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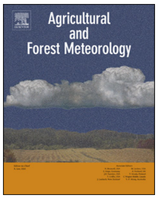

Parametrization of aerodynamic and canopy resistances for modeling evapotranspiration of greenhouse cucumber

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ABSTRACT

Estimating the latent heat flux accurately is important to improve greenhouse crops irrigation schedules. Aerodynamic and canopy resistances, as two key parameters in the Bulk transfer equations, are already difficult to measure in the open field and even more in greenhouses. In this study, an experiment was conducted in a Venlo-type cucumber greenhouse where meteorological data and the latent heat flux were measured with lysimeters. Two methods: (1) Inversing Bulk Transfer equation (IBTE-method) and (2) Appling a convective heat transfer coefficient (CHTC-method), were used to evaluate the aerodynamic resistance. A fixed aerodynamic resistance (= 35 s m^{-1}) was decided by analyzing the sensitivity of heat fluxes to its changes. The reproduced sensible and latent heat flux were compared to the measured values and the good agreements between measured and estimated values were obtained. The variation of daily canopy resistance which was calculated by IBTE-method was simulated by days after transplanting of cucumber plants and net radiation inside the greenhouse. Quadratic polynomial equations between canopy resistance and days after transplant were obtained, and were integrated into the Bulk transfer equation to predict the latent heat flux. The comparing of the measured and estimated latent heat flux showed that the Bulk transfer equation integrating the fixed aerodynamic resistance and canopy resistance sub-model could be used to predict the latent heat flux of greenhouse cucumber with the index of agreement higher than 0.8.

1. Introduction

The latent heat flux (*LE*) is an important component of the ecosystem energy balance and is strongly related to gross ecosystem production in vegetation (Law et al., 2002; Green et al., 1984). Knowing *LE* is a key issue to understand and improve the climatic conditions of plants in both the open field and greenhouse cultivation (Takakura et al., 2009). A better understanding of *LE* can help to investigate if irrigation can be improved and available water can be used more productively (Kite, 2000; Zhao et al., 2013; Yin et al., 2018; Nie et al., 2017). Due to the fast development of greenhouse crop production culture all around the globe, there is an urgent need for more information on greenhouse *LE*. Venlo-type greenhouses facilized with automatic environmental control systems have widely distributed all over the world (Xu et al., 2013). Many methods to estimate *LE* have been developed for open fields over the past 50 years (Allen et al., 1998; Katerji and Rana, 2006; Li et al., 2014; Yan et al., 2015a,b,c; Yan et al., 2017). Among them, the Penman-Monteith (PM) model and the Bulk Transfer equation are primarily used in greenhouse horticulture. The PM model was primarily developed for open field conditions by assuming homogeneity of both the thermodynamic conditions within the canopy and the air above the plants (Morille et al., 2013). Also, due to the differences in greenhouse type (Venlo-type glasses or plastic greenhouses) and ventilations system (automatic or force ventilation systems), the models and parameters applied in greenhouses showed quite different uncertainty (Kreith, 1965; Fujii et al., 1973; Stanghellini, 1987).

The FAO-56 (Allen et al., 1998) recommended to calculate *LE* by multiplying a reference evapotranspiration (ET_0) with a crop coefficient (K_c). The FAO-56 PM model is considered as a standard procedure for the estimation of ET_0 in the open fields (Payero and Irmak, 2013; Qiu et al., 2011; Luo et al., 2012). However, the limitation of its application

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in greenhouses is the determination of the aerodynamic resistance term due to the low wind speed (u_2) and non-logarithmic wind profile in the greenhouse. Assuming the wind speed equal to 0 might yield significant difference in calculating the *LE*.

The Bulk Transfer model links *LE* to the canopy surface to air vapour pressure deficit (VPD) and can be expressed as

$$LET = \frac{c_p \rho [e_*(T_s) - e_a]}{\gamma (r_a + r_c)} \tag{1}$$

where *LE* is latent heat flux (W m^{-2}), c_p is the specific heat of air (= 1.0 kJ kg^{-1} K), ρ is the density of air (= 1.225 kg m^{-3}), r_a is the aerodynamic resistance (s m^{-1}) and r_c is the canopy resistance (s m^{-1}), which consists of cucumber canopy resistance and soil surface resistance. T_s is the surface temperature of the cucumber field (°C), *i.e.* the surface temperature of the cucumber canopy and soil surface, it was determined by taking the average of canopy and soil surface temperature measurements, $e_*(T_s)$ is the saturated vapor pressure (kPa) at T_s and e_a is air vapor pressure (kPa).

To apply the Bulk Transfer model, the aerodynamic resistance (r_a) and canopy resistance (r_c) should be known. Often, they are estimated through their relationships with environmental variables. Generally, the r_a was determined by a logarithmic profile of wind speed which descripted the turbulent transfer of water vapour between the canopy surface and the atmosphere (Brutsaert, 1982). However, due to the quite low wind speed (close to 0) inside the greenhouse, r_a tends to infinity, so, this method may not suitable for greenhouses (Qiu et al., 2013). Many researchers tried to solve this using a convective heat transfer coefficient (CHTC-method) for individual leaves to calculate the r_a for greenhouse planting (Morille et al., 2013; Gong et al., 2017). But some researchers showed that under similar conditions, differences in calculated r_a occurred with the CHTC-method due to the difficulties in estimating the CHTC (Kreith, 1965; Fujii et al., 1973; Stanghellini, 1987). Also, the modeling of r_c is difficult for greenhouses. Hourly variation of r_c has been related to solar radiation, air temperature and humidity, VPD and soil water content (Stanghellini, 1987; Jarvis, 1976; Yan and Oue, 2011). Many researchers showed that solar radiation is the most correlated factor to canopy resistance (Bailey et al., 1993; Montero et al., 2001; Rouphael and Colla, 2004). Most researchers modeled r_c with different meteorological data based on their local climate conditions and focused on the open fields. For example, Jarvis (1976) modeled r_c with radiation and VPD by scaling up stomatal resistance to canopy resistance, however, the scaling up requires detailed porometry and leaf area data, also, due to different climatic conditions in comparison to greenhouse, the relevance of those empirical models needs to be validated. Some researchers (Rouphael and Colla, 2004; Qiu et al., 2013) demonstrated that r_c could be directly estimated using the relationships with different meteorological data for zucchini and hot pepper, however, the results among the researches showed big differences due to the differences in crop types and greenhouse climatic conditions.

Another method for determining the r_c and r_a is through simultaneous measurements of *LE* by lysimeter data and net radiation measurements. One can then calculate r_c and r_a by combining Eq. (1) with the energy balance equation (Eq. (2)) and the expression for sensible heat flux (Eq. (3)):

$$R_n = LET + H + G \tag{2}$$

$$H = \frac{c_p \rho (T_s - T_a)}{r_a} \tag{3}$$

where *H* is sensible heat flux (W m^{-2}), R_n is net radiation (W m^{-2}), *G* is soil heat flux (W m^{-2}). This method is called the “Inversing Bulk Transfer equation” (IBTE-method).

The study of r_c and r_a based on actual measurement of *LE* under greenhouse conditions is scarce. Accordingly, in this study, we calculated the variations of hourly and daily r_a and r_c based on the measured *LE* of cucumber by lysimeters and meteorological data with the Bulk transfer and energy balance equations; by analyzing the values of r_a from different methods, determined the characteristic value of r_a for the greenhouse condition. We analyzed the sensitivity of sensible and latent heat flux to the change of r_a; modeled daily values of r_c with days after transplant and net radiation inside the greenhouse and validated it with actual measurement of *LE* by lysimeters.

2. Material and method

2.1. Field observation

The experiment was conducted at a Venlo-Type greenhouse located in the Jiangsu province, China (31°56′N, 119°10′E, 23 m a.s.l) from April to July in 2015 and 2016. The experimental site is in a humid subtropical monsoon climatic zone with an average annual air temperature of 15.5 °C and a mean annual precipitation (rainfall) of 1058.8 mm y^{-1}. The rectangular greenhouse structure has an area of 32 m long × 20 m wide in horizontal dimensions, 3.8 m high with the longer side in an east-west orientation, which is the prevailing wind direction. The greenhouse was passively ventilated by opening side panels and roof vents for the exchange of hot exhaust air from the inside of the greenhouse to the outside. The heating system of the greenhouse was not switched on. The planting medium used in the greenhouse was a soil-biochar mixture with mean bulk density of 1.266 g/cm^3, field capacity of 0.408 cm^3/cm^3 and wilting-point water content of 0.16 cm^3/cm^3 in the depth of 0–30 cm. Cucumbers were transplanted into the soil troughs (0.65 m in width × 16.7 m in length) on 27th April 2015, and 3rd May 2016, with plant density equal to 6.63 per m^2. There was an aisle between two troughs and the distance between two troughs was 0.85 m. Seedlings were sowed 30 days before transplanting. To measure the latent heat flux (*LE*) of cucumbers inside the greenhouse, 3 cucumber plants were transplanted into 3 lysimeters (30 cm in diameter and 50 cm in depth). The lysimeters were placed in the greenhouse with similar density as the plants in the soil troughs. *LE* was measured by three accurate balances (accuracy = 1 g, METTLER TOLEDO, Switzerland) by weighing the decrease of the weight of the lysimeters with cucumbers. The lysimeter data were sampled every 10 s, averaged over 10 min and recorded on a data logger CR1000-NB (Campbell, USA). For a better establishment and to ensure seeding growth, the transplanted seedlings were immediately irrigated with the same volume of water (25 mm). Thereafter, the plants were watered by drip irrigation and the spatial interval of the emitters in each drip tape was 0.35 m. The designed discharge rate of each drip tape was 100 ml/min. Drip surface irrigation application was initiated 3 days after transplanting together with 200 ppm NPK fertilizer solution with concentration 25% N, 5% of P_2O_5 and 5% of K_2O applied directly to the cucumber plants. The different irrigation water treatments (total irrigation water: Treatment 1 (T1) = 330 mm, Treatment 2 (T2) = 270 mm, Treatment 3 (T3) = 203 mm) were applied every 2–3 days by three drip irrigation systems during the observation period (13th May to 12th July).

The net radiation inside the greenhouse was measured with a NR Lite 2 (Kipp & Zonen, the Netherlands) at 2.5 m above the canopy surface. Soil heat flux was measured at 2 cm depth with a soil heat plate HFP01-L10 (Campbell, USA). Soil water content and soil temperature at 5–10 cm were measured with Hydra Probe sensors (Stevens, USA). The canopy and soil surface temperatures were measured by two infrared thermometers SI-111 (Campbell, USA). The air temperature and relative humidity inside the greenhouse were measured both at 1.20 m and at 2.90 m heights from the ground level, respectively. Humidity and temperature sensors HMP155 (Vaisala, Finland) were used for the measurements. The low wind speed inside the greenhouse was measured using a two-dimensional wind speed sensor 1405-PK-021(Gill, England). All the meteorological data were sampled every 10 s, averaged over 10 min and recorded on a data logger CR1000-NB (Campbell,