *et al.*, 2013). The sensitivities of the hydrological responses to climate changes have been studied recently (Hamlet *et al.*, 2005; Wang and Zeng, 2011). In this study, we attempted the concept of sensitivity in potential evapotranspiration and tried to analyze the sensitivities of climatic factors on potential evapotranspiration. Based on the sensitivity coefficients, the effects of climate change on potential evapotranspiration could be calculated.

The coastal wetlands of northern China is located in semi-arid region, water resources in there are more important for maintaining wetland environment and habitat, taking them as the study object to analyze the change of potential evapotranspiration and its mechanism has a better importance. The purpose of this study is to: (*i*) identify if the phenomenon of "evaporation paradox" does exist in northern China; (*ii*) analyze the relationship of potential evapotranspiration with other climatic factors and indicate the cause of evaporation paradox; (*iii*) analyze the attributions of potential evapotranspiration change based on the sensitivity coefficients of other climatic factors and understand the mechanism of evaporation paradox.

2. Materials and method

2.1. *Study area*

The coastal wetlands in China and their adjacent land areas cover about 580 × 10^4 ha. And the coastal wetlands in northern China, which located in north of the Yellow River estuary, are mainly distributed in the Liaoning, Hebei, Tianjin and Shandong provinces and cities with an area of about 155.23 × 10^4 ha. The location and distribution of wetlands are shown in Fig. 1. The region has a continental monsoon climate with a mean annual precipitation of 500~800 mm. It is warm and humid and has distinct seasons, with an average annual temperature of 12~14 °C.

2.2. *Data*

Daily meteorological data were obtained from 21 national meteorological stations in the coastal wetlands of northern China from China Meteorological Administration (CMA) and National Meteorological Information Center of China (NMIC). All of these stations had complete records of all climate factors for calculating potential evapotranspiration (E_o) in the time series of 1960-2010, including atmospheric pressure, maximum, minimum and mean daily air temperature, relative humidity, wind speed and sunshine hours. The location of all meteorological stations can be seen in Fig. 1.

2.3. *Methodology*

2.3.1. *Potential evapotranspiration calculation*

The potential evapotranspiration data are calculated based on the FAO model (Allen *et al.*, 1998). This model has been widely used worldwide and is expressed briefly as:

$$E_o \frac{04.08\Delta(R_n - G) + \gamma \frac{C}{T+273}\mu_2(e_s - e_a)}{\Delta + \gamma(1+237.3)^2} \quad (1)$$

$$\Delta = 2503 \frac{e^{\frac{17.27T}{T+273.3}}}{(T+237.3)^2} \quad (2)$$

where:

E_o = daily potential evapotranspiration (mm)

Δ = slope of the saturation water vapor pressure versus air temperature (kPa · °C^{-1})

R_n = total net radiation (MJ/m^2)

G = total soil heat flux (MJ/m^2, assumed zero in this study)

γ = psychrometric constant (kPa · °C^{-1})

e_s = saturation vapour pressure (kPa)

e_a = actual vapour pressure (kPa)

μ_2 = mean wind speed at 2 m height (m/s)

C = unit conversion factor with a value of 900.

2.3.2. *Mann-Kendall test*

Mann-Kendall test is recommended by the international meteorological organization to detect significant trends of climatic variables in time series (Hamed, 2008; Liang *et al.*, 2010). The test statistic value of 'Z' is calculated as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, & if \quad S < 0 \end{cases} \quad (3)$$

The statistic S:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right) \quad (4)$$

$$sgn(x) = \begin{cases} 1, & if \quad x_j - x_i > 0 \\ 0, & if \quad x_j - x_i = 0 \\ -1, & if \quad x_j - x_i < 0 \end{cases} \quad (5)$$

where x_i and x_j are two generic sequential data values of the variable, n is the length of the data set.

The statistic S [$Var(S)$] can be calculated as:

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \quad (6)$$

2.3.3. *Sensitivity analysis method*

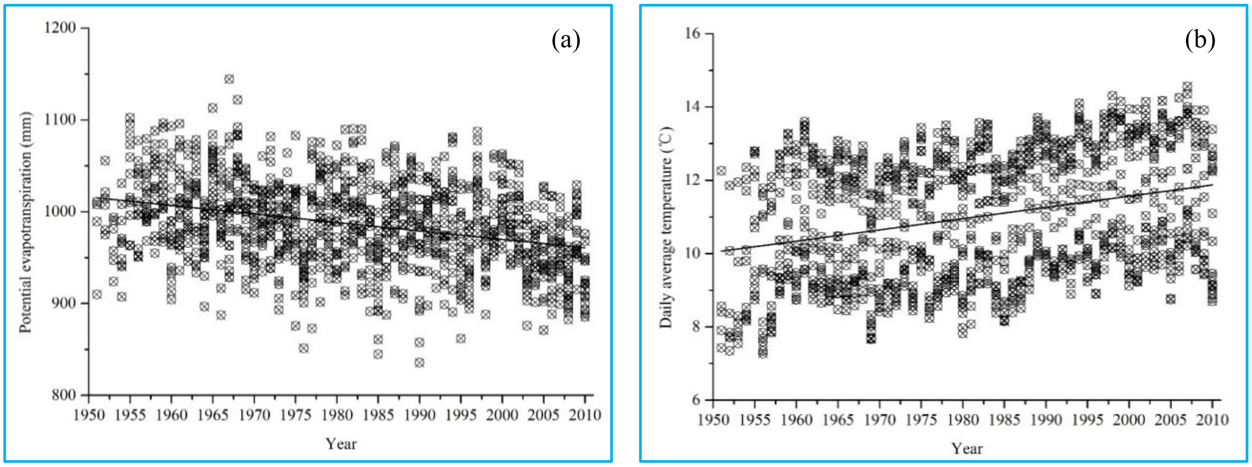
Schaake (1990) introduced a concept of 'elasticity' to evaluate the sensitivity of hydrological process to climate changes. Reference to the sensitivity analysis of hydrology, the sensitivity coefficient (ε) represents the proportional change in potential evapotranspiration (E_o) divided by the proportional change in a climatic variable (X) and is expressed as:

$$\varepsilon_X = \frac{\Delta E_o / \overline{E_o}}{\Delta X / \overline{X}} \quad (7)$$

when, X approaching $\overline{X}$, ΔX would be infinitely small and ε_X approaches infinity. To overcome the numerical problem, Sankarasubramanian *et al.* (2001) have further verified the nonparametric estimator as:

$$\varepsilon_X = median\left(\frac{\Delta E_o}{\Delta X}.\frac{\overline{X}}{\overline{E_o}}\right) \quad (8)$$

and then the effects of climatic factors could be expressed as:



Figs. 2(a&b). The variations of (a) Potential evapotranspiration and (b) Temperature of the meteorological stations in coastal wetlands of northern China

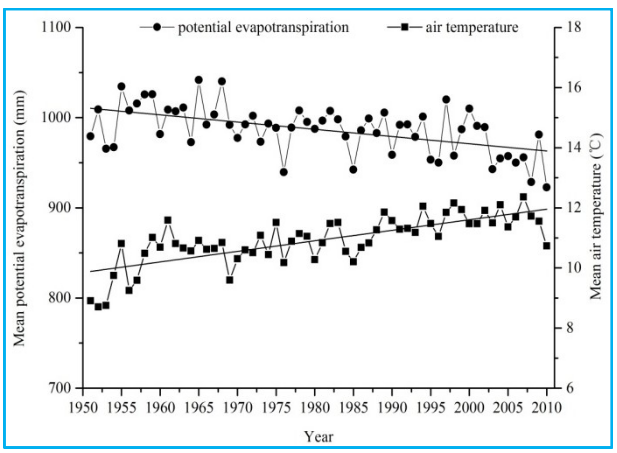


Fig. 3. The variations of mean potential evapotranspiration and mean air temperature in coastal wetlands of northern China

$$\Delta E_0 = \Delta E_0(X_1) + \Delta E_0(X_2) + \cdots + \Delta E_0(X_i)$$

$$= \varepsilon_{X_1} \cdot \frac{\Delta X_1}{\overline{X_1}} \cdot \overline{E_0} + \varepsilon_{X_2} \cdot \frac{\Delta X_2}{\overline{X_2}} \cdot \overline{E_0} + \cdots + \varepsilon_{X_i} \cdot \frac{\Delta X_i}{\overline{X_i}} \cdot \overline{E_0} \qquad (9)$$

3. Results

3.1. *Evaporation paradox in coastal wetlands of northern China*

Potential evapotranspiration and temperature are the most obvious indicators to reflect climatic characteristics. The temperature data were obtained directly from the national weather station and the mean annual potential evapotranspiration of coastal wetlands in northern China was calculated by the method of Penman Monteith Equation with meteorological data from the national weather station within the study watershed area of the time series of 1951-2010.

Trend analysis is widely used for understanding dynamics and behaviors of hydrological and climatic variables over a long-term period. The long-term variations of potential evapotranspiration (E_o) and temperature (T) of the meteorological stations in coastal wetlands of northern China were shown in Figs. 2(a&b), suggested that the annual potential evapotranspiration (E_o) of the meteorological stations all showed decreased trend and the annual temperature showed increased trend. And Fig. 3 showed the change of the mean value of all meteorological stations, also suggested that the mean annual potential evapotranspiration in northern China had a decreased trend and the mean annual temperature was an increased trend.

The Mann-Kendall test was applied to detect the change trend of climate over the study period of 1951 to 2010. Based on the Mann-Kendall test results, the Z statistic of annual mean potential evapotranspiration of coastal wetlands in northern China was -4.36, which suggested that over the whole study period from 1951 through 2010, the annual mean potential evapotranspiration of northern China showed a downward trend at the 0.01 confidence level. And the Z statistics of daily average temperature, daily maximum temperature and daily minimum temperature of northern China were 5.68, 4.76 and 6.33, respectively. Those mean the long-term variation of air temperature showed an obvious increase trend over the period of 1951 to 2010 in northern China and was at the 0.01 confidence level. Therefore, we can conclude that the phenomenon of evaporation paradox does exist in in coastal wetlands of northern China.

TABLE 1

The correlation between E_o and other weather factors

Correlation	E_p	T	T_{max}	T_{min}	RH	W	S
E_o	1	-	-	-	-	-	-
T	-0.309*	1	-	-	-	-	-
T_{max}	-0.055	0.942**	1	-	-	-	-
T_{min}	-0.123	0.957**	0.855**	1	-	-	-
RH	0.073	-0.134	-0.042	-0.159	1	-	-
W	0.538**	-0.412**	-0.395**	-0.493**	0.009	1	-
S	0.715**	-0.112	-0.066	-0.261*	0.030	0.648**	1

**Correlation is significant at the 0.01 level, *is significant at the 0.05 level

3.2. *The correlative factors of evaporation paradox*

3.2.1. *Relations between potential evapotranspiration and other climate factors*

A correlation analysis was conducted between potential evapotranspiration (E_o) with 6 basic climate factors, as mean daily air temperature (T), maximum daily air temperature (T_{max}), minimum daily air temperature (T_{min}), relative humidity (RH), wind (W), sunshine duration (S). Correlation coefficients results are shown in Table 1 and the bivariate correlation statistics was used to analyze the significance to potential evapotranspiration of independent variables.

As shown in Table 1, we can find that the potential evapotranspiration got significantly positive correlations at a 0.01 level with wind speed and sunshine duration and got significantly negative correlations with factors of mean daily temperature at a 0.01 level. While the minimum daily temperature, the maximum daily temperature and the relative humidity were not so related with potential evapotranspiration, the correlation coefficients were -0.055, -0.123 and 0.073, respectively.

3.2.2. *The change trends of correlative factors*

According to the results of Mann-Kendall test, the Z statistic of the mean daily temperature was 5.68. And also, the Z statistic of wind speed (W) and sunshine duration (S) were -6.82 and -4.37, respectively, which suggested that they showed downward trends during the study period of 1951 to 2010 at a 0.01 level. Then, we can draw a conclusion that the phenomenon of evaporation paradox in coastal wetlands of northern China may be caused by the combined effects the increase of temperature and the decrease of atmospheric pressure, wind speed and sunshine duration.

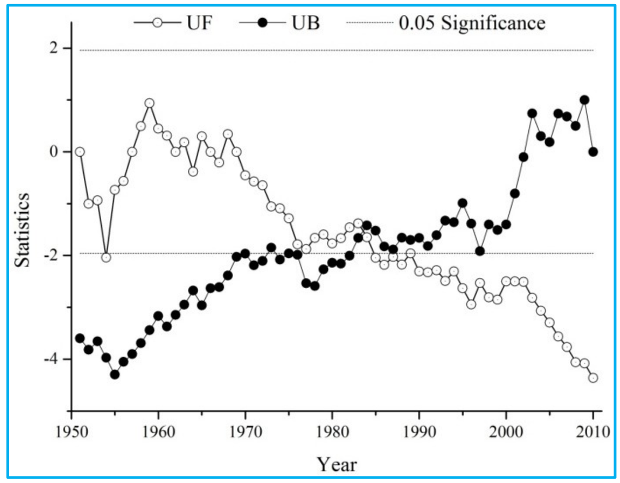


Fig. 4. Mann-Kendall mutation test of the annual potential evapotranspiration in coastal wetlands of northern China

3.3. *The attribution analysis of evaporation paradox*

Based on Eqs. 8, we got the sensitivity coefficients (ε) of potential evapotranspiration (E_o) to mean daily air temperature (T), maximum daily air temperature (T_{max}), minimum daily air temperature (T_{min}), relative humidity (RH), wind (W) and sunshine duration (S). The values of ε_T, ε_{Tmax}, ε_{Tmin}, ε_{RH}, ε_W and ε_S were 0.2169, 0.2555, 0.0786, -0.4440, 0.1401 and 0.4826, respectively. These mean that a 10% increase in T, T_{max}, T_{min}, RH, W and S would result in a 2.169% (increase 2.169%), 2.440%, 0.640%, -4.310% (decrease 4.310%), 1.413% and 4.416% in potential evapotranspiration (E_o), respectively.

Fig. 4 showed the result of Mann-Kendall change point test of the annual E_o data, the intersection of the curves indicates an abrupt change in 1984. And then, the study period (1951-2010) could be divided into a reference period (1951-1983) and a change period (1984-2010). Comparing the mean values between the two periods, the changes of E_o and the other 6 climatic factors (T, T_{max}, T_{min}, RH, W, S) could be simply calculated and can be seen in Table 2. Results showed that, in the change period, the E_o of coastal wetlands in northern China has decreased 24.95 mm.

According to the sensitivity coefficients (ε) and the change values, the effects of other climatic factors (T, T_{max}, T_{min}, RH, W, S) on potential evapotranspiration could be simulated by Eqs. 9 and the results were shown in Table 3. Results show that S (sunshine duration) had the largest effect on potential evapotranspiration which decreasing 33.03 mm accounting for 41.65% followed was wind (W), its effects was decreasing potential evapotranspiration 20.01 mm and accounting

TABLE 2

The changes of E_o and other climatic factors between the two periods

Period	E_o / mm	T / °C	T_{max} / °C	T_{min} / °C	RH / %	W / (m/s)	S / h
1951-1983	997.91	10.48	15.50	6.30	66.56	3.74	7.47
1984-2010	971.14	11.45	16.18	7.46	65.07	3.22	6.97
change /△	-26.76	0.97	0.68	1.16	-1.49	-0.51	-0.50

TABLE 3

The effects of 6 climatic factors on potential evapotranspiration

Effects	ΔE_o	ΔE_o (T)			ΔE_o (RH)	ΔE_o (W)	ΔE_o (S)	error
		ΔE_o ($T_{average}$)	ΔE_o (T_{max})	ΔE_o (T_{min})				
Quantity (mm)	-24.95	18.94	10.83	13.15	9.92	-20.01	-33.03	-2.04
		Average: 14.31						
Contribution rate	100%	18.04%			12.51%	25.23%	41.65%	2.57%

for 25.23% and the average effect of temperature rise on potential evapotranpiration was increasing 18.04 mm and accounting for 18.04% and the least effect was caused by relative humidity (*RH*) which increasing 9.92 mm and accounting for 12.51%.

4. Discussion

"Evaporation paradox" is a hot topic in evapotranspiration research and had been verified in Australia (Roderick and Farquhar, 2004), New Zealand (Roderick and Farquhar, 2005), Canada (Burn and Hesch, 2007), Italy (Moonen *et al.*, 2002), India (Jhajharia *et al.*, 2012) and many regions in China (Cong *et al.*, 2008; Ma *et al.*, 2012; Jiang *et al.*, 2013). Many researchers tried to figure out its mechanism, while did not get a unified understanding about the evaporation paradox. Many researchers discussed the mechanism of the decrease in potential evapotranspiration and suggested some reasons likely as the sunlight decrease due to the increase in cloud coverage (Peterson *et al.*, 1995; Roderick and Farquhar, 2002) or aerosol concentration (Stanhill and Cohen *et al.*, 2001), vapor pressure deficit decrease due to increasing air humidity (Huang *et al.*, 2015), or wind speed decrease due to monsoon change (Cohen *et al.*, 2002). And other researchers discussed that decreasing in solar radiation or sunlight, referred as global dimming, could be the primary cause, but this trend changed to the reverse direction in 1980s (Wild *et al.*, 2005; Pinker *et al.*, 2005).

In this study, the annual daily average temperature in coastal wetlands of northern China showed an upward trend at 0.01 confidence level, while the annual potential evapotranspiration showed a downward trend and that indicated a phenomenon of evaporation paradox. The correlation analysis of potential evapotranspiration and other climatic factors showed that, not only temperature, wind speed and sunshine duration also obviously affected potential evapotranspiration, they all showed positive correlations. Based on Mann-Kendall trend analysis, the annual wind speed and sunshine duration both showed significantly decreased trends and those might be the cause of potential evapotranspiration decrease.

More scientifically, to reveal possible causes, the attribution of historical potential evapotranspiration to climatic forcings, like air temperature, sunshine duration, wind speed and relative humidity, has been undertaken. In our study, the annual potential evapotranspiration in coastal wetlands of northern China had an obvious decreasing trend and we want to separate the effects and contributions of other climatic factors on potential evapotranspiration. Sensitivity analysis method was widely used in studying the impacts of climatic variation in stream flow (Potter *et al.*, 2011; Sankarasubramanian *et al.*, 2001), and here we used this method in our research to study the effects of factors on potential evapotranspiration. Our results showed the calculation was obviously accurate, the sum effect quantity of 7 factors was 38.01 mm, comparing with the actual change (39.68 mm), the method was appropriate for studying the effects of factors on potential evapotranspiration.

It is important to highlight that there remains some uncertainty in this statistical assessment of climate impacts on potential evapotranspiration. Many researches suggested the reason of evaporation paradox was the decrease of solar radiation which called "dimming" phenomenon. In our research, we used sunshine duration as the substitution and that may lead to some error in our results. And we analyzed the effects of mean daily air temperature (T), maximum daily air temperature (T_{max}), minimum daily air temperature (T_{min}), relative humidity (RH), wind (W) and sunshine duration (S) and whether they were all the factors? Some other possible reasons may need to discussed and we would make some modification in the future research.

5. Conclusions

Climate change is an indisputable fact over the past centuries, a better understanding of climate change is becoming increasingly important for hydrologic cycle, ecology system and other fields. In this study, we test the phenomenon of "evaporation paradox" and quantify the attribution analysis of potential evapotranspiration change to understand the mechanism. The findings can be summarized as follows:

(*i*) The potential evapotranspiration of in coastal wetlands of northern China is significantly decreased at the 0.1 confidence level and temperature is significantly increased at the 0.01 confidence level and "evaporation paradox" actually exists in study area.

(*ii*) The sensitivities of climate factors were that a 10% increase in T, T_{max}, T_{min}, RH, W and S would result in a 2.169% (increase 2.169%), 2.440%, 0.640%, -4.310% (decrease 4.310%), 1.413% and 4.416% in potential evapotranspiration (E_o), respectively.

(*iii*) The effects of 6 climatic factors on potential evapotranspiration were sunshine duration (41.65%) > wind (25.23%) > air temperature (18.04%) > relative humidity (12.51%). And the phenomenon of evaporation paradox in coastal wetlands of northern China was caused by the decrease of wind speed and sunshine duration.

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