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Sensitivity analysis of reference evapotranspiration (ETo) to climate change in Beijing, China

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ABSTRACT

In the present study, an attempt has been made to study the reference evapotranspiration (ETo) change and the sensitivity of estimated ETo to each climatic variable in a semi-humid and semi-arid region of Beijing in the north China using data from 1951 to 2010. Results show that in the past 60 years, yearly ETo was increasing with a rate of 19.5 mm per decade, and seasonal total ETo in wheat and corn seasons were increasing with rates of 13.1 and 5.3 mm per decade, respectively. Sensitivity analysis showed that mean air temperature was the first key factor for ETo change in the past 60 years, causing an annual total ETo increase of 7.4%, followed by relative humidity (5.5%) and sunshine hours (–3.1%); the less sensitivity factors were wind speed (0.7%), minimum temperature (–0.3%), and maximum temperature (–0.2%). A greater increase of total ETo (12.3%) in the past 60 years was found in wheat season, mainly because of mean temperature (8.6%) and relative humidity (5.4%), as compared to an increment of 6.0% in ETo during corn season due to sunshine hours (–6.9%), relative humidity (4.7%), and temperature (4.5%).

Keywords: Reference evapotranspiration; Penman–Monteith method; Changing trend; Sensitivity analysis; Climatic variables; Irrigation water requirement

1. Introduction

It has been confirmed that there has been a change in earth climate, which is closely related to the increases in atmospheric greenhouse gases CO_2, NOx concentrations, and other radioactively active gases [1]. These changes in climate are expected to cause major changes in various climatic variables such as precipitation, air temperature, relative humidity, and solar radiation [2] and hydrological cycle [3], and consequently affect evapotranspiration (ETo) or crop water requirement [4].

In recent years, numerous studies have been conducted to examine the potential impact of climate change on ETo. These studies show that the trend of ETo varies with climatic condition and regions [5]. Darshana et al. found the significant decreasing trends in almost all the months, annual, and seasonal ETos in the Tons River Basin in Central India and the magnitude of decrease in annual ETo varied from

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–1.75 to –8.98 mm y^{-1} [6]. Similarly, a significant decline in ETo (–0.3596 mm y^{-1}) was observed in the Platte River Basin, central Nebraska of USA [7]. They pointed out that the decline trend of ETo is most likely due to significant ($p < 0.05$) increase in precipitation (0.87 mm y^{-1}) that results in significant reduction in solar radiation (–0.0223 MJ m^{-2} y^{-1}) and, in turn in net radiation (–0.0032 MJ m^{-2} y^{-1}), which is the available energy to drive ETo [7]. In Iran, significant decreasing trends of ETo were more considerable in most regions, but the increasing trend were found in some areas especially in the recent years [8–10]. Due to increases in air temperature and solar radiation, and decreases in relative humidity, statistically significant increases in ETo were detected (up to 3.5 mm y^{-1}) in the Southern Spain by Espadafor et al. [11].

In China, climatic variations and their effects on ETo have been studied in national and regions scales. At national scale, the mean annual-ETo decreased significantly by –14.35 mm per decade from 1960 to 1992, and increased by 22.40 mm per decade from 1993 to 2011 [12]. The most sensitive climatic variables for national ETo change is vapor pressure, followed by solar radiation, air temperature, and wind speed, while at regional scales, the trend of ETo varied from place to place. ETo has significant decreasing trend in the whole Changjiang river catchment of middle China, which is mainly attributed to the significant decreasing trends in the net radiation and the wind speed [13]. Similarly, decreasing trends were observed in the Pearl River basin of southeast China [14], the Haihe river basin of north China [15], the Yunnan province of southwest China [16], and in the arid region of northwest China [17], while an increasing trend of ETo was found in the middle and upper Yellow River basin, the second largest river basin in China [18].

Beijing is located in semi-humidity and semi-arid region in north China, and has been seriously suffering from water shortage. Due to insufficient precipitation, crops are always irrigated by pumping ground water, which has caused serious environmental problems, such as groundwater level dropping by 1~2 m per year. Precision irrigation scheduling is a way for saving irrigation water and hence protecting groundwater. The irrigation scheduling mainly depends on the precipitation and crop water requirement (ET), which is generally estimated using crop coefficient and ETo [19]. Therefore, analyzing the trends of climate change and their effects on ETo is important for water resources management, and the sustainable development of agriculture and economy in Beijing. To our knowledge, there were few researches to comprehensively study the climatic variation and their effects on ETo in Beijing.

In this study, daily ETo in Beijing was calculated by the Penman–Monteith method [19] using meteorological data-sets from 1951 to 2010. Further, ETo trend and the key factors influencing ETo were carried out in Beijing area.

2. Data and methods

2.1. Meteorological data and ETo

The daily meteorological data namely atmospheric pressure, precipitation, mean maximum and minimum temperatures, mean relative humidity, mean wind speed, and sunshine hours from 1951 to 2010 were collected from national climatic station, located on south of Beijing city (39˚48´N, 116˚28´E, 31.3 m ASL). These data were used to calculate ETo following the FAO-56 modified Penman–Monteith method [19].

2.2. Sensitivity analysis method

Sensitivity analysis was employed to identify the climatic variables that mostly influence ETo following the method proposed by Möller et al. [20]. The processes of the sensitivity analysis is described as follows: (1) calculating the mean values of daily air temperatures, daily relative humilities, daily wind speeds and daily sunshine hours averaged over period from 1951 to 1959 (referring to 1950s), and the corresponding daily ETo; the same procedure was used to calculate these daily mean variables from 2000 to 2010 (referring to 2000s) and the corresponding daily ETo; (2) calculating ETos by setting one climatic variable to its respective data in 2000s and others to their reference data (i.e. the averaged values in 1950s in step 1); and (3) comparing the daily ETos calculated by replacing each variable using data in 2000s (in step 2) with the reference ETo in 1950s (in step 1) and find out the variables mostly influencing ETo.

2.3. Mann–Kendall test and Sen's slope estimator

The trend of reference ETo in time series was tested using the Mann–Kendall method [21,22] and the Sen's method [23] by adopting the EXCEL-based software of MAKESENS 1.0 developed by Salmi et al. [24].

3. Results and discussion

3.1. ETo trend

Fig. 1 shows the variation in annual ETo from 1951 to 2010 in Beijing area. Annual total ETo varied from 957 to 1,208 mm with a mean of 1,105 mm. The mean ETo in wheat season (from October to middle June) and corn season (from middle June to September) was 665 and 439 mm, respectively. It can be seen that, ETo in winter wheat season contributed mostly to the annual ETo, which is mainly due to the long growth season (about 240 days). Fig. 1 also shows that annual and crop-seasonal ETos in the past 60 years increased significantly ($p < 0.05$). From 1950s (1951–1959) to 2000s (2000–2010), the mean annual total ETo increased from 1,039 to 1,148 mm; in winter wheat season, they increased from 620 to 692 mm and from 423 to 450 mm in corn season. The rates of increase were 19.5, 13.1, and 5.3 mm per decade for annual, wheat and corn seasonal ETos, respectively. Increased ETo indicates an increased crop water requirement.

The increasing trend of ETo found in Beijing city in this study is different with those found in most places of China, where ETos showed decreasing trends [12–18,25]. The reason for this may be that Beijing is a metropolis and its urbanization rate is increasing in the recent decades. It has been found that urbanization generally causes temperature increase in urban areas, and reductions in wind speed, relative humidity, and number of foggy days [26–35]. Further, the reduction in sunshine duration has been found in big cities in China and other regions [36–38]. As a result of these climatic variations, energy and aerodynamic terms in ETo are changed, which in turn change the ETo. Rim found in Korea that, with the progress of urbanization, among the 56 study areas, 33 areas including the station in capital of Sokchol showed increasing ETo [5]. Then they concluded that, urbanization rate is positively correlated with ETo. The increasing trend of ETo in Beijing is in agreement with the conclusion of Rim [5].

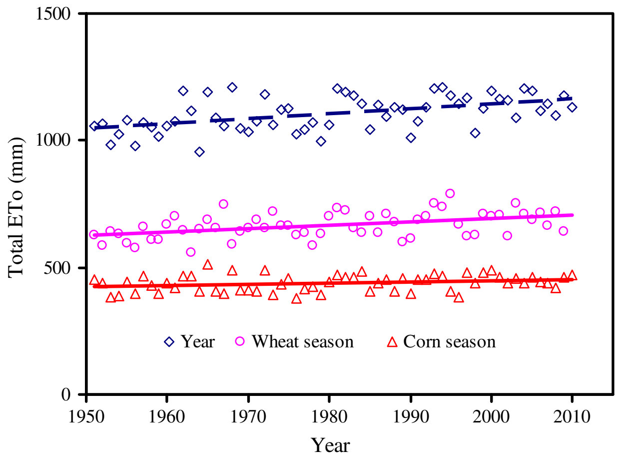

Fig. 1. Variations of yearly, wheat seasonal, and corn seasonal ETos from 1951 to 2010.

3.2. Sensitivity of ETo to each climatic variable change

The sensitivity analysis was carried out at monthly, seasonal (wheat and corn), and annual time scales and the results are listed in Table 1.

It can be seen from Table 1 that increases of daily *T*max and *T*min in the past 60 years resulted in small reduction of ETo, which is less than 0.02 mm d^{-1} or 1%. While the increasing of mean air temperature from 1950s to 2000s enhanced daily ETo from 0.08 to 0.34 mm d^{-1} with a mean increment of 0.20 mm day^{-1}. The highest increase in daily ETo was found in March, April, and May with values higher than 0.30 mm d^{-1}, and the lowest were found from October to January with values less than 0.15 mm d^{-1}. The increase in daily ETo (0.217 mm d^{-1}) caused by temperature increasing in the wheat season was close to that (0.193 mm d^{-1}) in the corn season.

The decreasing RH during the past 60 years caused ETo increase in each month and season. The highest increase in daily ETo caused by RH was found in March(0.368 mm d^{-1}), followed by July and August (0.20~ 0.30 mm d^{-1}), and the least were from December to February (less than 0.10 mm d^{-1}). Relative humidity decrease in the corn season caused a greater increase of 0.204 mm d^{-1} with respect to those in the wheat season (0.135 mm d^{-1}).

Changes of wind speed in the past 60 years caused daily ETo increases with rates of 0.007, 0.08 and 0.023 mm d^{-1} in wheat season, corn season and at annual base, respectively. However, it should be noted that wind changes in January, February and April resulted in a reduction of ETo, as compared to the increases in other months.

Reductions of sunshine hours in the past 60 years caused ETo decreases in most of the months. The greatest decrease of daily ETo caused by sunshine hours was –0.350 mm d^{-1}, in July, followed by –0.172 mm d^{-1} in August. The decreasing amounts of daily ETo in other months were less than 0.1 mm d^{-1}. The larger decreasing amounts in July and August contributed to a higher reduction rate of 0.298 mm d^{-1} in the corn season as compared to that in the wheat season.

Mean daily ETo of each month caused by the change in climatic variables during the past 60 years was increased by 4–40%. The largest change of daily

Table 1
ETo changes to each climatic variables' variation from 1950s to 2000s

	Tmean		Tmax		Tmin		RH		Wind		Sunshine hours		ETo	
	Change[*] amount, mm/d	Change percent, %	Change amount, mm/d	Change percent, %	Change amount, mm/d	Change percent, %	Change amount, mm/d	Change percent, %	Change amount, mm/d	Change percent, %	Change amount, mm/d	Change percent, %	Change amount, mm/d	Change percent, %
Jan	0.136	14.0	−0.004	−0.4	−0.009	−0.9	0.043	4.4	−0.076	−7.9	0.003	0.3	0.081	8.3
Feb	0.223	16.9	−0.008	−0.6	−0.010	−0.8	0.091	6.9	−0.038	−2.9	−0.009	−0.7	0.245	18.6
Mar	0.340	16.7	−0.013	−0.6	−0.011	−0.6	0.368	18.1	0.031	1.5	0.009	0.5	0.807	39.7
Apr	0.309	7.6	−0.005	−0.1	−0.015	−0.4	0.083	2.1	−0.059	−1.4	−0.093	−2.3	0.207	5.1
May	0.305	6.2	−0.007	−0.1	−0.015	−0.3	0.119	2.4	0.067	1.4	−0.084	−1.7	0.403	8.2
Jun	0.201	4.0	−0.003	−0.1	−0.011	−0.2	0.172	3.4	0.111	2.2	−0.003	−0.1	0.183	3.6
Jul	0.167	3.8	−0.004	−0.1	−0.006	−0.1	0.234	5.4	0.092	2.1	−0.340	−7.8	0.293	6.7
Aug	0.191	5.1	−0.005	−0.1	−0.007	−0.2	0.230	6.1	0.071	1.9	−0.172	−4.6	0.457	12.2
Sep	0.233	7.4	−0.006	−0.2	−0.015	−0.5	0.158	5.0	0.066	2.1	−0.006	−0.2	0.286	9.1
Oct	0.139	7.0	−0.003	−0.2	−0.011	−0.5	0.185	9.3	0.013	0.6	−0.048	−2.4	0.290	14.6
Nov	0.090	7.5	−0.004	−0.3	−0.006	−0.5	0.138	11.5	0.008	0.7	0.000	0.0	0.238	19.8
Dec	0.080	8.7	−0.002	−0.2	−0.007	−0.8	0.091	9.9	0.028	3.1	0.006	0.7	0.212	23.1
wheat season	0.217	8.6	−0.005	−0.2	−0.011	−0.4	0.135	5.4	0.007	0.3	−0.045	−1.8	0.308	12.3
corn season	0.193	4.5	−0.004	−0.1	−0.008	−0.2	0.204	4.7	0.080	1.9	−0.298	−6.9	0.258	6.0
annual	0.253	7.4	−0.005	−0.2	−0.010	−0.3	0.187	5.5	0.023	0.7	−0.104	−3.1	0.365	10.7

[*] "Change amount" in the ETo column indicates the difference in daily ETo between 1950s and 2000s, and those in other column is the variation of daily ETos caused by a special climatic variable from 1950s (1951–1959) to 2000s.

ETo was 0.807 mm d^{-1} in March, followed by May and August, whose increments were 0.403 and 0.457 mm d^{-1}, respectively. In half of the 12 months, the daily ETo increment was in the range of 0.20~0.30 mm d^{-1}. The least increment was 0.081 mm d^{-1} found in January. Mean daily ETo increased during the past 60 years by 0.308, 0.258, and 0.365 mm d^{-1}, with seasonal rates of 1.87, 1.57, and 2.22 mm y^{-1} in wheat season, corn season, and year base, respectively. A qualitatively similar increase of 1.3 mm d^{-1} for ETo was also found in this region by Tang et al. [15].

Among the six climatic variables, temperature and relative humidity were the first two key factors for ETo increase in the past 60 years, causing daily ETo increases by 7.4 and 5.7% at annual base, respectively. The third factor was sunshine hours, which caused daily ETo reduction by 3.1%. Wind speed, maximum and minimum temperatures had minor effects on ETo variation in the past 60 years. Generally, the key factors for ETo variations varied from place to place. For example, in Yunnan Province, southwest China, the variability of ETo rates is most sensitive to the variations of sunshine duration, followed by RH, maximum temperature, and wind speed [16]. In the whole Changjiang river catchment, ETo decreasing is mainly attributed to the significant decreasing trends in the net radiation and the wind speed [13]. Huo et al. found in the arid region of northwest China that, ETo variation is most sensitive to wind speed, followed by relative humidity, temperature, and radiation [17]. Under a desert in north of China where the deserts are dominated by dunes and low shrubs, ETo variation was controlled primarily by the available energy in summer and by wind speed in winter [25]. Tang et al. observed in the Haihe river basin of north China that, changes in ETo were firstly attributed to the variations in air temperature (1.7 mm y^{-1}), followed by wind speed (−1.3 mm y^{-1}), net radiation (−0.9 mm y^{-1}), and vapor pressure (−0.5 mm y^{-1}) [15]. Darshana et al. found in the Tons River Basin in central India that, maximum temperature and net solar radiation were the most dominant variables for ETo change [6].

The gradient of climatic variable effect on ETo in the wheat season was different than that in corn season. In the wheat season, ETo has increased by 12.3%, mainly because of mean temperature (8.6%) and relative humidity (5.4%). However, in the corn season, sunshine hours, relative humidity, and temperature caused ETo changes by –6.9, 4.7, and 4.5%, respectively. On a monthly base, climatic variables played different roles in ETo change. Under most months, mean temperature played the first important role for ETo change, followed by relative humidity, sunshine hours, and wind speed, and the less important factors were maximum and minimum temperatures, which was similar to the order of importance on yearly base. But in some months, the key factors for ETo change were different. For example, in March, August, October, November, and December, the first important factor was relative humidity, which caused ETo increase by 18.1, 6.1, 9.3, 11.5, and 9.9%, respectively. The first important factor in July was sunshine hours, which caused a reduction of ETo by 7.8%.

4. Conclusions

In Beijing city, an increased trend in ETo was found with a rate of 1.95 mm y^{-1} during the past 60 years. Sensitivity analysis showed that the mean air temperature and relative humidity in the past 60 years caused ETo increases by 7.4 and 5.5% at annual base, respectively. Further, sunshine hours increase caused ETo decrease by 3.1%. While wind speed, maximum and minimum temperatures variations had minor effect on ETo change during the past 60 years.

In wheat season, ETo has been increased by 12.3%, mainly because of changes in mean temperature (8.6%) and relative humidity (5.4%). But in the corn season, sunshine hours, relative humidity, and temperature caused ETo changes by –6.9, 4.7, and 4.5%, respectively.

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