Title page

Title： Difference Analysis on Meteorological Response Factors of Potential Evapotranspiration on Different Time Scales — Taking Beijing Station as an Example.

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Keywords: Time Scale; Potential Evapotranspiration; Sensitivity Coefficient; Contribution Amount; Meteorological Elements

Funding information: This National Natural ScienceFoundation of China (No. 51822907 and 51979287), and the Fund of China Institute of Water Resources and Hydropower Research (ID0145B742017 and ID0145B492017)

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METEOROLOGICAL RESPONSE FACTORS OF PET ON DIFFERENT TIME SCALES

Keywords: Time Scale; Potential Evapotranspiration; Sensitivity Coefficient; Contribution Amount; Meteorological Elements

Abstract: The response of meteorological elements to potential evapotranspiration(ET_0) varies greatly from different time-scale perspectives, but current research are mainly focused on a certain time-scale and lack the study on the response of various meteorological elements to ET_0 variations based on different time-scale perspectives. This situation results in the unilateral perception of variations in ET_0 caused by climate change. Therefore, this study qualitatively explore the sensitive factors of ET_0 on different time scales by sensitivity coefficients, and quantitatively characterize the actual contribution amounts of major meteorological elements to variations in ET_0 on different time scales by contribution rate combining the sensitivity coefficients with the relative variation rates of meteorological elements. Results are listed as follows. (1) The SRH is always negative, but SRn, ST and SU are positive. The main sensitivity factors of ET_0 vary on different time scales. Specifically, RH and Rn become the major sensitive factors alternately within a year. On an interannual basis, the Rn was the most sensitive factor from 1958 to 1963, and the most sensitive factor became RH from 1964 to 1978. RH and Rn became the most sensitive factors to ET_0 alternately from 1979 to 2017. (2) The contributions of each meteorological element fluctuate significantly. On the daily time scale, the GT and GU are large at the beginning and end of the year. The GRn and GRH are dominant in the middle of the year. On the monthly and seasonal time scales, RH contributes the most in spring and autumn and Rn does in summer. The GT and GU are dominant in winter. On the yearly and multi-yearly time scales, the main contributing factors are RH and T. In summary, the increase in ET_0 in Beijing area is mainly caused by the decrease in RH and the increase in T. The decreases in U and Rn also slow down the further increase in ET_0 in this area. This blocking effect caused by Rn in summer is highly evident.

Main text

1 Introduction

Evapotranspiration refers to the key hydrological process in which water vapor escapes from the land surface to the atmosphere; this process occurs among vegetation, soil, free water, and the atmosphere (Jung et al., 2010; Han and Zhang, 2018).,evapotranspiration is not only an important link affecting the water and energy balance between land and air (Taikan and Shinjiro, 2006) but also a key parameter for evaluating the efficiency of agricultural water use (Zhang et al., 2015).

Potential evapotranspiration (ET_0) is the theoretical maximum evapotranspiration of the underlying surface that is not subject to water stress and is determined by weather and climate conditions; the reference underlying vegetation height is 0.12 m, the fixed surface resistance is 70 m/s, and the albedo is 0.23 (Allen et al., 1998). Studies have shown that climate change causes changes in ET_0 by affecting the hydrological cycle (Vörösmarty et al., 2000). Consequently, changes in ET_0 will cause regional climate variation (Shukla and Mintz, 1982; Pan et al., 2015). The meteorological elements, such as temperature, relative humidity, and solar radiation, are undergoing a series of magnificent changes; ET_0 is a comprehensive hydrological parameter that is synergistically regulated by major meteorological elements, such as radiation, temperature, relative humidity, wind speed; therefore, the analysis on the temporal and spatial variation of potential evapotranspiration will help extensively understand climate change and its responding mechanism to the hydrological cycle (Haskett et al., 2000; Zuo et al., 2012). On this basis, many scholars have performed considerable research on the characteristics of the spatiotemporal variation of potential evapotranspiration and its responding mechanism. The spatiotemporal characteristics of ET_0 in China has been analyzed (Ni et al., 2006; Liu and Zhang, 2011; Han and Hu., 2012; Thomas., 2015.), and the main climatic affecting factors of ET_0 changes in the study area have been revealed (Gao et al., 2006; Yang and Yang., 2012; Huang et al., 2015; Li et al., 2016). Many methods, such as principal component analysis, partial correlation analysis, sensitivity coefficient, and the combination of sensitivity coefficient and relative variation rate, can be used to calculate the contributions of meteorological elements for the analysis on ET_0 response factors; among these methods, the sensitivity coefficient method is the most widely used. Sensitivity coefficient was first proposed by McCuen (1975) and is defined as the ratio between the variation rates of potential evapotranspiration and meteorological elements. Sensitivity analysis is important to understand the effect of various meteorological variables on ET_0 variations (Gong et al., 2012). The studies on the grassland ecosystems conducted by Saxton (1975), Beven (1979), Xu et al. (2006), and Yang et al. (2014) showed that ET_0 is most sensitive to radiation in the respective field. Ren et al. (2012) and Sergio et al. (2014) indicated that the main sensitive affecting factors of ET_0 variations are relative humidity and temperature. Other studies proposed that only the temperature (Sharifi and Dinpashoh, 2014; Guo et al., 2017) or relative humidity (Liang et al., 2008; Yin et al., 2010) is the first most sensitive factor to ET_0 in the respective region. The main sensitive factors to ET_0 in different regions vary.

At present, the sensitivity coefficient method is the main method for analyzing the causes of ET_0 variations. However, this method is still unsatisfactory when quantitatively characterizing the influence level of meteorological factors on ET_0. The contribution rate analysis combines the sensitivity coefficient with the variation rate of meteorological factors to calculate its contribution size to ET_0 for clarifying the attribution of ET_0 variations precisely (Zhao et al., 2015; Yang et al., 2018). The dominant factors that cause the variations in ET_0 vary due to the response of meteorological elements on different time scales. Gao et al. (2006) believed that the potential evapotranspiration of most river basins in China shows a decreasing trend on the annual and seasonal time scales. Liu et al. (2009) considered that ET_0 in the Haihe River Basin is most sensitive to water vapor pressure on the yearly and seasonal time scales in autumn and winter but is most sensitive to temperature in spring and summer. Ma et al. (2012) emphasized that wind speed is the dominant factor that causes ET_0 variations in the Heihe River Basin. Kang et al. (2018) concluded that the decrease in ET_0 on the yearly time scale in Altay regions is caused by the decrease in ET_0 in summer and emphasized that the decrease in wind speed is the main reason for ET_0 variations. Huan et al. (2015) proposed that ET_0 on the yearly and seasonal scales in Central Shandong is most sensitive to variations in relative humidity, and the major ET_0 sensitive factors differ from month to month. Moreover, the main contributing factors of ET_0 variations caused by yearly time scale are wind speed, percentage of sunshine, relative humidity, and temperature. The major contributing factors to seasonal and monthly ET_0 variations vary with the time scales. Zou et al. (2018) indicated that the decreases in wind speed and sunshine hours are the main reason for the decrease in ET_0 on the yearly and seasonal time scales on

Hainan Island. The increase in water vapor pressure is also one of the main reasons for the decrease in ET_0 in winter. The increase in ET_0 on the yearly and seasonal time scales is mainly caused by the increase in temperature. Yin et al. (2010) argued that wind speed and sunshine hours are the main meteorological elements to determine the annual ET_0 variations in China, whereas relative humidity and temperature contribute less.

The above-mentioned analysis indicates that the response of meteorological elements to ET_0 varies greatly from different spatial and temporal scales, but current research activities are mainly focused on a certain time scale and lack the study on the response of various meteorological elements to ET_0 variations from different time-scale perspectives. On this basis, this study uses the meteorological data in Beijing area from 1958 to 2017 to analyze the variation characteristics of the main meteorological elements and ET_0 on different time scales, qualitatively explore the sensitive factors of ET_0 on different time scales, and quantitatively characterize the actual contribution amounts of major meteorological elements to variations in ET_0 on different time scales. Accordingly, the cause of ET_0 variations on different time scales can be clarified, and a theoretical basis for the water resource regulation, irrigation system formulation, and crop water management in Beijing area can be provided.

2 Materials and methods

2.1 Study area

Beijing is the capital of China and the country's political, cultural, and international communication center. The city is located at 115.7°–117.4° east longitude and 39.4°–41.6° north latitude and has a total area of 16,412 m^2 and an average elevation of 43.5 m. The Beijing region is shown in Figure 1.

2.2 Data

All data come from the National Meteorological Information Center, China Meteorological Administration, from which the daily meteorological data from Beijing Station (39°48'N, 126°28'E) from 1958 to 2017 are selected, including maximum temperature, minimum temperature, average temperature, relative humidity, wind speed, and atmospheric pressure.

2.3 Methods

2.3.1 Computation of potential evapotranspiration (ET_0)

The Penman–Monteith (P–M) formula recommended by FAO56 is used to calculate the potential evapotranspiration (ET_0) in Beijing. The height of the reference vegetation and grassland is 0.12 m, the fixed surface resistance is 70 s/m, and the albedo is 0.23 (Allen et al., 1998).

$$ET_0 = \frac{0.408\Delta(Rn - G) + 900\gamma U_2(e_s - e_a)/(T + 273)}{\Delta + \gamma(1 + 0.34U_2)}, \quad (1)$$

where ET_0 is the potential evapotranspiration rate (mm/day); Rn is the net radiation on the crop surface (MJ/m^2/day); G is the soil heat flux (MJ/m^2/day) with daily value taken as 0; T is the daily average temperature (°C); U_2 is the wind speed (m/s) at a height of 2 m; e_s and e_a are the saturated and actual vapor pressure (kPa), respectively; (e_s–e_a) is expressed and replaced by RH; Δ is the slope of the saturated vapor pressure curve; and γ is the constant from a hygrometer (kPa/°C).

2.3.2 Sensitivity analysis

In this work, the sensitivity coefficient is used to describe the influence size of each meteorological element on ET_0; this coefficient is defined as the ratio between the variations in ET_0 and the change rate of meteorological elements (McCuen, 1975; Yin at al., 2010), that is,

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

where S_x is the sensitivity coefficient of meteorological element x; and ΔET_0 and Δx are the variable amounts of ET_0 and meteorological element x, respectively. The positive or negative S_x

represents the increase or decrease in ET_0 as the meteorological elements increase or decrease, respectively, while the size of their absolute values reflects the degree of sensitivity.

2.3.3 Contribution calculation

Multiplying the sensitivity coefficient of a single meteorological element with its multi-year relative variation rate is the contribution rate of such an element to the ET_0 variation (Yin ,2010 b. A positive value indicates that the variation of such an element causes the increase in ET_0 and the contribution is positive. A negative value indicates that the variation of such an element causes the decrease in ET_0 and the contribution is negative.

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

$$Con_x = S_x \times RC_x, \tag{4}$$

where $Trend_x$ is the meteorological trend rate of x and reflects the variation trend of the meteorological elements on the corresponding research scale with the changing years. If $Trend_x$ is positive, then the meteorological elements increase as the years increase. By contrast, if $Trend_x$ is negative, then the meteorological elements decrease as the years increase. The magnitude of the absolute value of $Trend_x$ indicates the rate of increase (or decrease). On the daily time scale, $Trend_x$ is the meteorological trend rate for the ordinal number x on the same day in each year. On the monthly time scale, $Trend_x$ is the meteorological trend rate for the ordinal number x in the same month in each year. On the yearly time scale, $Trend_x$ is the yearly meteorological trend rate. RC_x is the multi-yearly relative variation rate of x; n is the research year; av_x is the multi-yearly mean value; and Con_x is the contribution rate of the meteorological element x to ET_0 variation.

The total contribution to the variation is obtained when the contribution rate of each meteorological element is accumulated, that is,

$$Con = Con_{Rn} + Con_T + Con_{RH} + Con_U \text{ ,} \quad (5)$$

where Con_{Rn}, Con_T, Con_{RH}, and Con_U represent the contribution rates of net radiation, temperature, relative humidity, and wind speed to ET_0 variation, respectively; and *Con* represents the total contribution rate of each meteorological element to ET_0 variation.

$$G(x) = Con_x \times \bar{ET_0} \text{ ,} \quad (6)$$

$$G_{sum} = G(Rn) + G(T) + G(RH) + G(U) \text{,} \quad (7)$$

where *G(Rn)*, *G(T)*, *G(RH)*, and *G(U)* represent the actual contribution amounts of net radiation, temperature, relative humidity, and wind speed to ET_0 variation, respectively; and G_{sum} represents the total contribution amount of each meteorological element to ET_0 variation.

3 Results

3.1 Variations in main meteorological elements and ET_0

3.1.1 Intra-annual variations

The variation characteristics of net radiation, temperature, relative humidity, wind speed, and multi-yearly mean value of ET_0 within a year are shown in Figure 2. On the daily time scale, net radiation(Rn), temperature(T), relative humidity(RH), and ET_0 mean value show a single-peak curve variation of “first-increasing-then-decreasing.” The wind speed(U) presents the fluctuation variations of “first-increasing-then-decreasing-increasing-again.” The variation ranges of Rn, T, RH, U, and ET_0 are 1.13–14.40 (MJ(m^2/d)), −4.68 °C–27.04 °C, 37.25%–79.58%, 1.18–2.61 m/s, and 0.78–5.57 mm, respectively. The corresponding mean values are 7.70 (MJ/(m^2/d)), 12.52 °C, 56.03%, 1.79 m/s, and 2.89 mm.

On the monthly time scale, Rn is the lowest in December (1.29 (MJ/(m^2/d)) and the highest in June (13.57 (MJ/(m^2/d)). T is the lowest in January (−3.65 °C) and the highest in July (26.48 °C). RH is the lowest in January (43.39%) and the highest in August (75.25%). U is the smallest in August (1.30 m/s) and the largest in April (2.31 m/s). Monthly ET_0 value is the smallest in December (29.10 mm) and the largest in May (154.14 mm). The variation characteristics of the four meteorological elements and the mean value of ET_0 are consistent with those on the daily time scale. The variation trends in T, RH, Rn, and ET_0 are similar.

3.1.2 Interannual variation

Figure 3 shows the changing process of the main meteorological elements and ET_0 from 1958 to 2017. In this period, the maximum value of Rn was 8.49 (MJ/(m^2/d)) in 1965, and the minimum value was 7.01 (MJ/(m^2/d)) in 2006; the maximum value of T was 14.21 °C in 2017, and the minimum value was 10.60 °C in 1969; the maximum value of RH was 66.41% in 1964, and the minimum value was 49.10% in 2005; the maximum value of U was 2.43 m/s in 1972, and the minimum value was 1.24 m/s in 1959; the maximum value of ET_0 was 1146.36 mm in 1968, and the minimum value was 922.76 mm in 1964. In terms of amplitude of variation, the fluctuation of U is the largest, and that of Rn is the smallest. The variation trends indicate that RH, U, and Rn show decreasing trends at the rates of 1.47%/10a, 0.04 (m/s)/10a, and 0.16 (MJ/(m^2/d))/10a, respectively. T and ET_0 increase at the rates of 0.41 °C/10a and 7.77 mm/10a, respectively.

3.2 Variations in sensitivity coefficients of main meteorological elements

3.2.1 Variations in sensitivity coefficients within a year

Figure 4 shows the variations in the multi-yearly mean daily sensitivity coefficients of the main meteorological elements in Beijing area over the past 60 years. The variation ranges of the sensitivity coefficients of T, RH, U, and Rn are from 0.101 to 0.507, from 0.337 to 1.015, from 0.059 to 0.510, and from 0.217 to 0.847, respectively. In one year, the ST shows a trend of "approximate symmetrical distribution with double peaks and valleys." The coefficient reaches a maximum value of 0.507 on the 134th day and a minimum value of 0.101 on the 338th day. The SRH first decreases and then decreases throughout the year with a saw-tooth distribution and evident fluctuations among the ordinal numbers of adjacent days. The maximum value of the sensitivity coefficient is 1.015 on the 332nd day, and the minimum value is 0.337 on the 139th day. The SU first decreases and then increases throughout the year. The coefficient reaches a maximum value of 0.510 on the 348th day and a minimum value of 0.059 on the 209th day. The SRn first increases and then decreases throughout the year. The coefficient shows a single-peak distribution, with a maximum value of 0.847 on the 209th day and a minimum value of 0.217 on the 357th day. This finding is consistent with the variation in net radiation within a year.

(Note: *ST* is the sensitivity coefficient of temperature, *SRH* is the sensitivity coefficient of relative humidity, *SU* is the sensitivity coefficient of wind speed, and *SRn* is the sensitivity coefficient of net radiation.)

Table 1 shows the values of the trend rates of the four meteorological elements on the monthly and seasonal scales. The trend rate of T is positive, while the annual trend rates of RH (except January), U, and Rn are negative. This finding indicates that the T on the monthly time scale increases, while those of the RH (except January), U (except July, August, and September), and Rn decrease in each month. The T increases the most in March and is the smallest in June with an annual trend rate varying from 0.228 °C/10a to 0.647 °C/10a. RH increases only in January and decreases in the rest of the months, and it is especially fastest in March with an annual trend rate ranging from −2.9%/10a to 0.4%/10a. The U only increases in July, August, and September and decreases in the rest of the months with an annual trend rate ranging from −0.130 [(m/s)/10a] to 0.084 [(m/s)/10a]. The fastest decrease is in January, and the largest increase is in August. Rn decreases in each month with an annual trend rate varying from −0.420 [(MJ/(m^2/d))/10a] to −0.012 [(MJ/(m^2/d))/10a], and the largest and smallest reductions are in June and January, respectively. ET_0 decreases in January and June and increases in the rest of the months, with the largest increase in March and the most evident decrease in June. The annual trend rate range is from −2.076 (mm/10a) to 2.826 (mm/10a).

ET_0 is most sensitive to RH and Rn on the monthly and seasonal time scales. However, a difference in the order of sensitivity levels can be observed in each month and different quarters. On the monthly time scale, the orders of the sensitivity levels of ET_0 to the four climate factors in November, December, January, and February are $SRH>SU>SRn>ST$; those in March are $SRH>SRn>SU>ST$; those in April, May, and June are $SRn>ST>SRH>SU$; those in July, August, and September are $SRn>SRH>ST>SU$; and those in October are $SRH>SRn>ST>SU$. On the seasonal scale, the sensitivity levels of ET_0 to the four climate factors in spring are $SRn>ST>SRH>SU$; those in summer are $SRn>SRH>ST>SU$; those in autumn are $SRH>SRn>ST>SU$; and those in winter are $SRH>SU>SRn>ST$. From an annual mean, ET_0 is most sensitive to RH, followed by Rn and T, and the least sensitive to U.

3.2.2 Interannual variation of sensitivity coefficients

Figure 5 shows the interannual variations in the sensitivity coefficients of the main meteorological elements in Beijing area from 1958 to 2017. The figure shows that the SRH and SRn have shown a downward trend in the past 60 years with their meteorological trend rates of −2.2%/10a and −0.009 (MJ/(m^2/d))]10a, respectively. The ST and SU increase with their meteorological trend rates of 0.007 °C/10a and 0.015 (m/s)/10a, respectively. This finding indicates the positive and negative sensitivity levels of RH and Rn to ET_0, respectively. T gradually decreases, while the positive sensitivity levels of T and U to ET_0 gradually increase. The mean values of the ST, SRH, SU, and SRn are 0.408, −0.572, 0.244, and 0.555, respectively, with the variation ranges of from 0.374 to 0.434, from −0.453 to −0.783, from 0.170 to 0.305, and from 0.489 to 0.662. The amplitudes of variation for the ST, SU, and SRn are relatively small, while that of SRH fluctuates drastically. From 1958 to 1979, the SRH increased significantly to 0.71 and decreased to 0.50 in 1981. The coefficient then kept a slowly declining trend with the turning point of the declining SRH in 1979. On the yearly time scale, ET_0 is most sensitive to RH and Rn. Rn was the most sensitive factor from 1958 to 1963, and the most sensitive factor became RH from 1964 to 1978. After this period, RH and Rn alternately became the most sensitive factor to ET_0.

3.3 Contributions of main meteorological elements to ET_0 variation

3.3.1 Daily time scale

Figure 6 shows that the multi-yearly mean daily contribution amounts of the four meteorological elements to ET_0 are mainly concentrated on the variations between −2 and 4 mm. The amplitudes of variation of the contribution amounts of Rn and RH are relatively large, while those of T and U are relatively small within the year. The maximum G(Rn) is −1.650 mm on the 173rd day, while the minimum contribution is 0.350 mm on the 270th day with a daily mean contribution amount of −0.240 mm. The minimum G(T) is 0.003 mm on the 23rd day. The maximum contribution is in the mid-to-late February with a daily mean contribution amount of 0.280 mm. The maximum G(RH) is 0.989 mm on the 97th day, while the minimum contribution is 0.002 mm on the 326th day with a daily mean contribution amount of 0.260 mm. Meanwhile, the maximum G(U) is −0.560 mm, while the minimum contribution is 0.002 mm on the 180th day with a daily mean contribution amount of −0.070 mm. The daily mean contribution amounts of the meteorological elements on the daily time scale indicate that the contribution amounts of the four meteorological elements can be ranked as *G(T)>G(RH)>G(Rn)>G(U)*. However, the G(T) fluctuates considerably in the mid-to-late February. This phenomenon is mainly because the positive and negative distributions of the multiple-yearly T for these days are relatively symmetrical. Accordingly, the obtained mean value of T is very small, which in turn leads to the appearance of the singular points in the G(T) acquired from Formulas (3) to (6). The G(RH) and G(Rn) are higher than G(T). The process exhibits that the G(T) and G(U) at the beginning and end of the year are large, while those of G(Rn) and G(RH) play a dominant role in the middle of the year.

(Note: *G (T)* is the contribution amount of temperature, *G (RH)* is the contribution amount of relative humidity, *G (U)* is the contribution amount of wind speed, and *G (Rn)* is the contribution amount of net radiation.)

3.3.2 Monthly and seasonal time scales

The contribution amounts of the meteorological elements to ET_0 on the monthly and seasonal scales are shown in Table 2. The G(T) are all positive, while G(Rn) are all negative, G(RH） are all positive except for that in January, and G(U) are positive only in July, August, and September and are negative on the rest of the months. Specifically, the G(T) is the largest and reaches 7.38 and 11.17 mm in December and January, respectively. The G(Rn) is the smallest and reaches −1.26 and −2.93 mm in December and January, respectively. The G(U) is the largest and reaches −4.66 and −6.16 mm in February and April, respectively. The G(Rn) is the smallest and reaches −0.65 and −0.22 mm in February and April, respectively. The G(RH) is the largest and reaches 13.92, 9.62, 13.62, 7.96, and 5.58 mm in March, May, August, October, and November, respectively. The meteorological elements with the least contribution differ. The G(U) in May, August, and October are −3.51, 3.97, and −1.21 mm, respectively. The G(Rn) in March and November are −3.11 and −1.21 mm, respectively. The G(Rn) is the largest and reaches −19.93, −18.33, and −10.61 mm in June, July, and September, respectively, and the meteorological elements with the least contribution is U with contribution amounts of −0.57, 2.76, and 1.54 mm. On the entire monthly time scale, the contribution amount made by four meteorological elements to ET_0 is *G(RH)>G(Rn)>G(T)>G(U)*.

On the seasonal time scale, the G(T) and G(RH) are positive in the four seasons, the G(Rn) is negative, and the G(U) is positive only in summer and negative in the three other seasons. In spring, the meteorological elements with the largest and smallest contributions to ET_0 variation are RH and Rn with the contribution amounts of 36.51 and −14.83 mm, respectively. In summer, the meteorological elements with the largest and smallest contributions to ET_0 variation are Rn and U with the contribution amounts of −49.67 and 8.22 mm, respectively. In autumn, the meteorological elements with the largest and smallest contributions to ET_0 variation are RH and U with the contribution amounts of 23.29 and −5.63 mm, respectively. In winter, the meteorological elements with the largest and smallest contributions to ET_0 variation are T and Rn with the contribution amounts of 15.52 and −3.77 mm, respectively. On the entire seasonal time scale, the contribution amount made by four meteorological elements to ET_0 is *G(RH)>G(Rn)>G(T)>G(U)*, which is consistent with the monthly time scale.

Differences can be observed between the total contribution amounts of the four meteorological elements and the ET_0 variations whether on a monthly or seasonal time scale. This phenomenon is chiefly because the calculation of the ET_0 variations is characterized in the form of the product of the meteorological trend rate and the years for research. However, the meteorological trend rate cannot efficiently reflect the actual variation characteristics of meteorological elements when the meteorological elements vary in a complex linear manner. Accordingly, the ET_0 variations obtained by the calculation with this method may differ. The deviation between the total contribution amount of the meteorological elements and the ET_0 variation on the monthly time scale is smaller than that on the seasonal time scale. This condition is caused by the accumulation of the deviations of the shorter time scale in the longer time scale.

3.3.3 Yearly and multi-yearly scales

The contribution rates and annual mean contribution amounts of the meteorological elements to ET_0 on the yearly and multi-yearly scales are shown in Table 3. The main control factor of ET_0 on the yearly time scale is RH. The G(T) and G(RH) to ET_0 are positive, while G(U) and G(Rn) are negative. The contribution rates and annual mean contribution amounts of each meteorological element to ET_0 variations are ranked as *G(RH)>G(T)>G(Rn)>G(U)*. The negative of G(Rn) and G(U) and the positive of G(RH) increase with the extension of the time scale, while the positive of G(T) decreases. The annual mean contribution amount of each meteorological element on the multi-yearly scale varies mainly due to the interannual fluctuations of meteorological elements and the nonlinear characteristics between ET_0 and each meteorological element.

3.4 Discussion

On the basis of the daily value data of meteorological elements in Beijing area from 1958 to 2017, the P–M formula recommended by FAO56 is used to estimate the ET_0 on different times. The indicator of the meteorological trend rate is also adopted to quantify the variation characteristics of the four major meteorological elements and ET_0. The results show that T increases at a rate of 0.412 °C/10a, while RH, U, and Rn decrease at the rates of 1.474%/10a, 0.038 (MJ/(m^2/d)/10a, and 0.16 (m/s)/10a among the four meteorological elements. The dynamic variations of the four meteorological elements cause ET_0 to increase at a rate of 7.766 mm/10a. The research by some scholars found that the annual increase rate of ET_0 in Beijing area differs, and the distribution is between 5.9 and 19.3 mm (Zhao et al., 2013; Liu et al., 2013; Liu et al., 2014). This situation is mainly due to the difference in the starting year for the research that varies the trend intervals of ET_0. Consequently, the trend rate values of the ET_0 obtained by calculation differ.

Variations in the sensitivity coefficients for various meteorological elements during the year fluctuate significantly, and this finding is consistent with the results of previous research (Liu et al., 2009; Suat et al., 2006). The variation in the sensitivity coefficients significantly differs due to the variation in the length of the time scales. On the daily time scale, the ST shows a variation trend of “approximate symmetrical distribution with double peaks and valleys.” The SRH and SU first decrease and then increase throughout the year. However, the former shows a saw-tooth distribution, and the latter is similar to a U-shaped variation. The SRn first increases and then decreases throughout the year and shows a single-peak variation. From the perspective of sensitivity factors, ET_0 is most sensitive to the RH at the beginning and end of the daily time scale, while Rn is the most sensitive factor during the year. On the monthly time scale, ET_0 is most sensitive to RH in October, November, December, January, February, and March. Rn is the most sensitive factor in the remaining months. On the seasonal time scale, ET_0 is most sensitive to Rn in spring and summer and RH in autumn and winter. On the yearly time scale, the SRH and SRn gradually decrease, while ST and SU gradually increase. From 1958 to 1982, the SRH was much larger than that of the three other meteorological factors, was the first sensitive factor, and abruptly declined after 1982. RH and Rn become the most sensitive meteorological factors, and ET_0 is insensitive to U most of the time. The size and changing trend of the sensitivity coefficient are closely related to the time-varying characteristics of the meteorological elements and the structure of ET_0 to the partial differential equation of the meteorological factors. The sensitivity factor varies with the time scales, and its sensitivity coefficient fluctuates evidently on the short time scale.

In this research, the contributions of the four meteorological elements on different time scales to the variation in ET_0 vary dynamically in Beijing area. The main contributing factors differ. The contribution amounts of the meteorological elements to ET_0 variation on different time scales are the result of the combined effect between the sensitivity coefficients of the meteorological elements and the relative variation rate. On the daily time scale, the G(T) and G(U) at the beginning and end of the year are relatively large, while G(Rn) and G(RH) dominate through the year. On the monthly time scale, the variation rates of ET_0 in December and January are 0.24 and −0.40 mm/10a, respectively. In the two months, the SU is only second to SRH. The relative variation rate of U is only second to that of T. Thus, the U contributes the most to ET_0 variation. In February and April, ET_0 increases at the rates of 0.82 and 1.67 mm/10a, respectively, with T contributing the most to ET_0 variation. This situation is mainly due to the large relative variation rate of T in February and large sensitivity coefficient of T in April. In March, May, August, October, and November, RH contributes the most to ET_0 variation. The SRH and its relative variation rate are relatively high. Thus, ET_0 increases at the rates of 2.83, 0.91, 1.86, 0.76, and 0.20 mm/10a. In June, July, and September, ET_0 varies at the rates of −2.08, 0.31, and 0.65 mm/10a, respectively. Rn contributes the most to ET_0 variation mainly because not only the SRn is large but also its relative variation rate is high. On the seasonal time scale, the RH contributed most in spring and autumn and Rn does in summer. U and T dominate in winter. Although the SRH is lower than SRn in spring and autumn, its relative variation rate is high. The sensitivity coefficient and relative variation rate are higher than those of T and U. The combined effect makes the RH a major contributing factor to the variation in ET_0 in spring and autumn. In summer, the SRn is much higher than that of the three other meteorological elements. Thus, Rn is the major contributing factor to affect ET_0 variation. Although the ST and SU are low in winter, their relative variation rates are large. Thus, they make large contributions to ET_0 variations. On the yearly time scale, the main contributing factors are RH and T. In summary, the increase in ET_0 in Beijing area is mainly caused by the decrease in RH and the increase in T. The decreases in U and Rn are the main reasons that blocked the further increase in ET_0 in this area. This blocking effect caused by the Rn in summer is highly evident.

4 Conclusions

The main conclusions obtained from this research are listed as follows:

(1) In the past 60 years, the multi-yearly mean value of ET_0 in Beijing area was 1055 mm, with an annual mean increasing rate of 0.77 mm. RH, U, and Rn have a downward trend. Only T has an upward trend. The increase in T and the decrease in RH are the main reasons to account for the increase in ET_0. The decreases in U and Rn are the main reasons that blocked the further increase in ET_0 in this area. This blocking effect caused by Rn in summer is highly evident.

(2) Differences can be observed in the amplitudes of variation of the sensitivity coefficients of four meteorological factors and the main sensitive factors of ET_0 on different time scales. Within a year, the fluctuations of the sensitivity coefficients of four meteorological elements are

enlarged. RH and Rn become the most sensitive factors alternately. On an interannual basis, the Rn was the most sensitive factor from 1958 to 1963, and the most sensitive factor became RH from 1964 to 1978. RH and Rn became the most sensitive factors to ET_0 alternately from 1979 to 2017.

(3) The contributions of the four meteorological elements on different time scales to the ET_0 differ. During the year, the contributions of each meteorological element fluctuate significantly. The G(T) and G(U) are large at the beginning and end of the year, and the G(Rn) and G(RH) are dominant in the middle of the year. On an interannual basis, the main contributing factors are RH and T.

(4) The response mechanisms of the four meteorological elements on different time scales to ET_0 variations differ. This difference is related to the periodic and fluctuating variations of the meteorological elements on different time scales and is closely related to the nonlinear coupling relation between ET_0 and various meteorological factors.

Acknowledgments

This research is supported by the Project of National Natural ScienceFoundation of China (No. 51822907 and 51979287), the Fund of China Institute of Water Resources and Hydropower Research (ID0145B742017 and ID0145B492017)

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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