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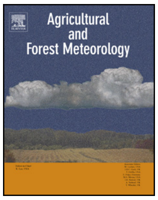

Spatiotemporal trends of reference evapotranspiration and its driving factors in the Beijing–Tianjin Sand Source Control Project Region, China

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ABSTRACT

In the water-limited Beijing–Tianjin Sand Source Control Project Region, reference evapotranspiration (ET_O) is a vital hydrological factor for the revegetation implementation, and its long-term variation is of much interest in climate change studies. In our study, temporal and spatial patterns in ET_O and related driving factors in the project region are evaluated for the period 1959–2011, based on daily data from 46 meteorological stations, using Mann–Kendall (M-K) test, Sen's slope estimator, and multivariate regression. The results indicated that annual ET_O had an insignificant decreasing trend in the study area, in which 15 stations showed significant negative trends and only 1 station showed significant positive trend at the 95% confidence level. Significant downward ET_O was detected in the north sub-region (I) in spring, in the west sub-region (II) in summer and autumn. Analysis of the impacts of meteorological variables on spatiotemporal trends of ET_O showed that wind speed was the most dominant factor affecting ET_O variation at 35 stations. Downward ET_O induced by decreased wind speed may be result from revegetation of Beijing–Tianjin Sand Source Control Project. In addition, ET_O change was influenced by sunshine duration in summer and maximum air temperature in winter. Better understanding ET_O response to climate change will enable efficient use of water resources and vegetation management, which could improve the ecological and environmental quality in Beijing, Tianjin, and the surrounding areas.

1. Introduction

Evapotranspiration (ET) plays an important role in the water and energy balance of terrestrial ecosystems (Jarvis and McNaughton, 1986; Wever et al., 2002), influencing closely related hydrological processes, such as soil moisture dynamics, groundwater recharge, and runoff generation (Xu and Singh, 2005; Zhang et al., 2011). In the context of global warming, understanding the link between ET and other biogeochemical processes allows the design of appropriate and reasonable water and vegetation management strategies in water-limited regions (Wever et al., 2002; Gavilan and Castillo-Llanque, 2009; Tabari et al., 2012b). Any change in meteorological variables, such as air temperature, humidity, wind speed, or solar radiation, will affect evapotranspiration and crop water requirements (Temesgen et al., 2005). Eventually, climate change will increase drought conditions by increasing potential evapotranspiration and aggravating land desertification in arid regions (Goyal, 2004). An in-depth understanding of spatiotemporal variations in evapotranspiration and accurate estimations of evapotranspiration response to climate change are essential for efficient use of water resources and vegetation management (Drogue et al., 2004; Chen et al., 2007; Han and Hu, 2012; Han et al., 2014), which can also serve as valuable reference data for regional studies of hydrological modeling, agricultural water requirements and irrigation planning.

Global mean surface air temperature rose by 0.74 °C from 1906 to 2005, which directly affected atmospheric water vapor content and circulation (IPCC, 2007; Jhajharia et al., 2012). Climate change has exerted significant impacts on eco-hydrological patterns (Porporato et al., 2002; Han et al., 2014), which in turn, affect evapotranspiration, causing a series of water resource problems (Li et al., 2007; McVicar et al., 2007), especially in arid and semi-arid regions. Although air temperature increased, ET decreased over the past 50 years in many parts of the world, e.g., United States (Lawrimore and Peterson, 2000; Hobbins, 2004; Burn and Hesch, 2007), Europe (Golubev et al., 2001), Australia (Roderick and

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Farquhar, 2004; Roderick et al., 2007), India (Chattopadhyay and Hulme, 1997; Bandyopadhayay et al., 2009), and China (Xu et al., 2006; Cong and Yang, 2008). This phenomenon has been denoted the evaporation paradox (Roderick and Farquhar, 2002), which has drawn much attention to reveal the cause of evapotranspiration changes (McVicar et al., 2008; Roderick et al., 2009a,b).

The FAO Penman–Monteith method for estimating reference evapotranspiration (ET_O), has gained wide acceptance and aroused the interest of researchers, planners and politicians (Ohmura and Martin, 2002; Oguntunde et al., 2006; Jia et al., 2009; Joshua et al., 2011). Potentially ET_O varations could be due to the confounding effects of changes in meteorological variables. Tabari et al. (2011) analyzed spatiotemporal variations of ET_O in arid and semiarid regions of Iran and revealed the main factor associated with decreasing ET_O was decreasing wind speed. Bandyopadhayay et al. (2009) reported that increases in relative humidity and decreases in radiation and wind speed could lead to decreasing ET_O in India. Irmak et al. (2012) found that ET_O reduction was caused by a significant decrease in solar radiation due to increased precipitation in the Platte River Basin, central Nebraska, USA. Liu et al. (2010) found that ET_O was more easily affected by solar radiation than other meteorological variables in the Yellow River basin, China. Wang et al. (2011) showed that wind speed and relative humidity were the main driving forces for decreasing ET_O in the Haihe River basin of China. However, increasing ET_O has also been proved in some other regions. Dinpashoh et al. (2011) witnessed statistically significant increasing and decreasing trends in ET_O at different sites in Iran. Milly and Dunne (2001) and Qian et al. (2007) found an increasing trend in ET_O for the Mississippi River basin. These research results suggest both positive and negative trends of ET_O variation, but controversy still exists. ET_O is determined by several principally meteorological parameters, not just changes in temperature, all of which have complicated spatial and temporal variations. The range of ET_O variations between climatic regions and in different combinations of meteorological variables may induce diverse trends under the influence of the same meteorological variables.

The Beijing–Tianjin Sand Source Control Project Region (BTSSCPR) is located in arid and semi-arid region of China, where land and vegetation degradation not only have strongly influenced regional agricultural production and human life, but also reduced environmental quality around Beijing and Tianjin. To reverse this kind of environmental degradation, the Chinese government launched the Beijing–Tianjin Sand Source Control Project in 2000, which has great strategic value as a regional ecological restoration project. Understanding mechanisms of spatiotemporal trends in ET_O under the influence of major meteorological factors can provide vitally scientific basis for future revegetation of desertified land and reasonable water resource management, which is strategically significant for socio-economic development, restoration of degraded ecosystems, and human welfare improvement in the project region.

In this study, the following objectives will be addressed: (1) the spatial distribution and temporal change of ET_O at annual and seasonal time scales were estimated in the BTSSCPR for the period 1959–2011 using the FAO Penman–Monteith (P-M) method; (2) the temporal trends of annual and seasonal ET_O series were detected with the Mann–Kendall test and Sen's slope estimator; (3) the spatial distribution of dominant meteorological variables that lead to ET_O changes was explored using multivariate regression.

2. Materials and methods

2.1. Study area

The BTSSCPR is located in northern China (36°49′–46°40′ N, 107°05′–119°20′ E) (Fig. 1), covers approximately 7.1×10^5 km^2 and includes Beijing, Tianjin, the northern parts of Hebei and Shanxi provinces, the central part of Inner Mongolia and a small part of Shan'xi Province. Plains, mountains, and plateaus are the main landform types. The western and southern parts are bordered by Yinshan Mountain and Yanshan Mountain, and the eastern part borders the Otindag sand land. The area has a typical temperate continental monsoon climate, characterized by hot and wet summers and cold and dry winters, dominated by arid and semi-arid conditions. The annual average temperature increases from east to west. However, the annual average precipitation decreases from 450 mm in the southeast to 150 mm in the northwest, of which more than 60% falls in the rainy season. The drainage system is divided into internal flow and outflow regional systems.

Table 1
Climatic characteristic of three sub-regions and the whole region.

Region	T_{max} (°)	T_{min} (°)	RH (%)	WS (m/s)	n (h)	ET_O (mm)
I	10.97	−2.12	54.03	2.38	2980.45	1031.86
II	15.07	1.82	52.52	1.87	3092.80	1110.80
III	13.92	1.53	56.88	1.97	2754.30	1000.68
Whole	12.90	0.02	54.55	2.12	2942.52	1042.96

Note: n indicated the annual average sunshine hours, which calculated based on daily data.

2.2. Data collection

Daily meteorological data were obtained for 46 stations in and around the BTSSCPR from 1959 to 2011. Variables used to estimate ET_O with the FAO Penman–Monteith equation were maximum air temperature (T_{max}, °C), minimum air temperature (T_{min}, °C), wind speed (WS, m/s), relative humidity (RH, %), and sunshine duration (n, h). Data were provided and quality controlled by the China Meteorological Administration (http://cdc.cma.gov.cn). Missing data were estimated from average values of other years observed at the same station. Locations of the stations are shown in Fig. 1 and climatic characteristics of the sub-regions are presented in Table 1. The study region was divided into the north sub-region (I), the west sub-region (II), and the south sub-region (III) to understand regional changes in ET_O. Annual and seasonal average values of potential evapotranspiration were then calculated from the daily measurements and used for the data analysis in this study.

2.3. FAO Penman–Monteith method for ET_O estimation

Owing to the difficulty of obtaining accurate field measurements, ET_O is commonly computed from weather data. The FAO Penman–Monteith method is the most reliable and universally accepted method to estimate ET_O under various types of climate and has been applied widely around the world (e.g. Yin et al., 2010; Jhajharia et al., 2012; Tabari et al., 2012a). In this study, the FAO Penman–Monteith method (Allen et al., 1998) for calculating daily ET_O can be expressed as:

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma(900/(T + 273))U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad (1)$$

where ET_O is the reference evapotranspiration (mm day^{-1}); R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}); G is the soil heat flux density (MJ m^{-2} day^{-1}); T is the mean daily air temperature at 2 m height (°C); U_2 is the wind speed at 2 m height (m/s); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa); $e_s - e_a$ is the saturation vapor pressure deficit (kPa); Δ is the slope of the vapor pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}) (Allen et al., 1998). In this study, ET_O was calculated using EToCalc software (Allen, 2000). Because soil heat flux is small compared with R_n, particularly when the surface is covered by vegetation, and because calculation time steps are