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# The Parameterization of Humid Tropical Surface-Layer Aerodynamic Resistance to Heat Transfer using Modified Louis Scheme

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## *Abstract*

***Accurate estimation of aerodynamic resistance to heat transfer ($r_a$)is needed in the characterization of turbulent heat fluxes for effective monitoring of the global energy budget.The original Louis ParameterizationScheme (LPS)was modified by the inclusion of near surface soil moisturefor calculating the aerodynamic resistance to heat transfer for a humid tropical region. The model outputs were compared with the $r_a$estimated from eddy correlation data obtained from Nigeria Micrometeorological Experimental site (NIMEX-1) observations. The modified LPS reduced the RMSE by 33.22 $sm^{-1}$and 4.18 $sm^{-1}$ for unstable and stable conditions respectively. Consequently, the modified LPSshowed a pattern very similar to the observations, although for stable conditions and periods with relatively low radiative cooling effect, the modification does not have noticeable effect on the aerodynamic resistance prediction, but the improvement becomes more significant for unstable conditions. The results showed that the diurnal values of aerodynamic resistance during daytime were higherfor dry periods than wet periods.The modifiedLPS can be used by atmospheric modeling system for more varied surfaces and a wide range of atmospheric stability.***

**Keywords:** Aerodynamic resistance, Soil moisture, Surface layer, Modeling, Diurnal.

## 1.0 Introduction

A reliable characterization of turbulent heat fluxes is important in effective monitoring of the surface energy balance of homogenous natural surfaces. The simulation of these energy fluxes can be improved by careful parameterizations of some input parameters like the radiative surface temperature computed from the surface energy balance equations and aerodynamic resistances for heat transfer ($r_a$)based on the prevailing weather conditions at the measurement site [1,2]. The most challenging part of the heat fluxes parameterization is perhaps the determination of the aerodynamic resistance parameters. The parameters may be estimated from physically-based methods or empirical relationships, but computation and parameterization of the resistances often suffer from lack of a commonly-accepted method. The aerodynamic resistances are often computed by integrating the reciprocal of the eddy diffusion coefficient and inverting the combination equation. Alternatively, where stability corrections are required, the resistance can be found bysolving for friction velocity and aerodynamic resistances analytically. The classical logarithmic wind profile equation is not applicable for the transfer of sensible heat flux because the transfer of heat encounters greater aerodynamic resistance than the transfer of momentum [3]. This translates to the sensible heat flux as having a lower effective source than the effective sink of momentum. The roughness length and surface temperature associated with sensible heat then become two unknowns in the energy balance and resistance equation. This has prompted researchers to add an extra aerodynamic resistance as a corrective term to the combination equations in estimating the sensible heat flux.

Louis [4] proposed a compact scheme by using the surface Richardson number as an independent parameter to avoid numerical iteration. This scheme is widely used in mesoscale models, and further developments and improvements have appeared in recent years. One of the problems in the Louis model is that it has two assumptions: (1) the momentum roughness length ($z_{0m}$) is the same as the heat transfer roughness, viz $z_{0m}= z_{0h}$, (2) the lowest heat (z) in the numerical models

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is much larger than the momentum roughness, viz. $z/z_{0m} >> 1$. These assumptions are generally valid for very smooth surfaces, and not for rough surfaces.A second problem is that, when Louis scheme was derived, the Businger stability functions [5] were used. They are only valid for a limited stability range for unstable and neutral conditions.Garratt [6] was one of the first to suggest an extension of the Louis scheme, in which some constants are determined by least squares fitting for values of $z_{0m}= z_{0h}$ different from unity. Mascart *et al*. [7] modified the scheme to allow for different values of $z_{0m}$ and $z_{0h}$by using a higher order polynomial fit for some constants, but as the Businger functions were used, the same problems exist as in the original derivation. Launiainen [8] suggested a relationship between $z=L$ and the bulk Richardson number that could be applied to calculate the fluxes. In the method, $k$ is taken as 0.40, but limited ranges for $z_{0m}$ of $10^{-5}$ to $10^{-1}$ m and $z_{0m}= z_{0h}$of 0.5 to 7.3 are considered. Van Den Hurk and Holtslag [9] compared some of the above parameterization methods using $k = 0.40$ for a wide range of stability and $z_{0m}= z_{0h}$. They found that the Launiainen parameterization agrees well with the numerical iterative solution for a limited range of stability and $z_{0m}= z_{0h}$. For $z_{0m}= z_{0h}>500$, an interpolation formulation suggested by Holtslag and Ek [10], combined with the Launiainen parameterization, provides a better approximation.Delage [11] modified the Louis scheme with a larger coefficient for stable conditions for use in a one dimensional model of the nocturnal boundary layer (NBL). The results are similar to those using the stable functions proposed by Beljaars and Holtslag [12], which are believed to give realistic results. Kot and Song [13] improved the Louis model by assuming $z_{0m}= z_{0h}$. They reported that the Louis model predicted more reasonable mean value during the stable period while the prediction was worst during the unstable periods. Since the influence of stratification is not only dependent on the universal function of stability parameter but they are also dependent on properties of the underlying surface [14]. So, the model needs to be improved for unstable atmospheric condition.

The modification of the original Louis equation was based on the fact that the model could not characterize the behaviour of the aerodynamic resistance to heat transfer during the unstable condition [13], meanwhile, meaningful observations were obtained for stable conditions which were due to lower levels of turbulence and the influence of homogeneneties in terrain [13]. However, the already accepted formulations could not be faulted, not even by a learner in this field. But carefully designed experiments and more recent theories can improve the parameterization in unstable boundary layers. The available literature on this issue revealed that the near soil moisture content variable (0.05 mdepth) is often neglected in most of these formulations. This parameter is crucial in the estimation of the $r_a$ for humid tropical region though it is somehow ignored in arid and semi-arid region [15]. The main reason for the neglect is the difficulty in obtaining near soil moisture at some depths close to the soil surface in arid and semi-arid regions [16]. This variable is available inNigeria Micrometeorological Experiment (NIMEX) datasets, especially for transitional period from wet to dry period in humid tropical region. In this paper, theoriginal LPS was modified usingnear soil moisture content variable to parameterize $r_a$for stable and unstable conditions in humid tropical region. Also, the diurnal variations of $r_a$were investigated during the transitional period.

## 2.0 Materials and Methods

### 2.1 Study Area

By climatological classification, the study area at the Obafemi Awolowo University campus Ile-Ife, Nigeria (7.55 ºN; 4.56 ºE) is situated within the tropical wet and dry belt of West Africa (Fig 1.0 a)[17]. It is located northeast of the main campus and is approximately 5 km away from the main campus by road (Fig 1.0 b). It spans about 1400 hectares and is partly cultivated. The area investigated has the dimension approximating 1000 m by 300 m. It is an open and a level terrain with low wild grasses and shrubs. The topsoil at the site is characterized as fine sandy clay loam [17]. The typical relative humidity of the area is about 80 % in the mornings, except in the dry season when the value drops to about 70 % [18]. The surface wind flow in the area is weak (the mean wind speed is less than 1.5 $ms^{-1}$);this is generally a typical characteristic of the tropical areas.

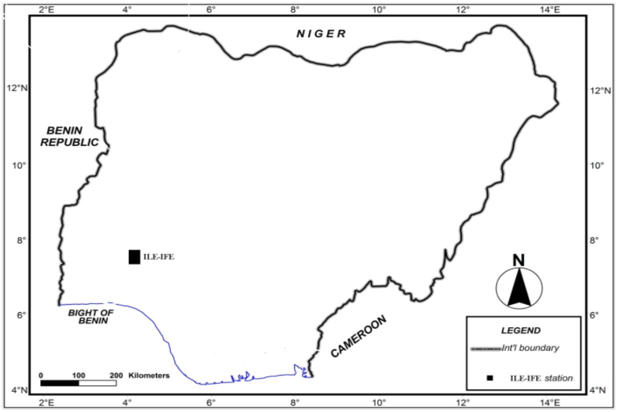

**Fig. 1a:** Map of Nigeria showing Ile-Ife

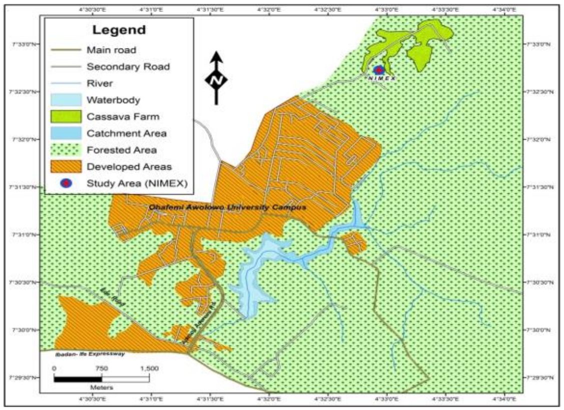

**Fig. 1b:** Map of the position of the measurement site in Ile-Ife, Nigeria.

## 2.2 Data Collection

The data collection was done during an intensive field campaign carried out in the period between February 24 and March 10th, 2004 as part of NIMEX-1 Project. The campaign involved the use of homogenous flat surface and different sensors for characterizing the state of the atmosphere and the soil physical characteristics. However, the mean and turbulent micrometeorological parameters in the surface layer were measured for duration of the NIMEX-1 project. Two meteorological masts were set up for profile measurements of the wind, temperature, atmospheric radiation, and the soil (sub-surface) parameters while a third was devoted for eddy covariance measurements of the turbulent fluxes. An eddy covariance system consisting of an ultrasonic anemometer together with a Krypton hygrometer placed on a 2 m mast was integrated to measure the turbulent fluxes. The combined arrangement produced the turbulent wind, acoustic temperature and humidity components. The sonic turbulence parameters were sampled at a frequency of 16 Hz [18].

## 2.3 The Parameterization of Aerodynamic Resistance to Heat Transfer

## 2.2.1 Original Louis Parameterization Scheme (LPS)-

Louis *et al*. [19] and Mahrt and Ek [20]developed a parameterization scheme for the total*aerodynamic resistance* including both neutral and non-neutral parts.This model fulfilled the Monin-Obukhov (M-O) similarities hypothesis as

$$\mathrm{r_a} = \frac{1}{C_q \overline{u}_z} \tag{1}$$

Where $C_q$is transfer coefficient

In unstable condition

$$C_q = \left[\frac{\kappa}{In(\frac{z_1+z_{o\mathrm{h}}}{z_{o\mathrm{h}}})}\right]\left[\frac{\kappa}{In\left(\frac{z_2+z_{om}}{z_{om}}\right)}\right]\left(1 - \frac{15Ri}{1-c(-Ri)^{1/2}}\right) \tag{2}$$

Where

$$c = \frac{75\kappa^2\left(\frac{z_2+z_{om}}{z_{o\mathrm{h}}}\right)^{1/2}}{\left[In\left(\frac{z_1+z_{om}}{z_{o\mathrm{h}}}\right)\right]^2} \tag{3}$$

In stable condition

$$Cq = \left[\frac{k}{In(\frac{z_2+z_{o\mathrm{h}}}{z_{o\mathrm{h}}})}\right]\left[\frac{k}{In\left(\frac{z_2+z_{om}}{z_{om}}\right)}\right]\left(\frac{1}{(1+15Ri)(1+5Ri)^{1/2}}\right) \tag{4}$$

## 2.2.2 Modified Louis Parameterization Scheme

This modified LPS estimated $r_a$ as function of surface soil moisture and average wind speed measured at two heights using second order closure parameterizations and Buckingham Pi Dimensional analysis [19].The surface soil wetness index$\theta_s$, which is a measure of moistureavailability was obtained using polynomial regression model of order two (best fit).

$$\theta_s = -7.22\theta_{0.05m}^2 + 3.96\theta_{0.05\mathrm{m}} - 0.061 \tag{5}$$

where $\theta$ is the instantaneous soil moisture measured at 0.05 m depth.

The $r_a$was obtained as,

$$r_a = \frac{1.057\kappa}{\ln\left(\frac{z_{0m}}{z_{0h}}\right)^2 \bar{u}_z} + 0.012\left(\frac{\theta}{\theta_s}\right)^{0.126} - 4.289, \tag{6}$$

The above equation containsnon-dimensional coefficients which were obtained by regression against the observed data. The influence of stratification is transferred to the constant since the functions are not only dependent on the universal function of stability parameter but they are also dependent on properties of the underlying surface [21].

The roughness length due to heat transfer was obtained using polynomial regression model of order three (best fit).

$$z_{0h} = -6.63z_m\left(\frac{u_{z_2}}{u_{z_1}}\right)^3 + 1.42\left(\frac{u_{z_2}}{u_{z_1}}\right)^2 - 0.34\left(\frac{u_{z_2}}{u_{z_1}}\right) + 0.05 \tag{7}$$

$$\text{where } \mathrm{z_{om}} = 0.1z_{0h}, \quad z_m = \sqrt{z_1 z_2}$$

The $\mathrm{z_{0m}} = \mathrm{z_{oh}}$ and $\mathrm{z_{0m}} \neq \mathrm{z_{oh}}$ assumptions were verified for this modified LPS [22].

## 2.2.3 Aerodynamic Resistance to Heat Transfer Estimated From Eddy Covariance Data

Since aerodynamic resistance is a very important parameter when estimating sensible and latent heat flux with resistance methods [16],there is the need to compare the estimated $r_a$ with $r_a$ obtained from eddycovariance measurement (used as reference data). Thom [3] and Liu *et al.* [16] pointed out that aerodynamic resistance for water vapour as for heat transfer will exceed the aerodynamic resistance for momentum transfer. An excess resistance is introduced to express their differences.

$$r_{av} = r_{aH} = \frac{\phi_v}{\phi_v} r_{am} + r_b = \frac{\phi_v}{\phi_v}\frac{u_z}{u_*^2} + r_b \quad (8)$$

$$r_{am} = \frac{u_z}{u_*^2} \quad (9)$$

where $r_{am}$is aerodynamic resistance for momentum transfer, $u_z$ is wind at the reference height z, $u_*$ is friction velocity, $r_b$ is excess resistance; $\emptyset_v$ and $\emptyset_m$ are stability correction functions for water vapour and momentum transfer respectively and can be expressed as [16]

$$\phi_v = \phi_m^2 = \left(1 - 16\frac{z}{L}\right)^{-\frac{1}{2}} \text{Unstable condition} \quad (10)$$

$$\phi_v = \phi_m = \left(1 - 5\frac{z}{L}\right)^{-\frac{1}{2}} \text{stable condition} \quad (11)$$

Where *z* is reference height, *L* is Obukhov length. Thom [3] thought that excess resistance is in proportion friction velocity

$$r_b = \alpha . u_*^{-\frac{2}{3}} \quad (12)$$

Where $\alpha$ is a constant, and is equals 0.662 for the unsaturated surface (homogenous). From above, it can be concluded that aerodynamic resistance can be determined by the eddy correlation data using measured wind speed u, friction velocity $u_*$ and Obukhov length *L*. The derived aerodynamic resistance from the eddy correlation system was used to evaluate the performance of aerodynamic resistance.

## 2.5 Research Data Analysis

To evaluate the efficiency of the modified LPS, their results are compared to the eddy correlation data considering statistical means. The Mean Bias Error (MBE) (average deviation between parameterized and measured data; and the RMSE (average positive distance between parameterized and reference data). The Mean Bias Error (MBE) and Root Mean Square Error (RMSE) were calculated

$$MBE = \sum_{i=0}^{n} \frac{(r_a(estimated) - r_a(\text{referencedata})}{n} \quad (13)$$

$$RMSE = \sqrt{\sum_{i=0}^{n} \frac{(r_a(estimated) - r_a(\text{referencedata}))^2}{n}} \quad (14)$$

Where n is the number of observation [23].

## 3.0 Result and Discussion

## 3.1 Model Performance of Aerodynamic Resistance to Heat Transfer as Compared with Eddy Covariance Data

The $r_a$ estimated from the eddy covariance data were used to assess the performance of the LPS. Figure .2 depicts the mean compositediurnal variation of the modeled $r_a$ using the original and modified LPS. It can be seen from the graph that the original LPS showed closeness to the eddy$r_a$at the early hours of the morning, though slight underestimation of about 25sm$^{-1}$to38 sm$^{-1}$ was still observed. Meanwhile, during the mid-day, early and late hours of the evening, the original LPS strongly overestimated$r_a$ (about 60sm$^{-1}$ to 80sm$^{-1}$).However, it estimated $r_a$ with little or no bias with respect to the eddy data in the morning around 900hr LST.Based on the large bias in the estimated $r_a$ by original LPS during most part of the day and night, the original LSP was modified by including surface near soil moisturein its formulation for a tropical station.The modified LPS is validbetween 0.1ms$^{-1}$ and 2.7 ms$^{-1}$ for weak average wind speed, and 0.01m$^3$m$^{-3}$ and 0.13m$^3$m$^{-3}$ for low soil moisture $\theta$ .The modified LPS performed well for all stability conditions. Assuming $z_{0h} \neq z_{0m}$ , the modified LPS approximated the eddy$r_a$ at the early hours of the morning, with a slight underestimation of about 20sm$^{-1}$ to 30 sm$^{-1}$. The modified LPS showed closeness during the late hours of night, with slight underestimation of about 6sm$^{-1}$ to 7sm$^{-1}$in $r_a$. Meanwhile, with assumption of$z_{0h} = z_{0m}$, the modified LPS showed a large underestimation of about 100sm$^{-1}$ to 120sm$^{-1}$and 70sm$^{-1}$ to 90sm$^{-1}$ for unstable and stable conditions, respectively.

Figure 3 shows the scatter plot between eddy covariance obtained $r_a$ and estimated $r_a$from modified LPS . It can be seen from Fig. 3 that scatter was small for modified LPS ($z_{0h} \neq z_{0m}$) with high $r^2$(0.97), low RMSE (4.18sm$^{-1}$) and MBE(0.05sm$^-$1), while the RMSE and MBE values for modified LPS ($z_{0h} = z_{0m}$) were 10.15 sm$^{-1}$ and 2.10 sm$^{-1}$ respectively. This implies that the assumption of equality of $z_{0h}$ and $z_{0m}$ might not be applicable for a tropical atmosphere. The inclusion of near surface soil moisture on the original LPS reduced the RMSE by 33.22sm$^{-1}$ and 4.18sm$^{-1}$ for unstable and stable conditions respectively (Table2).

**Table 1:** The linear regression (slope *a*, intercept *b* and coefficient of determination $r^2$) as well as MBE and RMSE for the tested parameterization approaches with respect to the measured value

| **Models** | **a** | **b** | $r^2$ | **MBE($sm^{-1}$)** | **RMSE ($sm^{-1}$)** |
|---|---|---|---|---|---|
| | | | **Wet periods** | | |
| Original LPS | 0.82 | 25.91 | 0.59 | 2.30 | 30.13 |
| Modified LPS($z_{0h} \neq z_{0m}$) | 0.34 | 29.07 | 0.97 | -1.14 | 6.94 |
| Modified LPS ( $z_{0h} = z_{0m}$) | -2.34 | 39.07 | 0.69 | 1.14 | 12.94 |
| | | | **Dry Periods** | | |
| Original LPS | 0.59 | 32.87 | 0.60 | 2.15 | 29.61 |
| Modified LPS($z_{0h} \neq z_{0m}$) | 0.70 | 30.26 | 0.94 | -0.67 | 3.87 |
| Modified LPS ( $z_{0h} = z_{0m}$) | -5.34 | 279.07 | 068 | 1.14 | 15.94 |

**Table 2:** The Precision Analysis of Aerodynamic Resistance Models

| MODELS | Bias ($sm^{-1}$) | | RMSE ($sm^{-1}$) | | $r^2$ | |
|---|---|---|---|---|---|---|
| | $Ri > 0$ | $Ri < 0$ | $Ri > 0$ | $Ri < 0$ | $Ri > 0$ | $Ri < 0$ |
| Original LPS | 3.19 | -0.72 | 7.42 | 43.63 | 0.45 | 0.78 |
| Modified LPS($z_{0h} \neq z_{0m}$) | -0.63 | -0.01 | 3.5610.41 | 10.41 | 0.96 | 0.96 |

When Richardson number $Ri > 0$, the number of samples $N$ equals to 128; when $Ri < 0$, $N = 37$.

The overall RMSE and MBE for modified LPS ($z_{0h} \neq z_{0m}$) were 6.94 $sm^{-1}$and -1.149 $sm^{-1}$while and the MBE for modified LPS ($z_{0h} = z_{0m}$) were 22.94$sm^{-1}$ and 5.14 $sm^{-1}$ for wet and dry periods, respectively (Table1). The modified LPS showed a pattern very similar to the eddy $r_a$, although for stable condition and periods with relatively low radiative cooling effect, our modification does not affect the aerodynamic resistance prediction as much, but the improvement becomes more significant for unstable condition (Table 2). The findings also affirmed that the modification becomes more significant for dry period (RMSE = -0.67$sm^{-1}$) than the wet period (RMSE= -1.14$sm^{-1}$).

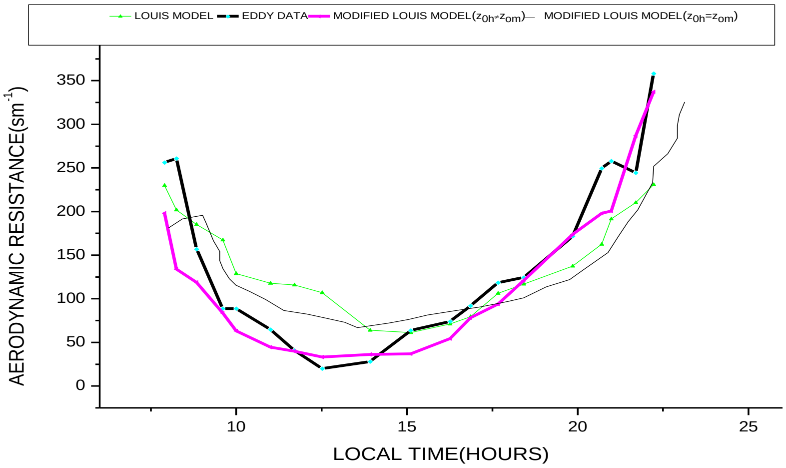

**Fig. 2:** The mean composite diurnal variation of the modeled aerodynamic resistance as compared with eddy data for DOY 55 -70, 2004

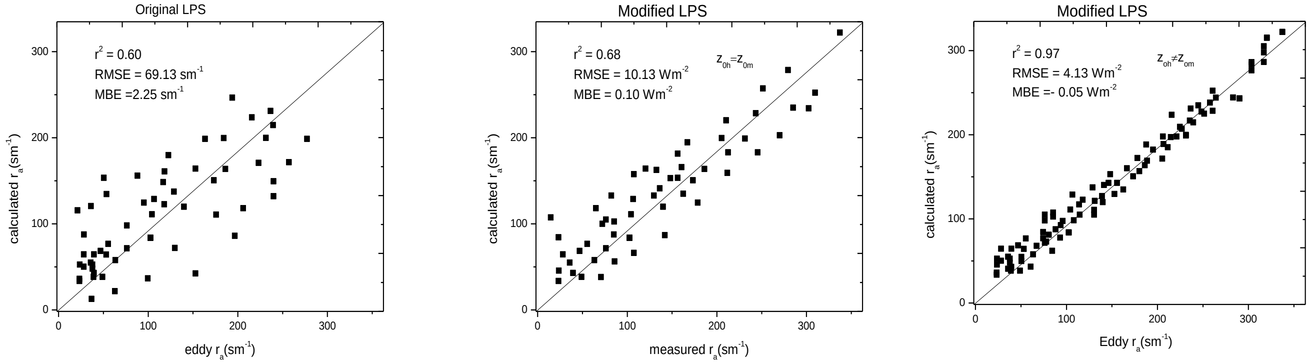

**Fig 3:** Scatter plots showing the modeled aerodynamic resistance versus the eddy data for DOY 57-70, 2004.

## 3.2 Diurnal Patterns of Aerodynamic Resistance using Profile Data

The values of the calculated and measured aerodynamic resistances are shown in Figure 4 for dry and wet periods. Relatively high values of $r_a$, ranging from 160 $sm^{-1}$ to 340 $sm^{-1}$ for wet periods and 100 $sm^{-1}$ to 400 $sm^{-1}$ for dry periods were observed during early morning and late night periods, when wind speed is low. On most days the value $r_a$is fairly constant from 100 $sm^{-1}$ to 120 $sm^{-1}$ between 1000 Hr LST to 1600 Hr LST. Higher values (order of 10 $sm^{-1}$ greater)were observed during dry period than wet period. Very low values are observed during early mornings for DOY 55-57. These low resistances are due to wetness because of the heavy rain that occurred the previous night except on DOY 55, which was dominated by intermittent cloudiness, the midday values range between 75-160 $sm^{-1}$. Over a bare soil, Lui *et al.*[16] reported values of aerodynamic resistance ranging between 100 $sm^{-1}$ and 130 $sm^{-1}$ for daytime and 200 $sm^{-1}$ and 600 $sm^{-1}$ for nighttime values. Shuttleworth *et al.* [24] observed aerodynamic resistance to momentum transfer over an Amazonian forest to range from 10 to 20 $sm^{-1}$ when wind speed (measured at 45 m, canopy height ≈ 35 m) exceeded 1.5$ms^{-1}$. Murphy *et al.* [25] measured $r_a$ over a loblolly pine plantation in the Southeastern United States and reported values between about 5$sm^{-1}$ and 40 $sm^{-1}$. Our values of $r_a$and that of Lui *et al.*[16] are higher than many values reported for several reasons. First, prevailing wind speeds were light to moderate (0.12 to1.3 $ms^{-1}$). Second, we assumed $z_{0m}$ is much smaller than $z_{oh}$ which is of the order of 0.0012 m to 0.0015 m during midday periods in our computation of $r_{a..}$ Summarily, the distribution of the aerodynamic resistance measured take a "U" type in the daytime and inverse "V" type during nighttime. Similar trends were reported by Lui *et al.* [16] and Verma *et al.* [26].

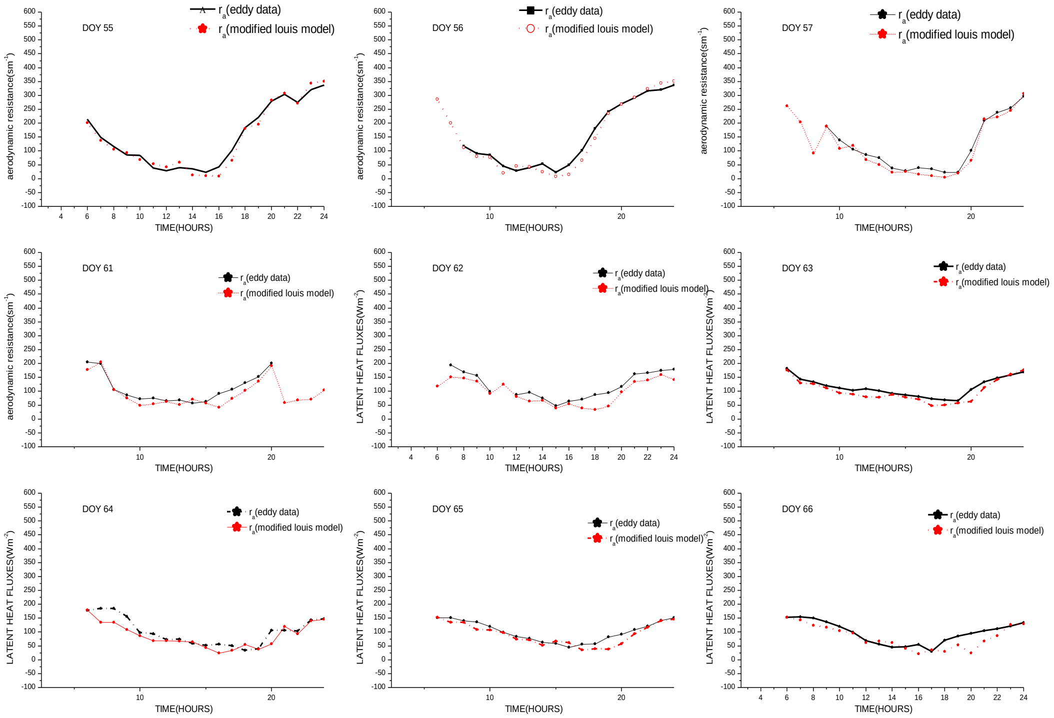

**Fig 4:** Diurnal variation of the measured and the simulated aerodynamic resistance$(z_{0m} \neq z_{0h})$ for DOY 55-70, 2004

## 4.0 Conclusion

The inclusion of the surface soil moisture as well as allowing for $z_{om}$ which is smaller than $z_{oh}$, improved the empirical parameterization of the Louis scheme. It was found that the difference in the estimated $r_a$ and eddy$r_a$was moderate. The modified LPS showed a pattern very similar to the observations, although for stable conditions and periods with relatively low radiative cooling effect, our modification does not affect the aerodynamic resistance prediction as much, but the improvement becomes more significant for unstable conditions. The findings also confirmed that the modification becomes more significant for dry periods than the wet periods. The distribution of the aerodynamic resistance takes a "U" type in the daytime and inverse "V" type at nighttime.

## 5.0 Acknowledgement

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