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The Effect of Energy Balance Closure Ratio on the Diurnal Variation of Excessive Heat Transfer Resistance Over a Tropical Station, Ibadan

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Abstract: The study investigated the effect of diurnal variation in excess heat transfer resistance on surface energy balance closure. Utilizing large-eddy covariance data, an algorithm combining the Monin–Obukhov similarity and the Brutsaert theoretical model was employed to estimate the excess heat transfer resistance. The study was conducted at the Ibadan site during the Nigerian Micrometeorological Experiment (NIMEX-1) in 2010. Results revealed the occurrence of negative excess heat transfer resistance values at night for the bare surface, irrespective of wet or dry conditions. During wet days, higher excess heat transfer resistance values (> 3sm^{-1}) led to improved energy balance closure, while during dry periods, daytime closure increased with excess heat transfer resistance until it surpassed 6 sm^{-1}. The study suggests that heat transfer efficiency outweighs momentum transfer at night and underscores the importance of selecting an appropriate excess heat transfer resistance value for achieving satisfactory closure ratios, particularly in tropical climates, with a more pronounced effect during dry periods than wet periods.

Keywords: Climate, Resistance, Closure Balance, Momentum and Heat

1.0 INTRODUCTION

A comprehensive understanding of the diurnal behavior of Excessive Heat Transfer Resistance $\varkappa B^{-1}$ is crucial for precise estimation of turbulent heat fluxes and monitoring the surface energy budget within the microlayer of the atmosphere. This knowledge is vital due to its direct influence on the exchange of heat between surfaces and the atmosphere, thereby shaping overall energy balance dynamics. While previous studies, such as those by Akinnubi and Adeniyi (2017; 2019), Stewart (1994), and Jia (2004), have documented instances of excess resistance on specific surfaces under high-speed airflow, a detailed examination of diurnal variations in excess resistance remains lacking. This knowledge gap poses a significant challenge in accurately modeling and predicting heat fluxes, particularly under varying environmental conditions and at different times of the day. Furthermore, accurate estimation of turbulent heat fluxes is critical for monitoring the surface energy budget, which is fundamental for understanding broader atmospheric processes and climate dynamics. Therefore, gaining insights into the diurnal behavior of $\varkappa B^{-1}$ is essential not only for improving understanding of local heat exchange processes but also for enhancing the accuracy of climate models and predictions.

Moreover, in accordance with the consensus among certain climate modelers, it is deemed imperative to formulate the diurnal excess resistance parameter for diverse experimental sites across varied regions, aiming to ascertain the behavior of $\varkappa B^{-1}$ across heterogeneous surfaces. Akinnubi and Adeniyi (2019) have addressed this need by developing excess resistance formulations for integration into aerodynamic resistance algorithms within General Circulation Models (GCMs), utilizing NIMEX surface layer observations under low wind speed conditions. However, despite this progress, the diurnal variation of excess resistance remains unexplored, particularly in tropical regions, and its impact on energy balance closure has not been adequately addressed, as it has primarily been employed for heat flux estimation. Their research findings also underscored the differences in atmospheric surface layer turbulence between low and moderate to high wind speeds, highlighting the prevalence of weak atmospheric turbulence within the Atmospheric Surface Layer (ASL) of equatorial regions (Akinnubi and Adeniyi, 2019).

There is a notable gap in research regarding the diurnal behavior of $\varkappa B^{-1}$ and its influence on energy balance closure within the microlayer of the atmosphere. To bridge this gap, comprehensive studies are required to investigate the

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diurnal variations of excess resistance throughout both daytime and nighttime periods under low wind speed conditions. Additionally, it is essential to examine the correlation between excess resistance and energy balance closure ratios. This thorough investigation is crucial for refining the precision of climate change predictions and deepening our comprehension of surface energy budgets.

2.0 Material and Methods

2.1 Experimental Sites

The Nigeria Micrometeorological Experiment (NIMEX) took place in Ibadan, Nigeria, situated at Latitude 7°33'N and Longitude 4°33'E, during the transition from the dry to the wet season, as depicted in Figure 1. This experiment was a follow-up to a previous NIMEX conducted at the same site in 2010. Intensive observations were carried out from February 19th to March 19th (DOY 55 through DOY 79) in 2010. Located in the humid equatorial region of West Africa, this site falls under the Aw class of the Köppen climate classification (Essenwanger, 2001). Positioned at an altitude of 288 meters above sea level, the vegetation of this site can be described as fallow bushland. The terrain is characterized by a flat and homogeneous ground surface. The soil composition is predominantly loamy sand, and it was at its permanent wilting condition at the onset of the experiment (Jegede et al., 2004; Mauder et al., 2007). During the experiment, the maximum and minimum air temperatures recorded were 46.33°C and 20.04°C, respectively, with an annual rainfall amount of 1225 mm (Otunla and Oladiran, 2013). Throughout the duration of the NIMEX project, mean and turbulent micrometeorological parameters within the surface layer were meticulously measured. To facilitate these measurements, three masts were erected: one equipped with fast response sensors for Eddy Covariance (EC) system measurements, and two for profiling wind, temperature, atmospheric radiation, and soil (sub-surface) parameters using low response sensors.

2.2 Parameterization of Excessive Heat Transfer Resistance for low wind speed condition

In this study, the parameterization proposed by Akinnubi and Adeniyi (2019) for excess resistance in low wind speed conditions was employed. This parameterization derived from the original Brutsaert functional form, as the exponent was substituted with n = 0.02 based on empirical data. It is worth noting that the applicability of the Brutsaert exponent has been restricted to neutral conditions, especially in stable conditions within equatorial regions, where NIMEX field-based coefficients replaced the drag and Stanton number coefficients. Consequently, the $\varkappa B^{-1}$ factor was modified in accordance with the experimental findings to suit the specific conditions under investigation.

$$\kappa B^{-1} = 6.66\, Re_*^{0.02} - 5.47 \qquad 1$$

where Re_* is the roughness Reynolds number?

$$Re_* = \frac{z_{0m} u_*}{\nu} \qquad 2$$

The kinematics molecular viscosity of air was assumed constant as 1.461×10^{-5} m^2 s^{-1}. The empirical constants in Eq. 1 are roughness sub-layer Stanton number and drag coefficient respectively. Due to the intermittent availability of measurements from the Eddy Covariance (EC) system and the inadequacy of roughness length models utilized in the aerodynamic resistance approach within Global Climate Models (GCMs), particularly for high wind speed conditions, a novel aerodynamic roughness length was suggested. This new parameter was derived using a second-order polynomial fit of zom (roughness length for momentum) estimated from EC data alongside wind speed measurements. The proposed z_{0m} formulation can be represented as a function of wind speed, as outlined in previous studies (Akinnubi, R. T and Adeniyi, M. O. 2019; Fairall et al., 2003).

$$z_{0m} = (0.21u_z^2 - 0.92u_z + 3.42) \times 10^2 \qquad 3$$

2.3 Evaluation of the Energy Balance Closure

The Energy Balance Closure ratio, defined as the sum of sensible (Q_H) and latent heat flux (Q_E) divided by the net radiation (Q_S), serves as an initial means to assess the NIMEX-1 data comprehensively. Its advantage lies in providing an overall evaluation of energy balance closure over longer time scales by averaging random errors in

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half-hour measurements. However, a drawback of this method is its potential to overlook biases in half-hourly data, such as overestimating positive fluxes during the day and underestimating negative fluxes at night (Mahrt, 1998). Nevertheless, the advantage of this approach is its disregard for possible random errors in flux estimation, especially in the absence of Eddy Covariance (EC) data, where the Bowen ratio method serves as a reference. The methodology employed to calculate the Energy Balance Ratio (EBR) involves the cumulative summation of available energy (Q_S-Q_G) and dependent fluxes (Q_H+Q_E) over analyzed periods (Gu*, et al.*, 1999).

$$EBR = \sum \frac{Q_H + Q_E}{Q_S - Q_G} \qquad 4$$

In considering energy balance closure, it is crucial to acknowledge the factors contributing to non-closure, as mentioned in the introduction. Sampling errors are intricately linked to the different footprints of energy balance components; for instance, net radiation and soil heat flux will never share the same footprint as sensible and latent heat flux. The measured soil fluxes typically exhibit much smaller magnitudes compared to other energy balance components. Regarding net radiation, while little variability is observed over different terrains in some studies (Twine et al., 2000; Stannard et al., 1994), errors of up to 6% are often assumed (Moncriff, 1996). An important consideration for net radiation is the absence of a widely accepted or standard measurement method, and errors in factory calibration for different sensors can surpass accuracy levels (Hall din and Lindroth, 1992). In their research, Cobos and Barker (2003) analyzed net radiation using NRlite instruments manufactured by Kipp and Zonen. They discovered a strong correlation between their findings and the combined total of four independently measured net radiation components across a wide array of field conditions. The study employed a variety of approaches to assess energy balance closure.

4.0 Result and discussion

4.1 Diurnal Variation of Excessive Heat Transfer Resistance

Figure 2 illustrates the diurnal fluctuations of excess resistance for the period spanning from DOY 55 to DOY 67 in 2004. The graphs depict a considerable variability in $\varkappa B^{-1}$, exhibiting diurnal patterns with higher values observed during the daytime and lower values at night. Similar trends were observed by Yang et al. (2008) when analyzing the variability of $\varkappa B^{-1}$over bare soil. Calculated hourly $\varkappa B^{-1}$ ranges from -2.5 to 10 for wet periods and -23.0 to 16 for dry periods, indicating a significant increase in values during dry surface conditions compared to wet periods. These ranges exceed 2.5, as reported by Stewart (1994) and Voogt and Grimmond (2000) for semi-arid areas. However, negative $\varkappa B^{-1}$values occurred during the night for both wet and dry periods, suggesting that heat transfer efficiency may surpass momentum transfer during nighttime, consistent with findings by Su et al. (2001) for forced convection. Verhoef et al. (1997) also reported negative values for nearly aerodynamically smooth bare soil surfaces, consistent with predictions by Kastus (1982). Consequently, it can be inferred that the NIMEX-1 site is aerodynamically smooth during wet periods (z_{0m}=0.34 mm) and fairly aerodynamically rough during dry periods (z_{0m} = 0.72 mm), possibly due to short growing grasses around the site during dry periods (Jegede et al., 2004). Additionally, momentum transfer is traditionally considered more efficient than heat transfer ($\varkappa B^{-1}$> 0) for aerodynamically rough flows due to enhanced pressure drag. The observed diurnal variations in $\varkappa B^{-1}$may be attributed to changes in boundary layer depth and the role of inactive (non-local) eddies in the outer layer. Hong et al. (2004) and Mc Haughtan (2004) reported that such inactive eddies with low frequency do not impact momentum but cause heat flux deviations from Monin-Obukhov Similarity theory.

Figure 3 provides a detailed exploration of the relationships between several key parameters and $\varkappa B^{-1}$, a vital factor in the parameterization of heat fluxes within atmospheric science. $\varkappa B^{-1}$ denotes the inverse of the von Kármán constant and is instrumental in describing the logarithmic profile of wind speed or temperature within the planetary boundary layer. The plot illustrates three distinct linear correlations: (a) between $\varkappa B^{-1}$ and air temperature (T_a) with an r^2 value of 0.60, (b) between $\varkappa B^{-1}$and the combined effect of surface temperature (T^s) and air temperature (T_a) with an r^2 value of 0.79, and (c) between wind speed (u) and the combination of surface and air temperatures (T_s and T_a) with an r^2 value of 0.60. Notably, the correlation between $\varkappa B^{-1}$ and u(T_s and T_a) shows the highest coefficient of determination (r^2 =0.79), indicating its superior ability to elucidate the diurnal variation of $\varkappa B^{-1}$) using profile data. Further analysis reveals nuanced insights into these relationships. Firstly, the moderately strong correlation between $\varkappa B^{-1}$ and air temperature alone implies that changes in air temperature correspond to variations in $\varkappa B^{-1}$, explaining 60% of its variability. Secondly, incorporating surface temperature alongside air temperature significantly enhances

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the explanatory power of the model, suggesting that surface temperature plays a crucial role in predicting $\varkappa B^{-1}$. Lastly, while wind speed in conjunction with surface and air temperatures exhibits a moderate correlation with $\varkappa B^{-1}$, its contribution to $\varkappa B^{-1}$ variability is comparatively lower than that of temperature variables. Additionally, the derived regression equation $\varkappa B^{-1}$ = 0.876 (T_s and T_a) - 11.17) offers a predictive model for estimating ϰB^(-1) based on temperature data. This equation facilitates the characterization of the diurnal behavior of $\varkappa B^{-1}$ over time, providing valuable insights into its temporal variability. In summary, these findings underscore the importance of considering both surface and air temperatures, alongside wind speed, in understanding $\varkappa B^{-1}$ variability. Such understanding is essential for accurately parameterizing heat fluxes in atmospheric models. Moreover, the study highlights the necessity of caution when applying $\varkappa B^{-1}$ values obtained by other researchers, emphasizing the importance of considering specific temperature conditions under which they were derived.

4.2 THE EFFECT OF AERODYNAMIC EXCESS RESISTANCE ON ENERGY BALANCE CLOSURE RATIO.

Table 1 provides regression correlation results between Closure Ratio (CR) and excess aerodynamic resistance (r_b) using an exponential model, categorized by wet and dry periods as well as daytime and nighttime conditions. During the wet period, a moderately strong negative correlation between CR and r_b is observed in the daytime, indicating that as aerodynamic resistance decreases (ra increases), the closure ratio tends to increase, signifying improved energy balance closure. This relationship is captured by the regression equation with an r^2 value of 0.62, suggesting a relatively good fit of the model to the data. Conversely, during wet nighttime, the correlation between CR and r_b weakens (r^2 = 0.21), with the regression equation indicating a slight decrease in CR with increasing r_b, though the relationship is not as pronounced as during the daytime. In the dry period, a similar pattern is observed, with a moderately strong negative correlation between CR and r_b during the daytime (r^2 = 0.58). Here, too, decreasing aerodynamic resistance corresponds to an increase in closure ratio, indicating better energy balance closure. The regression equation captures this relationship adequately, although the Root Mean Square Error (RMSE) was slightly higher compared to the wet daytime period. During dry nighttime, however, the correlation between CR and r_a weakens further (r^2 = 0.12), with the regression equation suggesting a very slight decrease in CR with increasing ra, though the relationship is not statistically significant. Overall, the regression analysis underscores the importance of aerodynamic resistance in determining energy balance closure, particularly during daytime periods. The results suggest that aerodynamic resistance plays a crucial role in influencing energy balance closure, with different implications for wet and dry periods as well as daytime and nighttime conditions. While wet daytime periods exhibit the strongest correlation between CR and r_b, other factors may come into play during nighttime periods, leading to weaker correlations.

Fig 4 delineates the effect of excess resistance (r_b) on energy balance closure (EBC), showing that higher values of r_b (> 3.0 sm^{-1}) yield better closure of energy balance. In wet period, as the daytime EBC increased, so did the r_b, and when the value of r_b exceeds 3.0 sm^{-1}, the value of EBC was 0.82. The contribution of r_b to EBC in unstable condition was very poor. The value of EBC seems to increase as the r_b value increase for nighttime situation $(\sim 0.30 - 0.10)$. The EBC declines gradually when the value of r_b exceeds 4.0 r_b (CR=0.50). In dry period, the daytime CR increased as function of r_b, but there was a decline when the value of r_b exceed 6.0 sm^{-1}. The value of CR was less than 0.2 for 20 % of the energy involved, suggesting that the EBC impact of the other factors was greater in dry period (Xia *et al*, 2011). The smallest CR was > 0.2 for higher values of r_b (>5.5 sm^{-1}), while higher values of r_b yields CR of 0.5-0.6 for wet period. This means that the effect of r_b in beterring CR was more pronounced in dry period than wet period. When r_b reaches 3.5 sm^{-1}, the CR was 1.00 for dry period. And the daytime CR increases significantly with r_b leading to CR > 0.40(<2.5 sm^{-1}) and 0.70(3.7 sm^{-1}). The study reveals that EBC become higher wwhen r_b was greater while EBC was lower at low value of r_b. This means that there is an optimal value of r_b when good closure can be reached for wet (CR$\sim 0.80\ when\ r_b = 3.5\ sm^{-1}$ and dry period $CR\sim 1.00.\ when\ r_b = 5.5\ sm^{-1}$).

5.0 CONCLUSION

The diurnal variations of excess resistance ($\varkappa B^{-1}$) for the period analyzed exhibited substantial variability, with distinct patterns observed during both wet and dry periods. Higher $\varkappa B^{-1}$ values were recorded during the day, contrasting with lower values at night. These findings align with previous studies and suggest that heat transfer efficiency may surpass momentum transfer during nighttime conditions. Additionally, the aerodynamic

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characteristics of the site were found to vary between wet and dry periods, indicating aerodynamic smoothness during wet periods and increased roughness during dry periods, likely due to the presence of short grasses. Furthermore, our analysis revealed significant correlations between $\varkappa B^{-1}$and various atmospheric parameters, particularly temperature and wind speed. The observed linear relationships provide insights into the diurnal variation of $\varkappa B^{-1}$and suggest that $\varkappa B^{-1}$values derived by other researchers may not be directly applicable to parameterize heat fluxes but can inform the characterization of $\varkappa B^{-1}$ behavior over time. Moreover, our investigation into the effect of aerodynamic excess resistance (r_b) on energy balance closure (EBC) demonstrated that higher r_b values corresponded to better closure of energy balance, particularly during wet periods. However, the impact of r_b on EBC was more pronounced in dry periods, highlighting the complex interplay of several factors influencing energy balance closure. Overall, our findings emphasize the importance of considering diurnal variations in excess resistance and aerodynamic properties when evaluating energy balance closure, particularly in heterogeneous environments like the study site. Further research is warranted to explore the optimal values of r_b for achieving energy balance closure under different meteorological conditions.

6.0 ACKNOWLEDGEMENT

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Table 1 Regression Correlation between Closure Ratio and Aerodynamic resistance using exponential Model.

Period	**Equations**	r^2	**RMSE**	**RSS**	$\pm\sigma_a$	$\pm\sigma_b$
Wet period						
(a) Daytime	$CR = 0.1747 - 1.380\, e^{-0.030 r_a}$	0.62	0.06	1.02	0.148	0.20
(b) Nighttime	$CR = -1.784 - 5.712 \times 10^{-6} e^{0.016 r_a}$	0.21	1.37	11.94	0.390	0.04
Dry period						
(c) Daytime	$CR = 0.320 + 5.466\, e^{-0.010 r_a}$	0.58	0.28	2.36	0.19	0.56
(d) Nighttime	$CR = 0.020 + 0.001\, e^{-0.04 r_a}$	0.12	0.05	15.98	0.44	0.013

RSS = Residual Sum of Square
$\pm\sigma_a$ = Standard Error of Intercept
$\pm\sigma_a$ = Standard Error of Slope

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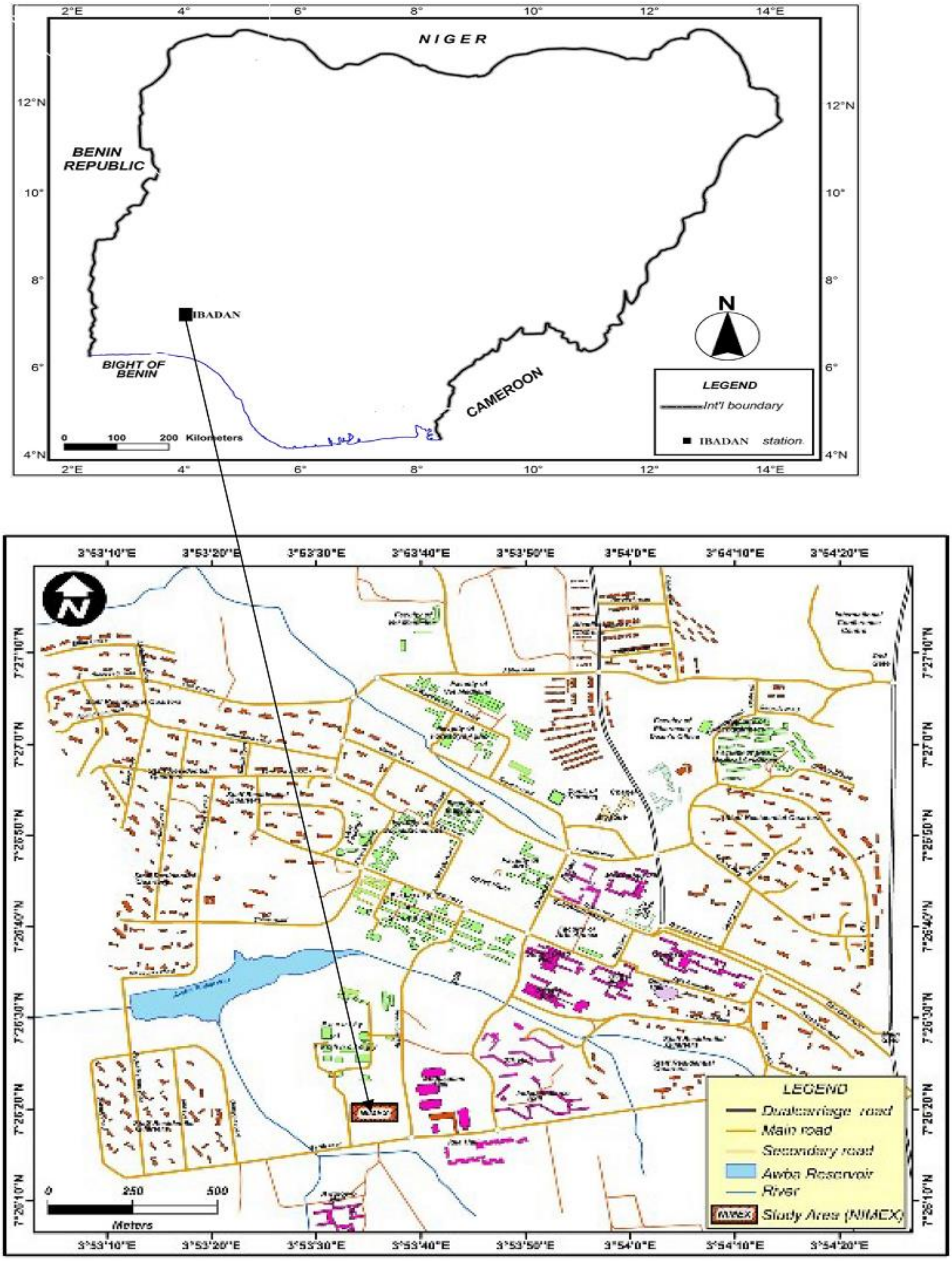

Figure 1: Location of The Experimental Site, (Source: Akinnubi and Adeniyi, 2019)

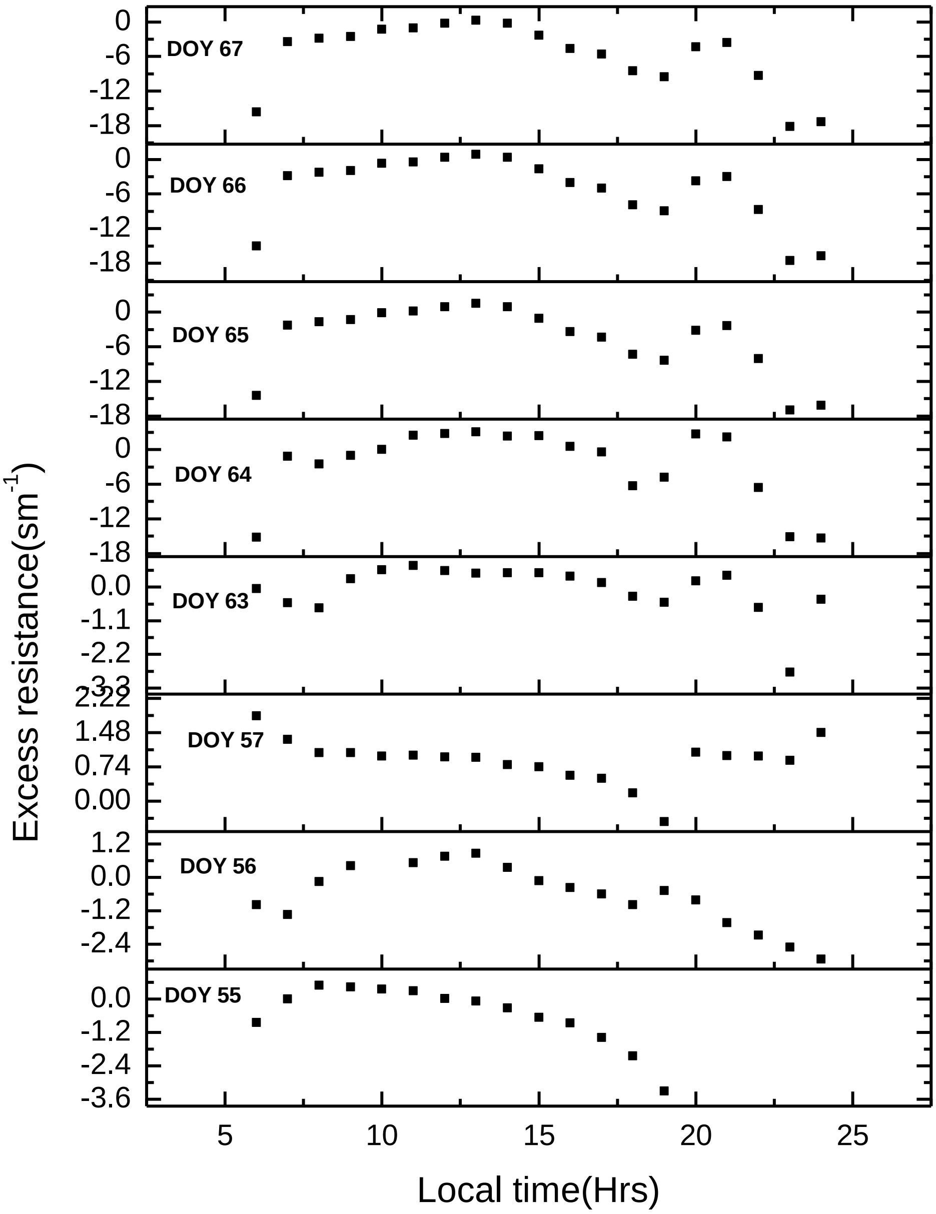

Figure 2: Diurnal Variations of Excess Resistance for DOY 55-67, 2010

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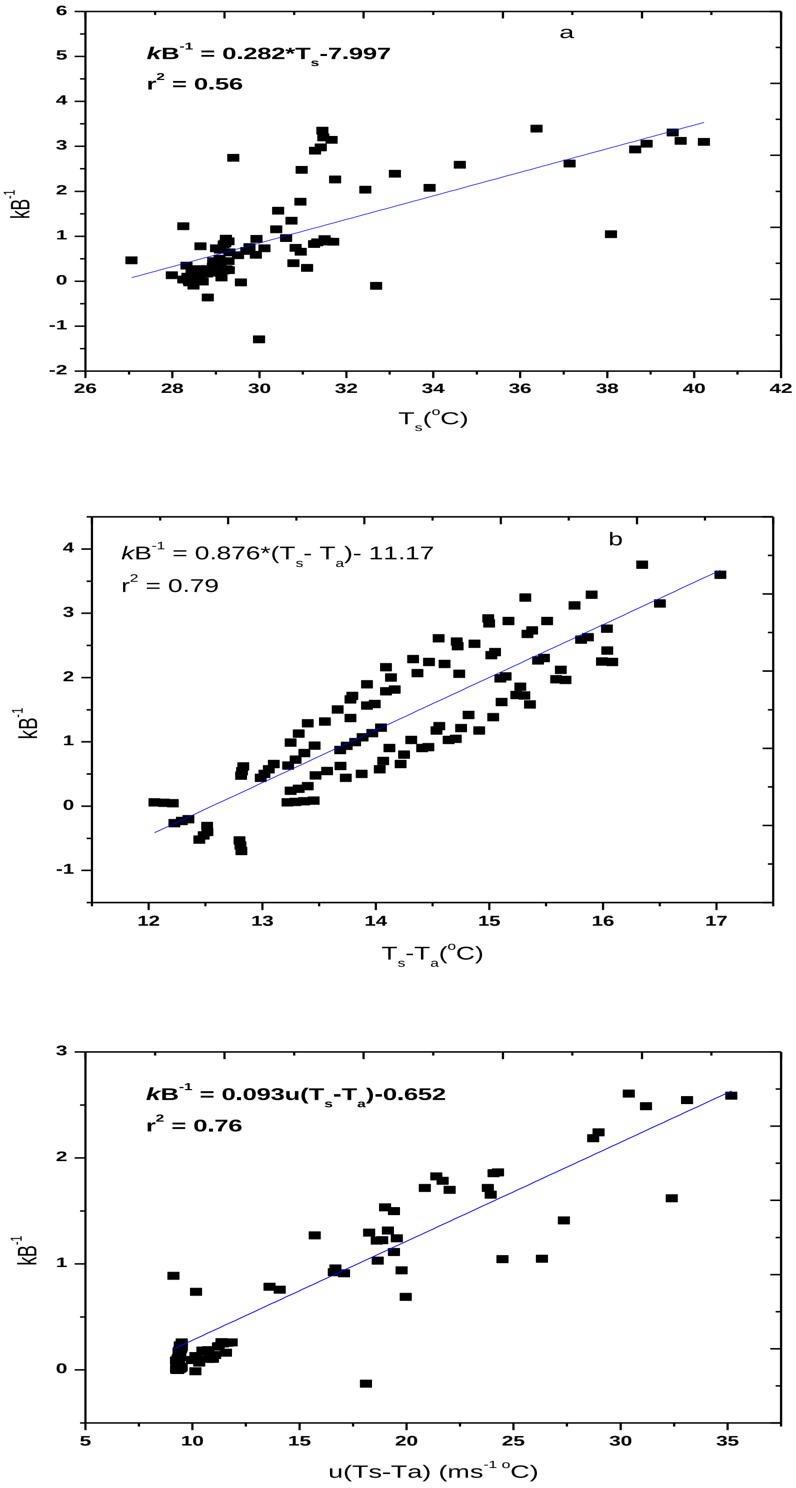

Figure 3: The Excess Resistance to Heat Transfer (KB^{-1}) plotted against Ts, Ts-Ta, and U (Ts-Ta) at the NIMEX site in Ibadan.

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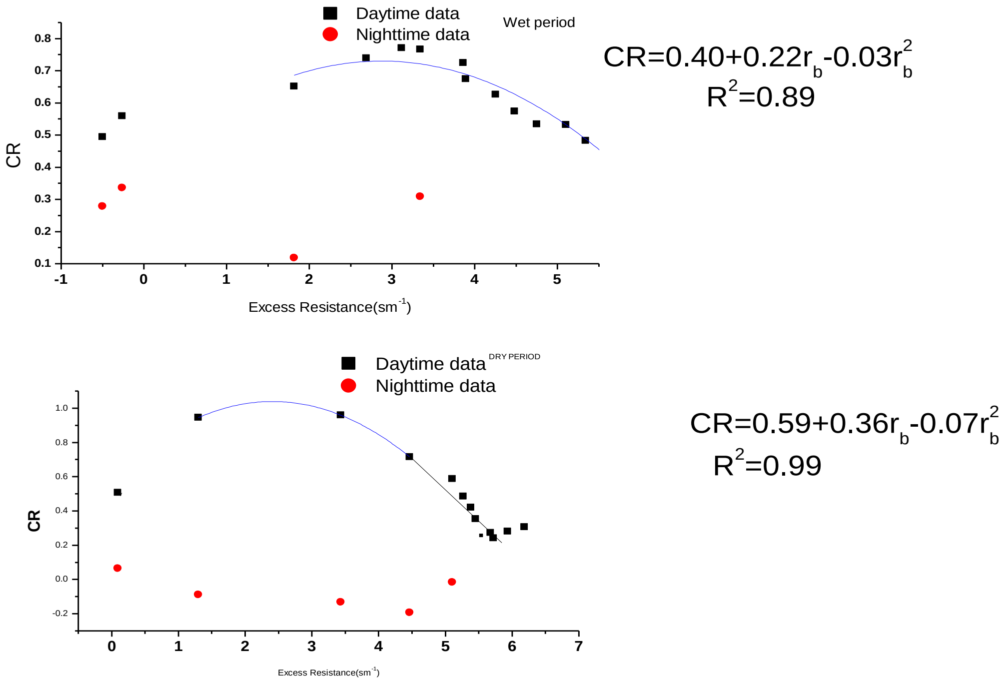

Figure 4: Seasonal Variation of Aerodynamic Excess Resistance and Its Impact on Energy Balance Closure.

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