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Measurement and estimation of the aerodynamic resistance

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Abstract

Using two methods of eddy correlation system and evaporation pan to measure respectively the aerodynamic resistance over bare soil surface and maize field, this paper analyses the diurnal variation of the aerodynamic resistance and its relationship with wind speed. Based on direct measurements by eddy correlation system, an evaluation of the aerodynamic resistance models is made. These models include Thom model, Verma-Ronsenberg model, Monteith-Hatfield model, XieXianqun model, Mahrt-Ek model, Choudhury-1 model and Choudhury-2 model. The results show that: the distribution of the aerodynamic resistance takes a "U" type in the daytime and inverse "V" type at night. The aerodynamic resistance is a power function of wind speed. The aerodynamic resistances measured by eddy correlation system are in agreement with those measured by evaporation pan, but big differences occur when the evaporation rate is very small at night or rainy day. Choudhury-1 model, XieXianqun model and Thom model give the better agreement with the measurements by eddy correlation system both over bare soil surface and the maize field, while Mahrt-Ek Model and Monteith-Hatfield model perform worse.

1 Introduction

Reliable estimation of surface sensible and latent heat fluxes is the most important process in the study of the exchanges of energy and mass among hydrosphere, atmosphere and biosphere. It is difficult for micrometeorological method, climatological method and hydrological method to be used to estimate areal sensible and latent heat flux over the heterogeneous surface. Since 1970s, remote sensing technology has brought the hope of estimating areal sensible and latent heat flux over heterogeneous surface. The development of high resolution, multi-bands, multi-temporal and multi-angular remote sensing data has made it possible to obtain geometric structure, water and heat conditions of surface comprehensively. So compared with other methods, the remote sensing method has obvious superiority to estimate areal sensible and latent heat flux over heterogenrous surface.

For remote sensing method, sensible heat flux is estimated following Ohm's Law, using the difference between surface temperature retrieved from remote sensing data and air temperature. Then latent heat flux can be calculated according to surface energy balance equation expressed as:

$$LE = R_n - G - \rho c_p \frac{(T_s - T_a)}{r_{ah}} \quad (1)$$

Where LE is latent heat flux; R_n is net radiation; G is soil heat flux; ρ is air density; C_p is the specific heat of air at constant pressure; T_s, T_a are surface temperature and air temperature respectively; r_{ah} is the aerodynamic resistance to heat transfer.

From Eq. (1), we know that aerodynamic resistance is a very important parameter when estimating sensible heat flux and latent heat flux with remote sensing method. Based on Monin-Obukhov Similarity Theory, Monteith (1973), Brown and Rosenberg (1973), Verma-Rosenberg (1976), Thom (1975), Itier (1980), Hatfield (1983), Mahrt-Ek (1984), Choudhury (1986), ChenJingming(1986) and XieXianqun(1988) have proposed some models to estimate aerodynamic resistance respectively. Kalma (1990) compared models of Choudhury, Itier, Monteith, Hatfield, Mahrtand Ek with experimental data over wheat field. It was found that the calculated values of Choudhury's and Itier's model are in close agreement, while serious deficiencies were noted with the models of Monteith, Hatfield, Mahrt and Ek. XieXianqun (1991) indirectly validated some models, such as Brown-Rosenberg model, Verma-Rosenberg model, Hatfield model, ChenJingming model and XieXianqun model with Lysimetrically measured data on winter wheat field. The results showed that ChenJingming's model and XieXianqun's model are better than other models. Ham and Heilman (1991) evaluated above-canopy and within-canopy aerodynamic resistances with Bowen ratio measurements, stem flow measurements and meteorological data over sparse cotton field. The results suggested that aerodynamic resistances within and above the canopy were highly variable and only partially explained by average wind speed. Hall (2002) put forward an

aerodynamic resistance model of coppiced poplar. The resulting estimates of aerodynamic resistance are in agreement with values determined from the flux-gradient relationship for sensible heat. Because of lacking of aerodynamic resistance measurements, it is difficult to study the mechanics of aerodynamic resistance and aerodynamic resistance models comprehensively.

In this paper, the eddy correlation system and evaporation pan are used to measure the aerodynamic resistance over bare soil surface and maize field. The diurnal variation of aerodynamic resistance and its relationship with wind speed are analyzed. Based on direct measurements, this paper describes an evaluation of aerodynamic resistance models, including Thom model, Verma-Rosenberg model, Monteith-Hatfield model, XieXianqun model, Mahrt-Ek model, Choudhury-1 model and Choudhury-2 model.

2 Methods

2.1 Measurements of the aerodynamic resistance

2.1.1 Using the evaporation pan to measure the aerodynamic resistance

Monteith (1981) showed that evapotranspiration is determined by surface temperature, air humidity at reference height and the aerodynamic resistance to water vapor transfer over a saturated surface. So the aerodynamic resistance to water vapor transfer r_{av} can be calculated by:

$$r_{av} = \frac{\rho c_p}{\gamma} \frac{e_s(T_s) - e_d}{LE} \quad (2)$$

where r_{av} is the aerodynamic resistance for water vapor transfer; γ is the psychrometric constant; e_s is saturation vapor pressure; e_d is actual vapor pressure.

From Eq. (2), it is known that if all items of the right-hand side of Eq. (2) can be measured, the aerodynamic resistance to water vapor transfer r_{av} will be determined.

The apparatus to measure aerodynamic resistance consisted of four components (Zilin Zhu et al., 2002): 1) An evaporating pan with a fully water-saturated evaporating surface (made of a metal pan of 15-cm diameter and 5-cm depth. A piece of cotton cloth and sponge were immersed into it and both were saturated with water.). 2) An automatic balance (BAL-100, China) to measure the weight change of the evaporating pan and hence the evaporation rate. 3) A psychrometer consisting of web- and dry-bulb resistance thermometers (PT100, China) to measure the actual vapor pressure of the air at reference height. 4) Four precision platinum resistance thermometers (PT100, China) to measure the average temperature of the evaporation surface. Using the apparatus above, the aerodynamic resistance to water vapor transfer r_{av} can be determined by Eq. (2).

2.1.2 Using eddy correlation system to measure the aerodynamic resistance

Thom (1972) pointed out that the aerodynamic resistance for water vapor transfer or for heat transfer will exceed the aerodynamic resistance for momentum transfer. An excess resistance is introduced to express their differences (Stewart and Thom, 1973):

$$\begin{aligned} r_{av} &= r_{ah} = \frac{\Phi_v}{\Phi_m} r_{am} + r_b \\ &= \frac{\Phi_v}{\Phi_m}\frac{u_z}{u_*^2} + r_b \end{aligned} \tag{3}$$

where r_{am} is aerodynamic resistance for momentum transfer; u_Z is wind speed at reference height; u_* is friction velocity; r_b is excess resistance; Φ_v, Φ_m are stability correction functions for water vapor and momentum transfer respectively and can be expressed as (Dyer, 1970):
in unstable conditions

$$\Phi_v = \Phi_m^2 = \left(1 - 16\frac{z-d}{L}\right)^{-1/2} \tag{4}$$

and in stable conditions

$$\Phi_v = \Phi_m = 1 + 5.2\frac{z-d}{L} \tag{5}$$

where z is reference height; d is zero-surface displacement; L is Obukhov length.

Thom (1972) thought that the excess resistance r_b is in proportion with friction velocity u_*, that is:

$$r_b = a \cdot u_*^{-2/3} \tag{6}$$

where a is a constant and equals 6.266 for the unsaturated surface.

From above, it can be concluded that aerodynamic resistance can be determined by using the eddy correlation system to measure wind speed u, friction velocity u_* and Obukhov length L.

2.2 Models to estimate the aerodynamic resistance

2.2.1 Thom model

Thom (1975) presented a model to estimate aerodynamic resistance for heat and water vapor transfer (r_{ah} and r_{av}, expressed as r_a uniformly):

$$r_a = \frac{1}{k^2 u_z}\left[\ln\left(\frac{Z-d}{z_{0m}}\right) - \psi_m\left(\frac{Z-d}{L}\right)\right]\left[\ln\left(\frac{Z-d}{z_{0h}}\right) - \psi_h\left(\frac{Z-d}{L}\right)\right] \tag{7}$$

where κ is von Karman constant; Z_{0h}, Z_{0m} are roughness length for heat transfer and momentum exchange respectively; Ψ_h, Ψ_m are the integral form of the stability correction functions for heat transfer and momentum exchange respectively.

In unstable conditions, Ψ_h, Ψ_m can be expressed as (Webb, 1970; Businger et al., 1971)

$$\Psi_m = 2\ln\left[\frac{(1+x)}{2}\right] + \ln\left[\frac{(1+x^2)}{2}\right] - 2\arctan(x) + \frac{\pi}{2} \tag{8}$$

$$\Psi_h = 2\ln\left[\frac{(1+x^2)}{2}\right] \tag{9}$$

In stable conditions (Paulson, 1970)

$$\Psi_m = \Psi_h = -5\xi \tag{10}$$

where

$$\xi = (z-d)/L \tag{11}$$

$$x = (1-16\xi)^{1/4} \tag{12}$$

2.2.2 Verma-Rosenberg model

In neutral conditions, supposing the roughness length for heat transfer and momentum exchange are the same, Eq. (7) can be expressed as:

$$r_{aa} = \frac{\left[\ln\left(\frac{z-d}{z_{0m}}\right)\right]^2}{k^2 u_z} \tag{13}$$

r_{aa} is aerodynamic resistance in neutral conditions.

Based on Brown and Rosenberg (1973), Verma and Rosenberg (1976) put forward a model to estimate r_a with aerodynamic method to correct atmosphere stability:

$$r_a = \frac{K_M}{K_H} r_{aa} \tag{14}$$

where K_H is the transfer coefficient for heat; K_M is the transfer coefficient for water vapor.

In unstable conditions,

$$\frac{K_M}{K_H} = 1/(1-16Ri)^{0.25} \tag{15}$$

where Ri is Richardson number and can be calculated by

$$Ri = \frac{g}{\bar{\theta}}\sqrt{z_2 z_1}\ln\left(\frac{z_2}{z_1}\right)\frac{(\theta_2-\theta_1)}{(u_2-u_1)^2} \tag{16}$$

where θ_1, θ_2, u_1, u_2 are corresponding potential temperature and wind speed respectively at reference heights Z_1, Z_2; $\overline{\theta}$ is average potential temperature between Z_1 and Z_2.

In stable conditions

$$\frac{K_M}{K_H} = 1 \tag{17}$$

2.2.3 Monteith-Hatfield model

Using Monteith's stability correction function (Monteith, 1973; Hatfield, 1983) proposed a model to estimate r_a

$$r_a = r_{aa}\left[1 - n(z-d)\cdot g\cdot(T_s - T_a)/T_a u_z^2\right] \tag{18}$$

where n is empirical coefficient and equals to 5 here.

2.2.4 XieXianqun' model

Based on stability correction functions of Dyer (1970) for unstable conditions and Webb (1970) for stable conditions, XieXianqun (1988) presented a model to calculate r_a

$$r_a = r_{aa}\left[1 + \frac{\Phi_h}{\ln\left(\frac{z-d}{z_{0m}}\right)}\right] \tag{19}$$

Φ_h is stability correction function for heat transfer, in unstable conditions

$$\Phi_h = \left(1 - 16\frac{z-d}{L}\right)^{-1/2} \quad \frac{z-d}{L} < -0.03 \tag{20}$$

in stable conditions

$$\Phi_h = 1 + n\frac{z-d}{L} \quad \frac{z-d}{L} > 0 \text{ or } -0.03 < \frac{z-d}{L} < 0 \tag{21}$$

where n is empirical coefficient, when $\frac{z-d}{L}$<0, n=4.5; when $\frac{z-d}{L}$>0, n=5.2.

2.2.5 Mahrt-Ek model

Based on Louis (1979, 1982), Mahrt and Ek (1984) gave a simple method to calculate r_a

$$r_a = \frac{1}{c_q u_z} \tag{22}$$

where c_q is transfer coefficient.
In unstable conditions,

$$c_q = \left[\frac{k}{\ln\left(\frac{z+z_{0m}}{z_{om}}\right)}\right]^2 \left(1 - \frac{15Ri}{1 + c(-Ri)^{1/2}}\right) \tag{23}$$

where

$$c = \frac{75k^2\left(\frac{z+z_{0m}}{z_{0m}}\right)^{1/2}}{\left[\ln\left(\frac{z+z_{0m}}{z_{0m}}\right)\right]^2} \tag{24}$$

In stable conditions,

$$c_q = \left[\frac{k}{\ln\left(\frac{z+z_{0m}}{z_{0m}}\right)}\right]^2 \frac{1}{(1+15Ri)(1+5Ri)^{1/2}} \tag{25}$$

2.2.6 Choudhury-1 model

Choudhury et al. (1986) provided an expressions for r_a, which are based on an exact solution for stable conditions and a close approximation for unstable conditions.

$$r_a = \frac{\left[\ln\left(\frac{z-d}{z_{0h}}\right) - \Psi\right]\left[\ln\left(\frac{z-d}{z_{0m}}\right) - \Psi\right]}{k^2 u_z} \tag{26}$$

In stable conditions

$$\Psi = \frac{\left[b - \left(b^2 - 4ac\right)^{1/2}\right]}{2a} \tag{27}$$

$$a = 1 + \eta \tag{28}$$

$$b = \ln\left(\frac{Z-d}{z_{0m}}\right) + 2\eta\ln\left(\frac{Z-d}{z_{0m}}\right) \tag{29}$$

$$c = \eta\left[\ln\left(\frac{Z-d}{z_{0m}}\right)\right]^2 \tag{30}$$

$$\eta = 5(Z-d)g\frac{(T_s - T_a)}{T_a u_z^2} \tag{31}$$

when Ψ<−5, then Ψ=−5.
In unstable and neutral conditions,

$$r_a = \frac{\ln\left(\frac{z-d}{z_{0h}}\right)\ln\left(\frac{z-d}{z_{0m}}\right)}{k^2 u_z (1+\eta)^{3/4}} \tag{32}$$

2.2.7 Choudhury-2 model

Choudhury et al. (1986, 1988) also proposed an approximate equation for r_a in non-neutral conditions:

$$r_a = \frac{r_{aa}}{(1+\eta)^p} \tag{33}$$

In unstable conditions, p is 3/4; in stable conditions, p is 2.

Over maize field, roughness length of momentum transfer Z_{0m} and zero plane displacement d can be expressed as (Monteith, 1973)

$$z_{0m} = 0.13h \tag{34}$$

$$d = 0.63h \tag{35}$$

Where h is crop height.

Roughness length for heat transfer Z_{0h} is calculated by (Kustas et al., 1989)

$$\ln\frac{z_{0m}}{z_{0h}} = 0.17u_z\,(T_s - T_a) \tag{36}$$

Over bare soil surface, roughness length for momentum transfer Z_{0m} is 0.01, zero plane displacement d is 0, $\ln\frac{z_{om}}{z_{0h}}$ is taken as 2 (Garratt et al., 1973).

3 Site description and measurements

The experiment was conducted at Xiao Tangshan National Experimental Station for Precision Agriculture in Changping District, Beijing from 30 May to 6 July 2004. The experimental field was flat and open with an area of 167 hectares. The experimental field was at the southeast of the experiment station, 1000 m long from north to south and 500 m wide from east to west, a byway at the middle of the experimental field divided it into two small plots of south and north. The observation was conducted at the

southern plot. Its latitude, longitude and altitude are 116°26′52″ E, 40°10′41″ N and 35 m respectively. The southern plot was bare soil from 30 May to 17 June, and the maize emerged on 17 June. The evaporation pan to measure the aerodynamic resistance was laid closely to the ground over bare soil surface and laid at 2/3 of crop height over maize field. A set of automatic meteorological station was placed at the center of the plot, including air temperature, air humidity and wind speed at two heights (1.5 m, 3.5 m). Air temperature and humidity were measured by temperature and relative humidity probe (HMP45C, Vaisala). Wind speed and wind direction were measured by 3D sonic anemometer (Model 81000, USA). There was also an eddy correlation system at there, consisted of a 3D sonic anemometer (CSAT3, Campball) and a CO_2/H_2O analyzer (LI7500, Campball). The height of the eddy correlation system is 1.8 m, sampling at a frequency of 10 Hz. Surface temperature were obtained with an infrared thermocouple (IRt/c.sv, USA) with a 6.5–14 μm band pass and a 60° field of view. The infrared thermocouple was mounted at 1.2 m and pointed to the south under an angle of about 45° to the vertical. All above data was averaged every 10 min. Some ancillary parameters such as crop height were measured every 5 days.

4 Results and discussions

4.1 Diurnal variation of the aerodynamic resistance measured

Figures 1a, 1b, 1c, 1d, 1e, 1f, 1g, 1h present diurnal variations of the aerodynamic resistance measured by the evaporation pan (07:00–17:00) and eddy correlation system (00:00–24:00) on 6, 8, 10, 11, 19, 23, 24 and 27 June 2004 over bare soil surface and maize field respectively. It shows that whether over bare soil surface or maize field, the aerodynamic resistance measurements reach peak values at 04:00–05:00 in the early morning, then reduce continuously and are approximately stable after 09:00. About 16:00, the aerodynamic resistance measurements begin to increase again. The distribution of the aerodynamic resistance measured takes a “U” type in the daytime

(05:00–19:00) and inverse "V" type at night (19:00–05:00).

4.2 The effect of wind speed on the aerodynamic resistance

Figures 2a, b show the relationship between the aerodynamic resistance measured and wind speed over both bare soil surface and maize field with the evaporation pan and eddy correlation system respectively. It has been found that whether over bare soil surface or maize field, the variation trend of the aerodynamic resistance measured from the two methods is almost the same. When wind speed is smaller, the aerodynamic resistance measured sharply reduces with the increase of wind speed. When wind speed reaches at a certain level, about 4 m/s, its variation is gentler with wind speed increasing. The aerodynamic resistance measured from the two methods is all power functions of wind speed. The relationship between the aerodynamic resistance measured by the evaporation pan (R_{a1}) and wind speed u_z can be expressed as:

$$R_{a1} = 94.909u_z^{-0.9036} \tag{37}$$

$(N = 183,\ r = 0.7304)$

The relationship between the aerodynamic resistance measured by eddy correlation system (R_{a2}) and wind speedu_z can be expressed as:

$$R_{a2} = 87.54u_z^{-0.4277} \tag{38}$$

$(N = 490,\ r = 0.6064)$

4.3 Comparison of two methods to measure the aerodynamic resistance measured

Figure 3 shows the comparison of R_a measured from the evaporation pan and eddy correlation system. It has been found that whether over bare soil surface or maize field, the measured values of R_a from two methods are relatively the same, and most points scatter near the 1:1 line. Just when the aerodynamic resistance is larger, in other

words, the evaporating rate is smaller, the measured values ($R_{a1.}$) from the evaporation pan are smaller than those ($R_{a2.}$) from eddy correlation system. The linear relationship between them is

$$R_{a1} = 0.7066R_{a2} + 15.77 \tag{39}$$

$(N = 183\ \ r = 0.6725)$

In all, using eddy correlation system to measure the aerodynamic resistance is precise and reliable, but the operation is complex and the price is high. The evaporation pan method is simple, practical and cheap, but the measurement error is larger when the evaporating rate is smaller at night or rainy day.

4.4 Performance of models to estimate the aerodynamic resistance

Figures 4a, 4b, 4c, 4d, 4e, 4f, 4g show comparisons between the aerodynamic resistances measured by eddy correlation system and the calculated by various models over both bare soil surface and maize field. Whether over bare soil surface or maize field, there is a good agreement between the calculated by Choudhury-1 model, Xie Xianqun model and Thom model while Mahrt-Ek model and Monteith-Hatfield model give greater scatter. In detail, the line within plots represents a perfect agreement between the measured and the predictions of Thom model except measured R_a>80 s/m.

Verma-Rosenberg model and Monteith-Hatfield model underestimates aerodynamic resistance obviously both over bare soil and maize field. Verma-Rosenberg model and Monteith-Hatfield model significantly underestimates the measurements of R_a>120 s/m over maize field.

XieXianqun model and Choudhury-1 model give the better agreement with the measurements, especially when the measured R_a<80 s/m. Mahrt-Ek model underestimates when the measured R_a<60 s/m and overestimates when the measured R_a>60 s/m over both bare soil surface and maize field. Choudhury-2 model underestimates over both bare soil surface and maize field, especially when the measured R_a>120 s/m.

Compared with the measurements of eddy correlation system, the performance of these models is analyzed, which include Thom model, Verma-Ronsenberg model, Monteith-Hatfield model, XieXianqun model, Mahrt-Ek model, Choudhury-1 model and Choudhury-2 model. Model performance is quantitatively measured with the different statistics between the model predictions and the measurements of the aerodynamic resistance. The difference statistics include mean relative difference (MRD), mean absolute difference(MAD), correlation coefficient (r) and the index of agreement (IA). IA can be calculated as follows (Willmott, 1982):

$$IA = 1 - \left[\sum_{i=1}^{n} (P_i - O_i)^2 / \sum_{i=1}^{n} \left(\left| P_i - \overline{O} \right| + \left| O_i - \overline{O} \right| \right)^2 \right] \tag{40}$$

where P_i is the calculated value; O_i is the measured value; $\overline{O}$ is the average of the measurements.

The mean relative difference, mean absolute difference, the correlation coefficient and the index of agreement for various models are listed in Table 1. From the table, the following conclusions can be made: under stable conditions ($Ri>0$), the performance of Xie Xianqun model is best, having the smallest MRD and MAD, the largest r and IA. Choudhury-1 model and Thom model take second place. The performance of Mahrt-Ek model is worst, having the largest MRD and MAD, the smallest correlation r and IA. Under unstable conditions ($Ri<0$), Choudhury-1 model is the best, with smallest MRD and MAD, the largest r and IA. XieXianqun model and Thom model are better. Monteith-Hatfield model is the worst, with the largest MRD and MAD, the smallest r and IA. For Xie Xianqun model, Verma-Rosenberg model and Monteith-Hatfield model, the performance under stable conditions is better than unstable conditions. While for Mahrt-Ek model, the performance under unstable conditions is better than stable conditions. For other models, the difference of performance is not obvious. These quantitative results are consistent with the above qualitative findings about performance of these models from Fig. 4.

4.5 Sensitivity analysis

From the above, we can find the performance of models to estimate the aerodynamic resistance. But the question why some models performed better than others still is unanswered. In this section, we will attempt to address this question by analyzing the sensitivities of models to parameters. Because the values of parameters used in these models for the aerodynamic resistance contain a level of uncertainty. If the calculated values of a model are more sensitive to the uncertainty in the values of parameters, then significant differences between the calculated and measured may result from inherent errors associated with model parameters.

In this paper, the sensitivity S_x of an aerodynamic resistance model to a parameter X_i is defined as follows (X. Zhan et al., 1996):

$$S_x = \left| \frac{r_a(1.1X_i) - r_a(0.9X_i)}{r_a(X_i)} \right| \tag{41}$$

where r_a is the aerodynamic resistance calculated from the model, X_i is a parameter in the model.

The sensitivity of Thom model, Verma-Ronsenberg model, Monteith-Hatfield model, Xie Xianqun model, Mahrt-Ek model, Choudhury-1 model and Choudhury-2 model to common parameters and the parameters associated with a particular model is listed in Table 2.

From Table 2, we can know that these models show larger sensitivity to wind speed (U_z) and the stability parameter (Ri, L, η) compared to other parameters, the values of S_x are all larger than 0.1. Monteith-Hatfield model, Mahrt-Ek model, Verma-Rosenberg model and Choudhury-2 model are also to some degree sensitive to surface roughness Z_{om}, the values of S_x are 0.1. Because surface roughness is not easily determined over heterogeneous surfaces, so Choudhury-1 model, Xie Xianqun model and Thom model have significant advantages to estimate the aerodynamic resistance over complex surfaces.

In addition, Monteith-Hatfield model and Mahrt-Ek model show to some degree sensitivity to reference height Z, the values of S_x are lager than 0.1. The values of S_x in Table 2 indicate a large sensitivity of Monteith-Hatfield model to surface temperature T_s and air temperature T_a.

5 Conclusions

The following conclusions have been drawn from above analysis:

Using eddy correlation system to measure the aerodynamic resistance is precise and reliable, but the operation is complex and the price is high. The evaporation pan method is simple, practical and cheap, but large differences occur when evaporating rate is smaller at night or rainy day.

The distribution of the aerodynamic resistance takes a "U" type in the daytime (05:00–19:00) and inverse "V" type at night (19:00–05:00). The aerodynamic resistance reduces along with the increase of wind speed and is a power function of wind speed.

From the comparisons of estimated versus measured aerodynamic resistance over both bare soil surface and maize field, under stable conditions, Xie Xianqun model performs best, Choudhury-1 model and Thom model are better, while Mahrt-Ek model performs worst. Under unstable conditions, Choudhury-1 model performs best, Xie Xianqun model and Thom model take the second place, while Monteith-Hatfield model is the worst. So Choudhury-1 model, Xie Xianqun model and Thom model should be chosen to estimate the aerodynamic resistance for models of sensible heat flux by remote sensing.

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Table 1. The precision analysis of aerodynamic resistance models.

Model	MRD(%)		MAD(s/m)		*r*		*IA*	
	Ri>0	*Ri<0*	*Ri>0*	*Ri<0*	*Ri>0*	*Ri<0*	*Ri>0*	*Ri<0*
Thom	26.14	27.27	21.68	17.95	0.71	0.74	0.76	0.83
Verma-Rosenberg	28.97	38.80	24.02	25.53	0.67	0.59	0.70	0.60
Monteith-Hatfield	32.10	50.01	26.62	32.91	0.56	0.36	0.62	0.48
Xiexianqun	18.99	26.44	15.75	17.40	0.71	0.69	0.82	0.82
Mahrt-Ek	72.95	48.56	60.49	31.96	0.56	0.55	0.41	0.53
Choudhury-1	21.97	23.06	18.22	15.18	0.63	0.71	0.78	0.84
Choudhury-2	33.18	30.21	27.52	21.20	0.45	0.65	0.60	0.66

When Richardson number $Ri>0$, the number of samples N equals to 128; when $Ri<0$, $N=374$.

Table 2. The parameter sensitivity of models.

Parameter	Thom	Verma -Rosenberg	Monteith -Hatfield	Xie xianqun	Mahrt-Ek	Choudhury -1	Choudhury -2
Z	0.05	0.09	0.15	0.09	0.1	0.03	0.04
d	0.01	0.01	0.02	0.01	0.00	0.00	0.00
Z_{0m}	0.08	0.1	0.1	0.07	0.1	0.07	0.1
Z_{0h}	0.03					0.03	
U_z	0.20	0.20	0.30	0.20	0.20	0.20	0.20
Ri		0.12			0.14		
L	0.11			0.10			
η						0.13	0.13
T_s			1.11				
T_a			0.94				

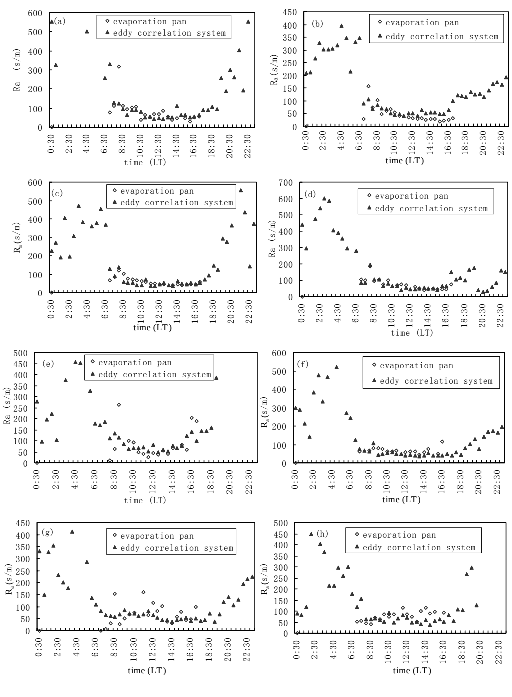

Fig. 1. Diurnal variation of the aerodynamic resistances measured by the evaporation pan and eddy correlation system: **(a) (b) (c) (d)** bare soil surface (6, 8, 10, 11 June); **(e) (f) (g) (h)** maize field (19, 23, 24, 27 June).

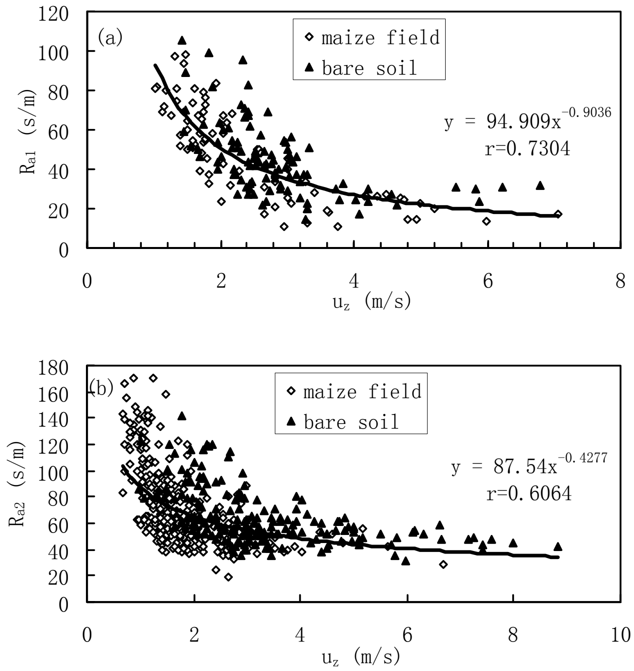

Fig. 2. The relationship between the aerodynamic resistances measured and wind speed over both bare soil surface and maize field by the evaporation pan and eddy correlation system respectively: **(a)** the evaporation pan; **(b)** eddy correlation system.

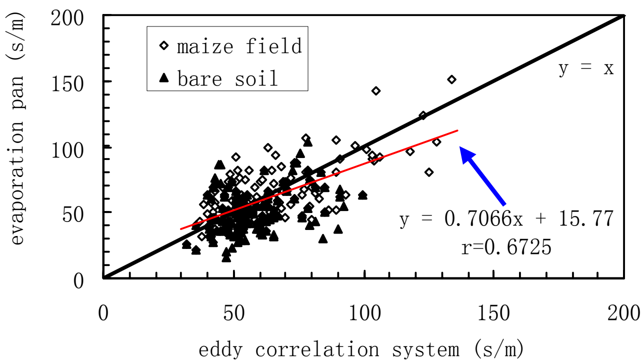

Fig. 3. Comparison between the aerodynamic resistances measured from the evaporation pan and eddy correlation system.

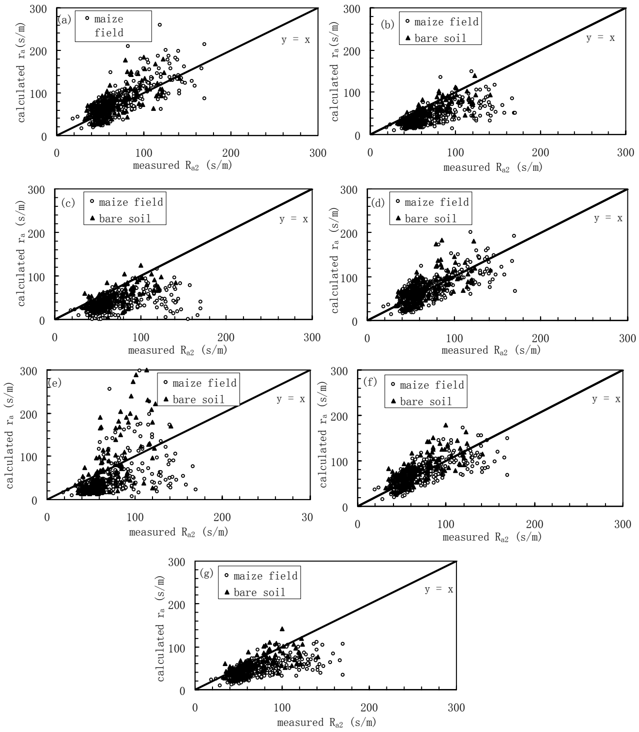

Fig. 4. Comparisons between the aerodynamic resistances measured by eddy correlation system and the calculated by various models over both bare soil surface and maize field: **(a)** Thom model; **(b)** Verma-Rosenberg model; **(c)** Monteith-Hatfield model; **(d)** Xie Xianqun model; **(e)** Mahrt-Ek model; **(f)** Choudhury-1 model; **(g)** Choudhury-2 model.