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DETERMINATION OF NEAR-SURFACE TURBULENT FLUXES AT A TROPICAL LOCATION: AN EVALUATION OF FLUX-PROFILE TECHNIQUE

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ABSTRACT

An experimental site at Obafemi Awolowo University's Teaching and Research Farm, in Ile-Ife, Nigeria, was used to conduct multilevel measurements of meteorological parameters, and turbulent fluxes of sensible and latent heat in the atmospheric surface layer (ASL) between June 1 and July 31, 2016. The framework provided by Monin-Obukhov Similarity Theory (MOST) for estimating the turbulent fluxes of sensible and latent heat through existing empirical flux-profile relationships was employed. The objective of this study was to evaluate the performance of the flux-profile technique based on direct measurements of turbulent fluxes obtained from an eddy covariance (EC) system set up at the same location. The results showed that the diurnal patterns of both sensible and latent heat fluxes estimated from flux-profile technique compared relatively well with the direct measurements of the EC system. Nighttime estimations under stably stratified conditions of the atmosphere strongly correlated (R = 0.98) with the directly measured values. However, during the daytime convective conditions, there were some consistent discrepancies in the performance of the flux-profile technique with errors in some of the estimated fluxes well within the uncertainty range of the EC measurements. For sensible heat flux estimates; the coefficient of determination, R^2 (0.71), the mean biased error, MBE (15.1 W/m^2) and the percentage error determined for the period averaged values of the daytime estimates indicated that the sensible heat flux was only overestimated by up to 20%. On the other hand, a negative MBE (-28.2 W/m^2), weak coefficient of determination, R^2 (0.58) and negative percentage error obtained for the period averaged values of the latent heat flux indicated there is an underestimation of up to 45%. It can be concluded the flux-profile relationships can be employed within certain limits of confidence interval at tropical locations especially for the estimation of sensible heat flux.

Keywords Eddy covariance, Latent heat flux, Sensible heat flux, Friction velocity.

INTRODUCTION

The main processes for the exchange of mass, energy, and momentum between the surface of the planet and the atmosphere are turbulent fluxes of sensible and latent heat (Stull, 1988; Ma *et al*., 2011; Han *et al*., 2015; Mamtimin *et al*., 2021). These dynamical phenomena have a big impact on occurrence of many atmospheric processes such as effluent dispersion, evapotranspiration, and cloud formation (Arya, 1999; Li *et al*., 2009; Srinivas *et al*., 2009; Katul *et al*., 2012; Babatunde *et al*., 2017; Pozníková *et al*., 2018; Bosman *et al*., 2019). Surface fluxes are essential variables for forecasting the development of boundary layers, atmospheric transport mechanisms, and mixing of dispersed solid particles (Dyer *et al*., 1982; Li *et al*., 2009; Liu *et al*., 2016; Park *et al*., 2017; Kim and Kwon, 2019). As a result, it is crucial to quantify these factors for a variety of applications such as weather forecasting, climate modeling, environmental impact assessments, and many others (Arya, 1999; Katul *et al*., 2012; Steiner *et al*., 2018). Fast-responding meteorological sensors that are able to record high-frequency (>10 Hz) turbulent changes in air temperature, humidity, and wind speed can provide direct measurements of the turbulent fluxes of sensible and latent heat (Leuning and Moncrieff, 1990; Foken and Napo, 2008; Sunmonu *et al*., 2019; Omokungbe *et al*., 2022). Weather instruments such as sonic anemometers, scintillometers, infrared gas analyzers, and other similar devices fall under this category. According to Lofstrom and Jegede (1997) and Lee *et al.* (2004), long-term deployment of continuous measurements of sensible and latent heat in the surface layer is capital-intensive and delicate. Researchers have used semi-empirical relationships derived from the Monin-Obukhov Similarity Theory (MOST) of the surface layer to estimate these fluxes for regular applications (Foken, 2006; Omokungbe *et al.*, 2022). Determining the mass and energy exchanges taking place at the soil-vegetation-atmosphere interface requires an understanding of the turbulent character of the atmospheric surface layer. It is difficult and extremely expensive to maintain a direct measurement of the turbulent fluxes of sensible and latent heat for long-term purposes (Adeyemi *et al.*, 2012; Babatunde *et al.*, 2017; Sunmonu *et al.*, 2019; Omokungbe *et al.*, 2022). As a result, utilizing consistent and realistic empirically derived parameters for the surface layer, one way to estimate these fluxes is from the profile (multilevel) measurements of the mean meteorological data. There are several of these flux-profile correlations that have been examined and verified to work in the mid-latitudes (Denby, 2001; Park *et al.*, 2009; Ishola *et al.*, 2020; Radi *et al.*, 2017; Mohan *et al.*, 2020). However, these correlations have not been thoroughly examined under various weather circumstances in the Sub-Saharan Africa due to the lack of experimental data for tropical areas, including Nigeria. Therefore, the purpose of this study is to assess how well current flux-profile relationships perform in the surface layer at a tropical location such as Ile-Ife, Nigeria. In order to improve the knowledge, description, and representation of atmospheric boundary layer processes in a tropical regime for applications in weather forecasting and climate modeling, this study will provide useful information.

INSTRUMENTATION AND METHODS

Description of Experimental Site

The study site is situated at Obafemi Awolowo University teaching and research farm at the OAU campus in Ile-Ife, Southwest Nigeria (Figure 1) and its coordinates are 7.5°N and 4.5°E. The measurement area is 18 m by 18 m in size, with low-level grass that is regularly mowed covering its surface at the time. Despite the fact that the study site did not have the required fetch for accurate flow measurement, it did have the advantage of not being surrounded by trees or other structures, which would have impeded surface flow and greatly increase surface roughness parameters. The field measurements took place for two months (June and July 2016). In addition, the study area is climatologically categorized into wet and dry seasons, with the wet season extending from March to October and the dry season lasting from November to February.

Figure 1: Google Earth Map of the study site at the Teaching and Research Farm Obafemi Awolowo University, Ile-Ife and in the foreground is the map of Nigeria showing Ile-Ife.

The variation of this season, according to (Jegede *et al.*, 2004), is as a result of the meridional movement of the Inter-Tropical Discontinuity (ITD), which separates the hot and dry North-Easterly trade winds from the warm and moist South-Westerly trade winds at the surface (Jegede *et al.*, 2006). Ile-Ife is in weather zone B during May and June, when the wet season there begins (this zone stretches 200–400 km south of the ITD's surface site). In contrast, during the region's peak wet season in August/September, Ile-Ife is located in weather zone D, which is characterized by stratus clouds and is occasionally accompanied by moderate thunderstorm activity. The zone is characterized by suppressed convection that mresults in cumulus clouds, and precipitation is limited to light showers (Ayoola *et al.*, 2014).

Instrumentation and Data Processing

Multilevel measurements of wind speed, air temperature, and moisture were conducted by installing meteorological sensors on a 15 m mast at the experimental site. Additionally, the uneven terrain posed by mountainous hills which is capable of significantly altering measurements were a remarkable about 3 km distant away from experimental site. The cup anemometers (model A100L2) and air temperature/relative humidity sensors (HMP60) were arranged in a log-linear position at five (5) heights of 1.14m, 1.88m, 3.30m, 6.30m, and 12.10m on the same mast (Figure 2). Simultaneously with the profile measurements, an eddy covariance (EC) system comprising a 3D ultrasonic anemometer (CSAT3) and an open path infrared gas analyzer (LI-7500) placed on a mast of height 1.81 m was co-located to measure the turbulent fluxes of momentum, sensible and latent heat, and stability parameters at the surface. On the same mast with EC set up is another 3D anemometer with no useful data provided due to faulty data logger. The instrumented masts were about 18m away from the porous-wire fence.

Data acquisition and storage were controlled by the use of two programmable CR1000 data loggers. The profile measurements were averaged and stored at one (1) minute value while the turbulent fluxes were recorded at 10 Hz.

Figure 2: Arrangement of sensors in the field at the experimental site, Teaching and Research Farm, Obafemi Awolowo University.

The profile measurements data were further averaged to one hour averages of mean wind speed, air temperature, and relative humidity for each day. The log-linear curve in equations 1, and 2 were fitted to the estimated profile using air potential temperature, wind speed, and air-specific humidity data using MATLAB.

$$\bar{\theta}(z) = az + b\ln z + c \qquad (1)$$

$$\bar{q}(z) = a'z + b'\ln z + c' \qquad (2)$$

where $\bar{\theta}$ and $\bar{q}$ are potential temperature, and specific humidity at height (z) respectively. Also, a,b,c, and a', b', c' are coefficients representing the slope and intercept of the log-linear equations.

From these fits, a gradient of the resulting profile was obtained for potential temperature and specific humidity given by equations 3 and 4 respectively:

$$\frac{\partial\bar{\theta}}{\partial z} = a + \frac{b}{z} \qquad (3)$$

$$\frac{\partial\bar{q}}{\partial z} = a' + \frac{b'}{z} \qquad (4)$$

In this study, the widely applied expression of (Businger *et al.*, 1971) has been used to obtain φ_h (ξ), equation (5) which is essentially equivalent to φ_q (ξ) (Foken, 2006).

The expression is given as:

$$\varphi_h = \begin{cases} 0.74(1-9\xi)^{-\frac{1}{2}} & (\textit{statistically unstable condition}) \\ 0.74 + 4.7\xi & (\textit{statistically stable condition}) \end{cases} \qquad (5)$$

Based on the Monin-Obukhov similarity theory for the horizontally homogenous and stationary surface layer, the non-dimensional profile functions of air potential temperature and air-specific humidity are expressed as equations 6 and 7:

$$\varphi_h(\xi) = \frac{kz}{\theta_*}\frac{\partial\bar{\theta}}{\partial z} \qquad (6)$$

$$\varphi_q(\xi) = \frac{kz}{q_*}\frac{\partial\bar{q}}{\partial z} \qquad (7)$$

where φ_h (ξ) and φ_q (ξ) are non-dimensional profile functions for heat and specific humidity respectively, k = (0.35) is the von Karman constant which is a universal constant independent of flow or surface characteristics and has been determined by many researchers throughout the last decades (Foken, 2006; Högström, 1988). For this study, z is the measurement height, u_* friction velocity (related to turbulent momentum flux), θ_* the scale temperature (related to turbulent heat flux), q_* the scale humidity (related to the latent heat flux), and $\xi = z/L$ is a stability parameter defined as the ratio of height, is a stability parameter defined as the ratio of height, z, to the Obukhov length, *L*, (characteristic height in the surface layer).

Having obtained the gradients and the non-dimensional similarity functions of heat φ_h (ξ), and specific humidity φ_q (ξ); θ_*, and q_* were determined from equations 6 and 7 above.

From the calculated θ_*, and q_*, the turbulent fluxes of sensible, H_s, and latent heat, H_L, were obtained from expressions given in equations 8 and 9 respectively:

$$H_s = -\rho C_p u_* \theta_* \qquad (8)$$

$$H_L = \rho \lambda q_* u_* \qquad (9)$$

where ρ is the air density, C_p is the specific heat capacity of heat at constant pressure, λ is the latent heat of vaporization, u_* is the friction velocity, θ_* is the scale temperature and q_* is the scale humidity as earlier discussed. The estimated fluxes were then superficially compared with the time series plot of direct measurement obtained from the EC system.

RESULTS AND DISCUSSION

Near-surface measurements of basic meteorological parameters and friction velocities used as input data for the estimation of turbulent fluxes of sensible and latent heat are presented in Figures 3, 4, and 5.

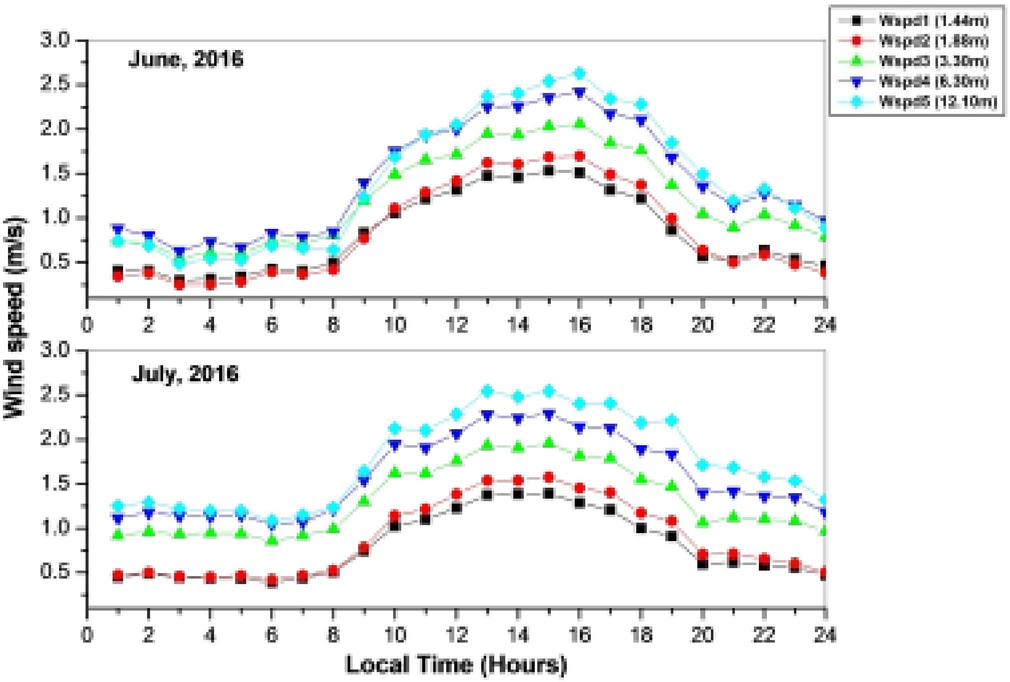

Figure 3: Diurnal variation of multilevel measurements of wind speed at the Teaching and Research Farm, O.A.U., Ile-Ife in June and July, 2016.

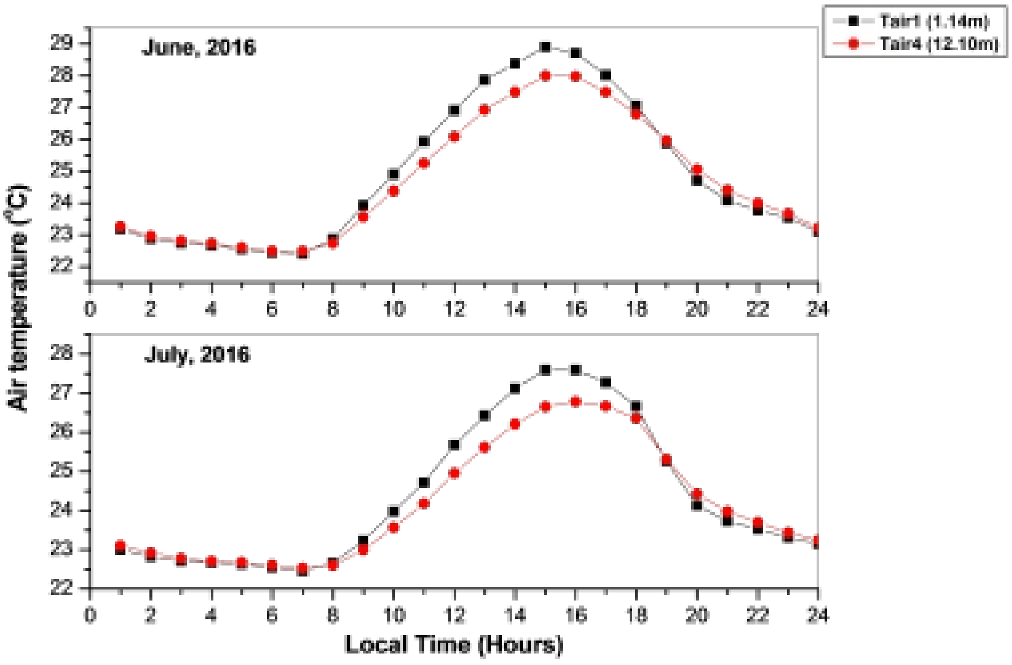

Figure 4: Diurnal variation of temperature profile measurements at the Teaching and Research Farm, O.A.U., Ile-Ife in June, 2016.

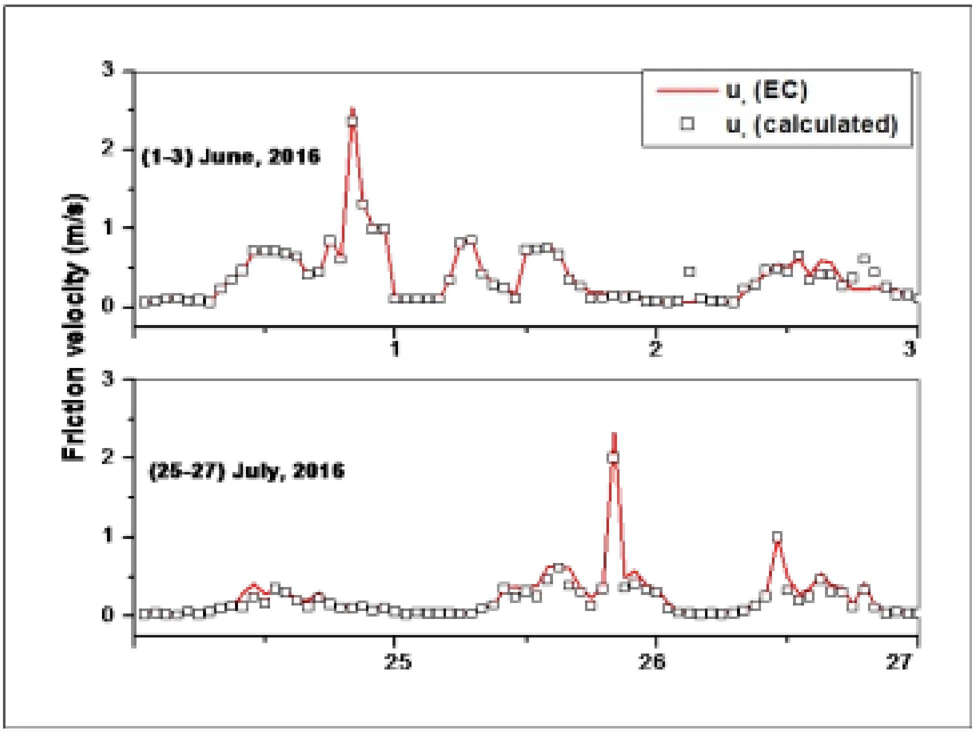

Figure 5: Diurnal variation of measured and calculated friction velocities at the Teaching and Research Farm, O.A.U., Ile-Ife for randomly selected days in June and July, 2016.

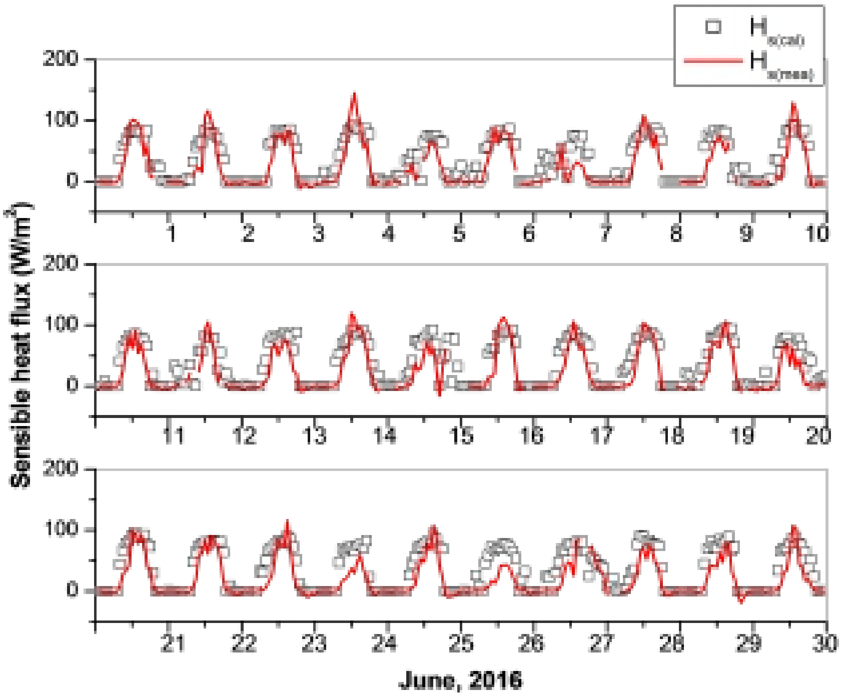

Figure 6: Diurnal variation of estimated and measured sensible heat flux at the Teaching and Research Farm, O.A.U., Ile-Ife in June, 2016.

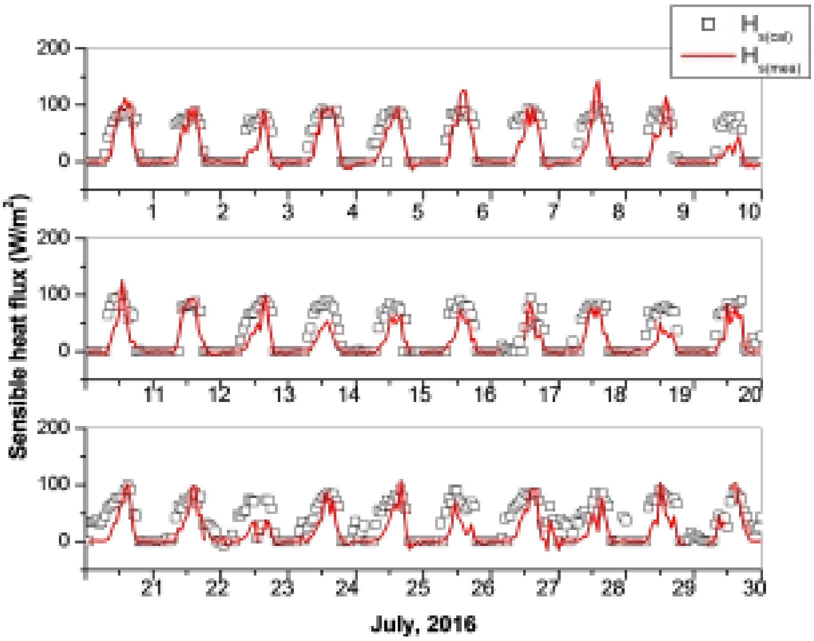

Figure 7: Diurnal variation of estimated and measured sensible heat flux at the Teaching and Research Farm, O.A.U., Ile-Ife in July, 2016.

The diurnal variation of the estimated and directly measured sensible heat flux for the month of June and July 2016 is presented in Figures 6 and 7 respectively.

From the figures, the diurnal pattern of sensible heat flux obtained from the flux-profile method compared relatively well with the direct measurement of the eddy covariance (EC) system. Sensible heat flux estimated by the flux profile method gave a maximum value of 96.4 W/m^2 in June while a maximum value of 145.2 W/m^2 was obtained from the direct measurement of the eddy covariance system for the same month. In July, the estimated sensible heat flux obtained from the flux-profile method gave a maximum value of 101.07 W/m^2 as compared to direct measurement with a peak value of 142.84 W/m^2. Throughout the study period, the sensible heat flux values obtained by the flux-profile approach were found to predominately overestimate direct measurement even though there were also observable instances of underestimation. The flux-profile method however consistently replicated similar diurnal pattern of directly observed sensible heat flux.

The mean biased error (MBE; 14.6 W/m^2 in June and 15.6 W/m^2 in July) obtained for the period averaged values and the percentage error obtained indicated that the flux-profile method overestimated sensible heat flux by about 20%. The overestimation of sensible heat by the flux-profile method was found to occur during the daytime convective periods. This overestimation of sensible heat flux observed during the daytime when convective activities are prominent has been attributed to specific surface conditions and variability in mean meteorological variables (such as air temperature difference, wind speed gradient, and local stability) associated with the flux profile method (Córdova *et al.*, 2020; Radic *et al.*, 2017). The results also show that, in the daytime, when wind speed attains its maximum values, the assumption of constant momentum flux in the flux profile method breakdown as u_* approaches zero, and at these periods the method underestimates u_*. This underestimation is much more pronounced in the calculation of sensible heat flux than for u_* because the reduced turbulence at wind speed maximum ($u \geq 3m/s$) leads to an increase in the air-surface temperature difference and consequently to an increase in the estimated sensible heat flux obtained from the flux-profile method. Similar results of the flux-profile method overestimating direct measurement of sensible heat flux have been reported in temperate climates (Andreas *et al.*, 2010; Arya, 1988; Denby, 2001). As observed, most of the values obtained were higher than 50

W/m^2 during daytime convective periods, which may be related to the intensity of thermal turbulence at the study location and consequently to larger heating of the surface. Generally, the Monin-Obukhov stability function used performed relatively well during the stable nighttime conditions at the study location with the coefficient of correlation, R>0.9 for both months.

Similarly, the diurnal variation of both estimated and directly measured latent heat flux at the study site is presented in Figures 8 and 9 respectively for comparative analysis.

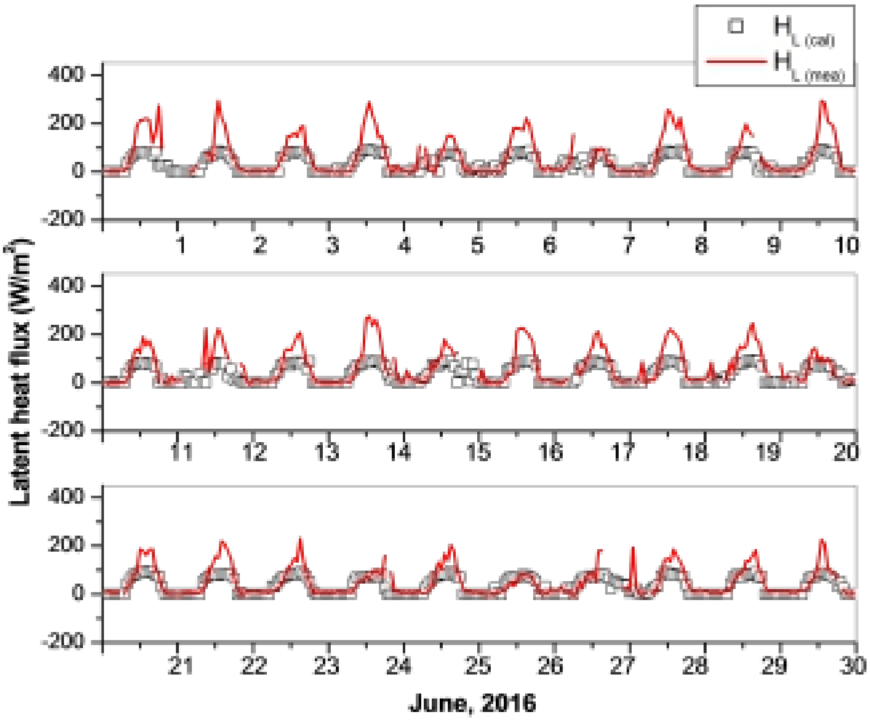

Figure 8: Diurnal variation of estimated and measured latent heat flux at the Teaching and Research Farm, O.A.U., Ile-Ife in June, 2016.

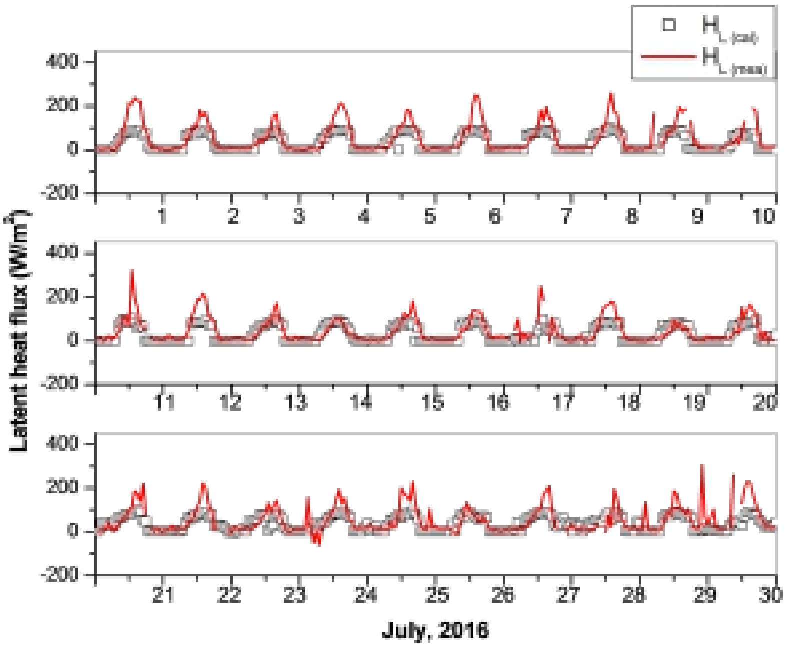

Figure 9: Diurnal variation of estimated and measured latent heat flux at the Teaching and Research Farm, Obafemi Awolowo University, Ile-Ife in July 2016.

From the figures, that flux profile method's nocturnal estimates of latent heat flow were remarkably accurate compared to direct measurements, while there was a clearly significant amount of scatter in the daytime estimate.

The latent heat flux estimated from the flux-profile method gave a maximum value of 98.4 W/m^2 in the month of June, which was found to appreciably underestimate the direct measurement obtained from the eddy covariance system with a maximum of 310 W/m^2. Similarly, in July, estimated values obtained from the flux profile method were found to underestimate directly measured values of latent heat flux. Estimated latent heat flux with a maximum value of 105.09 W/m^2 was given by the flux-profile method as compared to a peak value of 350 W/m^2 obtained by direct measurement. From the percentage error calculated, the flux-profile method underestimated daytime latent heat flux by up to 45%. The negative mean biased error (MBE) obtained for June (-27.4 W/m^2) and July (-18.6 W/m^2) is indicative of the underestimation of direct measurement of latent heat flux by the flux-profile method. This overestimation has been attributed largely to the assumption of similar physical processes involved in the transport of heat and moisture from the surface (; Steeneveld *et al*., 2008). This assumption led to the treatment of the non-dimensional similarity function of water vapor (φ_q) as an equivalent function of the nondimensional similarity function of heat (φ_h). Hence, an accurate determination of the non-dimensional similarity function of water vapor (φ_q) is suggested as one of many ways to reduce errors in the estimation of latent heat flux using the flux-profile method (Park *et al*., 2009). As observed, the values of estimated latent heat flux were directly related to the daily evolution of sunrise and sunset. It can therefore be said that a large radiative flux balance produced larger values of latent heat fluxes at the surface with a clear influence of cloud cover sometimes attenuating the observed values of the estimated energy flux.

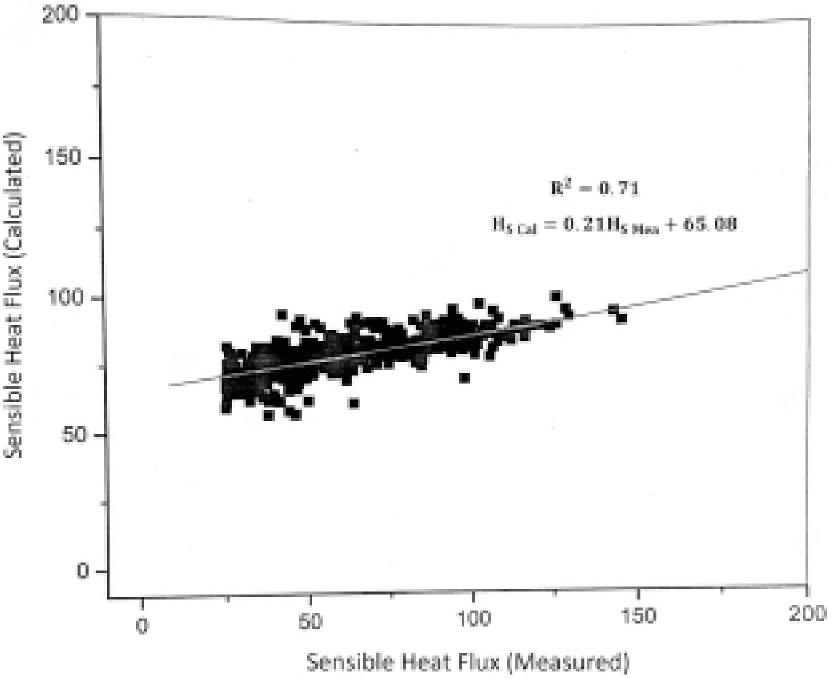

Figure 10a: Comparison of the estimated and directly measured sensible heat flux at the Teaching and Research farm, Obafemi Awolowo University, Ile Ife.

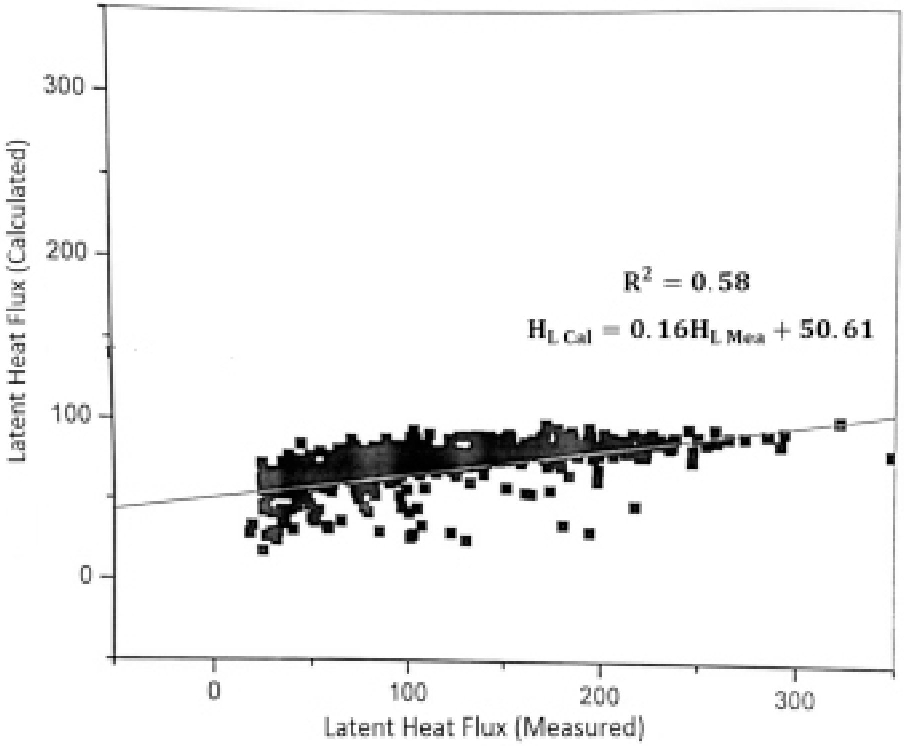

Figure 10b: Comparison of the estimated and directly measured latent heat flux at the Teaching and Research Farm, Obafemi Awolowo University, Ile Ife.

The scatter-plot between the measured and estimated sensible and latent heat fluxes is shown in Figures 10 (a) and (b). The measured and estimated sensible heat fluxes obtained have a coefficient of determination R^2 of 0.71. The approach performed well in estimating the sensible heat flux at the location, as seen by the relatively high value of R^2 for sensible heat flux. For latent heat flux, the plot showed R^2 of 0.58. The latent heat flux sporadically fluctuates in some of the days of the month due to the prevailing weather conditions (Sunmonu *et al.*, 2019) for those days, which may be why the latent heat R^2 exhibited an average value. This result demonstrates the method perform averagely in estimating latent heat flux.

CONCLUSION

In conclusion, the empirical constants involved in the flux profile relationships employed for the indirect determination of turbulent fluxes have been verified as valid at a tropical location like Ile Ife. Although the scheme has a tendency to overestimate sensible heat flux during convective periods, it has better agreement with the direct measurement under stably stratified conditions. Conversely, the scheme consistently underestimated latent heat flux throughout the study period. Thus, the flux-profile relationships can be employed within certain limits of confidence interval at tropical locations.

CONFLICT OF INTEREST

The authors declare that no conflict of interest exists.

DATA AVAILABILITY

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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