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Spatio-temporal variation of potential evapotranspiration and climatic drivers in the Jing-Jin-Ji region, North China

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ABSTRACT

Potential evapotranspiration (ET_0) is a key component of the water cycle and a main factor to water resources assessment. Analysis of variation in ET_0 is significant in understanding the climate change and agricultural water management; It is affected by multiple climatic factors, including air temperature, relative humidity, wind speed, and sunshine duration. To understand the variations of ET_0 in the Jing-Jin-Ji region (Beijing Municipality, Tianjin Municipality, and Hebei Province), values of ET_0 and other climatic parameters at 22 national meteorological stations from 1961 to 2015 were analyzed. Cramer's test showed a shift point in the ET_0 data at approximately 1991. Annual ET_0 decreased from 1961 through 1991 at a rate of −20.95 mm per decade, but annual ET_0 increased at a rate of 7.40 mm per decade from 1992 to 2015. Partial correlation analysis and multiple linear regression methods were used to determine the dominant climatic driving factors for ET_0, and to reveal the causes of change in ET_0. From 1961 to 1991, the decrease of wind speed and sunshine duration offset the effect of increased air temperature, leading to reduced ET_0. However, from 1992 to 2015, average air temperature was the most dominant factor contributing to the increase in ET_0. Increased of air temperature and wind speed, and decreased relative humidity caused an increase in ET_0. This change in ET_0 could impact hydrological cycle and agriculture irrigation management in the Jing-Jin-Ji region.

1. Introduction

Climate change has enormous environmental and socioeconomic implications. Many global issues potentially affected by climate change, such as food security, biodiversity loss and water scarcity, are affected by temperature, potential evapotranspiration, solar radiation and other factors together (Walther et al., 2002; Christensen et al., 2004; Zhao et al., 2014; Xu et al., 2017). Evapotranspiration, the only connection linking the water balance and land surface energy balance, is considered as a significant indicator for climate change and the water cycle (Tao et al., 2015). Due to lack of the observed evapotranspiration data, potential evapotranspiration is generally used to estimate the actual evapotranspiration, and is defined as the combined evaporation and transpiration by growing vegetation with access to an unlimited supply of water. ET_0 is influenced by incoming solar radiation, which provides the energy required to evaporate water, and also by wind, humidity and temperature (King et al., 2015). Trends in ET_0 directly affect regional and global water resources as part of the changing climate; analyzing trends in ET_0 can provide considerable insights into current climate change and its impact on water resources (Nam et al., 2015; Li et al., 2017). ET_0 is a main focus on water resource assessment, and also a foundation for the calculation of crop water requirements (Ma et al., 2012). Thus, the variation of ET_0 has been widely applied as valuable reference to assess agricultural water requirements, hydrological cycles, and ecological changes (Ning et al., 2016).

As the global climate becomes warmer and warmer, it is generally expected that the air will become drier. Evaporation from terrestrial water bodies will increase (Roderick and Farquhar, 2002). However, even as increasing air temperature has been observed over the last few decades, the pan evaporation or ET_0 has shown a steady downward trend; this is known as the 'evaporation paradox' phenomenon (Peterson et al., 1995). Decreased pan evaporation has been found in many locations, such as Italy, Australia, and New Zealand (Moonen et al. 2002; Roderick and Farquhar, 2005; Tabari and Marofi, 2010). Decreasing ET_0 has also been observed in the Haihe River basin (Ma et al., 2012), southwestern China (Li et al., 2014), northwest China (Xu

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et al., 2015), the Tibetan Platea (Zhang et al., 2007), the Loess Plateau (Ning et al., 2016) and many other regions of China (Tang et al., 2011; Ma et al., 2012; Zhu et al., 2012), but in recent years, increased pan evaporation or ET_0 has been identified in data since the 1980s in China. Cong et al. (2009) found that annual pan evaporation in China decreased from 1956 to 1985, related to decreasing daily maximum air temperature and wind speed. However, they also found that pan evaporation has increased since 1986, mainly due to an increasing vapor pressure deficit. Liu and Zhang (2013) investigated the ET_0 trends in the Northwest China from 1960 to 2010. ET_0 decreased from 1960 to 1993 mainly related to decreasing trends in wind speed, although it began to increase in 1994, mainly due to the increasing air temperature and wind speed. As changes in ET_0 differ greatly in different regions, it is essential to conduct regional research.

The Jing-Jin-Ji region (Beijing Municipality, Tianjin Municipality and Hebei Province), one of the three large regional economic communities in China, is located in semi-humid and semi-arid areas. Water resources are limited, but water demands have increased dramatically in this region, and there is a sharp conflict between urban growth and limited water resources (Dong et al., 2008). This region therefore has a large net water deficiency and faces a severe water shortage crisis. Agricultural irrigation is the largest water-consuming sector; data from 2003 to 2013 show that more than 70% of the supplied water in Hebei Province was consumed by agriculture. Agricultural water consumption accounted for 55% of the total water consumption in Tianjin Municipality, and approximately 33% of the consumption in Beijing Municipality (Fan et al., 2016). The rapid urbanization and economic development divert water from the agricultural sector to industrial and other sectors (Zhu et al., 2015), and agricultural water security and food security therefore face enormous pressure in the Jing-Jin-Ji region. Although water capacity in the Jing-Jin-Ji region may be improved after the South to North Water Transfer Project, the living standard might not to be improved because of the increasing population (Feng and Liu, 2006). ET_0 is the key component of water cycle, used for assessment of water deficiencies (Huang et al., 2014). Consequently, the analysis of ET_0 is an important indicator for understanding climate change, and also as a basis to improve water resource management.

The objectives of this study are: (1) to explore the spatio-temporal characteristics of ET_0 and climatic variables in the Jing-Jin-Ji region; (2) to identify the dominant climatic driving factors of ET_0; and (3) to reveal the reasons for changing ET_0 in the Jing-Jin-Ji region. The conclusions will improve the understanding of climate change, and provide valuable reference for regional water resources management and agriculture development.

2. Materials and methods

2.1. Study area

The Jing-Jin-Ji region (26°02´N–42°38´N, 113°25´–119°51´E) is part of the Haihe River basin, and is located in the northern part of the North China Plain (Fig. 1). The area consists of Beijing municipality, Tianjin municipality, and Hebei province, and has a total area of 213,600 km^2. Beijing is the capital city of China and has an area of 16,300 km^2. Tianjin is a municipality direct under the Central Government, as well as an expanding city with an area of 11,700 km^2. The area of Hebei province containing 11 major cities is 185,600 km^2 (Dong et al., 2008). There is a serious shortage of water resources in the region and a tremendous conflict between water supply and demand. This has resulted in severe environmental problems, including degradation of rivers and lakes, water pollution and land-surface subsidence due to over exploitation of groundwater (Xia et al., 2003).

2.2. Data source

We selected 22 meteorological stations in the Jing-Jin-Ji region for analysis of climatic parameters (Fig. 1). The climatic data from 1961 to 2015, including daily average air temperature (T_{mean}), minimum air temperature ($T_{\min}$), maximum air temperature ($T_{\max}$), relative humidity (RH), sunshine duration (SD), and wind speed (U_2), were downloaded from the National Climate Center, China Meteorological Administration (CMA) (http://data.cma.cn). These datasets are available and have been processed with quality control (Table 1).

2.3. Analytical methods

2.3.1. Calculation of ET_0

The Food and Agriculture Organization (FAO)56 Penman-Monteith (PM) model has been widely applied to calculate ET_0, and ET_0 at the 22 observation stations was calculated as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(900/(T_{mean} + 273))U_2\cdot(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{1}$$

where ET_0 is the daily reference ET rate (mm day^{-1}), R_n is the net radiation at the ground surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T_{mean} is the mean daily air temperature at 2 m height (°C), U_2 is the wind speed at 2 m height (m s^{-1}), 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 psychometric constant (kPa $°C^{-1}$).

Net radiation was estimated using the sunshine hours, maximum and minimum air temperatures data by following formulas:

$$R_n = R_{ns} - R_{nl} \tag{2}$$

$$R_{ns} = (1 - \alpha)R_s \tag{3}$$

$$R_s = \left(a_s + b_s\frac{n}{N}\right)R_a \tag{4}$$

$$R_a = \frac{24 \times 60}{\pi} \times G_{sc}\cdot d_r(\omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s) \tag{5}$$

where R_{ns} is the net short-wave radiation (MJ m^{-2} day^{-1}), α is the albedo coefficient, R_s is the incoming solar radiation(MJ m^{-2} day^{-1}), n is actual daily sunshine duration(h), which was measured in this study, N is the maximum possible duration of sunshine or daylight hours (h), R_a is the extraterrestrial radiation intensity (MJ m^{-2} day^{-1}), G_{sc} is solar constant (0.0820 MJ m^{-2} min^{-1}), d_r is inverse relative distance Earth-Sun, ω_s is sunset hour angle, ϕ is the station latitude, δ is solar declination. In this study, the coefficients α = 0.23, $a_s = 0.25$ and $b_s = 0.50$ following by the recommendation of the FAO (Allen et al., 1998).

R_{nl} is net outgoing long-wave radiation(MJ m^{-2} day^{-1}), and was estimated as:

$$R_{nl} = \sigma\left(\frac{T_{\max,K}^4 + T_{\min,K}^4}{2}\right)(0.34 - 0.14\sqrt{e_a})(1.35\frac{R_s}{R_{so}} - 0.35) \tag{6}$$

$$R_{so} = (0.75 + 2 \times 10^{-5}z)R_s \tag{7}$$

$$e_a = \frac{RH}{100}e_s \tag{8}$$

$$e_s = \frac{0.6108\exp[\frac{17.27T_{\max}}{T_{\max} + 237.3}] + 0.6108\exp[\frac{17.27T_{\min}}{T_{\min} + 237.3}]}{2} \tag{9}$$

where σ is the StefanBoltzman constant (4.903×10^{-9} MJ K^{-4} m^{-2} day^{-1}), $T_{\max,K}$ is maximum absolute temperature during the 24-h period (K), $T_{\min,K}$ is minimum absolute temperature during the 24-h period (K), R_{so} is clear-sky radiation (MJ m^{-2} day^{-1}), z is station elevation above sea level (m).

Soil heat flux density was calculated as :

$$G = c_s(T_i - T_{i-1})\Delta z, \tag{10}$$

where c_s is the soil heat capacity (2.1 MJ m^{-3} °C $^{-1}$), Δz is effective