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EVALUATION OF SELECTED PARAMETERIZATIONS OF AERODYNAMIC RESISTANCE TO HEAT TRANSFER FOR THE ESTIMATION OF SENSIBLE HEAT FLUX AT A TROPICAL SITE IN ILE-IFE, NIGERIA

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ABSTRACT

Aerodynamic resistance to heat transfer, r_{ah} is a well-known and important parameter for the estimation of sensible heat flux near the earth's surface. The values are highly variable over different surface types and conditions; and routinely can be determined from semi-empirical schemes incorporating parameterizations for surface-atmosphere energy exchanges. This study evaluated the performances of seven selected parameterizations of r_{ah} in order to establish the influence of aerodynamic resistance in the estimates of sensible heat flux over a grass canopy.

The estimated values of r_{ah} employing different parameterizations were used to estimate sensible heat flux and the results were compared to direct eddy covariance measurements. The findings revealed that parameterization schemes by Thom (1975) and Xie (1988) performed best for the estimation of r_{ah} and sensible heat flux at the study location. Schemes by Verma *et al.* (1976), Choudhury *et al.* (1986), Viney (1991) and Mahrt and Ek (1984) performed moderately, while that of Hatfield et al. (1983) had the least performance.

Keywords: Parameterization, aerodynamic resistance, sensible heat flux, roughness length.

1. INTRODUCTION

Parameterization of aerodynamic resistance to heat and water transfer is essential for the accurate modelling of the exchanges between the earth and the atmosphere; and for the estimation of turbulent heat fluxes (Liu *et al.*, 2007). Consequently, accurate estimation of turbulent heat fluxes is vital in the exchange of energy and mass between the earth's systems.

The aerodynamic resistance which is a function of the surface roughness, atmospheric stability and wind speed, emphasises the effect of the boundary layer on the land-atmosphere interaction. The sensible heat flux (H_s) can be estimated from the ratio of the difference of the surface-air temperature, (T_s-T_a) to the aerodynamic resistance to heat transfer (r_{ah}):

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

where ρ is the air density and C_p is the specific heat capacity of air at constant pressure.

Different researchers have developed different parameterizations to estimate r_{ah} using surface layer variables based on Monin-Obukhov Similarity Theory (MOST). These parameterizations are as published by Monteith (1973), Thom (1975), Verma *et al.* (1976), Louis (1979), Hatfield (1983), Mahrt and Ek (1984), Choudhury (1986), Xie Xianqun (1988), Viney (1991), Lee (1997) and Yang *et al.* (2001).

There have been several studies conducted on the evaluation of these parameterizations by Kalma (1989), Itier (1980), Hatfield *et al.* (1983), Mahrt and Ek (1984) and Choudhury *et al.* (1986). The results showed close agreement between the parameterizations of Itier (1980) and Choudhury (1986) for determination of r_{ah}. Some significant disparities were observed in the parameterizations by Monteith (1973), Hatfield *et al.* (1983) and Mahrt and Ek (1984). Ham and Heilman (1991) evaluated the aerodynamic resistances obtained above-canopy and within-canopy for sparse cotton field. Their results showed that aerodynamic resistances above and within the canopy varied extremely and only partially described by average wind speed. Xie (1991) evaluated the performance of the parameterizations in a winter wheat field and the results showed that the parameterizations by Chen (1988) and Xie (1988) were in good agreement with the measurements.

The above listed parameterizations have been evaluated and accepted upon agreement with data from which the methods were developed. However, there were discrepancies when applying the schemes to other data derived from surfaces that were different from the original situations. Therefore, the objectives of this study are to: (1) estimate selected parameterizations of r_{ah}, (2) compare the parameterizations of r_{ah} with the derivation of r_{ah} from the eddy covariance system and (3) use the different parameterizations of r_{ah} to estimate sensible heat flux over a grass canopy at a tropical site in Ile-Ife, Nigeria.

2. THEORY AND METHODOLOGY

2.1 Parameterization of Aerodynamic Resistance to Heat Transfer

From equation (1), the aerodynamic resistance to heat transfer (r_{ah}) can be determined from the sensible heat flux (H_s) as:

$$r_{ah} = \frac{\rho c_p (T_s - T_a)}{H_s} \qquad (2)$$

The 'measured' aerodynamic resistance values r_{ah} can be obtained from the surface and air temperature, whilst the eddy covariance system will be used to determine H_s. Based on MOST, the sensible heat flux (H_s) can also be calculated using the profiles of wind speed and air temperature as:

$$H_s = -\rho c_p u_* T_* \qquad (3)$$

where u_* is the friction velocity and T_* is the temperature scale. Wind and temperature profiles in a horizontally homogeneous surface layer can be expressed respectively as:

$$u = \frac{u_*}{k}\left[In\left(\frac{Z-d}{z_{0m}}\right) - \psi_m(\varsigma, \varsigma_{0m})\right] \qquad (4)$$

$$T_a - T_0 = P_{r0}\frac{T_*}{k}\left[In\left(\frac{Z-d}{z_{0h}}\right) - \psi_h(\varsigma, \varsigma_{0h})\right] \qquad (5)$$

where u is the wind speed at a reference height Z, d is the zero-plane displacement, T_0 is the aerodynamic surface temperature, z_{0m} is the roughness length for momentum transfer, z_{0h} is the roughness length for heat transfer, p_{r0} is the turbulent Prandt number which expresses the difference between the eddy diffusivities of momentum k_m and of heat k_h, $P_{r0} = \frac{K_m}{K_h}$.

The stability parameters ς, ς_{0m} and ς_{0h} are defined as: $\varsigma = \frac{z}{L}$, $\varsigma_{0m} = \frac{z_{0m}}{L}$, $\varsigma_{0h} = \frac{z_{0h}}{L}$, $z = Z - d$ and L is the Monin-Obukhov length expressed as:

$$L = -\frac{\rho c_p {u_*}^3 T_a}{kgH_s} \qquad (6)$$

where g is the acceleration due to gravity.

From Equations (1) to (6), the aerodynamic resistance to heat transfer can be written as:

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

In a neutral condition, the stability functions for wind and temperature in equations (4), (5) and (7) can be expressed as $\psi_m(\varsigma, \varsigma_{0m}) = \psi_h(\varsigma, \varsigma_{0h}) = 0$, hence, r_{ah} becomes

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

If the roughness length for momentum and roughness length for heat are equal, i.e. $z_{0m} = z_{0h}$, then,

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

where r_{am0} is the aerodynamic resistance to momentum transfer in a neutral condition.

In a stable condition, the integral stability functions for wind and temperature in eq. (4), (5) and (7) can be written as:

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

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

In an unstable condition,

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

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

where $x = (1-\gamma_m\varsigma)^{1/4}$, $x_0 = (1-\gamma_m\varsigma\frac{z_0}{z})^{1/4}$,

$y = (1-\gamma_h\varsigma)^{1/2}$, $y_0 = (1-\gamma_h\varsigma\frac{z_{0h}}{z})^{1/2}$, $\beta_m, \beta_h, \gamma_m, \gamma_h$ are experimental coefficients established on the observations of the atmospheric boundary layer (Paulson, 1970; Businger *et al.,* 1971; Garratt, 1977; Webb, 1982).

To estimate the aerodynamic resistance to heat transfer, eqs. (4) - (7) can be solved using eqs. (10) - (13). Under stable conditions, r_{ah} can easily be solved since, the profile functions are linear functions of the stability parameters and the coefficients in the wind and temperature profiles can be obtained from Webb (1970) and Businger *et al.* (1971). However, under unstable conditions, the profile functions are non-linear functions of the stability parameters and r_{ah} must be solved by iterative technique (Itier, 1980). Paulson (1970) proposed that $\beta_m = \beta_h = 5$ and $\gamma_m = \gamma_h = 16$ in an unstable condition. The estimation of aerodynamic resistance to heat transfer using eqs. (10) - (13) was first employed by Thom (1975) and has been generally referred to as the "standard parameterization" of r_{ah}.

The effect of atmospheric stability on the flux-gradient relationship, the bulk Richardson number, Ri_B, can be expressed as:

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

The ratio of the aerodynamic resistance in a stable condition to that in a neutral condition can be expressed as a function of the Richardson number, Ri_B:

$$\frac{r_{ah}}{r_{ah0}} = Ri_B \quad (15)$$

The roughness length for heat transfer z_{0h} and momentum transfer z_{0m} are essential parameters in the parameterization of r_{ah} that must be determined a priori. An excess resistance kB^{-1} expresses the difference between the roughness length for momentum transfer and heat transfer:

$$kB^{-1} = In\left(\frac{z_{0m}}{z_{0h}}\right) \quad (16)$$

where $z_{0m} = 0.13h_c$, $z_{0h} = 0.1z_{0m}$ and h_c is the canopy height.

The parameterizations selected to estimate the aerodynamic resistance to heat transfer in this study are listed in Table 1 and the statistical criteria for evaluating the performances are listed in Table 2.

Table 1: Selected parameterizations of aerodynamic resistance to heat transfer (r_{ah}) evaluated in this study

Models	Source	Parameterization of r_{ah}	Coefficients
I	Thom (1975)	$r_{ah} = \frac{1}{k^2u}\left[In\left(\frac{Z-d}{z_{0m}}\right) - \psi_m(\varsigma)\right]\left[In\left(\frac{Z-d}{z_{0h}}\right) - \psi_h(\varsigma)\right]$	$\varsigma_{0m} = \varsigma_{0h} = 0$
II	Verma *et al.* (1976)	$r_{ah} = \frac{1}{k^2u}\left[In\left(\frac{Z-d}{z_{0m}}\right)\right]^2 (1 - 16Ri_B)^{-1/4}$	
III	Hatfield *et al.* (1983)	$r_{ah} = \frac{1}{k^2u}\left[In\left(\frac{Z-d}{z_{0m}}\right)\right]^2 (1 + \beta Ri_B)$	$\beta = 5$
IV	Mahrt and Ek (1984)	$r_{ah} = \frac{1}{k^2u}\left[In\left(\frac{Z-d}{z_{0m}}\right)\right]^2 \left[\frac{1 + c(-Ri_B)^{1/2}}{1 + c(-Ri_B)^{1/2} - 15Ri_B}\right]$	$c = \frac{[75k^2(\frac{z+z_{0m}}{z_{0m}})^{1/2}]}{[In(\frac{z+z_{0m}}{z_{0m}})]^2}$
V	Choudhury *et al.* (1986)	$r_{ah} = \frac{1}{k^2u}\left[In\left(\frac{Z-d}{z_{0m}}\right)\right]\left[In\left(\frac{Z-d}{z_{0h}}\right)\right](1 - \beta\, Ri_B)^{-3/4}$	$\beta = 5$
V1	Xie (1988)	$r_{ah} = \frac{1}{k^2u}\left[In\left(\frac{Z-d}{z_{0m}}\right)\right]^2\left[1 + \frac{[1 - 16Ri_B In\left(\frac{Z-d}{z_{0m}}\right)]^{-1/2}}{In\left(\frac{Z-d}{z_{0m}}\right)}\right]$	-
V11	Viney (1991)	$r_{ah} = \frac{1}{k^2u}\left[In\left(\frac{Z-d}{z_{0m}}\right)\right]\left[In\left(\frac{Z-d}{z_{0h}}\right)\right][a + b(-Ri_B)^c]^{-1}$	a=$1.0591 - 0.0552In\{1.72 + [4.03 - In(\frac{z-d}{z_{0m}})]^2\}$ b=$1.9117 - 0.2237In\{1.86 + [2.12 - In(\frac{z-d}{z_{0m}})]^2\}$ c=$0.8437 - 0.1243In\{3.49 + [2.79 - In(\frac{z-d}{z_{0m}})]^2\}$

Table 2: Statistical criteria for evaluating the performances of the different parameterizations

Statistical Indicator	Symbols	Expression
Coefficient of Determination	R^2	$1 - \frac{\sum_{i=1}^{N}(E_i - M_i)^2}{\sum_{i=1}^{N}(E_i - \bar{M})^2}$
Mean Bias Error	MBE	$\frac{1}{N}\sum_{i=1}^{N}(E_i - M_i)$
Mean Relative Difference	MRD	$\frac{\sum_{i=1}^{N}(E_i - M_i)}{(n-1)\sum_{i=1}^{N} E_i}$
Index of Agreement	IA	$1 - [\frac{\sum_{i=1}^{N}(E_i - M_i)^2}{\sum_{i=1}^{N}(\lvert E_i - \bar{M}\rvert + \lvert M_i - \bar{M}\rvert)^2}]$

3. FIELD MEASUREMENT

3.1 Description of Site

The field study was conducted at the Meteorological (OAU Met) station located inside the Teaching and Research farm of Obafemi Awolowo University (OAU), Ile-Ife, Nigeria (7.55 °N; 4.56 °E) between January and March, 2019. The OAU Met station as shown in Fig. 1 is about 7 km away from the main campus (as the crow flies) in a north-east direction. The experimental area was open and level-terrain. The dimension of the field is approximately 50 m by 30 m. The mean wind speed at the location was about 1.2 ms^{-1} and prevailing wind direction at the surface was northerlies. The land cover of the site was grass, regularly maintained to mean vegetation height (h_c) of 0.05 m, the zero-plane displacement (d) is $\frac{2}{3}h_c$ and the surface emissivity (ε) is 0.694.

Fig. 1: Obafemi Awolowo University Meteorological Station, Ile-Ife, Nigeria

3.2. Instrumentation

An Open-Path Eddy Covariance (OPEC) system was deployed for the measurement of mass and energy fluxes (sensible heat, latent heat and carbon dioxide). The system consisted of a 3-D ultrasonic anemometer (model CSAT3, Campbell Scientific Instruments), Infrared gas analyser for CO_2/H_2O (model LI-7500, LI-COR Inc.) and a temperature-humidity probe, (model HMP60, Vaisala Inc.) as shown in Fig. 2. The OPEC system was deployed at a height of 1.8 m and the sampling frequency was 10 Hz. The CSAT3 measured the wind speed components along its three orthogonal dimensions. The positioning of the OPEC fast response sensor system was placed at the centre of the measurement area and moved into position such that its fetch was adequate (all sides) to ensure fetch-height ratio of 100:1 was maintained. This is to conform that both the steady-state (stationarity) and horizontal homogeneity conditions were met. The surface temperature was measured with an infrared thermometer (model CS220, Campbell Scientific Instruments) with a 60^{o} field of view and a 6.5 - 14 μm band pass. The spurious flux data were eliminated and the datasets were subjected to standardized Quality Control (QC) and Quality Assurance (QA) protocol. Also, the stationarity test was carried out on the datasets by following the assumptions provided by Foken and Wichura (1996). Finally, the data were reduced to 30 min averages.

Fig. 2: The Open Path Eddy Covariance System

4. RESULTS AND DISCUSSIONS

4.1. Diurnal Variation of Aerodynamic Resistance to Heat Transfer

The diurnal variation of the aerodynamic resistance to heat transfer, r_{ah} derived from the measurements of Eddy Covariance (EC) system are shown in Fig. 3. The diurnal variations of r_{ah} were observed on three days (January 4, February 27 and March 24, 2019). The choice of these three days was due to the clear sky condition (cloud-free) and consistency (gap-free) in the measurements by the EC system. The values of r_{ah} were observed to vary during the cause of a day. In the early mornings (00:00 to 08:00 Local Time LT), r_{ah} was high and fluctuating in the range 280 – 590 sm^{-1}; 280 – 490 sm^{-1}; 150 - 330 sm^{-1} on the respective days. From about 08:30 LT, r_{ah} continuously reduced and became stable (< 150 sm^{-1}) from about 09:30 to 18:30 LT. Between 19:00 to 24:00 LT, the values of r_{ah} began to increase and fluctuate again within the range of 275 – 530 sm^{-1}; 140 – 400 sm^{-1} and 90 – 340 sm^{-1} for the observed days.

The high values of r_{ah} recorded in the early morning and night time periods can be attributed to the stable atmosphere which inhibits vertical mixing. As such, the atmosphere is well stratified and separated into temperature layers. Thus, there is a drastic change in the wind speed over a short vertical distance which can be observed in Fig. 4 for the aforementioned days. The low values of r_{ah} observed in the afternoon occurred as a result of intense heat transfer in the grass canopy layer. Therefore, there is a large amount of heat exchange within the surface layer which brought the instability and hence, low aerodynamic resistance for the heat transfer. The reverse occurs in the early morning and night time. This observation is in agreement with that of Liu *et al.* (2006).

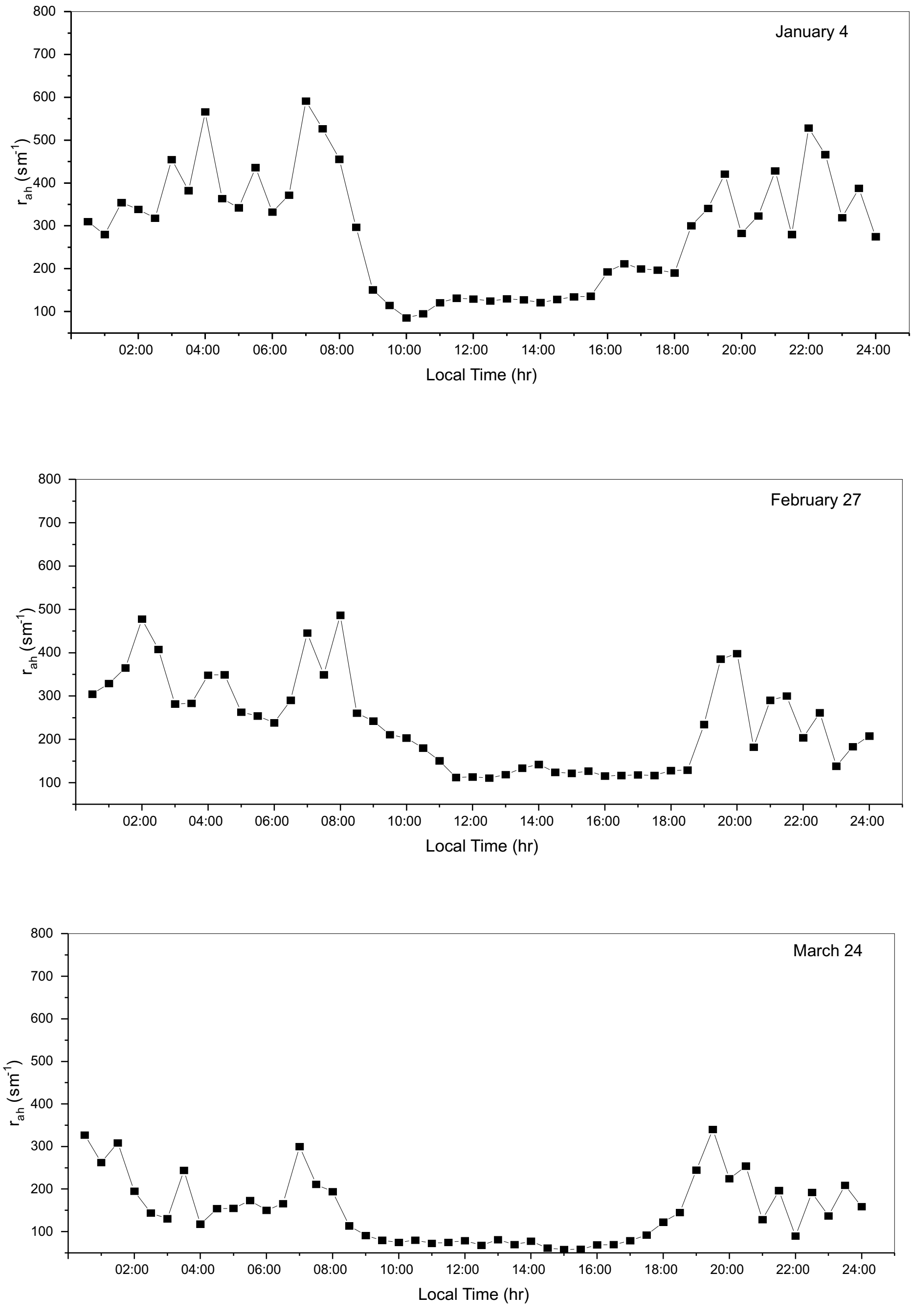

Fig. 3: Diurnal variations of aerodynamic resistance, r_{ah} derived from measurements by Eddy Covariance system

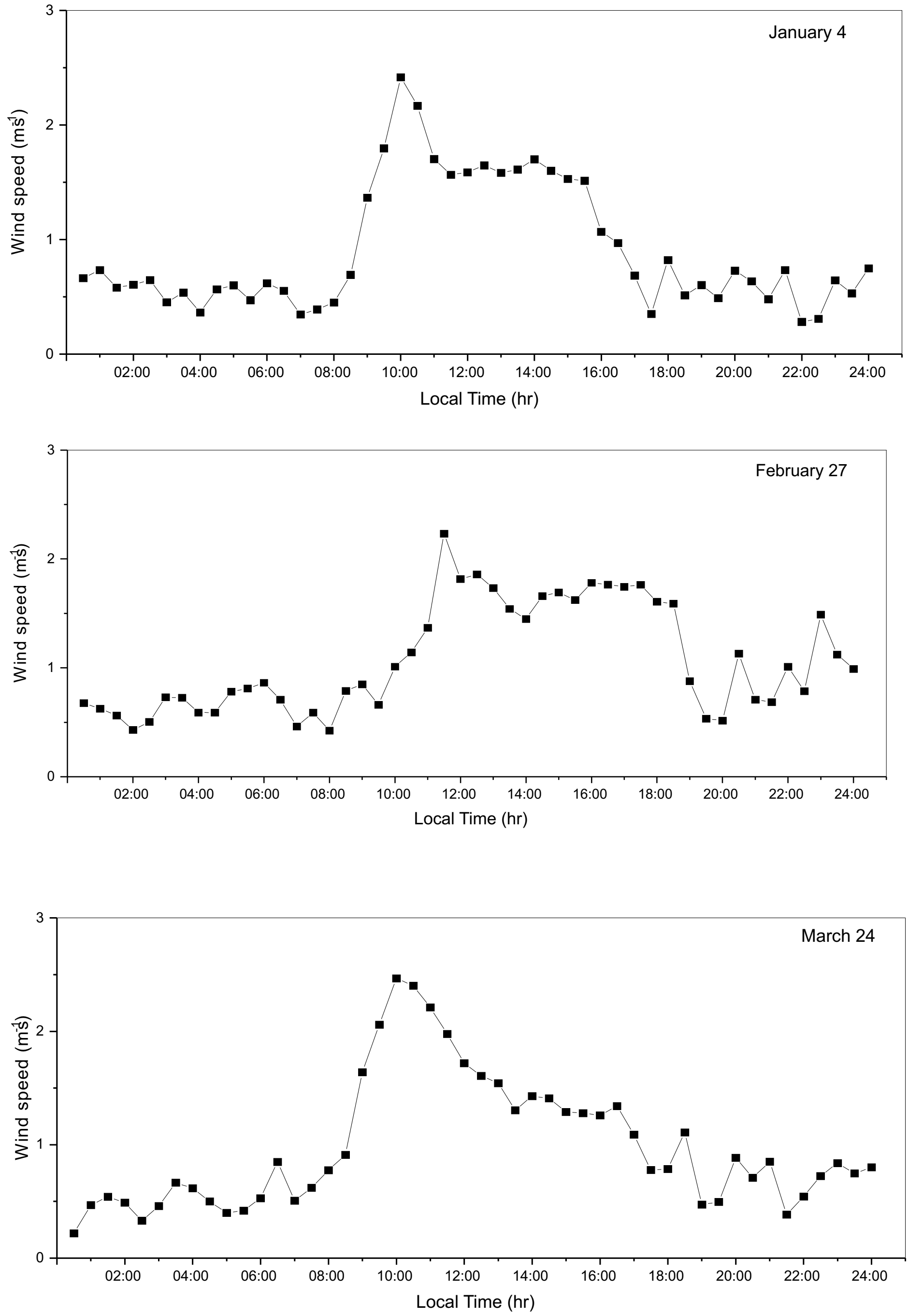

Fig. 4: Diurnal variations of wind speed for the aforementioned days at the study location

4.2. Evaluation of the Parameterizations of Aerodynamic Resistance

The aerodynamic resistance to heat transfer, r_{ah} was estimated with 1,030 effective data samples using the selected parameterizations given in section 2. The period was between January and March, 2019 and only unstable conditions were considered. The performances of the models when compared with direct measurements from the eddy covariance system are presented in Fig. 5. The coefficient of determination, R^2 of the models indicated that models V, VI, III, IV and VII showed a larger deviation from the observed values of r_{ah} having R^2 of 0.22, 0.27, 0.31, 0.48 and 0.49 respectively. However, the values of R^2 obtained from models I and II are close to unity (0.98 and 0.72 respectively), implying that the models are good fits for the estimation of r_{ah}.

The statistics obtained from evaluation of the parameterizations are described in Table 3. From the Table, the parameterizations by models I, II, III, IV, V and VII significantly underestimated (10 %, 74 %, 197 %, 80 %, 54 % and 43 % respectively) the values obtained for r_{ah}. The values obtained from parameterization by model VI overestimated r_{ah} by 72 %. The parameterization by model I had the least MBE (-13.41 sm^{-1}) and MRD (10 %) while model III had the highest MBE (-286.84 sm^{-1}) and MRD (197 %). This implies that model I showed the highest accuracy of estimating r_{ah}, while model III has the least accuracy of estimation of r_{ah}. The other models performed fairly in estimating the values of r_{ah} as indicated by their MBEs and MRDs.

Also, the Index of Agreement (IA) obtained for the models showed that model I has the highest IA (0.97), while model III has the least IA of 0.1. These findings indicated that model I (Thom, 1975) performed best, while model III (Hatfield *et al.*, 1983) has the least performance in the estimation of r_{ah} at the study location. This result is in agreement with the findings of Xie (1991) under unstable conditions.

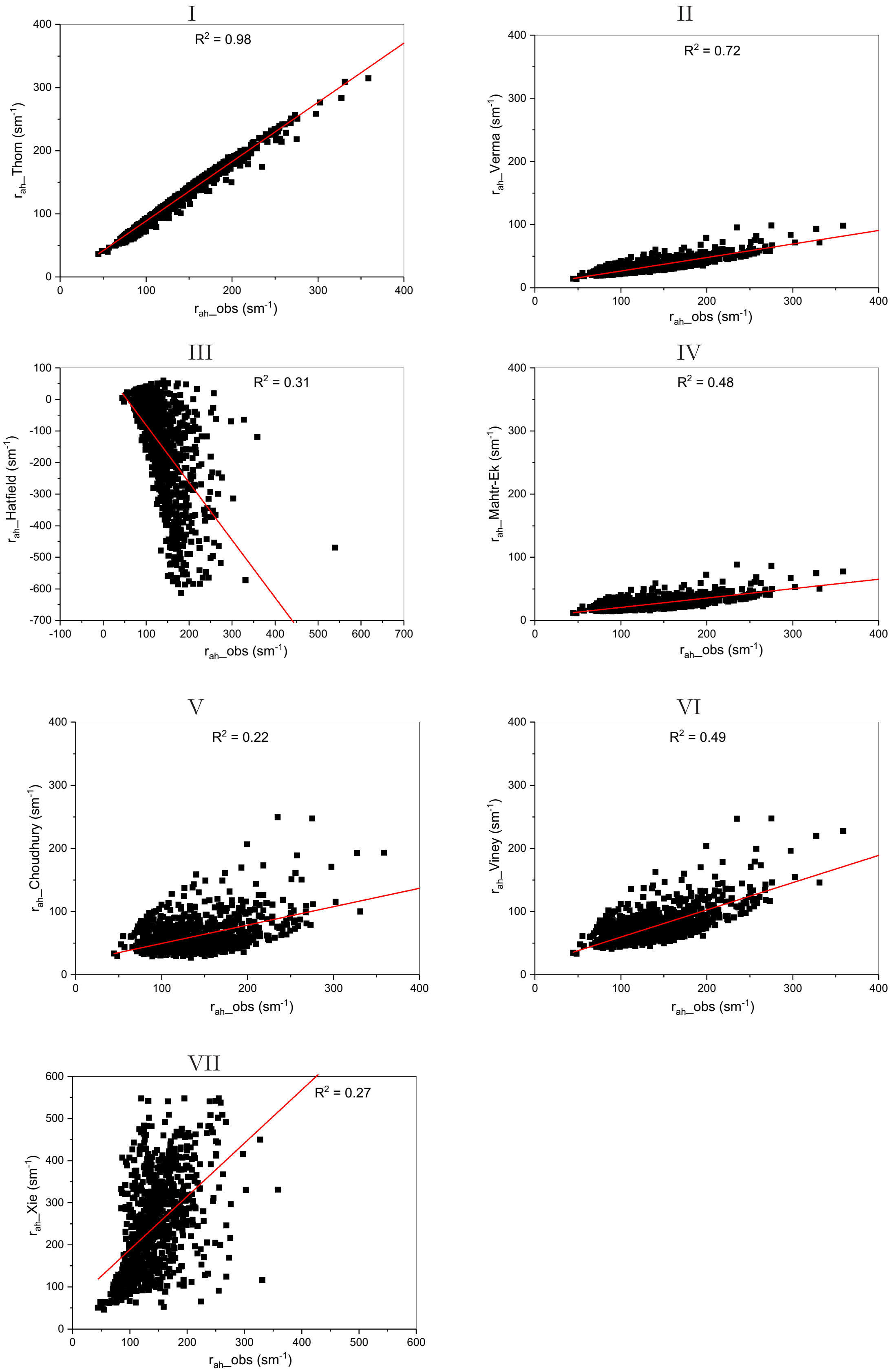

Fig. 5: Comparison of different parameterizations of aerodynamic resistance, r_{ah} with measurement of r_{ah}

Table 3: Statistics obtained from the parameterizations of aerodynamic resistance, r_{ah}

Model	Parameterization	MBE (sm^{-1})	MRD (%)	IA
I	Thom (1975)	-13.41	10	0.97
II	Verma *et al.* (1976)	-102.99	74	0.38
III	Hatfield *et al.* (1983)	-286.84	197	0.10
IV	Mahrt and Ek (1984)	-111.25	80	0.36
V	Choudhury *et al.* (1986)	-76.89	54	0.45
VI	Viney (1991)	-61.57	43	0.55
VII	Xie (1988)	105.65	72	0.53

It was observed that the highest errors from the estimates of r_{ah} were produced from the models where the roughness length for heat transfer, z_{0h} and for momentum transfer, z_{0m} were assumed to be identical such as the parameterizations of Verma *et al.,* 1976; Hatfield *et al.,* 1983; Mahrt and Ek, 1984; and Xie, 1988. In order to account for the difference between z_{0h} and z_{0m}, the above-mentioned parameterizations were modified. The modified parameterizations are presented in Table 4 and the results obtained are shown in Fig. 6.

Table 4: Modified parameterizations of aerodynamic resistance to heat transfer, r_{ah}

Model	Source	Modified parameterization of r_{ah}
II	Verma *et al.* (1976)	$r_{ah} = \frac{1}{k^2u}\left[In\left(\frac{Z-d}{z_{0m}}\right)\right]\left[In\left(\frac{Z-d}{z_{0h}}\right)\right](1-16Ri_B)^{-1/4}$
III	Hatfield *et al.* (1983)	$r_{ah} = \frac{1}{k^2u}\left[In\left(\frac{Z-d}{z_{0m}}\right)\right]\left[In\left(\frac{Z-d}{z_{0h}}\right)\right](1+\beta Ri_B)$
IV	Mahrt and Ek (1984)	$r_{ah} = \frac{1}{k^2u}\left[In\left(\frac{Z-d}{z_{0m}}\right)\right]\left[In\left(\frac{Z-d}{z_{0h}}\right)\right]\left[\frac{1+c(-Ri_B)^{1/2}}{1+c(-Ri_B)^{1/2}-15Ri_B}\right]$
VI	Xie (1988)	$r_{ah} = \frac{1}{k^2u}\left[In\left(\frac{Z-d}{z_{0m}}\right)\right]\left[In\left(\frac{Z-d}{z_{0h}}\right)\right]\left[1+\frac{[1-16Ri_B In\left(\frac{Z-d}{z_{0m}}\right)]^{-1/2}}{In\left(\frac{Z-d}{z_{0m}}\right)}\right]$

The statistical analysis of the parameterizations of the modified models as presented in Table 5 indicated that all the models except model III showed improvement. The MBE of model II improved from -103.0 to -68.3 sm^{-1}; model IV improved from -111.3 to -95.8 $sm^{-1}$and model VI improved from 105.7 to -71.3 sm^{-1}. The MRD of model II improved from 74 % to 37 %; model IV improved from 80 % to 53 % and model VI improved from 72 % to 50%. Also, the IA of models II, IV and VI increased from 0.38 to 0.66; 0.36 to 0.51; and 0.53 to 0.82 respectively. The increment in IA signifies better agreement between the estimated and measured values of r_{ah} by the models. There was no significant increase in the coefficient of determination, R^2 of models II and IV, while model III showed increase in R^2 (from 0.31 to 0.48). However, there was a substantial improvement in the value of R^2 (from 0.27 to 0.80) obtained from model VI.

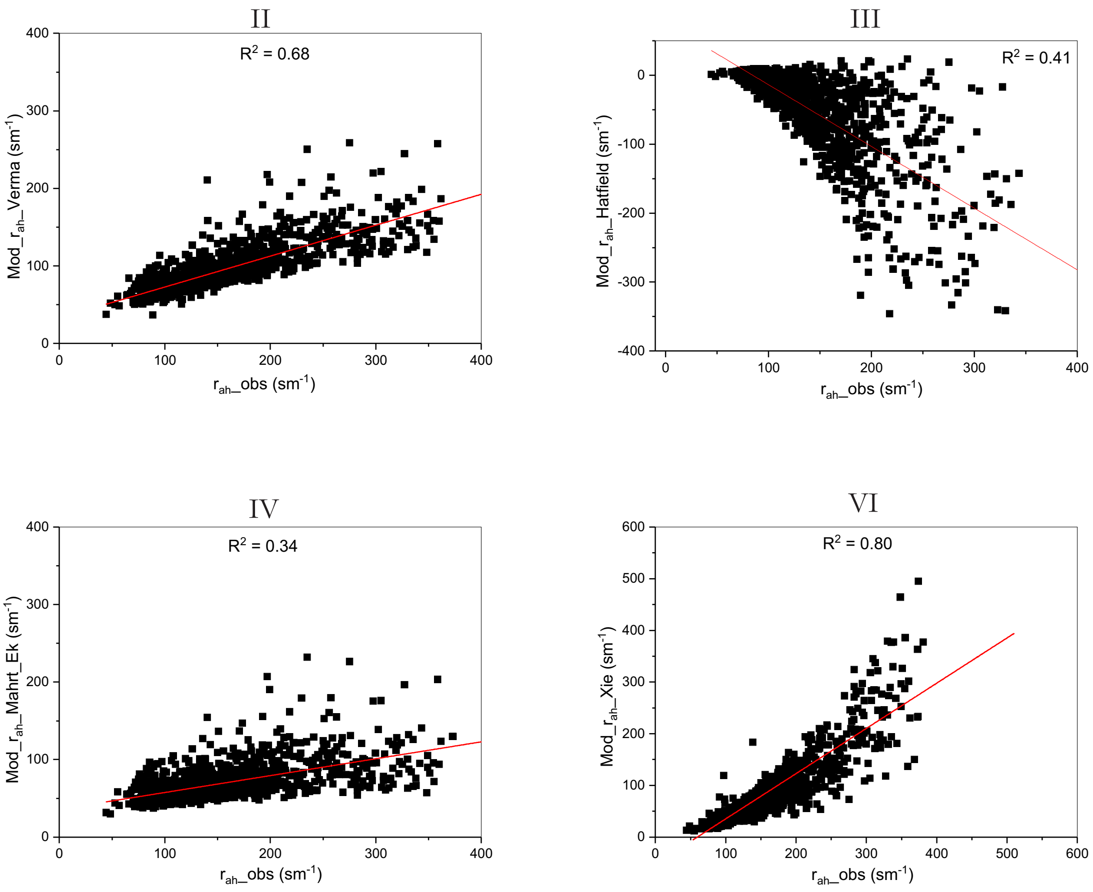

Fig. 6: Comparison of modified parameterizations of aerodynamic resistance, r_{ah} with measurement of r_{ah}

Table 5: Statistics obtained from the modified parameterizations of aerodynamic resistance r_{ah}

Model	Parameterization	MBE (sm⁻¹)	MRD (%)	IA
II	Verma *et al.* (1976)	-68.3	37	0.66
III	Hatfield *et al.* (1983)	-286.4	147	0.11
IV	Mahrt and Ek (1984)	-95.78	53	0.51
VI	Xie (1988)	-71.25	50	0.82

4.3 Estimation of Sensible Heat Flux

The estimated values of H_s (H_s*_est*) using different parameterizations of r_{ah} were compared with the measurements of H_s (H_s*_mea*) from the eddy covariance system as depicted in Fig. 7. The coefficient of determination, R^2 of models I, II, V, VI and VII are in the range of 0.48 and 0.51 suggesting that these models display large deviations between the estimated and measured values of H_s. Model III showed an enormous deviation (R^2 = 0.01) between H_s*_est* and H_s*_mea* while model IV indicated a minimum deviation (R^2 = 0.71) between H_s*_est* and H_s*_mea*.

Table 6 shows the statistics obtained from the estimations of H_s by the different parameterizations. All the models except IV and V underestimated the sensible heat flux. The two methods also have large values of MRD (566 % and 443 % respectively) and low IA values of 0.10 and 0.42 respectively, implying low performances of these methods in estimating H_s. The parameterizations by models II, V and VII performed moderately having low values of MBE (-19.7 Wm^{-2}, 7.8 Wm^{-2} and -8.4 Wm^{-2} respectively), high MRD (62%, 89% and 71% respectively) and high IA (0.71, 0.72 and 0.72 respectively). The parameterizations by models I and VII have minimum errors as given by their MBEs (-4.8 Wm^{-2} and -6.4 Wm^{-2} respectively) and low value of MRD (52%) and high value of IA (0.71). Therefore, the parameterizations by models I and VI (Thom, 1975 and Xie, 1988 respectively) were rated the best performing methods of estimating sensible heat flux having a low MBE, low MRD and high IA.

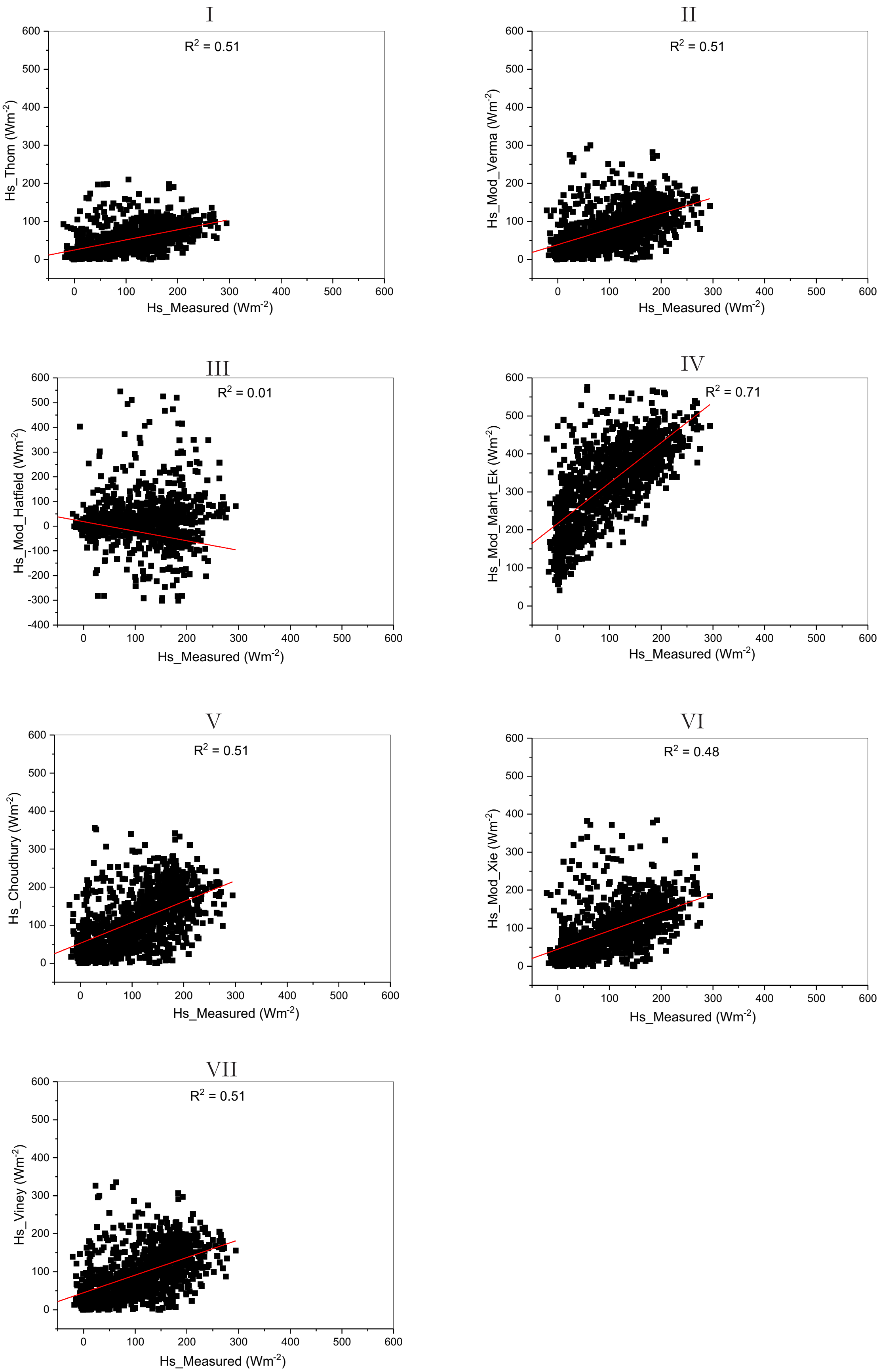

Fig. 7: Comparison of measured and estimated values of sensible heat flux, H_s obtained from different

Table 6: Statistics obtained from the estimation of H_s using the parameterizations of r_{ah}

Model	Parameterization	MBE (Wm^{-2})	MRD (%)	IA
I	Thom (1975)	-4.8	52	0.71
II	Verma *et al.* (1976) (modified)	-19.7	62	0.71
III	Hatfield *et al.* (1983) (modified)	-301.3	566	0.10
IV	Mahrt and Ek (1984) (modified)	223.5	443	0.42
V	Choudhury *et al.* (1986)	7.8	89	0.72
VI	Viney (1991)	-8.4	71	0.72
VII	Xie (1988) (modified)	-6.4	52	0.71

5. SUMMARY AND CONCLUSION

The diurnal variation of the derived aerodynamic resistance was obtained using the eddy covariance system over a grass canopy. The aerodynamic resistance, r_{ah} exhibited a 'U' shape during the day time and an inverse 'V' shape during the night time. The values of r_{ah} were high and fluctuating in the early mornings (00:00 to 08:00 LT) and night times (19:00 to 24:00 LT) due to the atmosphere being stratified at this period. The reverse occurred from late morning throughout the afternoon (09:30 to 18:30 LT) due to high instability of the atmosphere.

The performances of seven semi-empirical parameterizations of r_{ah} were also evaluated. The schemes include those postulated by: (1) Thom (1975), (2) Verma *et al.* (1976), (3) Hatfield *et al.* (1983), (4) Mahrt and Ek (1984), (5) Choudhury *et al.* (1986), (6) Xie (1988) and (7) Viney (1991). The evaluation of the different schemes revealed that Thom (1975) performed best, while Hatfield *et al.* (1983) had the least performance in the estimation of r_{ah} at the study location. Also, the parameterizations of Thom (1975) and Xie (1988) performed best in the estimation of sensible heat flux. The parameterizations of Choudhury *et al.* (1986), Viney (1991), Verma *et al.* (1976) and Mahrt and Ek (1984) performed moderately while the parameterization of Hatfield *et al.* (1983) performed poorly in the study location.

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