

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

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Title: Parametrization of aerodynamic and canopy resistances for modeling
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Huang; Hanwen Fu

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) Applying a convective heat transfer coefficient (CHTC-method), were used to evaluate the aerodynamic resistance. A fixed aerodynamic resistance ($= 35 \text{ s m}^{-1}$) 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,

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 (r_a) and for the canopy resistance (r_c) 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 r_a 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 r_a 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 r_a results.

2. In the Penman-Monteith FAO56 method (Allen et al., 1998), the r_a 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 $r_a = 208 / u^2$ ratio for low wind speeds results in high and inconsistent r_a values.

An alternative in protected environment conditions is to use the proposed parameterization proposed by McNaughton & Jarvis (1983), considering $r_s = 70 \text{ s m}^{-1}$, 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 r_a 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 ET_0) 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 (r_a) 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 r_a . Better contextualize the problem.

Response:

Thank you for your comments, the problem on the difficulties in estimating r_a 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 r_c was modeled and what is the difficulties.

Response:

Thank you for your comments, we have added more references to explain the difficulties on estimating r_c . 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 r_a 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 r_a tends to infinity and ET₀ 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 r_a and r_c 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 r_a and r_c 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.

1 Running title: Modeling evapotranspiration of greenhouse cucumber

2 **Parametrization of aerodynamic and canopy resistances for**

3 **modeling evapotranspiration of greenhouse cucumber**

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14
15 **Novelty statement:**

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

1 **Abstract**

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

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

23 **1. Introduction**

24 The latent heat flux (LE) is an important component of the ecosystem energy

1 balance and is strongly related to gross ecosystem production in vegetation (Law et al.,
2 2002; Green et al., 1984). Knowing LE is a key issue to understand and improve the
3 climatic conditions of plants in both the open field and greenhouse cultivation
4 (Takakura et al., 2009). A better understanding of LE can help to investigate if irrigation
5 can be improved and available water can be used more productively (Kite, 2000; Zhao
6 et al., 2013; Yin et al., 2018; Nie et al., 2017). Due to the fast development of
7 greenhouse crop production culture all around the globe, there is an urgent need for
8 more information on greenhouse LE . Venlo-type greenhouses facalized with automatic
9 environmental control systems have widely distributed all over the world (Xu et al.,
10 2013). Many methods to estimate LE have been developed for open fields over the past
11 50 years (Allen et al., 1998; Katerji and Rana, 2006; Li et al., 2014; Yan et al., 2015 *a, b*;
12 Yan et al., 2017). Among them, the Penman-Monteith (PM) model and the Bulk
13 Transfer equation are primarily used in greenhouse horticulture. The PM model was
14 primarily developed for open field conditions by assuming homogeneity of both the
15 thermodynamic conditions within the canopy and the air above the plants (Morille et al.,
16 2013). Also, due to the differences in greenhouse type (Venlo-type glasses or plastic
17 greenhouses) and ventilations system (automatic or force ventilation systems), the
18 models and parameters applied in greenhouses showed quite different uncertainty
19 (Kreth, 1956; Fujii et al., 1973; Stanghellini, 1987).

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

1 due to the low wind speed (u_2) and non-logarithmic wind profile in the greenhouse.
2 Assuming the wind speed equal to 0 might yield significant difference in calculating the
3 *LE*.

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

$$6 \quad LE = \frac{c_p \rho [e_*(T_s) - e_a]}{\gamma(r_a + r_c)} \quad (1)$$

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

14 To apply the Bulk Transfer model, the aerodynamic resistance (r_a) and canopy
15 resistance (r_c) should be known. Often, they are estimated through their relationships
16 with environmental variables. Generally, the r_a was determined by a logarithmic profile
17 of wind speed which described the turbulent transfer of water vapour between the
18 canopy surface and the atmosphere (Brutsaert, 1982). However, due to the quite low
19 wind speed (close to 0) inside the greenhouse, r_a tends to infinity, so, this method may
20 not suitable for greenhouses (Qiu et al., 2013). Many researchers tried to solve this
21 using a convective heat transfer coefficient (CHTC-method) for individual leaves to
22 calculate the r_a for greenhouse planting (Morille et al. 2013; Gong et al. 2017). But
23 some researchers showed that under similar conditions, differences in calculated r_a

1 occurred with the CHTC-method due to the difficulties in estimating the CHTC (Kreth,
2 1956; Fujii et al., 1973; Stanghellini, 1987). Also, the modeling of r_c is difficult for
3 greenhouses. Hourly variation of r_c has been related to solar radiation, air temperature
4 and humidity, VPD and soil water content (Stanghellini, 1987; Jarvis, 1976; Tuzet et al.,
5 2003; Yan et al., 2011). Many researchers showed that solar radiation is the most
6 correlated factor to canopy resistance (Bailey et al., 1993; Montero et al., 2001;
7 Roupael and Colla, 2004). Most researchers modeled r_c with different meteorological
8 data based on their local climate conditions and focused on the open fields. For example,
9 Jarvis (1976) modeled r_c with radiation and VPD by scaling up stomatal resistance to
10 canopy resistance, however, the scaling up requires detailed porometry and leaf area
11 data, also, due to different climatic conditions in comparison to greenhouse, the
12 relevance of those empirical models needs to be validated. Some researchers (Roupael
13 et al., 2004; Qiu et al., 2013) demonstrated that r_c could be directly estimated using the
14 relationships with different meteorological data for zucchini and hot pepper, however,
15 the results among the researches showed big differences due to the differences in crop
16 types and greenhouse climatic conditions.

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

$$21 \quad R_n = LET + H + G \quad (2)$$

$$22 \quad H = \frac{c_p \rho (T_s - T_a)}{r_a} \quad (3)$$

23 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})

1 m⁻²). This method is called the “Inversing Bulk Transfer equation” (IBTE-method).

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

10 **2. Material and method**

11 **2.1 Field observation**

12 The experiment was conducted at a Venlo-Type greenhouse located in the Jiangsu
13 province, China (31°56'N, 119°10'E, 23 m a.s.l) from April to July in 2015 and 2016.
14 The experimental site is in a humid sub-tropical monsoon climatic zone with an average
15 annual air temperature of 15.5°C and a mean annual precipitation (rainfall) of 1058.8
16 mm y⁻¹. The rectangular greenhouse structure has an area of 32 m long × 20 m wide in
17 horizontal dimensions, 3.8 m high with the longer side in an east-west orientation,
18 which is the prevailing wind direction. The greenhouse was passively ventilated by
19 opening side panels and roof vents for the exchange of hot exhaust air from the inside of
20 the greenhouse to the outside. The heating system of the greenhouse was not switched
21 on. The planting medium used in the greenhouse was a soil-biochar mixture with mean
22 bulk density of 1.266 g/cm³, field capacity of 0.408 cm³/cm³ and wilting-point water
23 content of 0.16 cm³/cm³ in the depth of 0-30 cm. Cucumbers were transplanted into the
24 soil troughs (0.65 m in width × 16.7 m in length) on 27th April 2015, and 3rd May 2016,

1 with plant density equal to 6.63 per m². There was an aisle between two troughs and the
2 distance between two troughs was 0.85 m. Seedlings were sowed 30 days before
3 transplanting. To measure the latent heat flux (*LE*) of cucumbers inside the greenhouse,
4 3 cucumber plants were transplanted into 3 lysimeters (30 cm in diameter and 50 cm in
5 depth). The lysimeters were placed in the greenhouse with similar density as the plants
6 in the soil troughs. *LE* was measured by three accurate balances (accuracy = 1g,
7 METTLER TOLEDO, Switzerland) by weighing the decrease of the weight of the
8 lysimeters with cucumbers. The lysimeter data were sampled every 10 s, averaged over
9 10 min and recorded on a data logger CR1000-NB (Campbell, USA). For a better
10 establishment and to ensure seeding growth, the transplanted seedlings were
11 immediately irrigated with the same volume of water (25 mm). Thereafter, the plants
12 were watered by drip irrigation and the spatial interval of the emitters in each drip tape
13 was 0.35 m. The designed discharge rate of each drip tape was 100 ml/min. Drip surface
14 irrigation application was initiated 3 days after transplanting together with 200 ppm
15 NPK fertilizer solution with concentration 25 % N, 5 % of P₂O₅ and 5 % of K₂O applied
16 directly to the cucumber plants. The different irrigation water treatments (total irrigation
17 water: Treatment 1 (T1) = 330 mm, Treatment 2 (T2) = 270 mm, Treatment 3 (T3) =
18 203 mm) were applied every 2-3 days by three drip irrigation systems during the
19 observation period (13th May to 12th July).

20 The net radiation inside the greenhouse was measured with a NR Lite 2 (Kipp &
21 Zonen, the Netherlands) at 2.5 m above the canopy surface. Soil heat flux was measured
22 at 2 cm depth with a soil heat plate HFP01-L10 (Campbell, USA). Soil water content
23 and soil temperature at 5-10 cm were measured with Hydra Probe sensors (Stevens,
24 USA). The canopy and soil surface temperatures were measured by two infrared

1 thermometers SI-111 (Campbell, USA). The air temperature and relative humidity
2 inside the greenhouse were measured both at 1.20 m and at 2.90 m heights from the
3 ground level, respectively. Humidity and temperature sensors HMP155 (Vaisala,
4 Finland) were used for the measurements. The low wind speed inside the greenhouse
5 was measured using a two-dimensional wind speed sensor 1405-PK-021(Gill, England).
6 All the meteorological data were sampled every 10 s, averaged over 10 min and
7 recorded on a data logger CR1000-NB (Campbell, USA).

8 The leaf area and plant height of cucumber plants were measured at an interval of
9 5-14 days. The leaf length (L) and the highest leaf width (W_L) were measured with a
10 measuring tape, and the conversion coefficient of 0.65 for the leaf area was derived
11 from fitting the measured results to the one drawn using CAD software (Liu et al.,
12 2009). In this study, the measured maximum plant height and leaf area index were 1.8
13 m and 4.2, respectively.

14 Outside the greenhouse, the elements of radiation balance were measured: incoming
15 shortwave (R_s), down and upwelling longwave radiation were measured with a CNR-4
16 (Kipp & Zonen, the Netherlands) at 2.5 m above the canopy. The net radiation ($R_n = (1$
17 $- \alpha) R_s + L_d - L_u$) was calculated. Here, R_s is the global solar radiation (W m^{-2}), α is the
18 albedo of the ground surface, L_d is the downward long wave radiation from the
19 atmosphere and L_u is the upward long wave radiation from the ground (W m^{-2}). Air
20 temperature (T_a) and relative humidity above the canopy were measured with
21 thermohygrometer HMP155A (Vaisala, Finland). Wind speed was measured with three
22 three-cup anemometers A100L2 (MetOne, USA) at the same height as T_a . Rainfall was
23 measured with TE525MM (Campbell, USA). All the data were sampled every 10 s,
24 averaged over 10 min and recorded on a data logger CR3000-NB (Campbell, USA).

1 2.2 Aerodynamic resistance and canopy resistance

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

$$5 \quad r_a = \frac{c_p \rho (T_s - T_a)}{R_n - LE - G} \quad (4)$$

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

$$8 \quad r_c = \frac{c_p \rho [e_*(T_s) - e_a]}{\gamma LE} - r_a \quad (5)$$

9 As a comparison r_a was also calculated with CHTC-method as (Zhang and Lemeur,
10 1992; Morille et al., 2013; Gong et al., 2017)

$$11 \quad r_a = \frac{\rho c_p}{h_s} \quad (6)$$

12 where c_p is the specific heat of air (=1.0 kJ kg⁻¹ K), ρ is the density of air (=1.225 kg
13 m⁻³), h_s is the heat exchange coefficient (W m⁻² K⁻¹) expressed as a function of the
14 Nusselt number (Nu) according to the flat plate theory. The convection can be analyzed
15 by using non-dimensional groups, such as the Reynolds (Re), the Grashof number (Gr),
16 and the Nusselt number (Nu). The details about how to analyze the convection can be
17 found in Appendix 1.

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

1 Statistical analysis

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

$$6 \quad RMSE = \left[\frac{1}{n} \sum_{i=1}^n (P_i - M_i)^2 \right]^{1/2} \quad (7)$$

$$7 \quad MSE_s = \left[\frac{1}{n} \sum_{i=1}^n (\hat{P}_i - M_i)^2 \right]^{1/2} \quad (8)$$

$$8 \quad MSE_u = \left[\frac{1}{n} \sum_{i=1}^n (\hat{P}_i - P_i)^2 \right]^{1/2} \quad (9)$$

$$9 \quad d = 1 - \left[\frac{n \cdot RMSE^2}{\sum_{i=1}^n \left((|P_i - \bar{M}| + |M_i - \bar{M}|)^2 \right)} \right] \quad (10)$$

10 where P_i and M_i are estimated and measured hourly LE , i is the sample number, $i = 1,$
11 $2 \dots n$, \bar{M} is the average measured hourly LE . \hat{P} is the estimated hourly LE from least
12 square regression. The MSE_s estimates the model's linear (or systematic) error; hence,
13 the better the regression between estimations and observations, the smaller the
14 systematic error. The unsystematic difference is a measure of how much of the
15 discrepancy between estimations and observations is due to random processes or
16 influences outside the legitimate range of the model. A good model will provide low
17 values of the $RMSE$, explaining most of the variation in the observations. The
18 systematic error should approach zero and the unsystematic error should approach
19 $RMSE$. The index of agreement is a measure of the match between the departure of each
20 prediction from the observed mean and the departure of each observation from the

1 observed mean (Yan et al., 2015b).

2 **3. Results**

3 **3.1 Meteorological data inside and outside the greenhouse and soil moisture** 4 **variations under different irrigation water treatments**

5 The observed meteorological data inside and outside the greenhouse and soil
6 moisture variations during cucumber growing season in 2015 are shown in Fig.1. The
7 air temperature (T_a) and relative humidity (RH) inside the greenhouse during 27 April to
8 23 July, the first day after transplanting to final harvesting day, ranged from 13.1 to
9 42.6 °C and 26.4% to 100%, with average values equaled to 25.3 °C and 78.9%,
10 respectively; while the T_a and RH outside the greenhouse ranged from 12.1 to 33.6 °C
11 and 26.8% to 99% at the same time period, with an average value equaled to 22.9 °C
12 and 79.1%, respectively. On average, the T_a difference inside and outside the
13 greenhouse was around 2-3 °C, while the difference in RH was very small. The wind
14 speed inside the greenhouse was very low and close to 0, while the variation of wind
15 speed outside the greenhouse ranged from 0.2 to 7.7 m s⁻¹. Figure 1 (b) showed the
16 variation of net radiation (R_n) inside and outside the greenhouse. The daily R_n inside the
17 greenhouse ranged from -39.9 to 586.6 W m⁻², with an average value equaled 42.9 W
18 m⁻², while the R_n outside the greenhouse ranged from -90.85 to 721.7 W m⁻², with an
19 average value equaled 101.6 W m⁻². It means that the cucumbers inside greenhouse
20 received less than 50% energy from global solar radiation than the outside the
21 greenhouse, this result is quite different from the Harmandeep et al. (2016) that the
22 difference of R_n inside and outside greenhouse was only 7%, but quite close to the result
23 obtained by Liu et al. (2008) in a sunlight greenhouse. Accordingly, the reference
24 evapotranspiration (ET_0) inside the greenhouse was lower than outside the greenhouse

1 as shown in Fig.1(c). In this study, the ET_0 inside the greenhouse was calculated using
2 the FAO-56 Penman-Monteith (Allen, et al., 1998) equation by assuming wind speed
3 equaled 0. The soil water content at 5 cm depth for different irrigation water treatments
4 is shown in Fig. 2. The soil water content ranged from 29.3 - 53.9 %, 21.2 - 44.9 % and
5 12.9 - 35.9 % for treatment 1, 2 and 3, respectively.

6 **3.2 Determination of r_a and its validation**

7 The average value of r_a calculated from the CHTC-method (Eq. (6)) was 144 s m^{-1} ,
8 and the amplitude of hourly variation is quite small. This r_a value is close to the result
9 of Zhang and Lemeur (1992) ($r_a = 143 \text{ s m}^{-1}$) in which Nusselt number was calculated
10 by the equation of Fujii et al (1973), but it is lower than the result of Moeille et al. (2013)
11 ($r_a \approx 300 \text{ s m}^{-1}$) and higher than the result of Gong et al. (2017) ($r_a < 100 \text{ s m}^{-1}$) in which
12 the same method was applied in similar greenhouses. The reasons of the differences of
13 r_a among the studies might due to the differences in ventilation for the greenhouses
14 and/or the differences in crop type planted in the greenhouse. The values of r_a
15 calculated from the IBTE-method with the data from 2015 were lower than it calculated
16 using the CHTC-method (Eq. (6)). The variation of daily r_a which was calculated using
17 IBTE-method is shown in Fig. 3. As shown in Fig. 3, most values of r_a during the
18 observation period were in the range of $0\text{-}50 \text{ s m}^{-1}$ with slight variation with some
19 exceptions. The negative values for r_a in Fig. 3 might be due to the measurements errors
20 of R_n and LE , and/or due to neglecting the energy storage part in the energy balance
21 equation (Eq. (2)). To check the sensitivity of the H and LE towards the variation of
22 daily r_a , we increased r_a from the average value 35 s m^{-1} to 50 and 80 s m^{-1} , to
23 reproduce H and LE using the data from 2016. The comparison of measured and
24 calculated H and LE with varying r_a is shown in Fig. 4. In this study, the measured H

1 represents the H obtained from energy balance equation (Eq. (2)) with measured LE
2 with lysimeters. The regression analysis between measured and predicted H and LE
3 with different r_a is shown in Table 1. From Table 1, we could find that the modeled H
4 and LE with constant r_a ($= 35 \text{ s m}^{-1}$) were very close to measured values. The H was
5 sensitive to change in r_a , but much less effect on LE estimates. A similar result was
6 reported by Zhang and Lemeur (1992). The $RMSE$ for estimating LE with r_a equaled 35
7 s m^{-1} was 59.9 W m^{-2} , and the coefficient of determination was 0.74; while the $RMSE$
8 was 59.5 W m^{-2} with r_a equaled 35 s m^{-1} , and the coefficient of determination was 0.71.

9 **3.3 Modeling r_c based on days after transplanting**

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

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

1 160 W m⁻²). But the difference was obvious in the early growing stage (< 20 DAT) than
2 in the mid and late stages (20 < DAT < 76). Quadratic polynomial equations (r_c
3 sub-model) were obtained with R^2 equal to 0.69 and 0.71, respectively, for two R_n
4 ranges.

5 **3.4 Comparison of measured and predicted LE based on r_c sub-model**

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

14 **4. Discussion**

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

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

4 Accordingly, although the error of predicting H and LE using a fixed r_a existed, it
5 would be better than calculating r_a by a logarithmic wind profile equation with actual
6 wind speed inside the greenhouse. The calculated r_a from wind speed oscillated between
7 20800 and 2080 s m^{-1} and was much higher than the real r_a for several crops (Fernandez
8 et al. 2010).

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

21 The Bulk transfer equation which was applied in this study for estimating LE is
22 based on the Dalton-type equation and Fick's law of diffusion, and on the concept of
23 mass transfer theory, which states that the diffusion of heat and water vapour into the
24 atmosphere moves from high concentration to low concentration at a rate that is

1 proportional to the spatial gradient of that concentration. This method is straightforward
2 because it relies not only on relatively routine measurements of T_a and RH , but also on
3 canopy surface temperature (T_s) which is very difficult to measure. In this study, we
4 applied the measured T_s by infrared thermometers which were set toward different
5 positions of canopy surface and the average values of the temperature from different
6 positions were used in solving the Bulk transfer equations. Although this kind of
7 measurements do not represent the real canopy surface temperature, the results would
8 be the closest to the real canopy surface temperature. Hence, future research should
9 focus on constructing models for predicting T_s based on the easy to obtain climatic data
10 and plants structures.

11 **5. Conclusion**

12 In this study, an experiment was conducted in a cucumber greenhouse in south
13 China, where latent heat flux and meteorological data were measured for parameterizing
14 the aerodynamic and canopy resistance based on the Bulk transfer and energy balance
15 equation inside the greenhouse. By comparing the result of the aerodynamic resistance
16 calculated from: (1) IBTE-method and (2) CHTC-method, a fixed daily value of
17 aerodynamic resistance was found ($= 35 \text{ s m}^{-1}$), because it appeared that the fluxes were
18 rather insensitive to changes in daily aerodynamic resistance. The reproduced sensible
19 and latent heat flux using different aerodynamic resistance values were compared to the
20 observed values. A canopy resistance sub-model was constructed using days after
21 transplant of cucumber plants and net radiation inside the greenhouse. By integrating
22 the fixed aerodynamic resistance and canopy resistance sub-model, the latent heat flux
23 was reproduced and compared to the observations. The statistical analysis showed that
24 the latent heat flux could be reproduced by the Bulk transfer equation with the fixed

1 aerodynamic resistance and canopy resistance sub-model, the index of agreement
2 between modeled and measured values was higher than 0.8 for all growing stages. The
3 model constructed in the present study would be an easy and relatively accurate way to
4 determine greenhouse cucumber water consumption and to make the appropriate
5 irrigation schedule.

6 **Appendix 1**

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

$$8 \quad N_u = \frac{h_s \cdot d}{\lambda_a} \quad (\text{A1})$$

9 The Reynolds number (Re) can be expressed as

$$10 \quad Re = \frac{\rho_a \cdot V \cdot d}{\mu_a} \quad (\text{A2})$$

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

$$13 \quad G_r = \frac{g \cdot \beta \cdot \Delta T \cdot d^3 \cdot \rho_a^2}{\mu_a^2} \quad (\text{A3})$$

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

$$16 \quad d = \frac{2}{(1/L+1/W)} \quad (\text{A4})$$

17 where L and W are the length (m) and the width (m) of the leaf, respectively. N_u is the
18 Nusselt number, λ_a ($\text{W m}^{-1}\text{K}^{-1}$) is the air thermal conductivity, Re is the Reynolds
19 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
20 dynamic viscosity, g (m s^{-2}) is the acceleration of gravity, β (K^{-1}) is the volumetric
21 thermal expansion coefficient and ΔT (K) is the temperature difference between the
22 flat plate and the air. More details on the calculation of r_a can be referred in Morille et
23 al. (2013).

1 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 $Re < 3 \times 10^5$ | $Nu = 0.56Re^{(1/2)}$ |
| | Turbulent $Re > 5 \times 10^5$ | $Nu = 0.03Re^{(4/5)}$ |

2

3 **Competing interest**

4 There is no competing interest.

5 **Submission declaration and verification**

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

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2 **Reference**

- 3 Allen, R.G., Pereira, L.S., Raes, D., Smith, M., (1998). Crop evapotranspiration
4 guidelines for computing crop water requirements. *FAO irrigation and Drainage*
5 *Paper 56, Rome, Italy*
- 6 Brutsaert W., (1982). Evaporation in the atmosphere: theory, history, and application. D.
7 *Reidel, Higham, Mass*
- 8 Bailey, B.J., Montero, J.I., Biel, C., Wilkinson, D.J., Anton, A. & Jolliet O., (1993).
9 Evapotranspiration of *Ficus benjamina*: comparison of measurements with
10 predictions of the Penman-Monteith model and a simplified version, *Agricultural*
11 *and Forest Meteorology*, 65:229-243.
- 12 Baille, M., Baille, A., Laury, J.C., (1994). A simplified model for predicting
13 evapotranspiration rate of nine ornamental species vs. climate factors and leaf. *Acta*
14 *Hort. (ISHS)*, 59: 217-232.
- 15 Fujii, T., Honda, H. and Moriaka, I., (1973). A theoretical study of natural convection
16 heat transfer from downward-facing horizontal surfaces with uniform heat flux. *Int.*
17 *J. Heat Mass Transfer*, 16:611-627.
- 18 Fernandez, M.D. et al. (2010). Measurement and estimation of plastic greenhouse
19 reference evapotranspiration in a Mediterranean climate. *Irrig Sci.*, 28:497–509.
- 20 Green, A.E., Clothier, B.E., Kerr, J.P., Scotter, D.R., (1984). Evapotranspiration from
21 pasture: a comparison of lysimeter and Bowen ratio measurements with
22 Priestley-Taylor estimates, *New Zealand Journal of Agricultural Research*, 27:3,
23 321-327.
- 24 Gong, X., Liu, H., Sun, J. et al. (2017). A proposed surface resistance model for the

1 Penman-Monteith formula to estimate evapotranspiration in a solar greenhouse. *J.*
2 *Arid Land*, 9: 530. <https://doi.org/10.1007/s40333-017-0020-8>.

3 Harmandeep, S., Manoj, K.S., Paul, W.B., Robert, S., (2016). Soil moisture sensor
4 calibration, actual evapotranspiration, and crop coefficients for drip irrigated
5 greenhouse chile peppers. *Agricultural Water Management*,
6 doi.org/10.1016/j.agwat.2016.07.001.

7 Jarvis, P.J., (1976). The interception of the variations in leaf water potential and
8 stomatal conductance found in canopies in the field. *Philosophical Transactions of*
9 *the Royal Society of London*, B273:593-610.

10 Kreith, F., (1965). Principles of Heat Transfer. International Texbook Co. Scranton, PA,
11 656 pp.

12 Katerji, N. and Rana, G., (2006). Modelling evapotranspiration of six irrigated crops
13 under Mediterranean climate conditions. *Agricultural and Forest Meteorology*,138:
14 142–155.

15 Kite, G., (2000). Using a basin-scale hydrological model to estimate crop transpiration
16 and soil evaporation. *J. Hydrol.*, 229: 59–69.

17 Law, B.E., Falge, E., Gu, L., Baldocchi, D.D., Bakwin, P., Berbigier, P., Davis, K.,
18 Dolman, A.J., Falk, M., Fuentes, J.D. et al. (2002). Environmental controls over
19 carbon dioxide and water vapour exchange of terrestrial vegetation. *Agric. Forest*
20 *Meteorol.*, 113: 97–120.

21 Luo, Y., Jiang, Y., Peng, S., Khan, S., Cai, X., Wang, W., Jiao, X., (2012). Urban
22 weather data to estimate reference evapotranspiration for rural irrigation
23 management. *Journal of Irrigation and Drainage Engineering*, 138(9):837-842.

24 Li, S., Hao, H., Du, T., Tong, L., Zhang, J., Kang, S., (2014). A coupled surface

1 resistance model to estimate crop evapotranspiration in arid region of northwest
2 China. *Hydrol. Process*, 28: 2312–2323.

3 Liu, H., Sun, J., Duan, A., Sun, L., Shen, X., (2008). Experiment on soil evaporation
4 among plant of Chinese cabbage in sunlight greenhouse, *Journal of Soil and Water*
5 *Conservation*, 22(1):207-211. (In Chinese)

6 Liu, H., Sun, J.s., Duan, A.W. et al., (2009). Experiment on soil evaporation of radish in
7 sunlight greenhouse. *Transactions of the CSAE*, 25(1): 176–180. (In Chinese)

8 Montero, J.I., Antón, A., Muñoz, P. & Lorenzo, P., (2001). Transpiration from
9 geranium grown under high temperatures and low humidities in greenhouses,
10 *Agricultural and Forest Meteorology*, 107:323-332.

11 Morille, B., Migeon, C., Bournet, P.E., (2013). Is the Penman-Monteith model adapted
12 to predict crop transpiration under greenhouse conditions? Application to a New
13 Guinea Impatiens crop. *Scientia Horticulturae*, 152: 80-91.

14 Nie, Q., Luo, Y., Liu, F. et al. (2017) Assessment of risk-based irrigation
15 decision-making with consideration of future rainfall [J]. *Journal of Drainage and*
16 *Irrigation Machinery Engineering*, 35(3): 256-262. (In Chinese with English
17 abstract)

18 Oue, H., (2005). Influences of meteorological and vegetational factors on the
19 partitioning of the energy of a rice paddy field, *Hydrological Processes* 19(8):
20 1567–1583

21 Payero, J. and Irmak, S., (2013). Daily energy fluxes, evapotranspiration and crop
22 coefficient of soybean. *Agric. Water Management*, 129:31-43.

23 Qiu, R., Kang, S., Li, F., Du, T., Tong, L., Wang, F., Chen, R., Liu, J., Li, S., (2011).
24 Energy partitioning and evapotranspiration of hot pepper grown in greenhouse with

- 1 furrow and drip irrigation methods. *Sc. Hort.*, 129:790-797.
- 2 Qiu, R., Kang, S., Du, T., Tong, L., Hao, X., Chen, R., Chen, J., Li, F., (2013). Effect of
3 convection on the Penman–Monteith model estimates of transpiration of hot pepper
4 grown in solar greenhouse. *Sc. Hort.*, 160:163-171.
- 5 Rouphael, Y., Colla, G., (2004). Modelling the transpiration of a solar greenhouse
6 zucchini crop grown under a Mediterranean climate using the Penman–Monteith
7 equation and its simplified version. *Aust. J. Agric. Res.* 55 (9), 931–937.
- 8 Stanghellini, C., (1987). Transpiration of Greenhouse Crops: An Aid to Climate
9 management. *PhD dissertation, Agricultural University of Wageningen, the*
10 *Netherlands.*, 150 p.
- 11 Todorovic, M., (1999). Single-layer evapotranspiration model with variable canopy
12 resistance. *J.Irrig. and Drain. Eng.*125(5):235-245.
- 13 Takakura, T., Kubota, C., Sase, S., Hayashi, M., Ishii, M., Takayama, K., Giacomelli,
14 G.A., (2009). Measurement of evapotranspiration rate in a single-span greenhouse
15 using the energy-balance equation. *Biosystems Engineering*, 102: 298-304.
- 16 Tuzel, Y., Ui, M. A., Tuzel, I.H., (1994). Effects of different irrigation intervals and
17 rates on spring season glasshouse tomato production: II, Fruit quality. *Acta Hort*
18 *(ISHS)*, 366, 389-396.
- 19 Wight, J.R., Hanson, C.L., Wright, J.L., (1993). Comparing Bowen ratio-energy balance
20 systems for measuring ET. In: Allen RG, Van Bavel CMU (Eds.), Management of
21 Irrigation and Drainage Systems, Integrated Perspectives. *Am Soc Civ Eng, New York*,
22 pp. 953–960
- 23 Willmott, C. J., (1981). On the validation of models. *Physical Geography*, 2: 184-194.
- 24 Xu L., Su Y., Liang Y., (2013). Requirement and current situation of control-oriented

- 1 microclimate environmental model in greenhouse system[J]. *Transactions of the*
2 *Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 29(19):
3 1–15. (in Chinese with English abstract).
- 4 Yan, H. and Oue, H., (2011). Application of the two-layer model for predicting
5 transpiration from the rice canopy and water surface evaporation beneath the canopy.
6 *J Agric Meteorol*, 67(3):89–97
- 7 Yan, H., Zhang, C., Oue, H., Wang, G., He, B., (2015a). Study of evapotranspiration
8 and evaporation beneath the canopy in a buckwheat field. *Theoretical and applied*
9 *climatology*, 122:721-728.
- 10 Yan, H., Shi, H., Oue, H., Zhang, C., Xue, Z., Cai, B., Wang, G., (2015b). Modeling
11 bulk canopy resistance from climatic variables for predicting hourly
12 evapotranspiration of maize and buckwheat. *Meteorology and Atmospheric Physics*,
13 127(3):305–312.
- 14 Yan, H., Zhang, C., Peng G., Darko, R., Cai, B., (2015b). Modeling bulk canopy
15 resistance from climatic variables for predicting hourly evapotranspiration of maize
16 and buckwheat. *Meteorology and Atmospheric Physics*, 127(3):305–312.
- 17 Yin C., Fei L., Liu L. et al., (2018). Effects of water-fertilizer coupling on physiological
18 characteristics of facility planting cowpea [J]. *Journal of Drainage and Irrigation*
19 *Machinery Engineering*, 36(3): 267–276.
- 20 Zhang, L., Lemeur, R., (1992). Effect of aerodynamic resistance on energy balance and
21 Penman–Monteith estimates of evapotranspiration in solar greenhouse conditions.
22 *Agric. Forest Meteorol.* 58 (3–4), 209–228.
- 23 Zhao, N., Liu, Y., Cai, J., Paredes, P., Rosa, R.D., Pereira, L.S., (2013). Dual crop
24 coefficient modelling applied to the winter wheat–summer maize crop sequence in

1 North China Plain: Basal crop coefficients and soil evaporation component. *Agric.*
2 *Water Management*, 117, 93–105.

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5 plants inside the greenhouse
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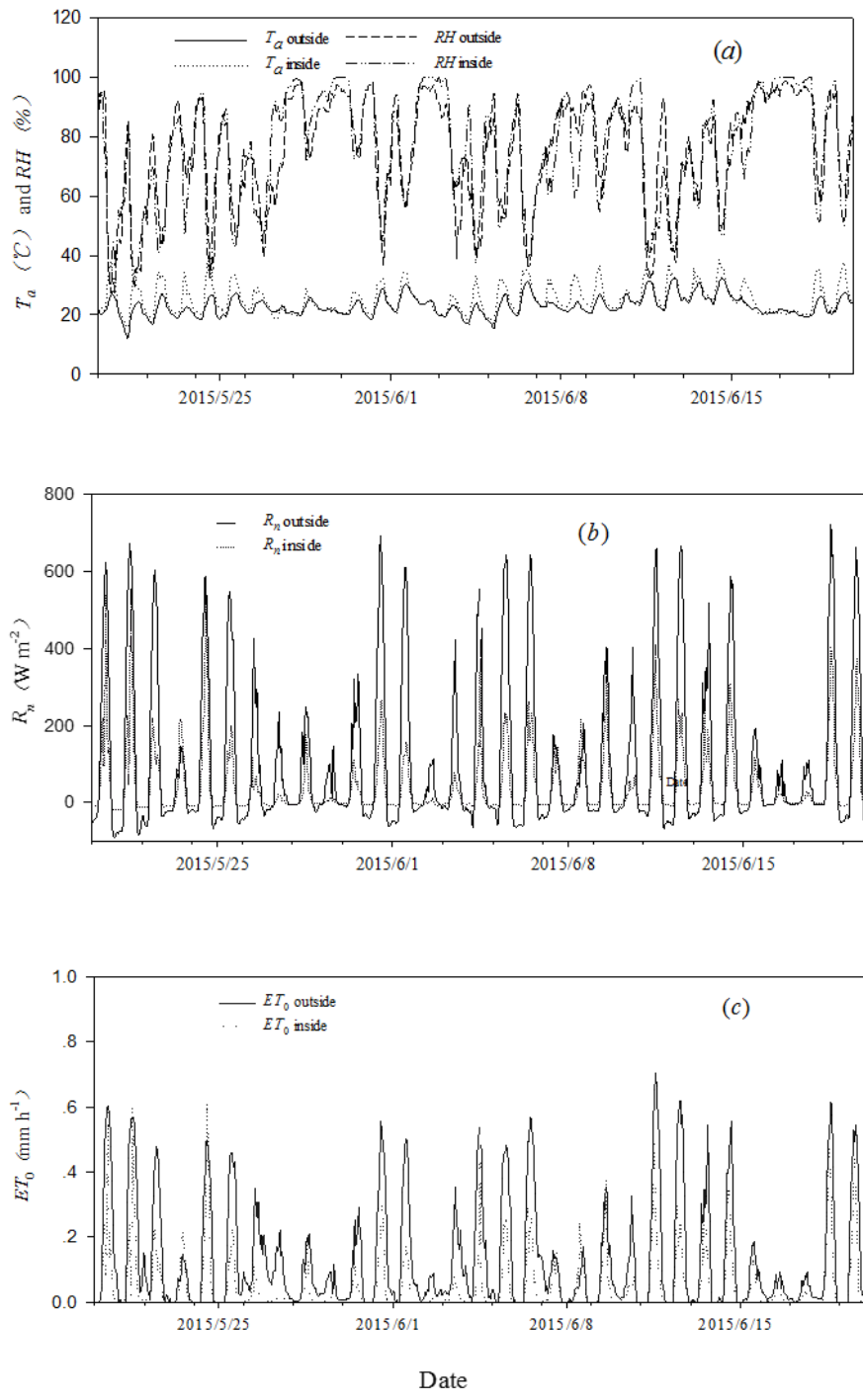
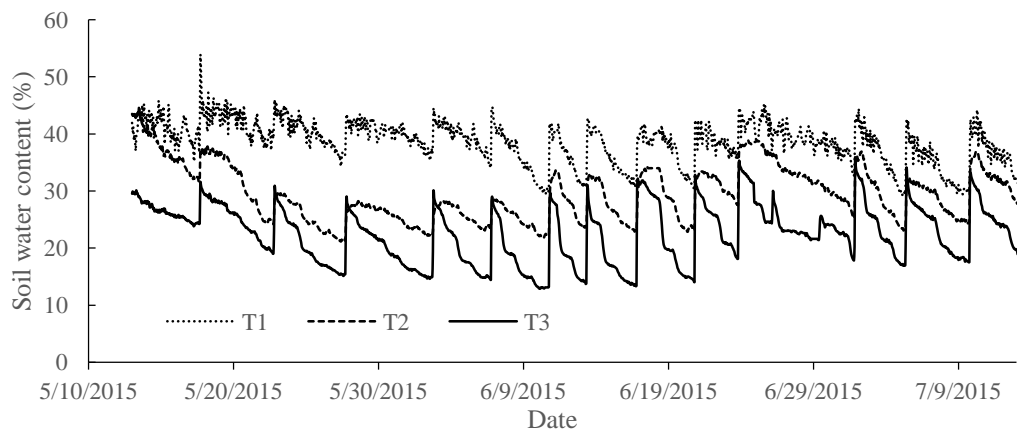


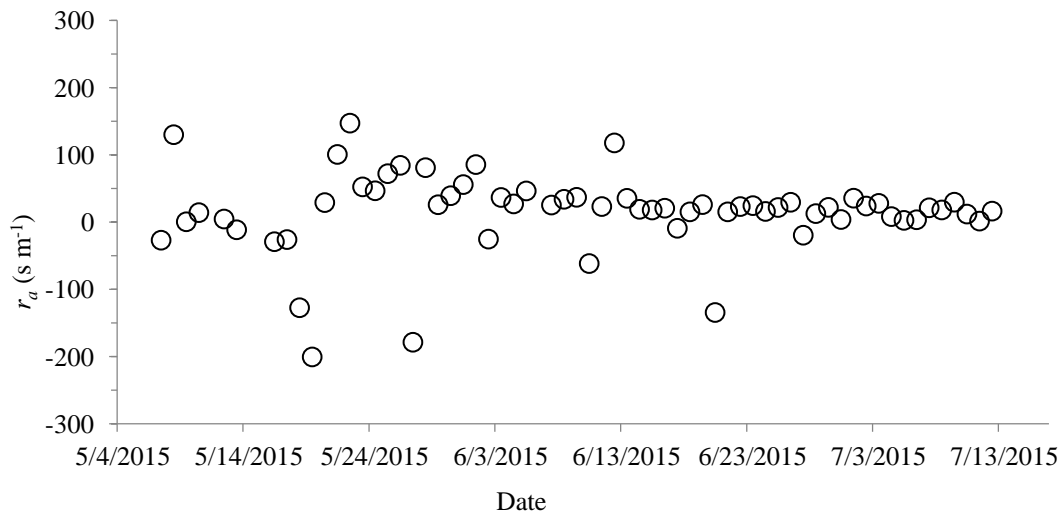
Fig.1 The observed hourly meteorological and ET_0 data inside and outside the greenhouse in 2015.

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Fig.2 The variations of soil water content at 5 cm depth during cucumber growing season in 2015 under different irrigation water treatments. T_1 , T_2 and T_3 represented three treatments of irrigation water amount.



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Fig.3 The variation of r_a calculated by IBTE-method with the measured T_s , T_a and estimated H from energy balance equation in the greenhouse in 2015

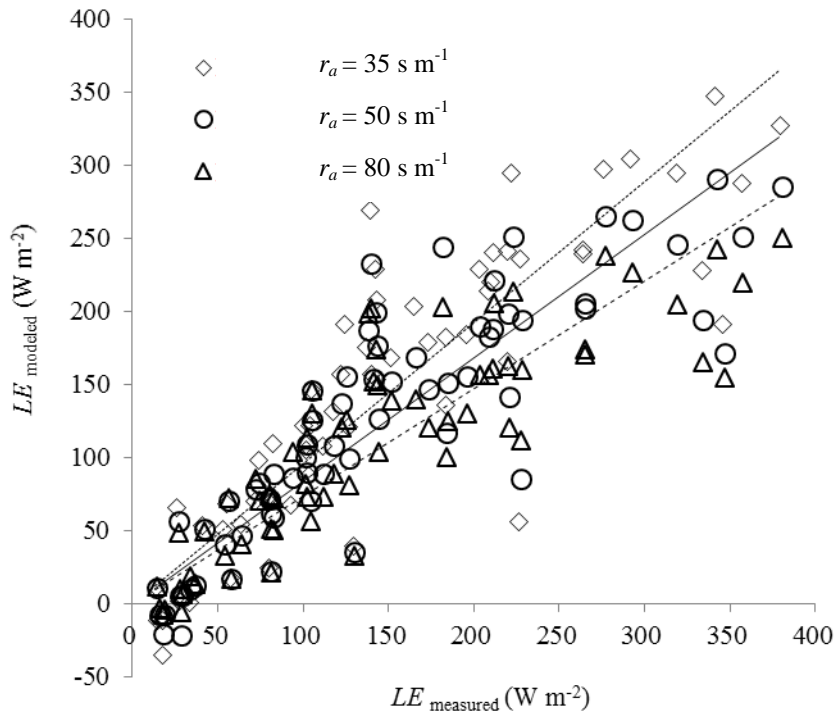
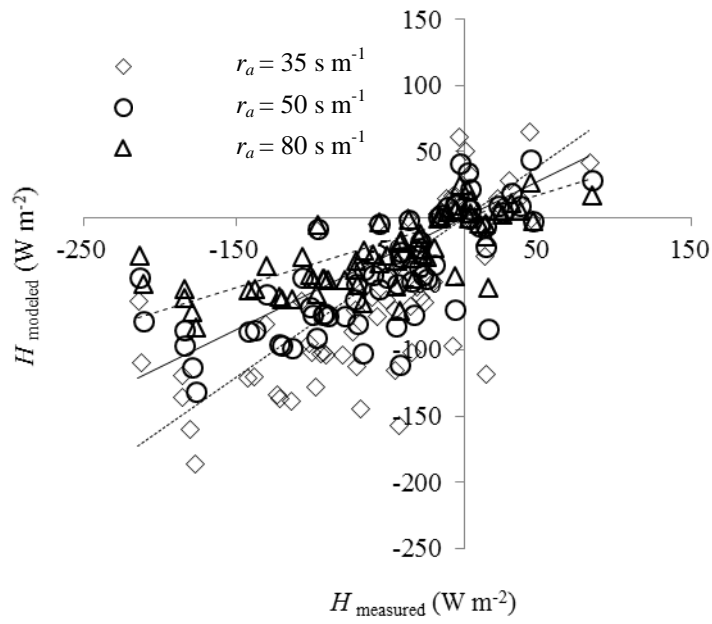
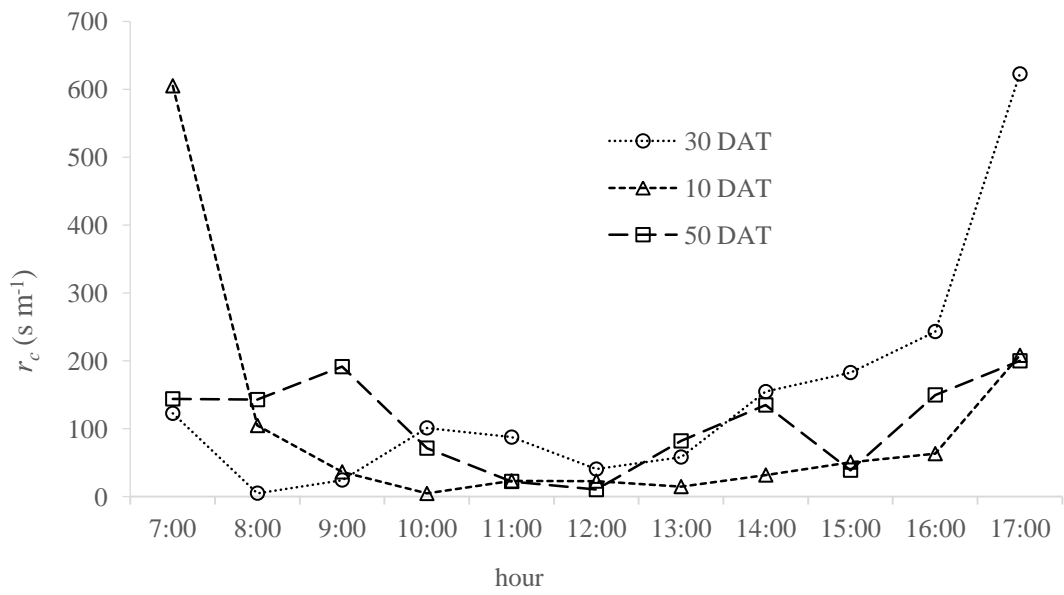


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Fig. 5 The variation of hourly r_c in different growing stages of cucumber plants in 2016.

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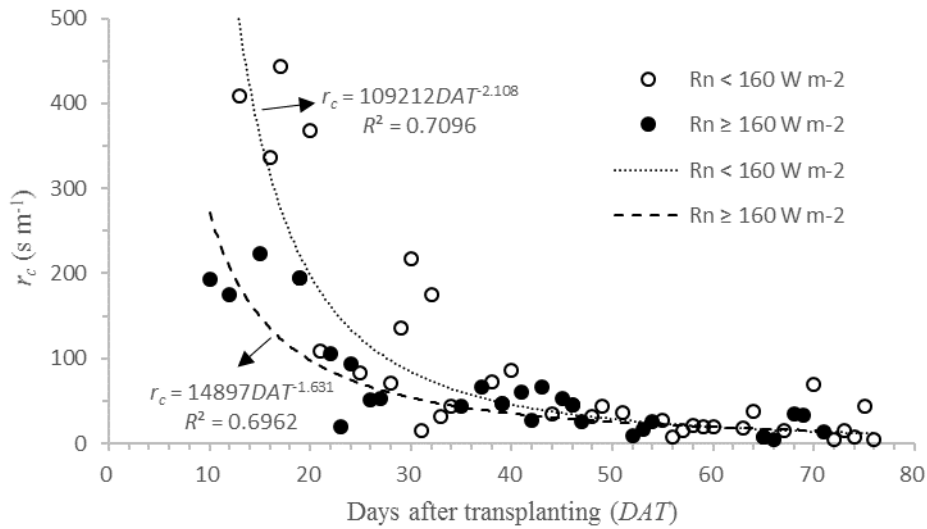


Fig. 6 The variation of daily r_c with the days after transplanting (DAT) during cucumber growing season in 2015.

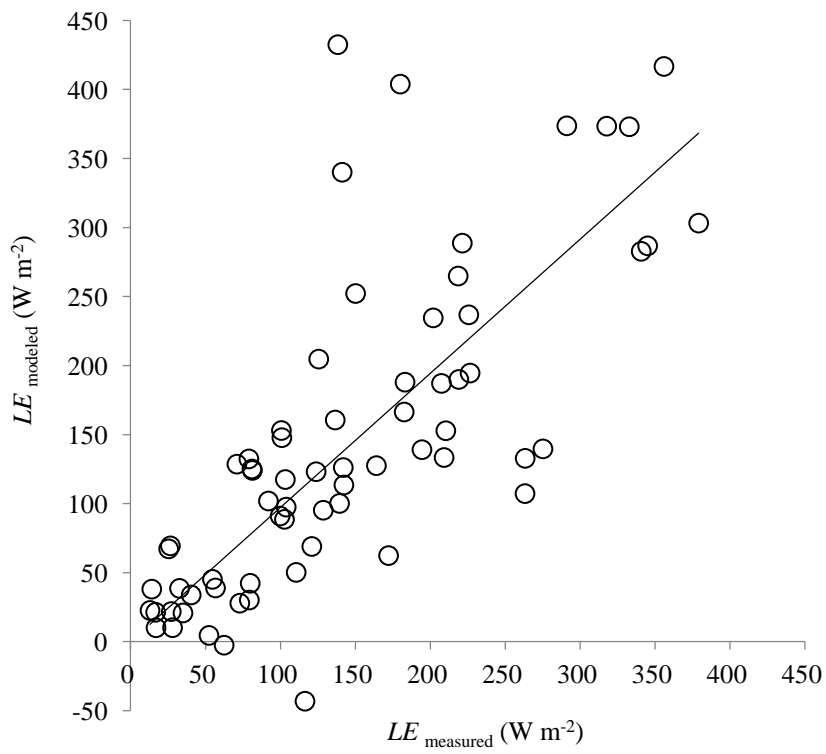


Fig. 7 The comparison between measured and estimated LE with fixed r_a and r_c sub-model, LE_{measured} represents that LE measured with lysimeters (in 2016)

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1 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 |

2 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
 3 square regression line, R^2 is coefficients of determination, $RMSE$ is root mean square error (W m^{-2}), d_H and d_{LET} are
 4 index of agreement for H and LE ; a , R^2 and d are dimensionless. The above calculations were based on the data from
 5 2016.

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

| | M_{LET} | P_{LET} | R^2 | a | $RMSE$ | MSE_s | MSE_u | 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 |

10 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
 11 coefficients of determination, $RMSE$ is root mean square error (W m^{-2}), MSE_s is systematic mean square error (W
 12 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
 13 above calculations were based on the data from 2016.