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.

Dear Dr. Vesala，

In your letter dated, 11 June 2018, you sent us the reviewers' comments on our paper, entitled, Parametrization of aerodynamic and canopy resistances for modeling evapotranspiration of greenhouse cucumber. We revised our manuscript according to the suggestions of the reviewers and resubmitted it through the online system. Please find our responses to the reviewers in the attachments.

We thank you for the opportunity to resubmit our manuscript to Agricultural and Forest Meteorology and hope that it is now suitable for publication. We look forward to hearing from you at your earliest convenience.

Yours sincerely,

***Response to Reviewers**

We are grateful to the reviewers the critical comments and useful suggestions that have helped us to improve our paper considerably. As indicated in the responses that follow, we have taken all these comments and suggestions into account in the revised version of our paper.

Reviewers' comments:

Reviewer #1: The manuscript entitled "Parameterization of aerodynamic and canopy resistances for modeling evapotranspiration of greenhouse cucumber" provides a parameterization for the aerodynamic resistance to the heat and water vapour transfer (ra) and for the canopy resistance (rc) of cucumber under greenhouse conditions. These resistances are used into the Penman-Monteith model to estimate the crop evapotranspiration under greenhouse conditions. This manuscript discusses an important theme for the management of irrigation in a protected environment and seeks to advance the understanding of the relations of water vapour exchanges between vegetation and the atmosphere in greenhouse conditions. It was well organized, and the content was within the scope of the AFM Journal, recommended to accept after moderate revision.

Specific comments:

1.Comparing the ra estimate by heat and mass transfer by convection with other studies, explain the reason for the differences. (see Zhang and Lemeur 1992, Zolnier et al., 2004 and Takakura et al., 2005)

Response:

Thank you for your comments. We compared the ra results estimated by heat and mass transfer by convection with other studies as shown in the manuscript (Page 12, line 1). We also added the possible reasons for the differences in ra results.

2. In the Penman-Monteih FAO56 method (Allen et al., 1998), the ra is parameterized for the hypothetical culture, considering the logarithm profile of the wind. In a greenhouse environment, the vertical wind profile differs from that predicted by the wind log law (applied only in the open field) and low wind speeds are observed. Thus, the ra = 208 / u2 ratio for low wind speeds results in high and inconsistent ra values.

An alternative in protected environment conditions is to use the proposed parameterization proposed by McNaughton & Jarvis (1983), considering rs = 70 s m-1, as suggested by FAO56.

Allen RG, Pereira LS, Raes D & Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. Roma, FAO, Irrigation and Drainage Paper 56. 300p.

McNaughton KG & Jarvis PG (1983) Predicting effects of vegetation changes on transpiration and evaporation. In: Kozlowski TT (Ed.), Water deficits and plant growth, vol. VII. New York, Academic Press. p.1-47

Explain why the FAO-56 recommended crop coefficient method was not applied for determination crop evapotranspiration in greenhouses condition.

Response:

Thank you for your comments. Yes, as you commented that in a greenhouse environment, the vertical wind profile differs from that predicted by the wind log law (applied only in the open field) and low wind speeds are observed. Hence, the results and the proposed ra methods by FAO-56 were not suitable in the greenhouse condition.

For the crop coefficient method which is widely applied in the open field, the reference evapotranspiration needs to be determined accurately, since the famous Penman-Monteith equation (for calculating ET0) could not be directly applied in the greenhouse any more, this will lead to the difficulties of determination of the crop coefficients for greenhouse crops. The related explanations on this could be found in Page 3 line 19.

3. Keywords: Delete modeling, which is repeated in the title.

Response:

Thank you for your comments, we have deleted the keyword.

4. Introduction: The problem of estimating the aerodynamic resistance (ra) in greenhouse is not only the low wind speed, but also that in this condition the logarithmic law of the wind it's not applied. The structure of the greenhouse produces turbulence related to its interaction with the flow, which is not predicted by the log profile of the wind. Under these conditions, eqs. (free and forced convection) are applied (see Zhang and Lemeur 1992; Zolnier et al., 2004; Takakura et al., 2005) to estimate ra. Better contextualize the problem.

Response:

Thank you for your comments, the problem on the difficulties in estimating ra in greenhouse are presented in page 3 line 15 and page 4 line 14.

5. Page 4 Line 24: add more references to explain how the rc was modeled and what is the difficulties.

Response:

Thank you for your comments, we have added more references to explain the difficulties on estimating rc. Page 5 line 6.

6. Material and methods:

Page 6: It is not clear if cucumber are planted directly into the soil or in buckets, or even of all the plants are in a bucket or only the weighted ones.

Response:

Thank you for your comments, in this study, we planted the cucumber plants both in field and buckets, 3 buckets were used for the lysimeter measurements. Page 6 line 14-18.

Page 6: The size of the lysimeters was 30 cm in diameter and 50 cm in depth, is this size enough for the irrigation water moving in the vertical and horizon directions? And how about the cucumber plants density in the lysimeter? Is it the same as field?

Response:

Thank you for your comments, since we applied drip irrigation and based on our calculation and observation, the size of the buckets is enough for the irrigation water movements at both vertical and horizon directions.

The explanation of cucumber density can be found in Page 6 line 20.

Page 7: Please specify the crop height. Climatic measurement occurs at 2.5 m but no info is given about the vertical space between crop top and sensors.

Response:

Thank you for your comments, the information about crop height can be found in Page 8 line 8, the sensors were placed at top of the plants canopy.

Page 7: What is the reason for applying different irrigation schedules?

Response:

Thank you for your comments, the reason for applying different irrigation treatments was to find the difference of LE among the treatments and the influence of irrigation amount on the plants growth.

Page 7: Please provide details of the instruments that compose the weather station that carried out the measurements inside the greenhouse.

Response:

Thank you for your comments, the detailed information of instruments can be found in Page 7 line 16.

7. For the ET0 calculation, PM-FAO56 was parameterized considering ra and the radiation balance in open environment. Thus, without proper modifications, it should not be used in a protected environment. Even though, by parameterization from FAO56, at low wind speeds ra tends to infinity and ETo to high values.

Response:

Thank you for your comments, in this study, the calculation of ET0 was just used for the comparison between greenhouse and outside, we assumed that wind speed equaled 0 for the calculation. Page 11, line18.

8. Results

The determination of ra and rc by inversion of sensible and latent heat flux often returns negative values. What was done with the negative values? Have they been disregarded since they are physically inconsistent?

Response:

Thank you for your comments, as you commented that sometimes there are negative values for ra and rc if we based on the hourly data. The calculation based on daily data did not show much negative values as we described in Page 12 line 11.

Reviewer #2: The goal of the submitted paper is original and I consider that this paper can be published with minor revisions, given that the well methodology employed to measure meteorological data and the latent heat flux by using lysimeters.

Minor revisions:

1. Introduction: a brief paragraph should be added to explain the importance of greenhouse crops in the world. That paragraph should include an explication about the different type of greenhouses, and a justification for the Venlo-type election in the performed study.

Response:

Thank you for your comments, we have added the description on the importance of greenhouse crops. Page 3 line 6 and line 15.

2. Conclusion: Lines from 13 - 24 should be removed since those are a summary of the study and not experimental conclusions.

Response:

Thank you for your comments. We summarized the study with one sentence to allow readers to understand the whole context easily.

Highlights

- A method to estimate aerodynamic resistance of greenhouse was presented.
- Latent heat flux of greenhouse cucumber was estimated with Bulk transfer equation.
- Canopy resistance was modeled with days after transplanting and net radiation.

Running title: Modeling evapotranspiration of greenhouse cucumber

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

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<u>Novelty statement:</u>

In general, aerodynamic resistance and canopy resistance are difficult to estimate, especially in greenhouse where wind speed equals 0 m s^{-1}. In this paper, we present a method to estimate aerodynamic in greenhouse by comparing the Bulk transfer equation and Convective heat coefficient method to predict the latent heat flux. The canopy resistance was modeled with days after transplanting and net radiation. The estimated the latent heat flux of greenhouse cucumber was compared with measured values by lysimeters.

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.

Keywords: latent heat flux, sensible heat flux, Bulk transfer equation, days after transplanting

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., 2015 *a*, *b*; 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 (Kreth, 1956; 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 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

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

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 (℃), *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 (Kreth, 1956; 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; Tuzet et al., 2003; Yan et al., 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 et al., 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 sub-tropical monsoon climatic zone with an average annual air temperature of 15.5^{o}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 = 1g, 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, USA).

The leaf area and plant height of cucumber plants were measured at an interval of 5-14 days. The leaf length (L) and the highest leaf width (W_L) were measured with a measuring tape, and the conversion coefficient of 0.65 for the leaf area was derived from fitting the measured results to the one drawn using CAD software (Liu et al., 2009). In this study, the measured maximum plant height and leaf area index were 1.8 m and 4.2, respectively.

Outside the greenhouse, the elements of radiation balance were measured: incoming shortwave (R_s), down and upwelling longwave radiation were measured with a CNR-4 (Kipp & Zonen, the Netherlands) at 2.5 m above the canopy. The net radiation (R_n = (1 – α) R_s + L_d – L_u) was calculated. Here, R_s is the global solar radiation (W m^{-2}), α is the albedo of the ground surface, L_d is the downward long wave radiation from the atmosphere and L_u is the upward long wave radiation from the ground (W m^{-2}). Air temperature (T_a) and relative humidity above the canopy were measured with thermohygrometer HMP155A (Vaisala, Finland). Wind speed was measured with three three-cup anemometers A100L2 (MetOne, USA) at the same height as T_a. Rainfall was measured with TE525MM (Campbell, USA). All the data were sampled every 10 s, averaged over10 min and recorded on a data logger CR3000-NB (Campbell, USA).

2.2 Aerodynamic resistance and canopy resistance

To calculate the resistances r_c and r_a, we use the IBTE-method and the r_a was also determined with the CHTC-method for comparison. The IBTE-method estimates r_a by inverting Eq. (3) with measured T_s and T_a and estimated H by Eq. (2) as

$$r_a = \frac{c_p \rho (T_s - T_a)}{R_n - LE - G} \tag{4}$$

While r_c can be estimated by inverting Eq. (1) with measured LE, $e_*(T_s)$, e_a and calculated r_a as

$$r_c = \frac{c_p \rho [e_*(T_s) - e_a]}{\gamma LE} - r_a \tag{5}$$

As a comparison r_a was also calculated with CHTC-method as (Zhang and Lemeur, 1992; Morille et al., 2013; Gong et al., 2017)

$$r_a = \frac{\rho c_p}{h_s} \tag{6}$$

where 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}), h_s is the heat exchange coefficient (W m^{-2} K^{-1}) expressed as a function of the Nusselt number (N_u) according to the flat plate theory. The convection can be analyzed by using non-dimensional groups, such as the Reynolds (Re), the Grashof number (Gr), and the Nusselt number (Nu). The details about how to analyze the convection can be found in Appendix 1.

The correlations between r_c and meteorological data were analyzed, and the days after transplanting (*DAT*) was used to simulate r_c with a polynomial relationship. The polynomial relationship between r_c and *DAT* was integrated to the Bulk transfer equation, the actual measurement of *LE* by lysimeter was used to validate the fixed r_a value and constructed r_c model.

Statistical analysis

Statistical indices Root Mean Square error (RMSE), Systematic Root Mean Square error (MSEs), Unsystematic Root Mean Square error (MSE_u), and Index of Agreement (d) (Willmott, 1981), were calculated for validating the accuracy of the constructed model:

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (P_i - M_i)^2 \right]^{1/2} \tag{7}$$

$$MSE_s = \left[\frac{1}{n} \sum_{i=1}^{n} (\hat{P}_i - M_i)^2 \right]^{1/2} \tag{8}$$

$$MSE_u = \left[\frac{1}{n} \sum_{i=1}^{n} (\hat{P}_i - P_i)^2 \right]^{1/2} \tag{9}$$

$$d = 1 - \left[\frac{n \cdot RMSE^2}{\sum_{i=1}^{n} \left(\left(\left|P_i - \overline{M}\right| + \left|M_i - \overline{M}\right| \right)^2 \right)} \right] \tag{10}$$

where P_i and M_i are estimated and measured hourly *LE*, i is the sample number, i =1, 2….n, $\overline{M}$ is the average measured hourly *LE*. $\hat{P}$ is the estimated hourly *LE* from least square regression. The MSE_s estimates the model's linear (or systematic) error; hence, the better the regression between estimations and observations, the smaller the systematic error. The unsystematic difference is a measure of how much of the discrepancy between estimations and observations is due to random processes or influences outside the legitimate range of the model. A good model will provide low values of the *RMSE*, explaining most of the variation in the observations. The systematic error should approach zero and the unsystematic error should approach *RMSE*. The index of agreement is a measure of the match between the departure of each prediction from the observed mean and the departure of each observation from the observed mean (Yan et al., 2015*b*).

3. Results

3.1 Meteorological data inside and outside the greenhouse and soil moisture variations under different irrigation water treatments

The observed meteorological data inside and outside the greenhouse and soil moisture variations during cucumber growing season in 2015 are shown in Fig.1. The air temperature (T_a) and relative humidity (RH) inside the greenhouse during 27 April to 23 July, the first day after transplanting to final harvesting day, ranged from 13.1 to 42.6 °C and 26.4% to 100%, with average values equaled to 25.3 °C and 78.9%, respectively; while the T_a and RH outside the greenhouse ranged from 12.1 to 33.6 °C and 26.8% to 99% at the same time period, with an average value equaled to 22.9 °C and 79.1%, respectively. On average, the T_a difference inside and outside the greenhouse was around 2-3 °C, while the difference in RH was very small. The wind speed inside the greenhouse was very low and close to 0, while the variation of wind speed outside the greenhouse ranged from 0.2 to 7.7 m s^{-1}. Figure 1 (*b*) showed the variation of net radiation (R_n) inside and outside the greenhouse. The daily R_n inside the greenhouse ranged from -39.9 to 586.6 W m^{-2}, with an average value equaled 42.9 W m^{-2}, while the R_n outside the greenhouse ranged from -90.85 to 721.7 W m^{-2}, with an average value equaled 101.6 W m^{-2}. It means that the cucumbers inside greenhouse received less than 50% energy from global solar radiation than the outside the greenhouse, this result is quite different from the Harmandeep et al. (2016) that the difference of R_n inside and outside greenhouse was only 7%, but quite close to the result obtained by Liu et al. (2008) in a sunlight greenhouse. Accordingly, the reference evapotranspiration (ET_0) inside the greenhouse was lower than outside the greenhouse as shown in Fig.1(*c*). In this study, the ET_0 inside the greenhouse was calculated using the FAO-56 Penman-Monteith (Allen, et al., 1998) equation by assuming wind speed equaled 0. The soil water content at 5 cm depth for different irrigation water treatments is shown in Fig. 2. The soil water content ranged from 29.3 - 53.9 %, 21.2 - 44.9 % and 12.9 - 35.9 % for treatment 1, 2 and 3, respectively.

3.2 Determination of r_a and its validation

The average value of r_a calculated from the CHTC-method (Eq. (6)) was 144 s m^{-1}, and the amplitude of hourly variation is quite small. This r_a value is close to the result of Zhang and Lemeur (1992) ($r_a = 143$ s m^{-1}) in which Nusselt number was calculated by the equation of Fujii et al (1973), but it is lower than the result of Moeille et al. (2013) ($r_a \approx 300$ s m^{-1}) and higher than the result of Gong et al. (2017) ($r_a < 100$ s m^{-1}) in which the same method was applied in similar greenhouses. The reasons of the differences of r_a among the studies might due to the differences in ventilation for the greenhouses and/or the differences in crop type planted in the greenhouse. The values of r_a calculated from the IBTE-method with the data from 2015 were lower than it calculated using the CHTC-method (Eq. (6)). The variation of daily r_a which was calculated using IBTE-method is shown in Fig. 3. As shown in Fig. 3, most values of r_a during the observation period were in the range of 0-50 s m^{-1} with slight variation with some exceptions. The negative values for r_a in Fig. 3 might be due to the measurements errors of R_n and *LE*, and/or due to neglecting the energy storage part in the energy balance equation (Eq. (2)). To check the sensitivity of the *H* and *LE* towards the variation of daily r_a, we increased r_a from the average value 35 s m^{-1} to 50 and 80 s m^{-1}, to reproduce *H* and *LE* using the data from 2016. The comparison of measured and calculated *H* and *LE* with varying r_a is shown in Fig. 4. In this study, the measured *H* represents the H obtained from energy balance equation (Eq. (2)) with measured LE with lysimeters. The regression analysis between measured and predicted H and LE with different r_a is shown in Table 1. From Table 1, we could find that the modeled H and LE with constant r_a (= 35 s m^{-1}) were very close to measured values. The H was sensitive to change in r_a, but much less effect on LE estimates. A similar result was reported by Zhang and Lemeur (1992). The $RMSE$ for estimating LE with r_a equaled 35 s m^{-1} was 59.9 W m^{-2}, and the coefficient of determination was 0.74; while the $RMSE$ was 59.5 W m^{-2} with r_a equaled 35 s m^{-1}, and the coefficient of determination was 0.71.

3.3 Modeling r_c based on days after transplanting

With fixed r_a, the r_c can be calculated by IBTE-method (Eq. (5)) using measured LE and other meteorological data during cucumber growing season in 2015. Figure 5 shows the hourly variation of r_c in different growing stages of cucumber plants. As shown in Fig.5, the r_c was higher in the early morning and late afternoon, while it was lower during mid-day (9:00-15:00). The average values of r_c during 9:00 to 15:00 for different growing stage were lower than 200 s m^{-1}, and the amplitude of variations were small.

From previous studies (Jarvis, 1976; Oue, 2005), we know that solar radiation is the most related factor determining hourly r_c. However, it was not the most correlated factor to daily r_c based on our analysis. According to the analysis of the correlations between daily data of r_c and different meteorological data (R_n and VPD), it was found that days after transplanting (DAT) was the most correlated factor with r_c. The variation of daily r_c along with DAT in different range of R_n is shown in Fig. 6. The r_c declined along with DAT, the daily maximum value of r_c obtained in present study was around 450 s m^{-1}, and decreased to lower than 100 s m^{-1} after 40 DAT. At the same growing stage (DAT), r_c was higher when R_n was lower (R_n < 160 W m^{-2}) than when R_n was higher (R_n ⩾

160 W m^{-2}). But the difference was obvious in the early growing stage (< 20 *DAT*) than in the mid and late stages (20 < *DAT* < 76). Quadratic polynomial equations (r_c sub-model) were obtained with R^2 equal to 0.69 and 0.71, respectively, for two R_n ranges.

3.4 Comparison of measured and predicted *LE* based on r_c sub-model

To validate the accuracy of predicted *LE* based on the fixed r_a and r_c sub-model, *LE* was estimated by Eq. (1) with the meteorological data from 2016. The comparison between measured (by lysimeters) and modeled (by Bulk transfer model based on fixed r_a and r_c sub-model) *LE* is shown in Fig. 7. Most of the regression points were scattered near the 1:1 line, which means the measured *LE* could be represented by the constructed sub-model with a good performance. The statistical indexes were calculated as shown in Table 2. The root mean square error was 73.4 W m^{-2} for the whole season, the index of agreement was higher than 0.8 for all the stages of cucumber growing season.

4. Discussion

The daily r_a value obtained from measured sensible heat flux and temperature difference with IBTE-method in this study is similar to the results of Yan et al. (2015*b*) with r_a lower than 100 s m^{-1} and slight variation, but quite lower than the results obtained by Fernandez et al. (2010) with r_a equal to 150 s m^{-1} for greenhouse grass and Bailey et al. (1994) with r_a oscillated between 100 and 500 s m^{-1} for several greenhouse crops. The hourly values of r_a obtained by a CHTC-method in this study are close to Zhang and Lemeur (1992) who calculated r_a for a free convention regime. They presented that the averaged r_a were 81, 143, 133 and 147 s m^{-1} based on different methods (Kreth, 1956; Fujii et al., 1973; Stanghellini, 1987 and energy balance equation) in a similar type of greenhouse. It can be found from their results that the magnitude of

r_a values depends on the used methods. They also presented similar results as our research that the sensible heat flux is sensitive to the errors in r_a, but these errors have much less effect on *LE*.

Accordingly, although the error of predicting *H* and *LE* using a fixed r_a existed, it would be better than calculating r_a by a logarithmic wind profile equation with actual wind speed inside the greenhouse. The calculated r_a from wind speed oscillated between 20800 and 2080 s m^{-1} and was much higher than the real r_a for several crops (Fernandez et al. 2010).

Frequently, researchers model hourly variations in r_c with radiation and VPD. For example, Todorovic (1999) developed a mechanistic model, where r_c is a function of climatic variables and r_a; Jarvis (1976) suggested that environmental factors such as solar radiation and VPD were the main influencing factors; Oue (2005) analyzed the influences of *SR*, VPD and plant height on hourly r_c by defining a parameter named critical resistance and assessed the influences of climatic factors on r_c. In this study, we took the average values for daily r_c, and we found that daily average radiation is not the primary influencing factor on daily r_c, but DAT or plant height are. Hence, the result of influencing factors on r_c based on the daytime average values is different from previous studies that based r_c on the hourly data. We did not use plant height into the r_c model, because the plant height of cucumber is difficult to accurately measure in the late growing stage with very long and not straight vines.

The Bulk transfer equation which was applied in this study for estimating *LE* is based on the Dalton-type equation and Fick's law of diffusion, and on the concept of mass transfer theory, which states that the diffusion of heat and water vapour into the atmosphere moves from high concentration to low concentration at a rate that is proportional to the spatial gradient of that concentration. This method is straightforward because it relies not only on relatively routine measurements of T_a and RH, but also on canopy surface temperature (T_s) which is very difficult to measure. In this study, we applied the measured T_s by infrared thermometers which were set toward different positions of canopy surface and the average values of the temperature from different positions were used in solving the Bulk transfer equations. Although this kind of measurements do not represent the real canopy surface temperature, the results would be the closest to the real canopy surface temperature. Hence, future research should focus on constructing models for predicting T_s based on the easy to obtain climatic data and plants structures.

5. Conclusion

In this study, an experiment was conducted in a cucumber greenhouse in south China, where latent heat flux and meteorological data were measured for parameterizing the aerodynamic and canopy resistance based on the Bulk transfer and energy balance equation inside the greenhouse. By comparing the result of the aerodynamic resistance calculated from: (1) IBTE-method and (2) CHTC-method, a fixed daily value of aerodynamic resistance was found (= 35 s m^{-1}), because it appeared that the fluxes were rather insensitive to changes in daily aerodynamic resistance. The reproduced sensible and latent heat flux using different aerodynamic resistance values were compared to the observed values. A canopy resistance sub-model was constructed using days after transplant of cucumber plants and net radiation inside the greenhouse. By integrating the fixed aerodynamic resistance and canopy resistance sub-model, the latent heat flux was reproduced and compared to the observations. The statistical analysis showed that the latent heat flux could be reproduced by the Bulk transfer equation with the fixed aerodynamic resistance and canopy resistance sub-model, the index of agreement between modeled and measured values was higher than 0.8 for all growing stages. The model constructed in the present study would be an easy and relatively accurate way to determine greenhouse cucumber water consumption and to make the appropriate irrigation schedule.

Appendix 1

The Nusselt number (N_u) can be expressed by the heat exchange coefficient h_s as:

$$N_u = \frac{h_s \cdot d}{\lambda_a} \tag{A1}$$

The Reynolds number (Re) can be expressed as

$$Re = \frac{\rho_a \cdot V \cdot d}{\mu_a} \tag{A2}$$

The Grashof number (G_r) is a function of the temperature difference between the flat plate and air:

$$G_r = \frac{g \cdot \beta \cdot \Delta T \cdot d^3 \cdot \rho_a^2}{\mu_a^2} \tag{A3}$$

The characteristic dimension of the leaf (m), d, can be calculated as follows (Montero et al., 2001):

$$d = \frac{2}{(1/L + 1/W)} \tag{A4}$$

where L and W are the length (m) and the width (m) of the leaf, respectively. Nu is the Nusselt number, λ_a(W m^{-1}K^{-1}) is the air thermal conductivity, Re is the Reynolds number, ρ_a(kg m^{-3}) is the air density, V (m s^{-1}) is the air speed, μ_a(Pa s) is the air dynamic viscosity, g (m s^{-2}) is the acceleration of gravity, β (K^{-1}) is the volumetric thermal expansion coefficient and ΔT (K) is the temperature difference between the flat plate and the air. More details on the calculation of r_a can be referred in Morille et al. (2013).

Table A1: Expressions of the Nusselt number for the flat plate

Free $Re^2 \ll Gr$	Laminar $10^4 < Gr < 10^9$	$Nu = 0.54Gr^{(1/4)}$
	Turbulent $10^9 < Gr < 10^{12}$	$Nu = 0.12Gr^{(1/3)}$
Mixed $Re^2 \approx Gr$	Laminar $10^3 < Gr < 10^9$	$Nu = 0.68(Re^{(3/2)} + Gr^{(3/4)})^{1/3}$
	Turbulent $10^9 < Gr < 10^{12}$	$Nu = 0.03(Re^{(12/5)} + 12.1Gr)^{1/3}$
Forced $Re^2 \gg Gr$	Laminar $Re < 3\times10^5$	$Nu = 0.56Re^{(1/2)}$
	Turbulent $Re > 5\times10^5$	$Nu = 0.03Re^{(4/5)}$

Competing interest

There is no competing interest.

Submission declaration and verification

We declare that the work described has not been published previously and it is not under consideration for publication elsewhere, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

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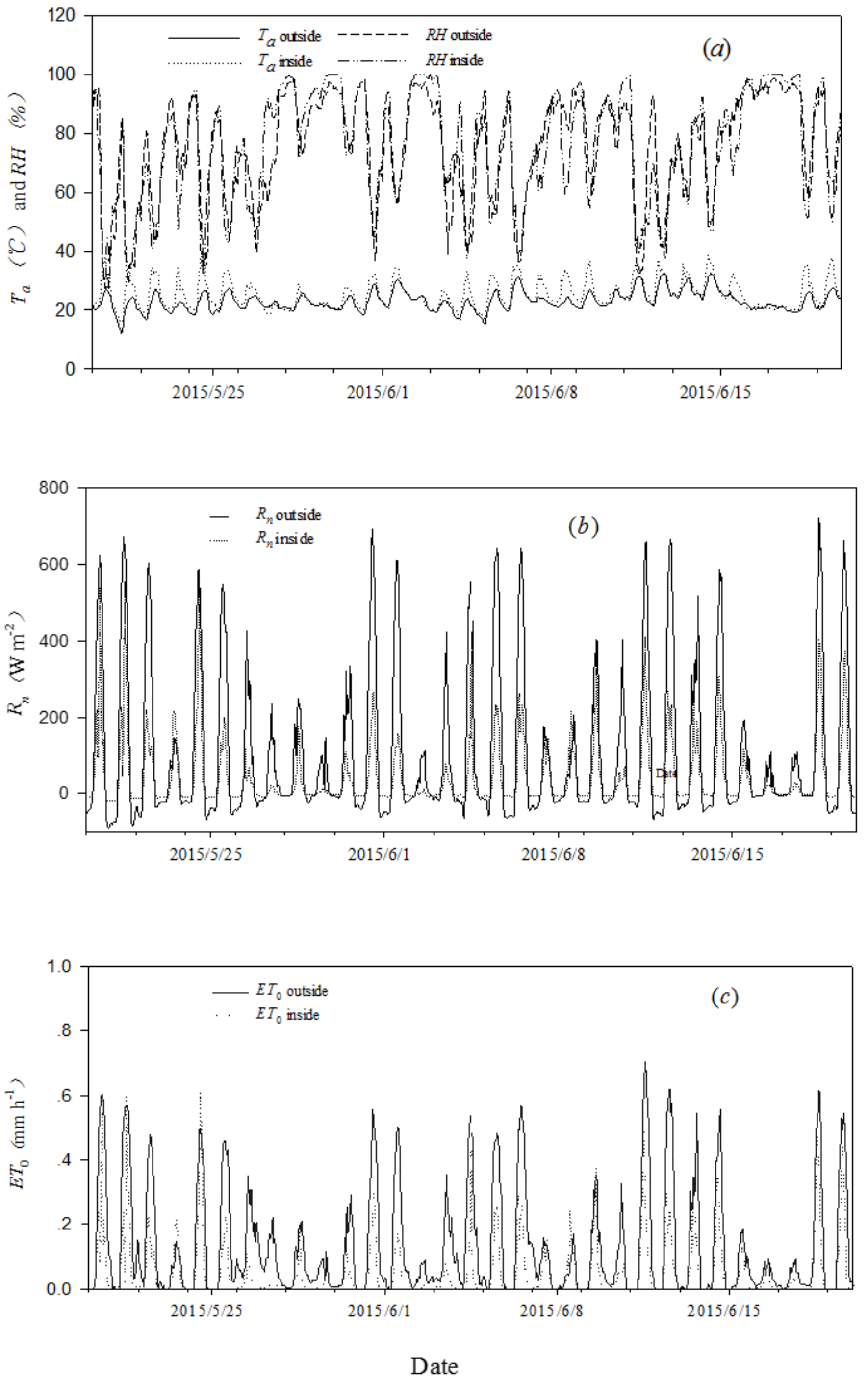

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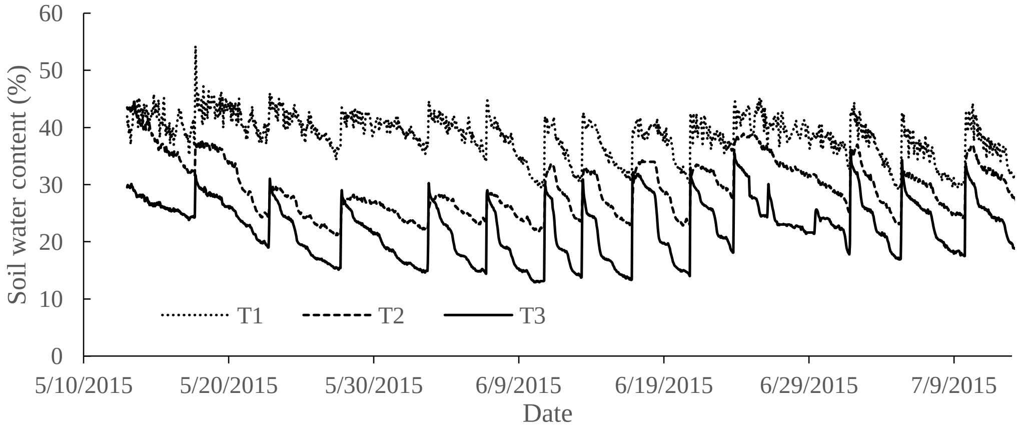

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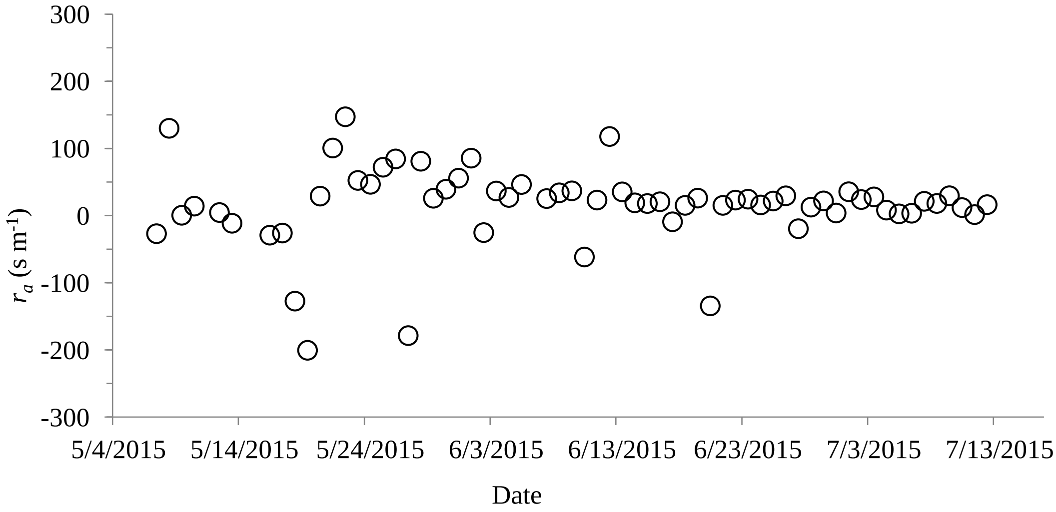

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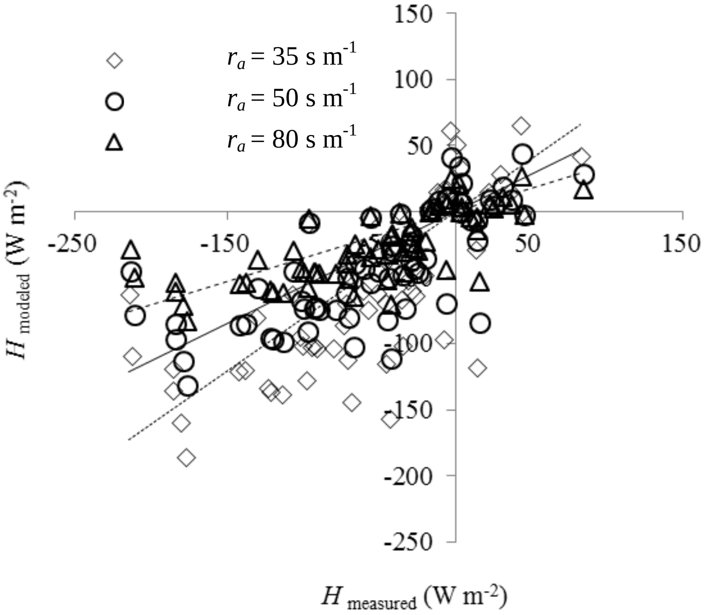

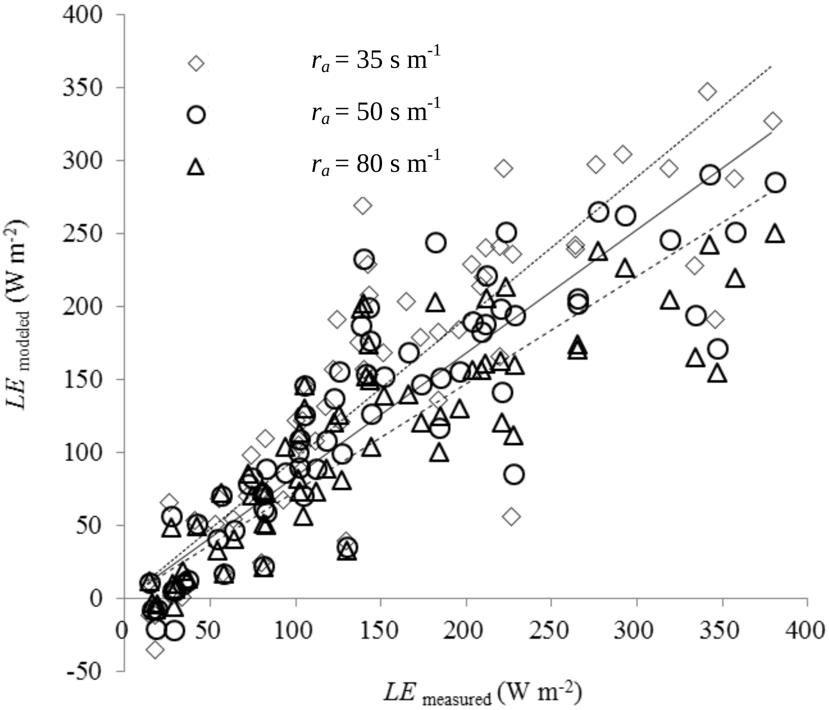

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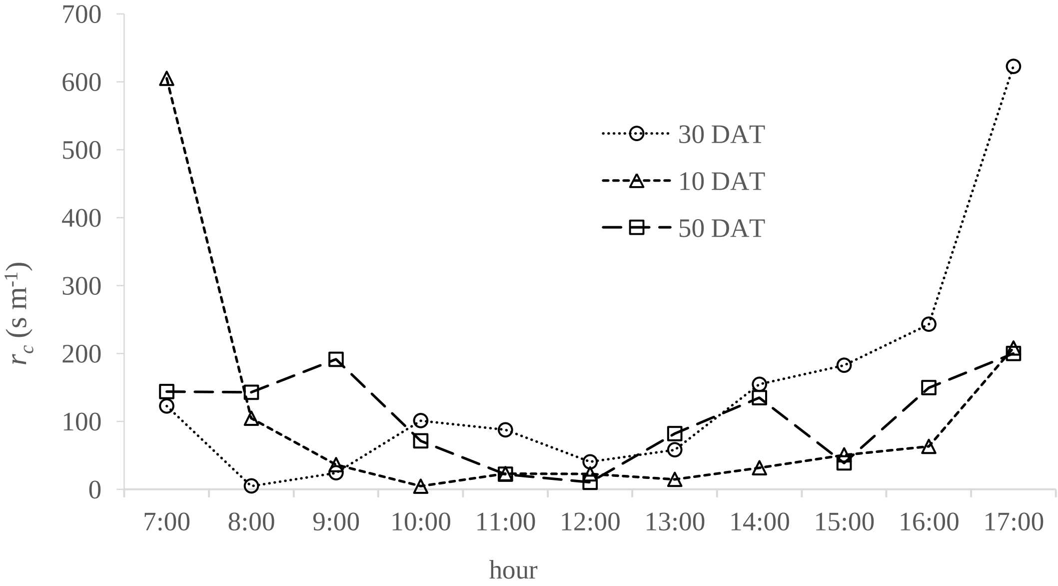

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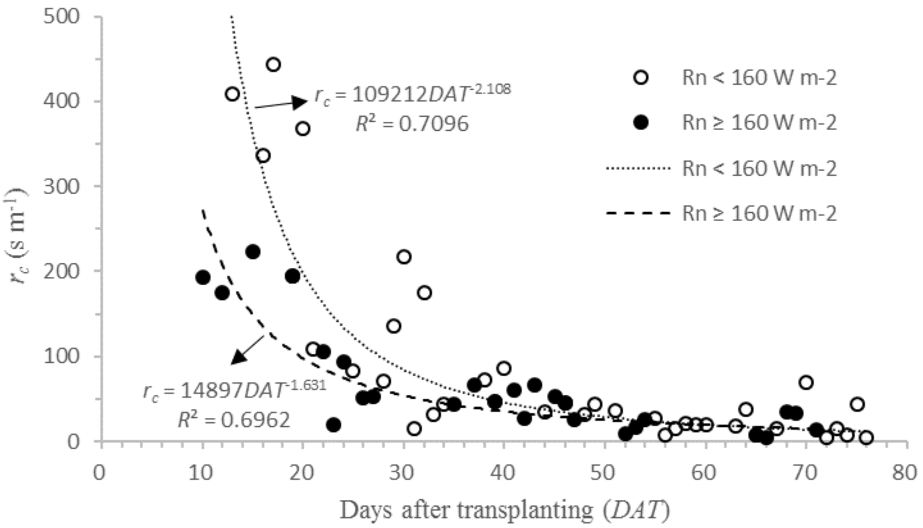

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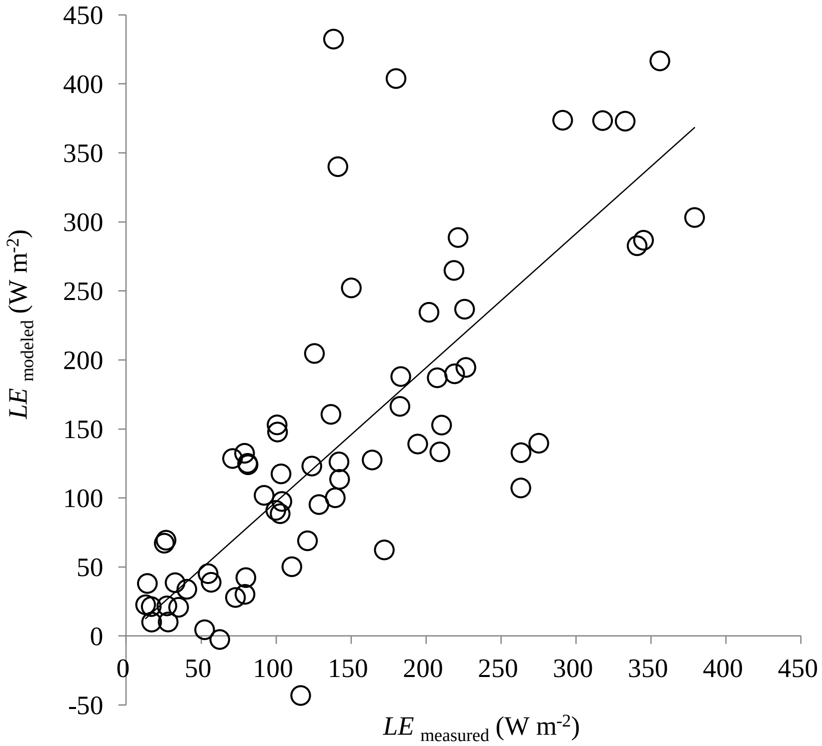

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Table 1 Regression analysis of measured and modeled *H* and *LE* based on different r_a (m s^{-1})

r_a	M_H	P_H	*RMSE*	d_H	R^2	*a*	M_{LET}	P_{LET}	*RMSE*	d_{LET}	R^2	*a*
35	-55.2	-53.3	50.5	0.83	0.45	0.81	144	144.8	59.9	0.93	0.74	0.96
50	-55.2	-37.3	50.3	0.77	0.45	0.57	144	126.1	50.2	0.92	0.75	0.84
80	-55.2	-23.3	59.5	0.63	0.45	0.35	144	112.1	59.5	0.87	0.71	0.74

Note: P_H and M_H, P_{LET} and M_{LET} are mean estimated and measured *H* and *LE* (W m^{-2}), respectively; *a* is slope of least square regression line, R^2 is coefficients of determination, RMSE is root mean square error (W m^{-2}), d_H and d_{LET} are index of agreement for *H* and *LE*; *a*, R^2 and *d* are dimensionless. The above calculations were based on the data from 2016.

Table 2 Error analysis statistics of the comparison between measured and estimated *LE* for cucumber plants inside the greenhouse

	M_{LET}	P_{LET}	R^2	*a*	*RMSE*	*MSEs*	*MSEu*	*d*
May	106.1	94.7	0.53	0.82	46	2.2	44.9	0.86
June	146.6	182.9	0.53	1.14	88.2	2.9	92.3	0.83
July	211.1	182.5	0.67	0.66	72.1	4.1	70.3	0.87
Total Mean	144.1	148.9	0.57	0.98	73.4	2.9	75.1	0.85

Note: P_{LET} and M_{LET} are mean estimated and measured *LE* (W m^{-2}); *a* is slope of least square regression line, R^2 is coefficients of determination, RMSE is root mean square error (W m^{-2}), MSE_s is systematic mean square error (W m^{-2}), MSE_u is unsystematic mean square error (W m^{-2}), *d* is index of agreement; *a*, R^2 and *d* are dimensionless. The above calculations were based on the data from 2016.