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Multi-scale evapotranspiration of summer maize and the controlling meteorological factors in north China

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ABSTRACT

Evapotranspiration (*ET*) scale effect influences the understanding of water and energy balance processes at different scales. However, there are fewer studies about the relationships between multi-scale *ET* and the controlling meteorological factors. In this study, the variations in leaf and plant transpiration and farmland *ET* of summer maize were systematically analyzed using three-successive-year data from an irrigation experiment station in north China, and the meteorological factors affecting *ET* at different scales were analyzed based on multivariate regression. The main findings include (1) the transpiration rate (T_r) and stomatal conductance (g_s) of sun and shade leaves reduced with the reduction of photosynthetically active radiation (*PAR*), and the T_r and g_s in shade leaves were about half of sun leaves. When the differences in *PAR* were smaller, leaf T_r and g_s at lower part of canopy were slightly lower than those at middle and upper parts of canopy. (2) The sap flow rate (plant transpiration) of summer maize was related to the net radiation but lagged 1 h. (3) Diurnal variation in latent heat flux (λET) of summer maize was similar to that in net radiation but lagged slightly. λET, sensible heat flux and ground heat flux accounted for 66.9–70.7, 23.4–26.1 and 4.0–9.2% of net radiation over the whole growing period, respectively. The Bowen ratio ranged from 0.33 to 0.37 over the whole growing period, and peaked at around 10:00 a.m. (4) Leaf transpiration and farmland *ET* can be characterized by net radiation, air temperature, vapor pressure deficit and wind speed, but plant transpiration cannot be well characterized by them, possibly due to the change of stored water in the stalk.

1. Introduction

As evapotranspiration (*ET*) influences water and energy cycles, and *ET* at different scales is unavoidable in biological and farmland ecosystem, the variation characteristics of multi-scale *ET* and the controlling meteorological factors must be understood to help manage the *ET* measurement limit. Maize is one of the three major food crops in China, and its water consumption has been studied at the different scales: leaf (Wu et al., 2011; Yu et al., 2001, 2004), plant (Gao et al., 2013; Hou et al., 2014; Stockle and Jara, 1998), farmland (Fang et al., 2014; Hupet and Vanclooster, 2004; Lei and Yang, 2010), and region (Eichinger et al., 2006; Gonzalez-Dugo et al., 2009; Kalma et al., 2008). Leaf transpiration is mainly determined using photosynthesis system (Wu et al., 2011; Yu et al., 2001, 2004). Plant transpiration is mainly measured using heat balance method (Baker and Van Bavel, 1987; Gao et al., 2013; Hou et al., 2014; Sakuratani, 1981). Farmland *ET* is mainly evaluated using water-balance method (Jiang et al., 2014; Rana and Katerji, 2000), eddy covariance method (Gharsallah et al., 2013; Li et al., 2013), and Bowen ratio–energy balance method (Mastrorilli et al., 1998; Zhang et al., 2008; Zhao et al., 2010). The regional *ET* is mainly measured using water balance and remote sensing methods (Gonzalez-Dugo et al., 2009; Shu et al., 2011).

These researches show that transpiration and evapotranspiration are controlled by climate, vegetation and soil characteristics. Among them, the meteorological factors such as radiation, temperature, vapor pressure deficit and wind speed are the main controlling factors. Previous studies indicated that radiation is the major driving factor for leaf transpiration and farmland evapotranspiration (Albertoa et al., 2014; Irmak et al., 2008; Law et al., 2002; Zhang et al., 2011), and temperature and vapor pressure deficit also have important influence (Jarvis, 1976; Kelliher et al., 1995;

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Wang et al., 2001; Zhang et al., 2008, 2011). However, Zhuang et al. (2000) showed that saturation deficit within the plant canopy has higher correlation with the sap flow. And the overall increases in transpiration with increasing vapor pressure deficit were observed for the maize plants (Hirasawa and Hsiao, 1999; Hsiao, 1990; Ray et al., 2002). So there are some differences in evapotranspiration at different scales and most controlling meteorological factors.

However, there are fewer studies about the characteristics of multi-scale *ET* and the difference of the quantitative response of leaf and plant transpiration and farmland *ET* to the meteorological factors, which limit the understanding of agricultural water and energy cycles. In this study, the variations in leaf and plant transpiration and farmland *ET* of summer maize were systematically analyzed using three-successive-year data, and then the difference of quantitative response of leaf and plant transpiration and farmland *ET* to the meteorological factors was performed using path analysis method. The study is significant in the in-depth understanding of multi-scale evapotranspiration for summer maize and the controlling meteorological factors in north China.

2. Materials and methods

2.1. Experimental site

Field experiments were conducted during June to October in 2008–2010 at Irrigation Experiment Station of China Institute of Water Resources and Hydropower Research (IWHR) at Daxing in Beijing (latitude 39°37′ N, longitude 116°26′ E and 40.1 m a.s.l. elevation), about 15 ha. The station is located in a semiarid to sub-humid climate zone, with a mean annual sunshine duration of 2600 h, mean annual temperature of 12.1 °C, annual accumulated temperature (>10 °C) of 4730 °C, mean frost-free days of 185 d, mean annual precipitation of 540 mm and mean annual evaporation from a free water surface of 1800 mm. An automatic weather station (Monitor Sensors, Caboolture QLD, Australia), located in the experimental station, provided the measurements of solar radiation, air temperature, relative humidity and wind speed at 2 m height, and precipitation measurements were performed above green grass. Data were recorded every 30 min. The climatic characterization relative to the experimental seasons is presented in Table 1.

The experimental maize field is 200 m in length and 200 m in width, and maize is the major crop in the surrounding farmland. The soil texture in the experimental area is a silt loam formed from loess deposits, with field capacity of 0.31–0.35 $m^3\ m^{-3}$ and wilting point of 0.10–0.16 $m^3\ m^{-3}$, respectively, averaging 0.334 and 0.128 $m^3\ m^{-3}$ in 1 m soil depth, respectively. And the details could be referred to Zhang et al. (2013). The total nitrogen application rate was about 245 kg N ha^{-1}.

2.2. Measurements

2.2.1. Leaf transpiration and stomatal conductance

An Li-6400 photosynthesis system (Li-COR, USA) was used to measure leaf transpiration rate (T_r), stomatal conductance (g_s) and photosynthetically active radiation (*PAR*) at the intervals of 10–15 d during the growing season, and the measurement was made five times and six times in 2008–2009, respectively. For each measurement, the measured leaves were kept perpendicular to the sun's rays and three leaves from the top, middle and lower parts of the canopy in each plant, and eight plants were selected, and these measurements were taken within 35 min to avoid the larger changes in the weather conditions. Measurements were made to represent the top, middle and lower leaves of the canopy. Hourly readings were taken from 8:00 to 16:00.

Moreover, in 2010, the transpiration rate (T_r), stomatal conductance (g_s) and photosynthetically active radiation (*PAR*) of sunlit and shaded leaves at the top, middle and lower parts of the canopy were measured using Li-6400 photosynthesis system under natural orientation. For each measurement, three sunlit leaves and three shaded leaves from the top, middle and lower parts of the canopy in each plant, and two plants were selected, and these measurements were taken in 35 min to avoid the larger changes in the weather conditions. Two-hourly readings were taken from 8:00 to 16:00.

2.2.2. Sap flow rate

Sap flow rates of maize were measured using the heat balance method. The SGB-25M sensors of sap flow (Dynamax Inc., USA) were installed on the second internode above the ground of the representative plants of maize after the jointing stage of maize. The sap flow rate was measured once every 30 min. And the detail description could be referred to Gao et al. (2013).

2.2.3. Farmland evapotranspiration

An open-path eddy covariance (EC) system (Campbell Scientific Inc., USA) was used to measure the actual evapotranspiration, installed near the south side of central maize filed to provide adequate fetch length because the dominant wind was northwest direction. The EC system consisted of a 3D sonic anemometer/thermometer (model CSAT3), a Krypton hygrometer (model KH20) and a temperature and humidity sensor (model HMP45C), a net radiometer (model CNR4) and two heat flux plates (model HFP01). The 3D sonic anemometer/thermometer and Krypton hygrometer measured vertical fluctuations of wind, temperature

Table 1
Weather course during the whole growing season of summer maize in 2008–2010.

Year	Meteorological factors	Late June	July	August	September	Early October	Growing season
2008	Solar radiation (W/m^2)	–	188.94	181.72	166.58	122.11	188.94
	Air temperature (°C)	–	25.77	24.68	19.24	14.19	25.77
	Relative humidity (%)	–	77.07	–	75.77	78.13	77.07
	Wind speed (m/s)	–	1.07	–	0.68	0.74	1.07
	Rainfall (mm)	–	62.8	70.8	123.4	24.6	281.6
2009	Solar radiation (W/m^2)	219.50	205.27	181.77	143.08	201.78	219.50
	Air temperature (°C)	25.86	25.51	23.74	19.24	19.34	25.86
	Relative humidity (%)	50.29	72.28	80.17	74.95	51.61	50.29
	Wind speed (m/s)	1.36	1.03	0.59	0.64	0.85	1.36
	Rainfall (mm)	15.0	205.2	103.2	21.4	0.2	345.0
2010	Solar radiation (W/m^2)	181.92	181.18	187.55	164.92	171.29	181.92
	Air temperature (°C)	24.75	26.81	24.75	19.14	16.01	24.75
	Relative humidity (%)	65.94	70.91	73.37	72.05	65.40	65.94
	Wind speed (m/s)	1.06	1.09	0.72	0.61	0.88	1.06
	Rainfall (mm)	0.2	35.0	140.6	69.4	13.6	258.8