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Quantitative Analysis of the Impact of Meteorological Factors on Reference Evapotranspiration Changes in Beijing, 1958–2017

Wenhui Liu ^{1,2} , Baozhong Zhang ^{1,2,*} and Songjun Han ^{1,2}

¹ State Key Laboratory of Simulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China; lwh1346593719@126.com (W.L.); hansj@iwhr.com (S.H.)

² National Center of Efficient Irrigation Engineering and Technology Research-Beijing, Beijing 100048, China

* Correspondence: zhangbaozhong333@163.com

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Abstract: The effects of meteorological factors on reference evapotranspiration (ET_0) are variable on different time scales, although research tends to focus only on certain time scales. Therefore, using the meteorological data from 1958 to 2017 of Beijing, China, ET_0 values over the last 60 years were calculated using Penman–Monteith method. The variation in ET_0 values was thus analyzed against four meteorological factors over different time scales. The sensitivity of ET_0 to these factors was assessed using a sensitivity coefficient, while the contribution of each factor to ET_0 change was quantified by combining this sensitivity coefficient with the factor's relative change rate over multiple time scales. The results showed that the sensitivity coefficient of relative humidity over different time scales were all negative, while the sensitivity coefficients of net radiation, temperature and wind speed were mostly positive. The main sensitivity factors of ET_0 on different time scales varied. On annual time scales, the main factors were relative humidity and temperature. Over annual time scales, relative humidity and net radiation alternated as the main sensitivity factor; while over interannual time scales, the most sensitive factor was relative humidity during 1958–1979 and net radiation thereafter. The contribution of these four meteorological factors to ET_0 also fluctuated greatly on intra-annual time scales. On daily time scales, the contributions of temperature and wind speed at the start and end of the year were large, while net radiation and relative humidity were dominant mid-year. On monthly to seasonal time scales, the contributions of these four meteorological factors to ET_0 were notable. The contribution of relative humidity was largest in spring and autumn; net radiation was dominant in summer, while temperature and wind speed were dominant in winter. This research on the temporal variability of ET_0 response factors is of great significance for understanding regional climate change.

Keywords: meteorological factors; reference evapotranspiration; sensitivity coefficient; Penman–Monteith; contribution amount

1. Introduction

Evapotranspiration refers to the key hydrological process of water vapor escaping from the land surface to the atmosphere, which occurs between vegetation, soil or open water and the atmosphere [1,2]. Reference evapotranspiration (ET_0) is defined as the maximum evapotranspiration of a hypothetical underlying surface of green grass 0.12 m in height, actively growing and adequately watered, with fixed surface resistance and albedo values of 70 m/s and 0.23, respectively [3,4]. ET_0 is considered one of the most important hydrological variables for scheduling irrigation systems because it affects the water and energy balance between land and air, and must be considered when calculating actual

evapotranspiration for a region or a basin [5–8]. ET_0 is also regarded as a key parameter for evaluating the efficiency of agricultural water-use [9].

Studies have shown that climate change alters ET_0 by affecting the hydrological cycle [10]. Other factors such as temperature (T), relative humidity (RH) and net radiation (RN), which influence ET_0 , also undergo changes in response to climate change. However, a change in ET_0 will, in turn, affect regional climate variation [11,12]. Therefore, analyzing the spatiotemporal variability of ET_0 will help us to understand climate change and its response to the hydrological cycle [13,14]. Many studies have investigated the temporal and spatial characteristics of ET_0 and the response mechanism of meteorological factors to changes in ET_0 [15–21]. In these studies, the climate tendency rate is used to describe the temporal and spatial changes of regional ET_0 . To study the climate response of ET_0 , various methods have been used, including principal component analysis, partial correlation analysis, sensitivity coefficient analysis and methods combining the sensitivity coefficients with the relative change rates to calculate the contribution of meteorological factors. Among these methods, the sensitivity coefficient method is the most widely used [22–24]. The sensitivity coefficient was proposed by McCuen et al. [25] and defined as the ratio of ET_0 change rate to meteorological factor change rate [26]. Gong et al. [27] believed that sensitivity analysis was vital to understanding the impact of climate variables on ET_0 change. Saxton et al. [28] found that ET_0 was most sensitive to RN. Ren et al. [29] and Sergio et al. [30] concluded that the main sensitive factors affecting the change of ET_0 were RH and T. Others have suggested that T or RH were the most sensitive factors affecting ET_0 [31]. Clearly, the main sensitive factors to ET_0 are different in various regions.

Although the sensitivity coefficient method is the main method used to analyze the underlying cause of ET_0 change, it does not quantify the impact of climate factors on ET_0 . Therefore, contribution rate analysis combines the sensitivity coefficients with the change rates of meteorological factors to calculate their contributions to ET_0 change. This can more accurately explain the causes of ET_0 change [32,33]. At the same time, given the response of various climate factors over different time scales, the factors driving ET_0 change can vary. Gao et al. [34] found that the ET_0 of most basins in China showed a decreasing trend on annual to seasonal scales. Ma et al. [35] found that ET_0 within the Heihe River Basin was sensitive to climate factors on monthly and seasonal scales, identifying wind speed (U) as the dominant factor causing the change in ET_0 in this region. Kang et al. [36] found that the annual decrease in ET_0 in the Altay region was caused by the decrease in summer ET_0 , concluding that the decrease in summer U was the main reason for this change in ET_0 . Huan et al. [37] believed that, on annual to seasonal scales in the central Shandong region, ET_0 was most sensitive to the change of RH, although the ranking of the main sensitive factors of ET_0 varied on quarterly and monthly scales. They identified the main contributing factors to ET_0 change as U, sunshine percentage, RH and T. Zou et al. [38] reported that decreases in U and sunshine hours were the main reasons for the decrease in ET_0 on annual and quarterly scales on Hainan Island, while the increase in water vapor pressure was the main reason for the decrease of ET_0 in winter.

From the above analysis, it is clear that the response of meteorological factors to ET_0 varies greatly on different spatial and temporal scales. However, most research focuses only on certain time scales and does not consider the response of meteorological factors to ET_0 changes on different time scales. Based on the meteorological data from 1958 to 2017 for Beijing, we analyzed four major meteorological factors (i.e., RN, T, RH and U) and ET_0 change characteristics on different time scales. We qualitatively analyzed the major meteorological factors on ET_0 over different time scales and quantitatively assessed the contributions of these meteorological factors to ET_0 on different time scales. Determining the causes of ET_0 change on different time scales will provide a theoretical basis for water resources regulation, irrigation system design and crop water management in Beijing.

2. Materials and Methods

2.1. Study Area

The study area is situated in Beijing (39.4°–41.6° N; 115.7°–117.4° E), with an average elevation of 43.5 m (Figure 1). It has a temperate semi-arid continental monsoon climate. The multi-year average temperature, wind speed and relative humidity are 12.1 °C, 1.2 m/s and 52%, respectively. There are 2502 h of annual sunshine, the effective accumulated temperature over 10 °C is 4730 °C, and the average daily solar net radiation is 171 W/m². There are 185 frost-free days throughout the year on average. The annual rainfall and average evaporation are 540 mm and 1021 mm, respectively. More than 80% of the annual rainfall occurs from June to September. The soil is mainly sandy loam, suitable for the growth of various crops. A wheat–corn rotation is the traditional cultivation system in Beijing. With this system, the annual crop water requirement is 876 mm, 453 mm of which is for winter wheat and 423 mm for summer corn [39,40]. Historical daily meteorological data from 1958 to 2017, including sunshine hours, T, RH and U, were obtained from China Meteorological Science (<http://cdc.cma.gov.cn>).

Figure 1. Study area and location of the Beijing region in China.

2.2. Calculation of Reference Evapotranspiration

The Penman–Monteith (P–M) equation, recommended by Food and Agricultural Organization guidelines (FAO-56), was used to calculate ET_0 values [3]:

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma U \left(\frac{900}{T+273} \right) (e_s - e_a)}{\Delta + \gamma(1 + 0.34U)} \quad (1)$$

where ET_0 is the reference evapotranspiration (mm d^{−1}); Δ is the slope of the saturated vapor pressure curve; Rn is the surface net radiation (MJ/m²/d); G is the surface soil heat flux (MJ/m²/d), could be neglected at daily scale [3]; γ is the psychrometric constant(kPa°C^{−1}); T is the daily average temperature (°C); U is the wind speed at 2 m height (m/s); e_s is the saturated vapor pressure (kPa); and e_a is the actual vapor pressure (kPa).

2.3. Sensitivity Analysis

A sensitivity coefficient was used to quantify the influence of each meteorological factor on ET_0 . This coefficient is the ratio between the variations in ET_0 and the change rate of each meteorological factor [25,41,42], defined as:

$$S_x = \lim_{\Delta x \rightarrow 0} \left(\frac{\Delta ET_0 / ET_0}{\Delta x / x} \right) = \frac{\partial ET_0}{\partial x} \times \frac{|x|}{ET_0} \quad (2)$$

where S_x is the sensitivity coefficient of a given meteorological factor, x ; and ΔET_0 and Δx are the variable amounts of ET_0 and meteorological factor x , respectively. A positive or negative S_x represents an increase or decrease in ET_0 , as the meteorological factor increases or decreases, respectively. Meanwhile, the absolute value of S_x reflects the degree of sensitivity to that factor.

2.4. Determination of Contributions

Multiplying the sensitivity coefficient of a single meteorological factor by its relative change rate over multiple years indicates the contribution rate of the factor to the change in ET_0 . A positive value indicates that the change related to this selected factor causes an increase in ET_0 , making a positive contribution. A negative value indicates that the change in the selected factor causes a decrease in ET_0 , making a negative contribution.

$$RC_x(\%) = \frac{n \times Trend_x}{|av_x|} \times 100 \quad (3)$$

$$Con_x = S_x \times RC_x \quad (4)$$

where RC_x is the multiannual relative variation rate of x ; n is a given year; $Trend_x$ is the meteorological trend of x and reflects the variation of a given meteorological factor on the selected space scale over multiple years; av_x is the multiannual mean value; and Con_x is the contribution rate of the meteorological factor x to ET_0 variation.

The contribution rate of each meteorological factor is accumulated to obtain the total contribution to the change in ET_0 , as follows:

$$Con = Con_{RN} + Con_T + Con_{RH} + Con_U \quad (5)$$

where Con_{RN} , Con_T , Con_{RH} and Con_U represent the contribution rates of RN, T, RH and U to ET_0 variation, respectively; and Con represents the total contribution rate of these meteorological factors to ET_0 variation.

$$Gx = Con_x \times \bar{ET}_0 \quad (6)$$

$$G_{sum} = G_{RN} + G_T + G_{RH} + G_U \quad (7)$$

where G_{RN} , G_T , G_{RH} and G_U represent the average contributions of RN, T, RH, and U to ET_0 variation, respectively; and G_{sum} represents the total contribution of these four meteorological factors to ET_0 variation.

3. Results

3.1. Changes in Meteorological Factors and ET_0 at Different Time Scales

3.1.1. Intra-Annual Variations

Annual variations in RN, T, RH, U and ET_0 indicated by multiannual averages are shown in Figure 2. At daily scales, RN, T, RH, U and ET_0 ranges were 1.13–14.40 MJ/m²/d, −4.68–27.04 °C, 37.25%–79.58%, 1.18–2.61 m/s and 0.78–5.57 mm, with average values of 7.70 MJ/m²/d, 12.52 °C, 56.03%, 1.79 m/s and 2.89 mm, respectively. On monthly scales, RN, T, RH, U and ET_0 ranges were 1.29–13.57 MJ/m²/d, −3.65–26.48 °C, 43.39%–75.25%, 1.30–2.31 m/s and 29.10–154.14 mm, with average values of 7.68 MJ/m²/d, 12.45 °C, 55.94%, 1.79 m/s and 87.92 mm, respectively, the changes in these four meteorological factors and ET_0 were consistent with those observed at daily scales, with similar trends in RN, T, RH, U and ET_0 (Figure 2). The ranking of standard deviations of four climatic factors and ET_0 at daily scales was as follows: RH > T > RN > ET_0 > U, while in monthly scales, this ranking became ET_0 > RH > T > RN > U. This shows that RH and ET_0 are the most concentrated factors at

daily and monthly time scales, respectively, while the U are the most scattered factor when it is a daily or monthly time scale.

Figure 2. *Cont.*

Figure 2. Cont.

Figure 2. Annual variations in meteorological factors and potential evapotranspiration (ET_0) based on multiannual averages. The δ means standard deviations, illustrating annual variability of meteorological parameters. A higher standard deviation indicates meteorological factor values are more dispersed, while a lower value indicates more concentrated.

3.1.2. Interannual Variations

The main meteorological factors and ET_0 changes from 1958 to 2017 are shown in Figure 3. At interannual scales, the fluctuations of U were the largest, while fluctuations of RN were the smallest. The RN , RH and U decreased at rates of $0.16 \text{ (MJ/m}^2\text{/d)/10a}$, $1.47\%/10a$ and 0.04 (m/s)/10a , respectively. Meanwhile, T and ET_0 increased at rates of $0.41 \text{ }^\circ\text{C/10a}$ and 7.77 mm/10a over the study period. The ranking of the four climate factors and ET_0 changes as follows $ET_0 > T > RN > U > RH$. Significance test results show that at a significant level of 0.05, the four climate factors and ET_0 show significant changes. The five factors are fitted with a linear function, and the ranking of correlation coefficients is $RN > T > RH > U > ET_0$.

3.2. Variations in the Sensitivity Coefficients of Meteorological Factors

3.2.1. Intra-Annual Variations in Sensitivity Coefficients

The daily sensitivity coefficient changes for each of the four meteorological factors in Beijing over the past 60 years are shown in Figure 4. The sensitivity coefficients of RN , T , RH , and U were 0.217–0.847, 0.101–0.507, 0.337–1.015 and 0.059–0.510, respectively. Over the course of 1 year, the T sensitivity coefficient had two peaks and two valleys, with an approximately symmetrical distribution. The RH sensitivity coefficient first decreased and then increased over the year, with a zigzag distribution. The U sensitivity coefficient first decreased and then increased over the year. Meanwhile, the RN sensitivity coefficient first increased and then decreased, with a single-peak distribution.

Table 1 shows rates of change of the four meteorological factors on monthly to seasonal scales. The annual trend in T was positive, while the annual trends in RN , RH (except for January) and U

were negative. These values suggest that, on monthly scales, T increased each month, while RN, RH (except January) and U (except July, August and September) decreased each month in the past 60 years. T increased the most in March and the least in June, having an annual change rate varying from $0.228\text{ }^{\circ}\text{C}/10\text{a}$ to $0.647\text{ }^{\circ}\text{C}/10\text{a}$. RH increased only in January and decreased in all other months (especially in March), having an annual change rate varying from $-2.9\%/10\text{a}$ to $0.4\%/10\text{a}$. U increased only in July, August and September and decreased in all other months, having an annual change rate varying from $-0.130\text{ (m/s)}/10\text{a}$ to $0.084\text{ (m/s)}/10\text{a}$. RN decreased most in January and least in August, having an annual change rate varying from $-0.420\text{ (MJ/m}^2\text{)}/10\text{a}$ to $-0.012\text{ (MJ/m}^2\text{)}/10\text{a}$. Meanwhile, the biggest and the smallest RN values were recorded in June and January, respectively. ET_0 decreased in January and June, but increased in all other months, with the largest increase in March and the largest decrease in June. The annual change rate of ET_0 varied from $-2.076\text{ mm}/10\text{a}$ to $2.826\text{ mm}/10\text{a}$.

Figure 3. Interannual variations of meteorological factors and reference evapotranspiration (ET_0). (* indicates significance level of 0.05). ((a–e) represent the interannual variations of T, RH, U, RN and ET_0 , respectively)

Figure 4. Variations in the annual average daily sensitivity coefficients of the four meteorological factors.

Table 1. Change rates and sensitivity coefficients of the four meteorological factors on monthly and seasonal scales.

Time Scale	Meteorological Trend Rate					Sensitivity Coefficient (%)				Sensitive Factor
	Trend _T (°C/10a)	Trend _{RH} (%/10a)	Trend _U (m/s)/10a	Trend _{RN} (MJ/m ²)/d/10a	Trend _{ET₀} (mm/10a)	S _T	S _{RH}	S _U	S _{RN}	
Jan	0.43	0.40	−0.13	−0.01	−0.40	20.2	−63.1	49.6	20.7	RH
Feb	0.58	−1.20	−0.09	−0.06	0.82	9.2	−55.2	36.5	34.5	
Mar	0.65	−2.90	−0.07	−0.11	2.83	25.0	−47.4	28.5	44.1	
Apr	0.49	−1.50	−0.09	−0.08	1.67	45.9	−42.2	25.5	51.2	RN
May	0.37	−1.30	−0.04	−0.21	0.91	51.3	−40.2	21.3	60.7	
Jun	0.23	−0.60	−0.01	−0.42	−2.08	50.0	−45.2	16.4	69.9	
Jul	0.31	−2.20	0.05	−0.35	0.31	46.8	−55.6	9.4	79.8	
Aug	0.40	−2.50	0.08	−0.22	1.86	45.8	−56.2	8.4	81.3	
Sept	0.44	−1.70	0.02	−0.24	0.65	46.7	−61.1	16.3	70.6	RH
Oct	0.38	−1.70	−0.02	−0.14	0.76	40.7	−75.0	28.0	55.0	
Nov	0.27	−1.50	−0.09	−0.04	0.20	19.5	−92.1	45.6	30.6	
Dec	0.39	−0.90	−0.09	−0.03	0.24	9.3	−81.4	55.2	16.6	RN
Spring	0.50	−1.90	−0.07	−0.14	0.09	44.4	−42.9	24.6	52.5	
Summer	0.32	−1.80	0.04	−0.33	1.62	47.6	−52.8	11.5	76.9	RH
Autumn	0.36	−1.70	−0.03	−0.14	−0.02	40.2	−74.4	27.4	54.8	
Winter	0.47	−0.50	−0.10	−0.06	7.77	10.9	−64.3	47.0	24.1	RH
Annual mean	0.41	−1.47	−0.04	−0.16	0.77	34.2	−59.6	28.4	51.3	

It can be seen that ET_0 was the most sensitive to RH and RN on monthly and seasonal scales, but the ranking of sensitivity varied in different months and seasons (Table 1). On monthly scales, during November–February, the sensitivity of ET_0 to the four climatic factors was as follows: $RH > U > RN > T$. In March, this ranking became $RH > RN > U > T$; in April, May and June it was $RN > T > RH > U$; in July, August and September, it was $RN > RH > T > U$, while in October, it was $RH > RN > T > U$. On seasonal scales, the sensitivity of ET_0 to the four climatic factors also varied. In spring, the ranking was $RN > T > RH > U$; in summer, this ranking became $RN > RH > T > U$; in autumn, it was $RH > RN > T > U$; and in winter, it was $RH > U > RN > T$. According to annual averages, ET_0 was most sensitive to RH, followed by RN and T, and was least sensitive to U (Table 1).

3.2.2. Interannual Variation of Sensitivity Coefficients

The interannual variations of the sensitivity coefficients of the four meteorological factors in Beijing from 1958 to 2017 are shown in Figure 5. Over the last 60 years, the sensitivity coefficients of

RH and RN have declined at rates of $-2.2\%/10a$ and $-0.009 (MJ/m^2/d)/10a$, respectively. Meanwhile, the sensitivity coefficients of T and U have increased at rates of $0.007 ^\circ C/10a$ and $0.015 (m/s)/10a$, respectively. These changes indicate that the positive sensitivity of ET_0 to both RH and RN has decreased, while its positive sensitivity to T and U has increased. The sensitivity coefficients of RN, T, RH and U were 0.555, 0.408, -0.572 and 0.244 , respectively, with the ranges of $0.489\text{--}0.662$, $0.374\text{--}0.434$, $-0.453\text{--}0.783$ and $0.170\text{--}0.305$. The sensitivity coefficients of T, U and RN varied slightly, while the sensitivity coefficient of RH fluctuated markedly.

Figure 5. Interannual variations in the sensitivity coefficients of the four meteorological factors. (* indicates significance level of 0.05). ((a–d) represent the interannual variations in the sensitivity coefficients of T, RH, U and RN, respectively)

From 1958 to 1979, the sensitivity coefficient of RH increased from -0.47 to -0.71 , then decreased to 0.50 in 1981, and has continued to slowly decline. The turning point for this decline in the RH sensitivity coefficient occurred in 1979. On an annual scale, ET_0 showed strongest sensitivity to RH and RN. From 1958 to 1963, RN was the most sensitive factor; while from 1964 to 1978, the most sensitive factor was RH; and then from 1979 to 2017, RH and RN were alternately the most sensitive factors affecting ET_0 .

3.3. Contributions of Meteorological Factors to Variation in Potential Evapotranspiration

3.3.1. Daily Time Scales

At daily time scales, the contributions of the four meteorological factors to ET_0 are shown Figure 6. These factors made contributions on ET_0 that typically varied between -2 and 4 mm. According to the average contributions of these four factors on a daily basis, the ranking of their contributions was $T > RH > RN > U$. However, the contribution of T fluctuated greatly in mid to late February, mainly because positive and negative distributions of T were relatively symmetrical over the study period,

yielding a small mean value for T , when derived from Formulas (3) to (6). Because there were singular points in the contribution from T , the net contributions of RH and RN were greater than T . Clearly, the contributions of T and U at the start and end of the year were large, while contributions of RN and RH were dominant mid-year.

Figure 6. Contributions of the four meteorological factors on daily scales to changes in reference evapotranspiration (ET_0). G_{RN} , G_T , G_{RH} and G_U are the average contributions of net radiation, temperature, relative humidity and wind speed, respectively.

3.3.2. Monthly and Seasonal TIME Scales

Table 2 shows the contributions of the four meteorological factors to ET_0 on monthly and seasonal scales. The contribution of T to the change in ET_0 was positive, the contribution of RN to the change in ET_0 was negative, while the contribution of RH to the change in ET_0 was negative in January and positive for all other months. The contribution of U to the change in ET_0 was positive in July, August and September, and negative for other months. Specifically, in December and January, U contributed the most to ET_0 change, with contributions of -4.66 and -6.16 mm, while RN contributed the least to ET_0 change, with contributions of -0.65 and -0.22 mm, respectively. In February and April, T contributed most to ET_0 change, with contributions of 7.38 and 11.17 mm, while RN contributed least to ET_0 change, with contributions of -1.26 and -2.93 mm. In March, May, August, October and November, the contributions of RH to ET_0 change were greatest, with contributions of 13.92 , 9.62 , 13.62 , 7.96 and 5.58 mm, respectively. On monthly scales, the ranking of the average contributions of the four meteorological factors to ET_0 was $RH > RN > T > U$.

On seasonal scales, the contributions of T and RH to ET_0 were positive for all four seasons, while the contributions of U to ET_0 change was negative in all other seasons, but only in summer was positive. From spring to winter, the maximum meteorological factors contributing to ET_0 change were RH , RN , T , and U , with contributions of 36.51 , -49.67 , 23.29 and 15.52 mm respectively. On seasonal scales, the average contributions of the four meteorological factors to ET_0 were ranked: $RH > RN > T > U$, which was consistent with monthly scales.

Clearly, there was a difference between the total contributions of the four meteorological factors to ET_0 change on both monthly and seasonal scales. This is because the calculation of ET_0 change was characterized by the product of climate tendency and research year. However, meteorological factors are not a single linear change, the climate tendency does not reflect the changes in these meteorological factors. Therefore, the variation in ET_0 calculated using this method becomes large. Notably, the differences between total contributions of meteorological factors and the change in ET_0 on smaller than seasonal scales reflect the accumulation of differences in shorter cycles over the long term.

Table 2. Contributions of the four meteorological factors to reference evapotranspiration (ET_0) on monthly and seasonal scales.

Time Scale	Contribution of Meteorological Elements on ET_0 (mm)					ΔET_0 (mm)	Main Control Factor
	G_T	G_{RH}	G_U	G_{RN}	G_{sum}		
Jan	4.38	−1.03	−6.16	−0.22	−3.04	−2.41	U
Feb	7.38	3.36	−4.02	−1.26	5.46	4.93	T
Mar	12.05	13.92	−4.00	−3.11	18.86	16.96	RH
Apr	11.17	10.06	−7.15	−2.93	11.15	9.99	T
May	8.46	9.62	−3.51	−9.37	5.19	5.46	RH
Jun	4.27	3.87	−0.57	−19.93	−12.36	−12.45	RN
Jul	4.55	13.56	2.76	−18.33	2.54	1.84	RN
Aug	5.35	13.62	3.97	−11.08	11.86	11.16	RH
Sep	5.77	8.82	1.54	−10.61	5.52	3.93	RN
Oct	4.51	7.96	−1.21	−5.38	5.89	4.57	RH
Nov	2.63	5.58	−5.24	−1.21	1.76	1.19	RH
Dec	3.91	2.74	−4.66	−0.65	1.36	1.43	U
Spring	34.08	36.51	−15.28	−14.83	40.47	32.41	RH
Summer	14.61	32.95	8.22	−49.67	6.11	0.54	RN
Autumn	13.63	23.29	−5.63	−16.02	15.27	9.70	RH
Winter	15.52	4.53	−15.36	−3.77	0.91	3.95	TU
seasonal mean	19.46	24.32	−7.01	−21.07	15.69	11.65	RH

3.4. Discussion

Based on the daily data for meteorological variables in Beijing from 1958 to 2017, the ET_0 for different time scales was calculated by using the P–M formula recommended by the FAO-56. The characteristics of change of the four main meteorological factors and ET_0 were quantified using climate trends. The dynamic changes of these four meteorological factors led to an increase in ET_0 of 7.766 mm/10a in Beijing, which is within the range of values reported in many former studies (5.9–19.3 mm) [43–45]. The differences in rates obtained in these studies likely reflect different study periods, having different ET_0 ranges and trends.

Generally, the changes in sensitivity coefficients varied depending on the time scale considered. On daily scales, the sensitivity coefficients fluctuated markedly, and were derived for each variable. Suat et al. [46] found that the wind speed sensitivity coefficient fluctuated greatly, while the changes in the sensitivity coefficients of the other three meteorological factors (T_{max} , T_{min} and R_s) were smaller in eight regions in the United States. We found that RH was most sensitive to ET_0 at the start and end of the day, while RN was the most sensitive factor in the middle of the day, which is consistent with the results of Hupet et al. [47], Liu et al. [48] and Zhao et al. [45]. On a monthly scale, ET_0 was most influenced by RH from October to March, while RN played the biggest role in other months. Liu et al. [43] found that relative humidity was the most important factor in March, August, October, November and December, but in July it was sunshine. On seasonal scales, ET_0 was most sensitive to RN in spring and summer, but to RH in autumn and winter. On annual scales, sensitivity coefficients of RH and RN decreased gradually, while those of T and U increased gradually. For 1958–1982, the RH sensitivity coefficient was far larger than the sensitivity coefficients of any other meteorological factor. After 1982, its influence declined sharply, leading to RH and RN being alternately the most sensitive meteorological factor, ET_0 was not sensitive to U. The magnitudes and trends of the sensitivity coefficients were closely related to variations of the meteorological factors and the structure of the ET_0 partial differential equation incorporating these meteorological factors. The sensitivity factors varied over all time scales, although they fluctuated more obviously on shorter time scales.

At present, research on the contribution of meteorological factors to changes in ET_0 remains scarce. Zhao et al. [45] found that the VPD contributed greatly to the annual ET_0 change. Conversely, Huan et al. [37] reported that the wind speed was the major contributor to ET_0 change. On a monthly scale, Kang et al. [36] found that T, U and RH contributed the most to monthly ET_0 change; only T contributed to the change of ET_0 in winter and spring, while wind speed and humidity influenced

ET_0 in summer and on an annual scale. Yin et al. [41] found that U and sunshine hours were the main meteorological factors controlling changes in ET_0 in China, with minor contributions from RH and T. However, most research focuses only on certain time scales and does not consider the response of meteorological factors to ET_0 changes at different time scales. Meanwhile, the quantitative analysis of the impact of meteorological factors on ET_0 changes is imperfect in Beijing under different time perspectives.

In this study, we found that the contributions of the four meteorological factors on different time scales to the ET_0 change reflected the magnitude of their sensitivity coefficients and their relative rates of change. On daily scales, the contributions of T and U at the start and end of the day were larger than those of RN and RH in the middle of the day. On monthly scales, the rate of ET_0 change in December and January was 0.24 and -0.40 mm/10a, respectively. The U sensitivity coefficient in these 2 months was second only to the RH sensitivity coefficient, while the relative U change rate was second only to the relative T change rate, which resulted in U contributing most to ET_0 change in these months. In February and April, ET_0 increased at 0.82 and 1.67 mm/10a, respectively. T contributed most to the ET_0 changes in these months because of its relatively high change rate in February and large sensitivity coefficient in April. In March, May, August, October and November, RH contributed the most to ET_0 change. The value of the RH sensitivity coefficient and the relative change rates of ET_0 were high, with rates of 2.83, 0.91, 1.86, 0.76 and 0.20 mm/10a in these months. In June, July and September, ET_0 changed at rates of -2.08 , 0.31 and 0.65 mm/10a, respectively. RN contributed greatly to ET_0 change in these months, linked to a large RN sensitivity coefficient and a relatively high change rate. On seasonal scales, the contribution of RH was the largest in spring and autumn, RN in summer, and U and T in winter. In spring and autumn, although the RH sensitivity coefficients were lower than the RN sensitivity coefficients, its relative rates of change were higher. This led RH to become the main contributing factor to ET_0 change in spring and autumn. In summer, the RN sensitivity coefficient was much larger than all other factors, making it the main contributing factor to ET_0 change in this season. In winter, although the T and U sensitivity coefficients were small, their relative change rates were high, so their contributions to ET_0 change were the greatest. Thus, the rise in ET_0 in Beijing has been caused mainly by the decrease in RH and increase in T over the long term. Concurrently, the decrease in U and RN hinders further rise in ET_0 in Beijing, with RN being the most inhibitory in summer.

A limitation of this research is that the application of contribution rate analysis method was only done for Beijing; therefore, the scale should be expanded in future work. Additionally, Gong et al. [27] noted that the ET_0 response to climate change will differ by region and season because of the large spatiotemporal variability of the sensitivity coefficients. The characteristics of the relative change rate of meteorological factors are also closely related to the spatiotemporal scale, which leads to variability in the main ET_0 control factors on different time scales. Thus, an important focus area for research will be analyzing the contribution of meteorological factors to changes in ET_0 on larger spatial scales and different temporal scales.

4. Conclusions

In this paper, we qualitatively characterize the sensitivity factors to ET_0 under different time perspectives, also quantitatively analysis of the impact of meteorological factors on ET_0 changes by combining sensitivity coefficient with the factor's relative change rate over multiple time scales in Beijing. On the one hand, determining the main control factors of changes in ET_0 will provide a theoretical basis for water resources regulation, irrigation system design and crop water management in Beijing, on the other hand, exploring the temporal variability of ET_0 response factors is of great significance for understanding regional climate change. The main conclusions are as follows:

- (1) Over the last 60 years, RH, U and RN values have all declined, and only T has continued to rise. The rise in T and decline in RH are the main reasons underlying the ET_0 increase. However, the decline in U and RN hinder further increases of ET_0 in Beijing, with RN being the most inhibitory in summer. Determining the main control factors of ET_0 change on different time scales

will provide a theoretical basis for water resources regulation, irrigation system design and crop water management in Beijing.

- (2) The variations of sensitivity coefficients of the four meteorological factors over different time scales has resulted in variation in the main sensitivity factor affecting ET_0 . Over the course of 1 year, the sensitivity coefficients of four meteorological factors fluctuated greatly, with RH and RN being alternately the most sensitive factor. Between 1958 and 1979, RH was the most sensitive factor, but it has since become RN.
- (3) The contributions of the four meteorological factors to ET_0 varied on different time scales, reflecting their annual fluctuations. The contributions of T and U were large at the start and the end of the year, while the contributions of RH and RN were dominant mid-year. On interannual scales, the main contributing factors were RH and T.
- (4) A limitation of this research is that the application of contribution rate analysis method was only done for Beijing, also, the ET_0 response to climate change will differ by region and season because of the large spatiotemporal variability of the sensitivity coefficients and relative change rate. Thus, an important focus area for research will be analyzing the contribution of meteorological factors to changes in ET_0 on larger spatial scales and different temporal scales. Meanwhile, it is worth noting that the applicability of the contribution rate method in different climate zones still needs to be discussed.

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