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Evaluating parameterizations of aerodynamic resistance to heat transfer using field measurements

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Abstract. Parameterizations of aerodynamic resistance to heat and water transfer have a significant impact on the accuracy of models of land – atmosphere interactions and of estimated surface fluxes using spectro-radiometric data collected from aircrafts and satellites. We have used measurements from an eddy correlation system to derive the aerodynamic resistance to heat transfer over a bare soil surface as well as over a maize canopy. Diurnal variations of aerodynamic resistance have been analyzed. The results showed that the diurnal variation of aerodynamic resistance during daytime (07:00 h–18:00 h) was significant for both the bare soil surface and the maize canopy although the range of variation was limited. Based on the measurements made by the eddy correlation system, a comprehensive evaluation of eight popularly used parameterization schemes of aerodynamic resistance was carried out. The roughness length for heat transfer is a crucial parameter in the estimation of aerodynamic resistance to heat transfer and can neither be taken as a constant nor be neglected. Comparing with the measurements, the parameterizations by Choudhury et al. (1986), Viney (1991), Yang et al. (2001) and the modified forms of Verma et al. (1976) and Mahrt and Ek (1984) by inclusion of roughness length for heat transfer gave good agreements with the measurements, while the parameterizations by Hatfield et al. (1983) and Xie (1988) showed larger errors even though the roughness length for heat transfer has been taken into account.

1 Introduction

Reliable estimation of surface sensible and latent heat fluxes is an important issue in the study of exchange processes of energy and mass between hydrosphere, atmosphere and biosphere. Traditional micrometeorological, climatological, and hydrological methods, usually developed and validated at local scales, are difficult to use in the estimation of regional sensible and latent heat fluxes over heterogeneous land surfaces. Remote sensing technology has brought the hope to overcome this difficulty due to the efficient temporal and large spatial coverage provided by satellite observations of land surfaces (e.g. Jackson, 1985; Kustas et al., 1989; Moran et al., 1994). The development of high resolution, multi-band, multi-temporal and multi-angular remote sensing data has made it possible to obtain surface geometric structure and other state variables characterizing water and heat transfer at the land – atmosphere interface (e.g. Menenti et al., 2005). Compared with other methods, remote sensing methods have a significant advantage in estimating regional sensible and latent heat fluxes over heterogeneous surfaces because of measuring spatial patterns of the land surface properties which determine the land surface energy balance (e.g. Basitiaanssen et al., 1998; Su, 2002; Ma et al., 2003)

In a remote sensing method, the sensible heat flux density is usually estimated by following the Ohm's Law, i.e. using a ratio of the surface-air temperature difference ($T_s - T_a$) and an aerodynamic resistance to heat transfer (r_{ah}), where the surface temperature (T_s) is retrieved from thermal infrared remote sensing measurements. The latent heat flux LE can then be calculated according to the surface energy balance equation as

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

where R_n is the net radiation flux, G is the soil heat flux, ρ is the density of air, C_p is the specific heat of air at constant pressure, T_a is the air temperature.

The net radiation flux R_n in Eq. (1) is usually calculated from the surface albedo, surface temperature and emissivity combining atmospheric water vapor content and aerosol optical depth which all are retrieved from remote sensing

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observations of reflectance and radiance. The soil heat flux can be parameterized by a simple relation with net radiation and canopy structure properties although the coefficients involved need to be calibrated and evaluated for different types of canopies. As a consequence, the aerodynamic resistance becomes a very important parameter when estimating sensible heat flux and latent heat flux using remote sensing measurements by the energy balance method as shown in Eq. (1). Based on the Monin-Obukhov similarity theory, many authors, such as Monteith (1973), Brown and Rosenberg (1973), Verma et al. (1976), Louis (1979), Louis (1982), Itier (1980), Riou (1982), Hatfield et al. (1983), Mahrt and Ek (1984), Choudhury et al. (1986), Xie (1988), Byun (1990), Viney (1991), Lee (1997) and Yang et al. (2001), have proposed different parameterizations to estimate aerodynamic resistances to heat transfer. These parameterizations could be grouped into three categories. One group follows the Monin-Obukohv similarity theory, the other group is the empirical method. The third group includes so-called semi-empirical parameterizations. While these parameterizations have been evaluated and given an acceptable agreement with data upon which the methods were developed, deviations were found when applying them to other data.

Some studies on comparisons between different parameterizations have been done by different researchers either using field data (e.g. Kalma, 1989; Xie, 1988) or using randomly generated data sets (e.g. Viney, 1991). Using the experimental data of Choudhury et al. (1986) from a wheat canopy, Kalma (1989) compared the parameterizations proposed by Choudhury et al. (1986), Itier (1980), Monteith (1973), Hatfield et al. (1983), and Mahrt and Ek (1984). It was found that the values calculated with the parameterizations by Choudhury (1986) and Itier (1980) were close to each other, while deviations from the measurements were significant when using the parameterizations proposed by Monteith (1973), Hatfield et al. (1983), and Mahrt and Ek (1984).

Xie (1991) used lysimeter measurements in a winter wheat field to evaluate some parameterizations such as those of Brown and Rosenberg (1973), Verma et al. (1976), Hatfield et al. (1983), Chen (1988) and the one proposed by himself (Xie, 1988). The results showed that the parameterizations by Chen (1988) and Xie (1988) were in better agreement with measurements than others.

Among many comparison studies, most of the findings and discussions are either related to the derivation and validity of the stability correction functions, or to the degrees of simplification in the solution. Very few studies have emphasized the distinction of eddy diffusivities between momentum and heat transfer. For instance, Viney (1991) has showed the different performances of several parameterizations by taking $z_{0m}=z_{0h}$ and $z_{0m}\neq z_{0h}$. His results showed only slight differences between the two conditions. Unfortunately, his study was based on a synthetic data set and the analysis was done by comparing the parameterizations with the "reference solution" different from field measurements. As a matter of fact, some of the parameterizations were addressed by assuming identical eddy diffusivities for momentum and for heat transfer, which might be acceptable for the situations where the parameterizations were developed, in most of cases over relatively dense vegetation canopies without water stress. Unfortunately these parameterizations were sometimes applied to surfaces that were different from the original situations, for instance, sparsely vegetated surfaces.

In this paper, measurements by an eddy correlation system from a developing maize canopy (i.e. from bare soil through the emergence of the crop and on to full vegetative development) are used to derive aerodynamic resistances over bare soil surface and a maize field. Diurnal variations are analyzed together with the diurnal variation of excess resistance and surface-air temperature difference. The role of the difference in roughness length for momentum transfer and for heat transfer in determining aerodynamic resistance and in the estimation of sensible heat flux density estimate is evaluated. The derived aerodynamic resistance from the sensible heat flux measurements by the eddy correlation system is used to evaluate several parameterizations for aerodynamic resistance selected from literature. These parameterizations are commonly used in heat flux estimates using remote sensing observations, including Thom (1975), Verma et al. (1976), Hatfield et al. (1983), Mahrt and Ek (1984), Choudhury (1986), Xie (1988), Viney (1991) and Yang et al. (2001).

2 Theory and methodology

2.1 Measurements of aerodynamic resistance

The aerodynamic resistance to heat transfer can be determined by:

$$r_{ah} = \rho C_p (T_s - T_a)/H \tag{2}$$

where H is the sensible heat flux.

The measurements of sensible heat flux, air temperature, together with the surface temperature measurements are used to calculate aerodynamic resistance to heat transfer r_{ah} from Eq. (2). It is referred to as "measured aerodynamic resistance" in this paper and will be used to evaluate different parameterizations of r_{ah}. Estimates of H obtained with the eight different parameterizations of r_{ah} described below will also be evaluated against the measurements of H by an eddy correlation system.

2.2 Monin-Obukhov Similarity Theory

According to the Monin-Obukhov Similarity (MOS) theory, the integral gradient of the wind and temperature profiles in a horizontally homogeneous surface layer can be formulated as

$$u=\frac{u_*}{k}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)-\psi_m\left(\varsigma,\varsigma_{0m}\right)\right] \tag{3}$$

$$T_a-T_0=\mathrm{P_{r0}}\frac{T_*}{k}\left[\ln\left(\frac{Z-d}{z_{0h}}\right)-\psi_h\left(\varsigma,\varsigma_{0h}\right)\right] \tag{4}$$

where k is the von Karman constant, u is the wind speed at the reference height Z, u_* is the friction velocity, T_* is the temperature scale, T_0 is the aerodynamic surface temperature, z_{0m} is the roughness length for momentum transfer and z_{0h} is the roughness length for heat transfer, d is the zero-plane displacement, ς, ς_{0m} and ς_{0h} are stability parameters defined as $\varsigma=\frac{z}{L}$, $\varsigma_{0m}=\frac{z_{0m}}{L}$ and $\varsigma_{0h}=\frac{z_{0h}}{L}$ respectively ($z=Z-d$). $\mathrm{P_{r0}}$ is the turbulent Prandt number describing the difference between the eddy diffusivities of momentum K_m and of heat K_h, i.e. $\mathrm{P_{r0}}=\frac{K_m}{K_h}$. L is the Monin-Obukhov length given by

$$L=-\frac{\rho\,C_p\,u_*^3T_a}{kgH} \tag{5}$$

where g is the gravitational acceleration. The sensible heat flux is linked to the profiles of wind speed and air temperature through

$$H=-\rho\,C_p u_* T_* \tag{6}$$

The difference between air temperature and the potential temperature has been ignored in Eqs. (4) and (5).

Combining Eqs. (2)–(6), the aerodynamic resistance to heat transfer is

$$r_{ah}=\frac{1}{k^2u}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)-\psi_m\left(\varsigma,\varsigma_{0m}\right)\right]\left[\,\ln\left(\frac{Z-d}{z_{0h}}\right)-\psi_h\left(\varsigma,\varsigma_{0h}\right)\,\right] \tag{7}$$

In neutral conditions, $\psi_m\left(\varsigma,\varsigma_{0m}\right)=\psi_h\left(\varsigma,\varsigma_{0h}\right)=0$, the aerodynamic resistance to heat transfer r_{ah0} can be simplified to:

$$r_{ah0}=\frac{1}{k^2u}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)\right]\left[\ln\left(\frac{Z-d}{z_{0h}}\right)\right] \tag{8}$$

Further simplification can be made by assuming that roughness length for momentum and for heat are identical, which implies the aerodynamic resistance to heat transfer is assumed to be identical to the one to momentum transfer, this leads to

$$r_{ah0}=r_{am0}=\frac{1}{k^2u}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)\right]^2 \tag{9}$$

In Eq. (9), r_{am0} is the aerodynamic resistance to momentum transfer under neutral conditions. For stable conditions, the integral stability functions for wind and temperature in Eqs. (3), (4) and (7) are expressed as

$$\psi_m\left(\varsigma,\varsigma_{0m}\right)=-\beta_m\left(\varsigma-\varsigma_{0m}\right) \tag{10}$$

$$\psi_h\left(\varsigma,\varsigma_{0h}\right)=-\beta_h\left(\varsigma-\varsigma_{0h}\right) \tag{11}$$

For unstable conditions,

$$\psi_m\left(\varsigma,\varsigma_{0m}\right)=2\ln\left(\frac{1+x}{1+x_0}\right)+\ln\left(\frac{1+x^2}{1+x_0^2}\right)-2\tan^{-1}x+2\tan^{-1}x_0 \tag{12}$$

$$\psi_h\left(\varsigma,\varsigma_{0h}\right)=2\ln\left(\frac{1+y}{1+y_0}\right) \tag{13}$$

with $x=(1-\gamma_m\varsigma)^{1/4}$, $x_0=\left(1-\gamma_m\varsigma\frac{z_0}{z}\right)^{1/4}$, $y=(1-\gamma_h\varsigma)^{1/2}$, $y_0=(1-\gamma_h\varsigma\frac{z_{0h}}{z})^{1/2}$ (note that $z=Z-d$). β_m, β_h, γ_m, and γ_h in Eqs. (10)–(13) are experimental coefficients. Different values of these coefficients can be found based on atmospheric boundary layer observations (Webb, 1970; Dyer and Hicks, 1970; Businger et al., 1971; Garratt, 1977; Wieringa, 1980; Dyer and Bradley, 1982; Webb, 1982) and the review of Dyer (1974).

2.3 Parameterization of aerodynamic resistance to heat transfer

With observations of u and T_a at the reference height in the surface layer and knowing the surface properties (i.e. z_{0m} and z_{0h}), the aerodynamic resistance to heat transfer can be obtained by solving Eqs. (3)–(7) with the help of Eqs. (10)–(13). Under stable conditions, the profile functions are linear functions of the stability parameters and the exact solution for aerodynamic resistance can be easily obtained. Under unstable conditions, on the contrary, the profiles are highly non-linear equations of the stability parameters and an iterative technique (e.g. Busch et al., 1976; Itier, 1980) must be applied to obtain an exact solution of r_{ah}. The concept of estimating aerodynamic resistance to heat transfer using Eqs. (9)–(13) was first addressed by Thom (1975) and has been widely considered as the "reference parameterization" because of the better theoretical foundation. The values of the coefficients in the wind and temperature profiles were taken from Webb (1970) and Businger et al. (1971) for stable conditions, and from Paulson (1970) for unstable conditions, i.e. $\beta_m=\beta_h=5$, and $\gamma_m=\gamma_h=16$. It has been assumed that $\mathrm{P_{r0}}=1$. Taking $z=Z-d$ with Z being the reference height above the ground, the integral expression of Thom's stability functions ($\psi_m\left(\varsigma\right)$ and $\psi_h\left(\varsigma\right)$) is given by Eqs. (10)–(13) with $\varsigma_{0m}=\varsigma_{0h}=0$. The aerodynamic resistance to heat transfer r_{ah} is then solved numerically and exactly by iteration over Eqs. (3)–(7) and (10)–(13) . The results of aerodynamic resistance from this iteration procedure by using Thom's parameterization are referred to as the "standard solution" in this study.

For the sake of saving computing time in heat flux modeling, various parameterizations have been developed to simplify the calculation of r_{ah} for unstable conditions. Some of these efforts have focused on parameterization of ψ_m and

Table 1. List of various parameterizations of the aerodynamic resistance r$_{ah}$ being evaluated in this study. Only unstable conditions are concerned.

Source	Parameterization of r$_{ah}$	Solution or coefficients	Type/Assumption
Thom (1975)	$r_{ah}=\frac{1}{k^2u}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)-\psi_m(\varsigma)\right]\left[\ln\left(\frac{Z-d}{z_{0h}}\right)-\psi_h(\varsigma)\right]$	Precise solution by iteration. $\psi_m(\varsigma)$ and $\psi_h(\varsigma)$ are from Eqs. (10)–(13) ($\varsigma_{0m}=\varsigma_{0h}=0$).	MOS $z_{0m}\neq z_{0h}$
Yang et al. (2001)	$r_{ah}=\frac{1}{k^2u}\left[\ln\left(\frac{z}{z_{0m}}\right)-\psi_m\left(\varsigma,\varsigma_{0m}\right)\right]\left[\ln\left(\frac{z}{z_{0h}}\right)-\psi_h\left(\varsigma,\varsigma_{0h}\right)\right]$ $\psi_m\left(\varsigma,\varsigma_{0m}\right)$ and $\psi_h\left(\varsigma,\varsigma_{0h}\right)$ are from Eq.(10)–(13)	$\varsigma=\left[\mathrm{Ri}_B\frac{[\ln(z/z_{0m})]^2}{\ln(z/z_{0h})}\left(\frac{z}{z-z_{0m}}\right)\right]\Big/\left[1-2\mathrm{Ri}_B\frac{(1-z_{0m}/z)}{(1-z_{0h}/z)}\cdot p\right]$, $p\approx\sum c_{ijk}\,[\ln(-\mathrm{Ri}_B)]^i\left[\ln\left(\ln\frac{z}{z_{0m}}\right)\right]^j\left[\ln\left(\ln\frac{z}{z_{0h}}\right)\right]^k$, c_{ijk} is from Yang et al. (2001) for profiles of Dyer (1974)	MOS $z_{0m}\neq z_{0h}$
Choudhury et al. (1986)	$r_{ah}=\frac{1}{k^2u}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)\right]\left[\ln\left(\frac{Z-d}{z_{0h}}\right)\right](1-\beta\,Ri_B)^{-3/4}$	$\beta=5$	Semi-empirical $z_{0m}\neq z_{0h}$
Verma et al. (1976)	$r_{ah}=\frac{1}{k^2u}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)\right]^2(1-16Ri_B)^{-1/4}$	–	Empirical $z_{0m}=z_{0h}$
Hatfield et al. (1983)	$r_{ah}=\frac{1}{k^2u}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)\right]^2(1+\beta\,Ri_B)$	$\beta=5$	Empirical $z_{0m}=z_{0h}$
Mahrt and Ek (1984)	$r_{ah}=\frac{1}{k^2u}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)\right]^2\left[\frac{1+c(-Ri_B)^{1/2}}{1+c(-Ri_B)^{1/2}-15Ri_B}\right]$	$c=\left[75k^2(\frac{z+z_{0m}}{z_{0m}})^{1/2}\right]\Big/\left[\ln(\frac{z+z_{0m}}{z_{0m}})\right]^2$	Empirical $z_{0m}=z_{0h}$
Xie (1988)	$r_{ah}=\frac{1}{k^2u}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)\right]^2\left[1+\frac{\left[1-16R_{iB}\ln\left(\frac{Z-d}{z_{0m}}\right)\right]^{-1/2}}{\ln\left(\frac{Z-d}{z_{0m}}\right)}\right]$	–	Empirical $z_{0m}=z_{0h}$
Viney (1991)	$r_{ah}=\frac{1}{k^2u}\left[\ln\left(\frac{Z-d}{z_{om}}\right)\right]\left[\ln\left(\frac{Z-d}{z_{oh}}\right)\right]\left[a+b\,(-Ri_B)^c\right]^{-1}$	$a=1.0591-0.0552\ln\left\{1.72+\left[4.03-\ln\left(\frac{Z-d}{z_{0m}}\right)\right]^2\right\}$ $b=1.9117-0.2237\ln\left\{1.86+\left[2.12-\ln\left(\frac{Z-d}{z_{0m}}\right)\right]^2\right\}$ $c=0.8437-0.1243\ln\left\{3.49+\left[2.79-\ln\left[\frac{Z-d}{z_{0m}}\right]\right]^2\right\}$	Semi-empirical $z_{0m}\neq z_{0h}$

ψ_h on the basis of the MOS theory by introducing assumptions and simplifications applicable to the specific conditions of each study. The past decades have seen the rapid development of boundary-layer physics, which has ignored those very simple formulations. Some new developments have been made recently (e.g. Lee, 1997; Yang et al., 2001). We refer to this type of methods as "Monin-Obukhov Similarity" method (MOS in short).

The influence of atmospheric stability on the flux-gradient relationship in the surface layer can also be accounted for by inclusion of the bulk Richardson number Ri_B (Monteith, 1973),

$$Ri_B=\frac{g}{T_a}\frac{(T_a-T_s)\,(Z-d)}{u^2} \tag{14}$$

An alternative manner to take into account atmospheric stability is to use the ratio between the stability-corrected aerodynamic resistance and the one in neutral conditions, which is generally expressed as a function of the bulk Richardson number Ri_B

$$\frac{r_{ah}}{r_{ah0}}=F\,(Ri_B) \tag{15}$$

This method is referred to as the "empirical" method.

Some of the parameterizations belong to a category "in-between" the previous two, i.e. with a closer numerical approximation of the stability effects than the "empirical" method but more simplified than the "MOS" method. We refer to this type of parameterizations as "semi-empirical" methods.

In this paper, among the parameterizations reviewed in the introduction, we have selected eight parameterizations for the estimation of aerodynamic resistance to heat transfer in unstable conditions in particular. Table 1 gives the list of these parameterizations together with their formulations and categories.

These parameterizations involve different assumptions and levels of simplification and perform differently when comparing estimates of r_{ah} with measurements. Some of these parameterizations are widely used to estimate heat flux density using measurements of radiometric surface temperature by field, airborne and spaceborne (imaging) radiometers. We will only give a brief review of the eight parameterizations readers are encouraged to refer to the original papers. Note that some of the parameterizations in Table 1 have been algebraically modified from their original forms so that the formulas can be expressed as explicit functions of the bulk Richardson number.

Yang et al. (2001) investigated a procedure to explore the solution by first finding the analytical solution of the Monin-Obukhov flux-profile relations in slightly unstable conditions, i.e. $-1<<\varsigma<0$, and then extended this solution to general unstable conditions with a modified factor. Coefficients involved in the calculation of this factor depend on profile functions, the profiles of Dyer (1974) are used in this study.

In the study by Choudhury et al. (1986), they have first given an exact solution for stable conditions. By analogy with the expression of stability function in stable conditions and by a trial-and-error procedure in unstable conditions, Choudhury et al. (1986) found that the aerodynamic resistance in unstable conditions can be approximated by applying a simple function of the Richardson number to the aerodynamic resistance for neutral conditions.

The parameterizations by Verma et al. (1976), Hatfield et al. (1983) and Mahrt and Ek (1984) are all based on the assumption that the eddy diffusivities for momentum and for heat are the same, i.e. $z_{0m}=z_{0h}$, Pr =1, $\Psi_h=\Psi_m$. Hatfield et al. (1983)'s parameterization is more adequate in stable and near-neutral unstable conditions ($-0.2<R_{iB}<0$). Values of R_{iB} that are smaller than –0.2 lead to negative resistance values which are physically meaningless. One should keep this in mind when analyzing the results.

The parameterization proposed by Xie (1988) used the non-dimensional flux-profile function in the integral form as a correcting factor to account for the stability. It was assumed that the friction velocity for neutral conditions could be used under non-neutral conditions. As with other simple empirical parameterizations, it has been assumed that $z_{0m}=z_{0h}$. As a consequence of these assumptions, the stability correction is ultimately expressed as a function of the bulk Richardson number and surface aerodynamic properties.

Viney (1991) has proposed a relationship between the non-neutral and neutral aerodynamic resistances by a diagnostic analysis of a randomly generated dataset (n=2464 realizations in total). The coefficients in the stability correction function were found to be related to the term of $\ln\left(\frac{Z-d}{z_{0m}}\right)$.

We will evaluate the performances of these parameterizations using sensible heat flux measurements from an eddy correlation system together with other micrometeorological data obtained in a field with surface properties evolving during the growth of a maize crop, i.e. from bare soil through the emergence of the crop to full vegetative development. The site and measurements will be described in the next section.

2.4 Determination of surface roughness parameters

In this paper, the roughness length for momentum transfer z_{0m} is determined by minimizing the cost function (Yang et al., 2003):

$$J=\sum_t\sum_{i=1}^{n}\left\{u_*^t-ku_i^t/\left[\ln(z_i/z_{0m})\right.\right.$$
$$\left.\left.-\psi_m(z_{0m}/L^t, z_i/L^t)\right]\right\}^2 \tag{16}$$

where n is the number of measurement levels (n=1 in this study, at a height of 1.8 m) , t represents the time serials of data. We have assumed that z_{0m} can be considered as constant over a short period of time: a 10-day period was taken for the maize crop in this study.

The zero-plane displacement height d is calculated by means of a simple relationship between d and the vegetation canopy height h_c, i.e. $d=\frac{2}{3}h_c$.

The roughness length for heat transfer z_{0h} is also a parameter needed in the parameterizations of aerodynamic resistance, which must be determined a priori. The difference between the roughness length for momentum and for heat transfer is described as an excess resistance parameter kB^{-1} given by (Owen and Thompson, 1963; Chamberlain, 1968):

$$kB^{-1}=\ln\left(\frac{z_{0m}}{z_{0h}}\right) \tag{17}$$

This parameter can be calculated from the in-situ measurements as:

$$kB^{-1}=\rho C_p\frac{(T_s-T_a)}{H}ku_*-\ln\left(\frac{Z-d}{z_{0m}}\right)+\psi_h(\frac{Z-d}{L}) \tag{18}$$

The sensible heat flux, friction velocity and Monin-Obukhov length required in Eq. (18) are obtained from the measurements by the eddy correlation system. The parameter kB^{-1} is calculated for each 10-min interval of the flux measurements.

3 Site description and the measurements

The experiment was carried out at Xiaotangshan Experimental Station for Precision Agriculture (116°26′52″ E, 40°10′41″ N, 35 m above sea level) in Beijing from 30 May till 6 July 2004. The experimental field was flat and open, 1000 m long from north to south and 500 m wide from east to west, divided into two equal smaller sub-plots (southern and northern) by an east-west oriented path. The fetch for the prevailing wind direction is sufficient to ensure the Monin-Obukhov similarity theory to hold. Land cover in the southern sub-plot field was bare soil between 30 May and 11 June, while the maize plants started emerging around 12 June. The instruments used for this study were located in the central zone of the southern sub-plot. Table 2 gives the summary of the surface characteristics of the field for the entire duration of the experiment.

The measurements used in this study are summarized in Table 3 and a brief introduction is given below.

The eddy correlation system used for sensible heat flux measurements includes a three-dimensional anemometer (CSAT3, Campbell) and a CO_2/H_2O analyzer (LI7500, LI-COR). The measurement height was 1.8 m above the ground. The sampling frequency was 10 Hz. A set of temperature and humidity probes (HMP45C, Vaisala) was set up at 1.8 m height to measure the air temperature and humidity. The downward and upward shortwave and longwave radiation fluxes were measured using a net radiometer for the four separate components (CNR-1, Kipp and Zonen). All the measurements were averaged over 10 min.

Table 2. Surface properties and measurements in Xiatangshan site during 30 May and 6 July in 2004.

Date (2004)	Surface type	Mean veg. height h_c(m)	Mean veg. cover f_c(%)	z_{0m} (m)	d(m)	Surface emissivity ε
30 May–11 June	Bare soil	0	0	0.00580	0	0.974
12–24 June	Maize (emerging)	0.166	25	0.01857	$2/3h_c$	0.980
25 June–7 July	Maize	0.405	60	0.02590	$2/3h_c$	0.982

Table 3. Measurements and instruments used this study in the Xiaotangshan site in China during 30 May–7 July in 2004.

Variables	Instruments	Instrument height (m)
Air temperature T_a	Temperature probe (HMP45C, Vaisala)	1.8
Sensible heat flux H Friction velocity u_* Monin-Obukhov length L Wind speed u	3-D sonic anemometer (CSAT3, Campbell) and a CO_2/H_2O analyzer (LI7500, LI-COR)	1.8
Incident shortwave radiation flux $R_{S\downarrow}$ Outgoing shortwave radiation flux $R_{S\uparrow}$ Incident longwave radiation flux $R_{L\downarrow}$ Outgoing longwave radiation flux $R_{L\uparrow}$	Net radiometer (CNR1, Kipp& Zonen) Wavelengths between 0.3–3 μm, 5–50 μm.	1.5
Canopy height h_c	–	–
Fraction of vegetation cover f_c	Landsat TM images	–

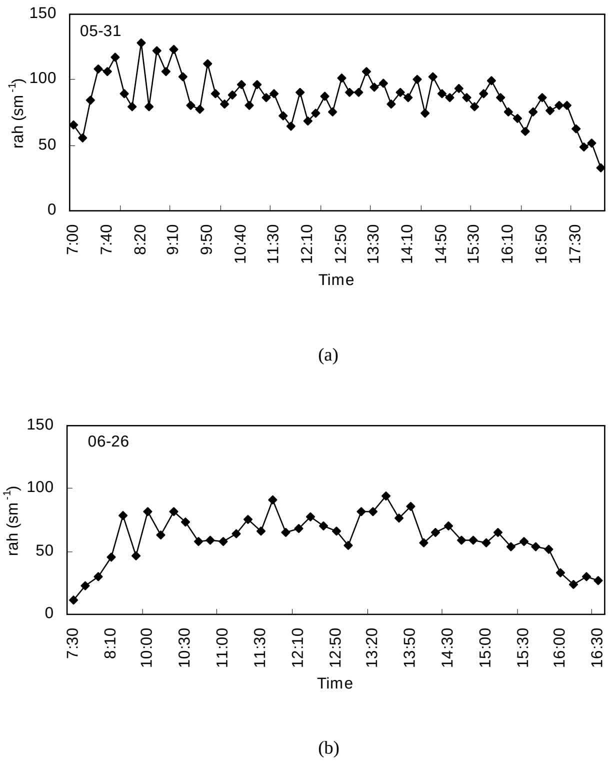
Surface temperature (T_s) was calculated by the Stefan-Boltzman law from measurements of the longwave radiation fluxes, i.e. $T_s=\left(\frac{R_{L\uparrow}-(1-\varepsilon)R_{L\downarrow}}{\varepsilon\sigma}\right)^{1/4}$, where σ is the Stefan-Boltzmann constant, (σ=5.678 × 10^{-8}), $R_{L\uparrow}$ is the upwards longwave radiation flux from the surface, $R_{L\downarrow}$ is the incident longwave radiation flux. ε is the emissivity of the surface (either the bare soil or the maize canopy). The component surface emissivity of soil ε_s and maize leaves ε_l were measured in the field by a specific device for emissivity measurements (see Xu et al., 2004 for more information about the instruments and the measurements). The maize canopy emissivity was then calculated from $\varepsilon=f_c\varepsilon_l+(1-f_c)\varepsilon_s$ in which f_c is the fractional cover of the maize and varies with the growth of the maize. The emissivity of the bare soil was 0.974 while the emissivities for the maize canopy were 0.980 and 0.982 for the second and the third growing period shown in Table 2. Some ancillary parameters such as crop height and fractional vegetation cover (derived from Landsat TM images) were measured about every 10 days.

To ensure the required data quality, only the data that met the following criteria were selected for further analysis: 1) wind speed $u>1.0\,\mathrm{ms}^{-1}$; 2) friction velocity $u_*>0.01\,\mathrm{ms}^{-1}$ (bare soil surface) or $u_*>0.1\,\mathrm{ms}^{-1}$ (maize field); 3) absolute difference between surface temperature and air temperature larger than 0.1K; 4) sensible heat flux $H>10Wm^{-2}$; 5) the sensible heat flux has the same sign as (T_s-T_a); 6) no rainfall; 7) measurements done between 07:00 and 18:00. There are in total 1110 effective measurements which fall in the above criteria.

4 Results and discussions

4.1 Diurnal variation of aerodynamic resistance

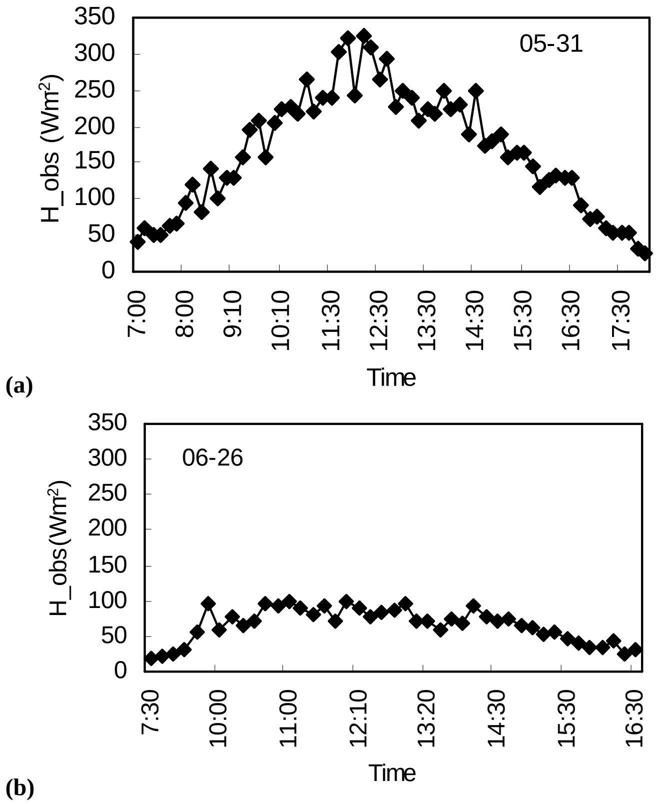
Due to instrument maintenance, rainfall, clouds and irrigation, there were gaps in the daily measurements by the eddy correlation system. After data screening, two "golden" days (31 May and 26 June 2004) were chosen for the diurnal variation analysis, one was before the maize emergence, i.e. with bare soil conditions and the other was about 2 weeks after the maize emergence. Data on these two "golden days" were collected continuously during the daytime. The weather was cloud-free and there was no sprinkling irrigation on these two days. Diurnal variations of aerodynamic resistance derived from the measurements by the eddy correlation system are shown in Fig. 1. Diurnal variations of r_{ah} were observed on both days either over the soil surface or over the maize canopy. Larger values were found over bare soil than over the maize canopy accompanied by a significant difference in the sensible heat flux on these two days (Fig. 2). Consistently, large differences between the surface and air temperature were observed over the bare soil surface on 31 May 2004



(a)

(b)

Fig. 1. Diurnal variation of aerodynamic resistance on the two "golden" days: **(a)** 31 May 2004 with bare soil; **(b)** 26 June 2006 with maize canopy, two weeks after the emergence.



(a)

(b)

Fig. 2. Diurnal variation of sensible heat flux on the two "golden" days: **(a)** 31 May 2004 with bare soil; **(b)** 26 June 2006 with maize canopy, two weeks after the emergence.

(Fig. 3). The excess resistance in terms of the kB^{-1} parameter was larger over the bare soil on 31 May than that over the maize canopy on 26 June (Fig. 3).

Negative values of kB^{-1} occurred in the morning and in the late afternoon hours over the maize canopy when the surface temperature was very close to the air temperature. The change of kB^{-1} values implies a change in the relative vertical position of the effective heat source (z_{0h}) and of the effective momentum sink (z_{0m}) within the canopy. More precisely $kB^{-1}<0$ implies that the heat source is higher than or very close to the momentum sink (see Eq. 18). This is likely to happen when the upper portion of the canopy is warmer than the lower one. Indications that this might really be the case have been given by Jia (2004) who studied in detail the within canopy variability of radiative and convective fluxes in relation with foliage and soil temperature.

4.2 Comparison of parameterization results with "standard solution"

The aerodynamic resistance to heat transfer r_{ah} was calculated using the eight different parameterizations described in Sect. 2 for the whole data set (1110 effective samplings after data quality checks described in Sect. 3). Since the parameterization of Thom (1975) basically gives a "precise" solution by iteration, we took this precise solution as the reference (referred to as "standard solution") to evaluate all the other parameterizations. In general, the estimation by the "MOS" method and by the "semi-empirical" methods were in good agreements with the "standard solution" both over the bare soil surface and the maize field (Fig. 4). On the contrary, the "empirical" methods showed large deviations from the "standard solution".

The parameterizations from Verma et al. (1976), and Mahrt and Ek (1984) significantly underestimated r_{ah} when compared with the "standard solution", in particular when r_{ah} is larger than $50\,\mathrm{sm}^{-1}$. In most cases, the estimated values of resistance by these two parameterizations are limited to a range that is smaller than $100\,\mathrm{sm}^{-1}$. The parameterization by Hatfield et al. (1983) has resulted in a number of negative values. This is not surprising because Hatfield et al. (1983)'s parameterization is only applicable in near-neutral unstable conditions ($-0.2<R_{iB}<0$). Xie (1991) has also found in his dataset that the aerodynamic resistance calculated by the parameterization of Hatfield et al. (1983) was negative under strong unstable condition (i.e. $T_s - T_a>5\,\mathrm{K}$, $u\leq 1.0\,\mathrm{ms}^{-1}$). Although the results from Xie (1988)'s parameterization are distributed around the 1:1 line, the data points

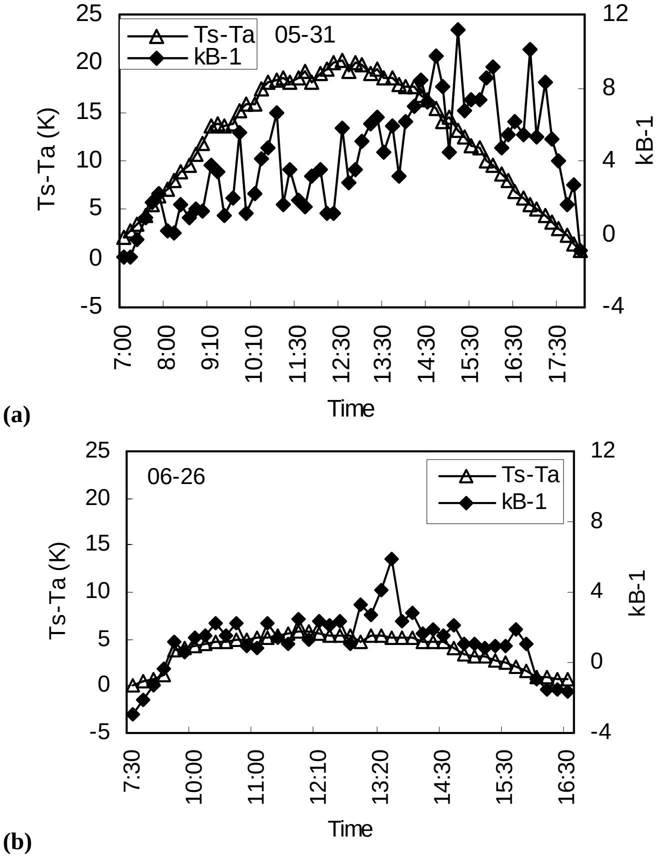


Fig. 3. Diurnal variation of surface – air temperature difference and of excess resistance in terms of kB^{-1} on the two "golden" days: **(a)** 31 May 2004 with bare soil; **(b)** 26 June 2006 with maize canopy, two weeks after the emergence.

show considerable scatter.

The results from Viney (1991) and Choudhury et al. (1986) are in good agreement with the "standard solution" at low values of r_{ah} ($r_{ah}<150\,\mathrm{s\,m^{-1}}$). Large deviations from the reference values are found in the results from Choudhury (1986) when r_{ah} is large.

The results from the parameterization by Yang et al. (2001) are closest to the "standard solutions". Yang (2001)'s method is the only one among the seven parameterizations that works across the entire range of stability conditions, while other parameterizations are either very simple empirical formulas (Verma et al., 1976; Mahrt and Ek, 1984; Hatfield et al., 1983; Xie, 1988) or semi-empirical ones (Choudhury et al., 1986; Viney, 1991). Yang (2001)'s method gives an approximated solution of the stability parameter $\varsigma=\frac{z}{L}$ and applies the parameterized $\varsigma=\frac{z}{L}$ to the classical Thom (1975) model to estimate the flux-profile relationships for wind speed and air temperature.

The correction functions for stability in all the empirical and semi-empirical methods are plotted against the bulk Richardson number Ri_B (Fig. 5). The functions of Hatfield et al. (1983) and by Xie (1988) deviate considerably, while the stability correction functions in the parameterizations of Verma et al. (1976), Mahrt and Ek (1984), Choudhury et al. (1986) and Viney (1991) are characterized by similar curves against Ri_B. One would expect that such similar functions would result in limited differences in the estimated aerodynamic resistance r_{ah} providing that the same value of r_{ah} in neutral conditions is applied to all the parameterizations. In the following section, we will investigate the possible reasons of the poor performance of the parameterizations by Verma et al. (1976), Hatfield et al. (1983), Mahrt and Ek (1984), and Xie (1988).

4.3 Importance of the excess resistance parameter kB^{-1}

A wide range of kB^{-1} values has been found in many studies over different land surfaces (Kustas et al., 1989; Beljaars and Holtslag, 1991; Stewart, 1994; Troufleau et al., 1997; Jia, 2004). This implies that the difference between the roughness lengths for momentum and heat transfer can be quite large, in particular over sparse canopies. In the data set used in this study, the difference between z_{0m} and z_{0h} (in terms of kB^{-1}) is varying over a wide range during the whole experimental period as shown in Fig. 6. This implies that the excess resistance caused by the different transfer mechanism for momentum and heat has a significant impact on the values of r_{ah}.

As shown above, the poorest estimates of r_{ah} occurred with those methods in which the roughness length for momentum transfer and for heat transfer were assumed to be identical (e.g. Verma et al., 1976; Hatfield et al., 1983; Mahrt and Ek, 1984; Xie, 1988). Taking into account the difference between z_{0m} and z_{0h}, these parameterizations can be modified into the following forms:

The modified parameterization of Verma et al. (1976) is

$$r_{ah}=\frac{1}{k^2u}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)\right]\left[\ln\left(\frac{Z-d}{z_{0h}}\right)\right](1-16Ri_B)^{-1/4} \quad (19)$$

The modified parameterization of Hatfield et al. (1983) is

$$r_{ah}=\frac{1}{k^2u}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)\right]\left[\ln\left(\frac{Z-d}{z_{0h}}\right)\right](1+\beta\,Ri_B) \quad (20)$$

The modified parameterization of Mahrt and Ek (1984) is

$$r_{ah}=\frac{1}{k^2u}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)\right]\left[\ln\left(\frac{Z-d}{z_{0h}}\right)\right]\left[\frac{1+c(-Ri_B)^{1/2}}{1+c(-Ri_B)^{1/2}-15Ri_B}\right] \quad (21)$$

where c is given in Table 1.

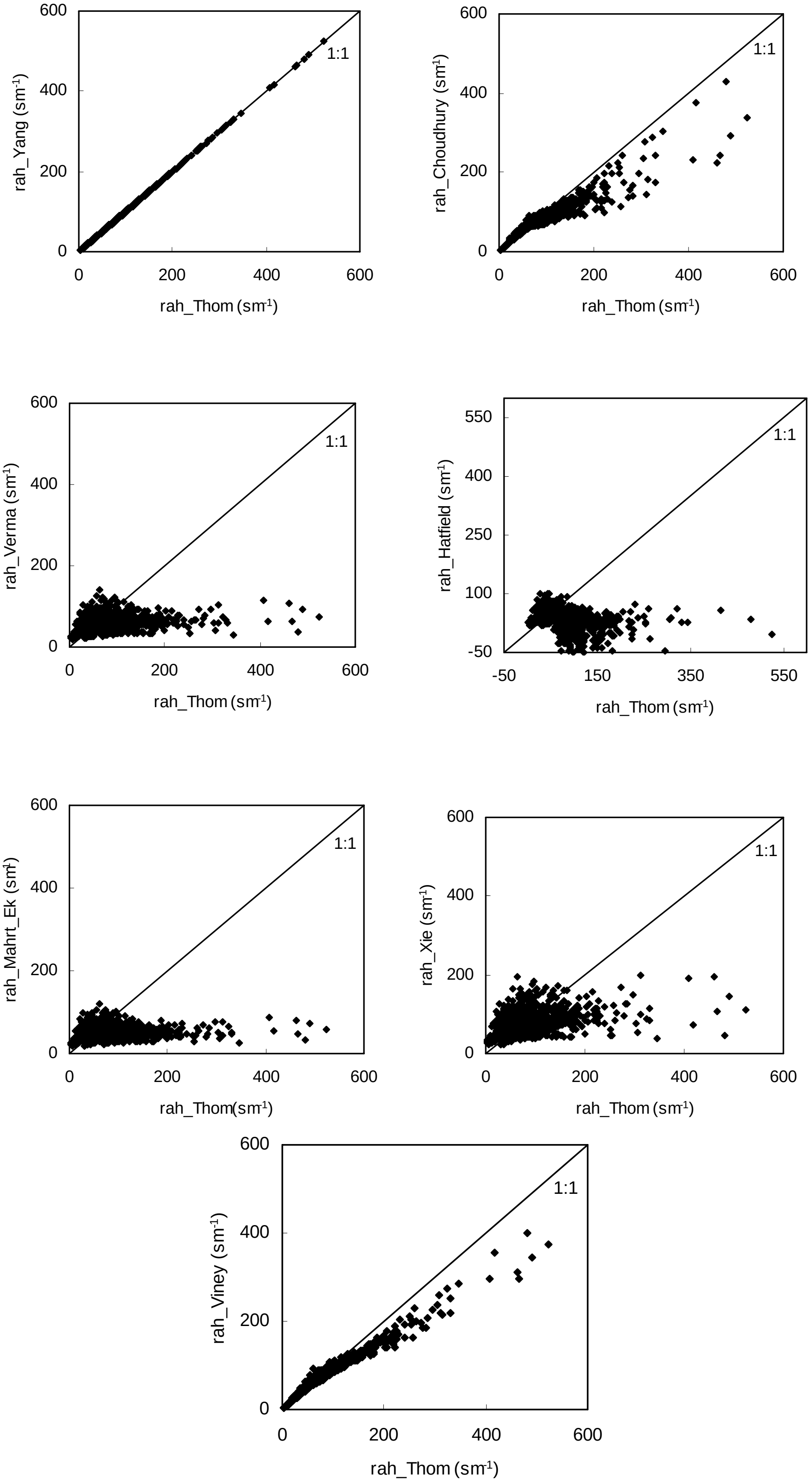


Fig. 4. Comparison of r_{ah} between the estimation by the seven parameterizations and the "standard solution".

Table 4. Overview of statistics between the (modified) parameterizations and the measurements of aerodynamic resistance r_{ah} during 30 May and 7 July 2004 in Xiaotangshan experimental site. The mean values of r_{ah} over n=1110 measurements is 80.8 sm^{-1} with a standard deviation of 29.8 sm^{-1}.

Parameterization	MAPD (%)	RMSD (sm^{-1})	R^2	Linear regression
Thom (1970)	21.9	28.6	0.80	Y = 1.1229 X, R^2 = 0.79
Yang et al. (2001)	20.1	26.9	0.80	Y = 1.0922 X, R^2 = 0.80
Choudhury et al. (1986)	18.8	23.1	0.76	Y = 0.9326X, R^2 = 0.67
Verma et al. (1976) (modified form)	20..6	23.4	0.79	Y = 1.0429 X, R^2 = 0.74
Hatfield et al. (1983) (modified form)	67.9	130.9	0.05	Y = 0.1246 X, R^2 = –0.05
Mahrt and Ek (1984) (modified form)	18.0	23.2	0.78	Y = 0.8671 X, R^2 = 0.71
Xie (1988) (modified form)	55.4	59.2	0.74	Y = 1.4840 X, R^2 = 0.72
Viney (1991)	18.3	21.5	0.78	Y = 0.9621 X, R^2 = 0.74

MAPD: mean absolute percent difference;
RMSD: Root Mean Square Difference.
R^2: determination of coefficient (R: correlation coefficient).

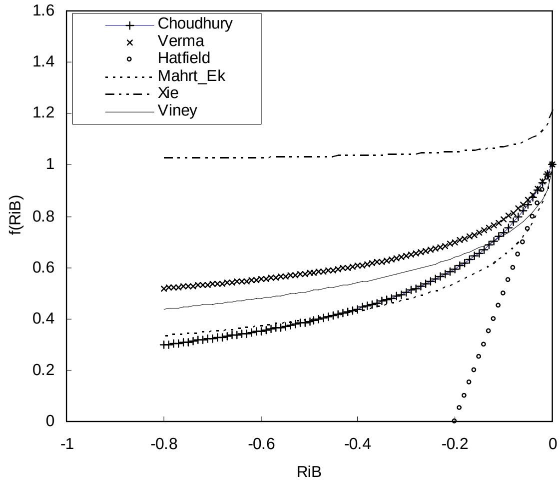


Fig. 5. Relationship between the bulk Richardson number and stability correction functions in the empirical and semi-empirical methods of aerodynamic resistance parameterizations evaluated in this paper.

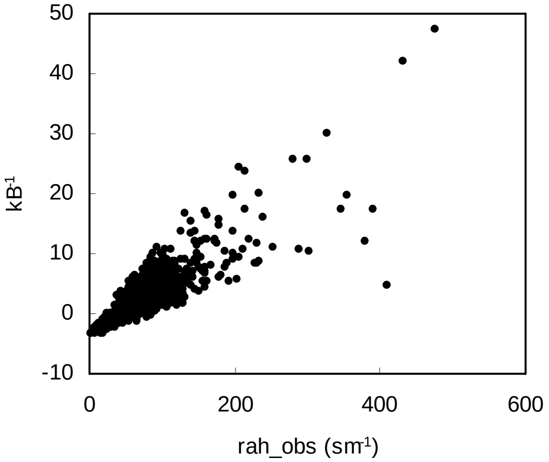


Fig. 6. Variation of the parameter kB^{-1} calculated from Eq. (18) in relation with the aerodynamic resistance measured by the eddy correlation system.

The modified parameterization of Xie (1988) is

$$r_{ah} = \frac{1}{k^2 u}\left[\ln\left(\frac{Z-d}{z_{0m}}\right)\right]\left[\ln\left(\frac{Z-d}{z_{0h}}\right)\right] \left\{1+\frac{1}{\left[1-16Ri_B \ln\left(\frac{Z-d}{z_{0m}}\right)\right]^{1/2}\ln\left(\frac{Z-d}{z_{0m}}\right)}\right\} \qquad (22)$$

To evaluate the estimates of these eight parameterizations, results from the original formulas of Thom (1975), Choudhury et al. (1986), Viney (1991) and Yang et al. (2001) and from the modified formulas of Verma et al. (1976), Hatfield et al. (1983), Mahrt and Ek (1984), and Xie (1988) are compared with the measurements of r_{ah} (Fig. 7). Table 4 gives the summary of the comparisons of all the (modified) parameterizations with the measurements represented by the statistics: the determination of the coefficient R^2 (R is the correlation coefficient), the Root Mean Square Difference (RMSD), and the Mean Absolute Percent Difference (MAPD).

In general, all the (modified) parameterizations, except the ones by Hatfield et al. (1983) and Xie (1988), are in good agreements with the measurements (Fig. 7) and show quite similar values of R^2, RMSD and MAPD (Table 4).

The modified formula of Xie (1988) overestimated r_{ah} by about 50% as shown by the slope of the linear regression between the estimates and the measurements. The modification by including z_{0h} in the formula of Hatfield et al. (1983) did not help to avoid the unexpected negative values of r_{ah},

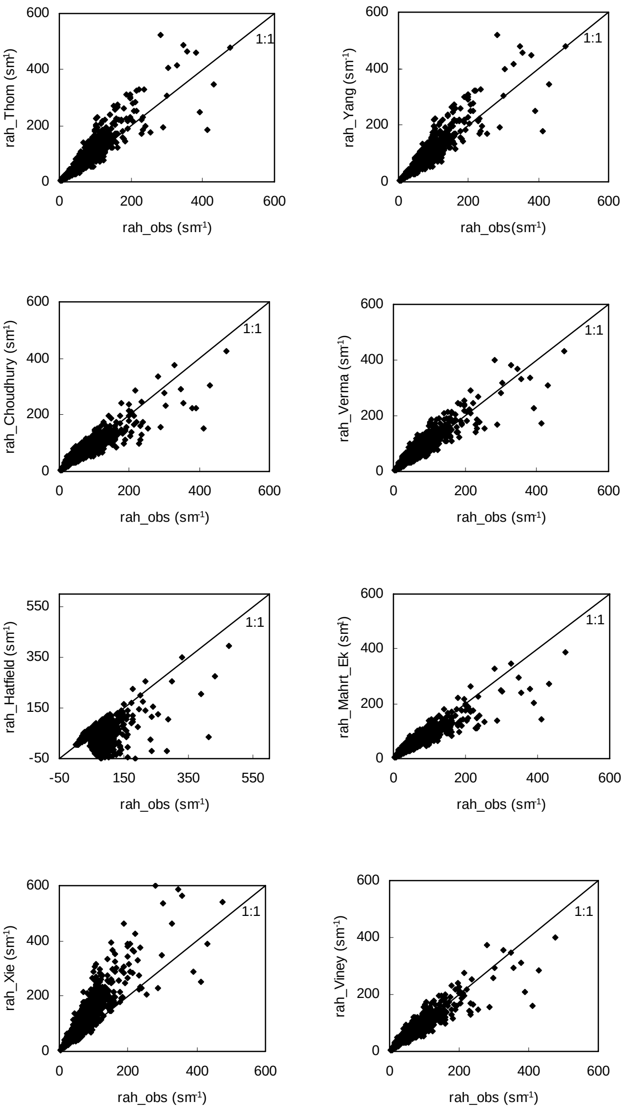


Fig. 7. Comparisons of aerodynamic resistance estimated by the original forms of Thom (1975), Yang et al. (2001), Choudhury et al. (1986) and Viney (1991), the modified forms of the parameterizations by Verma et al. (1976), Hatfield et al. (1983), Mahrt and Ek (1984), and Xie (1988) with measurements.

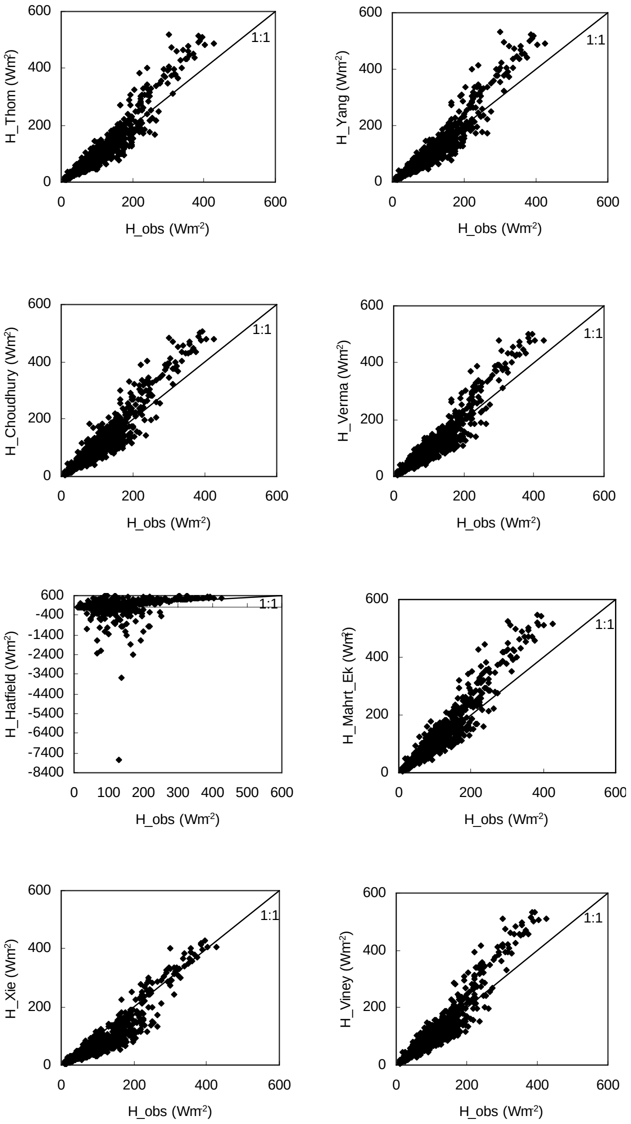


Fig. 8. Comparisons of sensible heat flux between the measurements and the estimates by applying the original forms of Thom (1975), Yang et al. (2001), Choudhury et al. (1986), Viney (1991), the modified forms of the parameterizations by Verma et al. (1976), Hatfield et al. (1983), Mahrt and Ek (1984), and Xie (1988) for aerodynamic resistance estimates.

the correlation of the estimation with the measurements is still very poor as indicated by a almost zero determination of coefficient R^2 shown in Table 4. As mentioned before the formula by Hatfield et al. (1983) is limited to stable or near-neutral unstable conditions. Analysis of the results showed that large deviation of r_{ah} estimated by the modified form of Hatfield et al. (1983) appeared under unstable conditions, in particular when Ri_B is smaller than -0.2.

The modified form of Mahrt and Ek (1984) parameterization slightly underestimate r_{ah}. The results from Viney (1991) and Choudhury et al. (1986) compare quite well with the measurements of aerodynamic resistance. One would expect that the parameterization by Yang et al. (2001) would give the closest estimates to the measurements of aerodynamic resistance. However, it slightly overestimates the aerodynamic resistance. Moreover, the "standard solution" (Thom, 1975) did not show a better accuracy in the estimate of r_{ah} than the parameterizations being evaluated here. This might be a result of the errors in the input variables of the parameterizations and of the sensitivity of the parameterizations to these input variables. We will discuss this issue in the sensitivity study in Sect. 4.5.

Table 5. Overview of statistics of sensible heat flux estimates by the (modified) parameterizations against the measurements during 30 May and 7 July 2004 in Xiaotangshan experimental site in China. (The mean value of the sensible heat flux of the data set is 95.5 $\mathrm{Wm^{-2}}$ with a standard deviation 50.8 $\mathrm{Wm^{-2}}$).

Parameterization	MAPD (%)	RMSD ($\mathrm{Wm^{-2}}$)	R^2	Linear regression
Thom (1970)	19.2	29.6	0.90	$Y = 1.0326$ X, $R^2 = 0.88$
Yang et al. (2001)	18.6	30.2	0.90	$Y = 1.0612$ X, $R^2 = 0.88$
Choudhury et al. (1986)	19.1	27.8	0.90	$Y = 1.0939$ X, $R^2 = 0.89$
Verma et al. (1976) (modified)	19.9	27.4	0.90	$Y = 1.0246$ X, $R^2 = 0.88$
Hatfield et al. (1983) (modified)	451.0	6064.4	0.00	$Y = 2.0856$X, $R^2 = 0.004$
Mahrt and Ek (1984) (modified)	20.3	32.3	0.91	$Y = 1.1731$ X, $R^2 = 0.90$
Xie (1988) (modified)	32.6	39.2	0.86	$Y = 0.7911$ X, $R^2 = 0.84$
Viney (1991)	19.4	29.0	0.90	$Y = 1.0963$X, $R^2 = 0.89$

Table 6. Reference values and error ranges of the input parameters for the sensitivity analysis of the parameterizations for aerodynamic resistance. The reference values of aerodynamic resistance and sensible heat flux density of the data set are also given (the reference r_{ah} was calculated from the reference input variables and H listed in the table).

Parameters/ variables	Reference values	Range	Errors
u	2.3 $\mathrm{ms^{-1}}$	1.0∼10.0 $\mathrm{ms^{-1}}$	±0.5 $\mathrm{ms^{-1}}$
T_a	28.8°C	17.0∼41.0°C	±0.5°C
T_s	35.3°C	17.0∼54.0°C	±2°C
z_{0m}	0.016 m	0.006∼0.026 m	±50%
d	0.097 m	0∼0.410 m	±50%
kB^{-1}	3.1	–5.0∼48.0	±25%
H	95.5 $\mathrm{Wm^{-2}}$	10.0∼427.0 $\mathrm{Wm^{-2}}$	–
r_{ah}	77.0 $\mathrm{sm^{-1}}$	2.0∼477.0 $\mathrm{sm^{-1}}$	–

4.4 Estimation of sensible heat flux

The original parameterizations of aerodynamic resistance from Thom (1975), Yang et al. (2001), Choudhury et al. (1986), and Viney (1991) and the modified forms of Verma et al. (1976), Hatfield et al. (1983), Mahrt and Ek (1984), and Xie (1988) (Eqs. 19, 20, 21 and 22) were applied to Eq. (2) to calculate the sensible heat flux using the same dataset described before and the results were compared to the measurements by the eddy correlation system (Fig. 8). The statistics of the sensible heat flux between the estimation by the parameterizations and the measurements are given in Table 5.

The methods by Thom (1975), the modified Verma et al. (1976), Choudhury et al. (1986), Viney (1991) and Yang et al. (2001) showed quite similar performance with MAPD less than 20%, RMSD less than 30 $\mathrm{Wm^{-2}}$ and the coefficient of determination of about 0.9 comparing with the measurements of sensible heat flux by the eddy correlation system. All these parameterizations slightly overestimated the sensible heat flux. The modified parameterization of Mahrt and Ek (1984) also works also well, but overestimates the sensible heat flux by about 17%. The modified Xie's method has underestimates sensible heat flux by about 21%. As expected, Hatfield et al. (1983) is not applicable to estimate the sensible heat flux.

4.5 Sensitivity analysis

We have analyzed the performances of different parameterizations to estimate the aerodynamic resistance. Why do some models perform better than others? We will try to answer this question by analyzing the sensitivities of these parameterizations to some crucial parameters. Measurements or estimates of parameters needed by these parameterizations may contain various degrees of uncertainties. If a model is sensitive to a specific parameter, significant difference between the calculated and measured flux may result from small errors in the estimate or measurement of the parameter.

For this analysis, the parameterizations for aerodynamic resistance were evaluated with respect to the input meteorological variables (u and T_a), surface temperature (T_s) and surface characteristics (z_{0m}, d and kB^{-1}). The choice of

Table 7. Sensitivity of the estimated aerodynamic resistance to the input parameters. The results are given in relative errors (%).

variables	errors	Thom	Yang	Choudhury	Verma	Hatfield	Mahrt_Ek	Xie	Viney
T_s	+2 ^{o}C	–3.1	–2.2	–5.4	–3.6	–15.2	–5.4	–0.9	–3.6
	–2°C	3.8	2.5	6.1	4.4	15.2	6.8	1.3	4.5
T_a	+0.5°C	0.9	0.8	6.2	4.4	15.5	7.0	1.3	4.5
	–0.5°C	–0.9	–0.9	–1.4	–1.0	–3.9	–1.5	–0.3	–1.0
u	+0.5 ms^{-1}	–14.3	–15.5	–12.3	–13.8	–4.4	–11.7	–16.5	–13.8
	–0.5 ms^{-1}	19.8	22.0	14.3	18.8	–12.1	14.7	25.3	18.6
z_{0m}	+50%	–13.2	–13.2	–13.5	–13.5	–13.5	–13.8	–12.5	–13.5
	–50%	24.8	24.7	25.2	25.2	25.2	26.8	23.4	26.2
kB^{-1}	+25%	12.1	11.3	10.0	10.0	10.0	10.0	10.0	10.0
	–25%	–12.2	–11.3	–10.0	–10.0	–10.0	–10.0	–10.0	–10.0
d	+50%	–0.6	–0.8	–0.5	–0.6	0.4	–0.4	–0.8	–0.6
	–50%	0.6	0.7	0.4	0.6	–0.5	0.4	0.8	0.6

the ranges of the parameters in our sensitivity study is based on observational accuracies or estimated errors of these parameters. We have assessed the observational accuracies of wind speed and air temperature as 0.5 ms^{-1} and 0.5°C, respectively. The error in surface temperature was taken as 2 K which is the accuracy achieved by the current satellite thermal infrared measurements after atmospheric correction (Kohsiek et al., 1993). Errors in the estimates of z_{0m} and d might be about 50% (Verhoef et al., 1997). We took the same errors of 50% for roughness length for heat transfer, this is equivalent to about 25% errors in the estimate of kB^{-1}. The reference values of the parameters being evaluated were taken as the mean values of the whole dataset (n=1110 samplings) and given in Table 6. The reference values of aerodynamic resistance for all the parameterizations are therefore calculated based on the above reference input parameters.

The changes of aerodynamic resistance were calculated for each of the eight parameterizations with respect to the errors in each of the model parameters. The results are given in Table 7 in relative errors (%).

All the parameterizations are very sensitive to wind speed, in particular when the wind speed is underestimated. The uncertainties in the estimated aerodynamic resistance can be as large as about 22% due to underestimates of 0.5 ms^{-1} in wind speed. The "MOS" methods, i.e. Thom (1975) and Yang et al. (2001), are slightly more sensitive to wind speed than the empirical and semi-empirical methods. In contrast, the "MOS" methods are less sensitive to air temperature than the empirical and semi-empirical methods. In general, all the parameterizations are moderately sensitive to the surface temperature. The most crucial parameters in accurately determining the aerodynamic resistance are surface roughness lengths for momentum and for heat transfer. All the parameterizations have shown pronounced sensitivity to roughness length for momentum. An underestimation of 50% in z_{0m} can result in errors in the estimated aerodynamic resistance as much as about 25% on average. The "MOS" methods show a slightly larger sensitivity on the factor kB^{-1} than the empirical and semi-empirical methods.

The impact of the uncertainties in the estimates of aerodynamic resistance on the uncertainties of sensible heat flux estimate are analyzed by assigning ±5%, ±10%, ±20% and ±30% errors to the reference values of r_{ah} in Table 6. Figure 9 shows the sensitivities of the estimated sensible heat flux to these error ranges in r_{ah}. For the data set used in this study, underestimate of 15% in r_{ah}, which is the largest error of underestimate in Table 7 (corresponding to errors in wind speed), will result in about 20% overestimate in sensible heat flux. Overestimate of 25% in r_{ah}, which is the maximal error in r_{ah} shown in Table 7, will lead to the uncertainty in sensible heat flux estimate larger than 30%.

5 Summary and conclusions

The measurements of aerodynamic resistance to heat transfer were analyzed and eight parameterizations for aerodynamic resistance were evaluated using the measurements of sensible heat flux from the eddy correlation system. The following conclusions were drawn from this study:

The diurnal variations of aerodynamic resistance during the daytime (07:00∼18:00) were observed both over the bare soil and over the maize canopy. The excess resistance in terms of the kB^{-1} parameter has also a significant diurnal variation. It is found that the kB^{-1} parameter was larger over the bare soil on 31 May than over the maize canopy on 26 June. Changes of kB^{-1} in the morning and in the late afternoon over the maize canopy imply a change of the relative vertical position of the effective heat source (z_{0h}) and of the effective momentum sink (z_{0m}) within the canopy.

The evaluation of the eight parameterizations of aerodynamic resistance show that inclusion of the difference in the roughness length for momentum and for the heat transfer improves some of the empirical parameterizations. It is found that the difference in the estimated aerodynamic resistances between the "MOS" methods and the (semi-)empirical methods was moderate. The study also suggests that some of the parameterizations (e.g. Hatfield et al., 1983; Xie, 1988) are not suitable to estimate sensible heat flux using remotely sensed surface temperature measurements.

Our sensitivity study has indicated that the most crucial parameters in the estimation of aerodynamic resistance are the roughness lengths for momentum and for heat transfer, and the wind speed. The land surface temperature is a moderately critical variable in determining precisely the aerodynamic resistance, while it is the most important variable for sensible heat flux estimates. In general, the "MOS" methods are slightly more sensitive to wind speed than the empirical and semi-empirical methods.

Further studies should be carried out concerning the change in the relative vertical position of the effective heat source and of the effective momentum sink within the canopy over different surfaces when the surface is heating up and cooling down. This improves our understanding of heat exchange over thermally heterogeneous surfaces.

The evaluation on the parameterizations should also be tested over a wider range of surface and climate conditions.

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