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Biological factors dominate the interannual variability of evapotranspiration in an irrigated cropland in the North China Plain

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ABSTRACT

Understanding the interannual variability (IAV) and investigating the physical and biological controls on the IAV of evapotranspiration (ET) is fundamental for better simulating the hydrological processes in cropland where ET is the dominant component of water cycle. However, this topic has not been fully studied, although the number of long-term field observations is growing. By using a combination of long-term field observations (10 years) and agro-hydrological modelling, this study attempted to examine the IAV of ET and the physical and biological controls on the IAV of ET in an irrigated cropland in the North China Plain. This study reveals that the IAV of ET was only 7% in the selected dry subhumid area, which was much smaller than that of water supply (i.e., the sum of precipitation and irrigation). Moreover, the water supply was not the primary controlling factor that influenced the IAV of annual ET. Biological factors, including the leaf area index and bulk stomatal conductance, were found to be the dominant contributors to the IAV of annual ET. Irrigation was an essential water source for crop growth, particularly for winter wheat growth, whereas its contribution to the IAV of ET was smaller than that of precipitation because of the sufficient amount of irrigation. This study demonstrates that the variability of biological factors should be adequately represented in eco-hydrological models to accurately simulate the IAV of annual ET.

1. Introduction

Evapotranspiration (ET) plays an important role in the water balance of agroecosystems, especially in non-humid croplands (Sanford and Selnick, 2013). In managing agricultural water resources, the interannual variability (IAV) of ET is a critical measure of changes in water resource consumption, which is an important basis for irrigation scheduling. The controlling factors of ET are diverse, including climactic factors, in part through their influence on surface conductance (Monteith and Unsworth, 1990). Surface conductance in turn depends on biological factors such as the leaf area index (LAI) and stomatal conductance. Furthermore, these physical factors can be divided into those related to water supply (e.g., precipitation (PPT) and irrigation) and those related to atmospheric demand (e.g., radiation and air temperature) (Monteith, 1965). Therefore, identifying the sources of the IAV of ET and understanding the relative roles that climate and vegetation play in controlling the IAV of ET are critical for predicting how water balance will respond to future physical and biological perturbations.

Over the past three decades, the seasonal and diurnal variations in ET and its controlling factors have been widely reported thanks to the development of the Bowen ratio method and the eddy covariance technique (EC) (e.g., Bi, 2007; Gu et al., 2005; Qin et al., 2008; Hollinger et al., 1999; Vourlitis et al., 2005; Baldocchi, 2014). In contrast to the intra-annual variability, the IAV of ET and its driving mechanisms have received much less research attention, despite the fact that some study sites feature ET time series that are longer than a decade, and long-term EC flux measurements are currently being conducted (Baldocchi et al., 2016; Tsuruta et al., 2016; Chu et al., 2017). Among these long-term measurements, a few studies that have focused on the IAV of ET have shown that the variability in ET at this scale is controlled in a complicated manner. For example, the IAV of ET was shown to be predominantly controlled by the IAV of vegetation factors in some studies (Suzuki et al., 2007; Ryu et al., 2008), but more controlled by climate factors in other studies (Williams and Albertson, 2005). A more complicated study revealed that whether biological drivers dominated the IAV of ET depended on the vegetation types and water availability (Stoy et al., 2006). These studies indicate that the IAV of ET depends on climate, vegetation type and seasonality and may greatly differ from the variability in ET on diurnal and seasonal scales.

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In irrigated cropland, the water balance is affected by irrigation and cropping systems. In water-limited areas, the amount of irrigation water can even exceed the amount of PPT (Hu and Jia, 2015); thus, the effects of water stress from PPT deficits can be buffered by irrigation. Consequently, the mean annual ET (AET) generally equals a large fraction of or even exceeds the mean annual precipitation (MAP) (Hu and Jia, 2015; Liu and Feng, 2012). The North China Plain is characterized by a dry subhumid climate. Winter wheat and summer maize are the main crops in this area, and the productions of these two crops can reach up to 50% of their national totals (Jeong et al., 2014). This cropland is irrigated because wheat grows during the dry season (i.e., from October to May) during which PPT is only 157 ± 66 mm (± S.D.) (averaged during 1961–2012). Based on publications, seven flux tower sites are located in this plain in addition to our site (Li et al., 2010; Jia et al., 2012; Shen et al., 2013; Chen et al., 2015; Zhang et al., 2016a,b; Li et al., 2017). Although previous studies have analyzed the variability of ET in this area, none has focused on the long-term IAV of ET. In this study, we ask the following questions for the croplands in this plain. (1) What is the IAV of ET in this irrigated cropland? (2) How do the physical and biological factors determine the IAV of ET? (3) What role does irrigation play in controlling the IAV of ET?

Our previous study analyzed the seasonal and interannual variations in ET by using three-years (October 2005–September 2008) of data from an EC tower at an irrigated cropland in the North China Plain (Lei and Yang, 2010a). This same tower had been running for a 10-year period from 2005 to 2016. This 10-year measurement period covered episodes of extremely high to low annual PPT and higher air temperatures relative to the past 50 years (i.e., 1961–2012). Therefore, this dataset provides an opportunity to investigate the response of site-specific ET to climate variability and changes in crops over time in more detail.

2. Materials and methods

2.1. Site description

The Weishan flux site, which was established on 2005–03–18, is located in the central North China Plain. Here, the MAP is 605 ± 173 mm (± S.D.), and the mean annual temperature is 13.4 °C. The United Nations Environment Programme (UNEP) aridity index is 0.61, indicating that this site experiences a dry subhumid climate (the range of the aridity index for this climate type is 0.5–0.65, UNEP, 1997). Normally, the cropping system comprises winter wheat and summer maize, which are planted in rotation. The growing period of winter wheat generally occurs from mid-October to early June of the following year, and the growing period of summer maize generally occurs from mid-June to early October. Accordingly, the average lengths of the growing periods of wheat and maize are 229 days (among which approximately 100 days pass from the turning stage to the harvest stage) and 105 days, respectively. However, some exceptions occurred in the cropping system in portions of the farmland within the source area of the EC system during the study period. In the summer of 2010, sorghum was planted in a small portion of the cropland around the flux tower. In the 2012 summer maize season and the 2012–2013 winter wheat season, shorter-than-normal experimental varieties of maize and wheat were planted in the same plot. Irrigation is an indispensable water supply for crops, particularly for winter wheat. At this site, irrigation water was derived from the Yellow River via an irrigation channel. Thus, the irrigation timing was determined by both the water availability of the Yellow River and channel management, which produced an irregular irrigation timing. Normally, flood irrigation occurred approximately 2–4 times (i.e., early November, early March, early April, and mid-May) during the wheat growing season, and approximately once or twice times (i.e., in June before maize sowing, and in late July depending on the rainfall conditions) during the maize growing season. Irrigation amount used in each application was subjectively determined by the farmers but was approximately 60–120 mm.

2.2. Measurements

Meteorological data, including air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), wind speed (05103, Young Co., Traverse City, Ml. USA), and shortwave and longwave radiation (CNR-1, Kipp & Zonen, Delft, the Netherlands), were recorded at 10-min intervals. Soil moisture sensors (TRIME-EZ/IT, IMKO, Ettlingen, Germany) were embedded at depths of 5, 10, 20, 40, 80, and 160 cm, and two soil profiles were located to the east and west of the tower. A groundwater table sensor (CS420-10, Campbell Inc., Logan, UT, USA) was installed in a well under the tower.

The EC system was mounted at a height of 3.7 m above the ground. This system comprised a three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Inc., Logan, UT, USA) to measure the wind velocity and virtual temperature and a LI7500 open-path infrared gas analyzer (LI-COR, Inc., Lincoln, NE, USA) to measure the H_2O and CO_2 density. The slope between the available daily energy flux (net radiation minus soil heat flux) and the sum of the daily sensible and latent heat fluxes at this site was 0.77. Compared to previously reported ranges (Wilson et al., 2002; Li et al., 2005), the energy balance closure at our site was reasonable. Approximately 90% of the measured flux was expected to originate from the nearest 420 m during the wheat season and the nearest 166 m during the maize season. To supplement the ET flux observations, the daily soil evaporation was measured using four microlysimeters from March to June during the 2010 wheat season (Lei and Yang, 2014). This method was limited because the representativeness of the microlysimeter was much smaller than that of the EC method. Details regarding the observations at this site are provided in Lei and Yang (2010a,b).

2.3. Data acquisition and post-processing

Missing daily meteorological data (except for rainfall data) were gap-filled using meteorological data from nearby sites, depending on their data availability (i.e., the Chiping meteorological site (16.23 km, 36°35′, 116°13′) before 2013-01-01, and the Guduiwang irrigation site (30.16 km, 36°23′5.83″, 116°7′57.01″) after 2013-01-01). Furthermore, missing rainfall data before 2005-03-18 were gap-filled using data from the Chiping rain gauge (18.95 km, 36°35′, 116°15′), and missing data after 2005-03-18 were gap-filled using data from the Gaoying rain gauge (where the recorded data were almost identical to those at our site), which was located only 250 m from our flux tower. Most missing data occurred during the period before the setup of our tower and were used for model spin-up. The amount of irrigation in each application was estimated based on changes in the soil water storage in the two soil profiles (0–160 cm depth) within one day after an irrigation event. This estimation method was confirmed to be reasonable based on the results of two sampling measurements with a water meter (i.e., 100 and 80 mm from our method vs. 120 and 100 mm from the meter measurement, respectively). Although this method exhibited uncertainty when estimating the amount of irrigation, it ensured the time consistency of the irrigation data and allowed the estimated data to be used to examine the temporal variability.

LAI data were estimated using the remote sensing normalized difference vegetation index (NDVI), which was calculated using the MODIS reflectance product (MOD09Q1, 250 m and eight-day interval, which is the highest spatial resolution for NDVI calculations). The form of the relationship between the NDVI and LAI was obtained from Gitelson et al. (2007) and calibrated based on the observed LAI data which were obtained by directly measuring the area of leaves that were sampled from the field with an optical area meter at our site (Lei et al., 2013). The NDVI data in the pixel where the flux site was located were used, to match the source area of the EC system. Spikes were present in