Determination of Near-Surface Turbulent Fluxes at a Tropical Location: An Evaluation of Flux-Profile Technique

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Abstract

Multilevel measurements of mean meteorological variables and turbulent fluxes of sensible and latent heat in the atmospheric surface layer (ASL) were undertaken at the experimental site located within the Teaching and Research Farm of Obafemi Awolowo University, Ile-Ife, Nigeria, between the 1st of June and 31st of July, 2016. Existing empirical flux-profile relationships under the framework of Monin-Obukhov similarity theory (MOST) were used to estimate the turbulent fluxes of sensible and latent heat. The performance of the flux-profile technique was then evaluated based on direct measurements of turbulent fluxes obtained from an eddy covariance system. The results showed that the sensible heat flux estimated from flux-profile relationships has a maximum value of 96.4 W/m^2 (daytime mean value of 52.02 W/m^2) in June while a peak value of 145.2 W/m^2 (daytime mean value of 63.1 W/m^2) was obtained from direct measurement. In July, a maximum value of 101.07 W/m^2 was estimated as compared to 142.84 W/m^2 that was obtained from direct measurement. The percentage error calculated for the period averaged values showed that the sensible heat flux was overestimated by up to 25%. The latent heat flux estimated gave a maximum value of 98.4W/m^2 in June whereas a peak value of 310 W/m^2 was obtained from the direct measurement. In July, a maximum value of 105.09 W/m^2 was estimated as compared to 350 W/m^2 recorded from direct measurements of the EC system. Negative Mean Bias Error, MBE values of -27.4 and – 18.6 W/m^2 obtained for June and July respectively indicated the underestimation of latent heat flux by the flux-profile method.

1.0 Introduction

Turbulent fluxes of sensible and latent heat are major mechanisms for mass, energy, and momentum exchanges between the earth's surface and the atmosphere (Han et.al., 2015; Mamtimin et.al., 2021). These dynamical phenomena significantly influence the occurrence of several atmospheric processes such as effluent dispersion, evapotranspiration, and cloud formation (Srinivas et al., 2009; Katul et al., 2012; Babatunde et.al 2017; Poznicova, 2018; Bosman et al., 2018). Surface fluxes are fundamental quantities for predicting boundary layer growth, atmospheric transport processes, and convective mixing (Liu et al., 2016; Park et al., 2017; Kim and Kwon, 2019). As such, the quantification of these parameters is important for weather forecasting, climate modeling, environmental impact studies, and many other applications (Grachev *et al.*, 2006; Katul et al., 2012; Steiner et al., 2018). Direct measurements of the turbulent fluxes of sensible and latent heat can be obtained from fast response meteorological sensors that can capture high frequency (> 10 Hz) turbulent fluctuations in air temperature, humidity, and wind speed (Sunmonu et al., 2019). Such instruments include sonic anemometers, scintillometers, infrared gas analyzers, etc. Continuous measurements of sensible and latent heat in the surface layer (SL) are capital intensive and fragile for long-term deployment (Lee et al., 2004). For routine applications, investigators have resorted to alternative approaches to estimating these fluxes by using semi-empirical relationships that are derived from the Monin-Obukhov Similarity Theory (MOST) of the surface layer. Understanding the turbulent nature of the atmospheric surface layer (ASL) is critical for the determination of mass and energy exchanges occurring at the soil-vegetation-atmosphere interface. Direct measurement of the turbulent fluxes of sensible and latent heat is cumbersome and very expensive to maintain for continuous investigations (Adeyemi et al., 2012; Babatunde et.al 2017). As such, an alternative to estimate these fluxes is from the profile (multilevel) measurements of the mean meteorological quantities using consistent and realistic empirically determined parameters for the SL. Several of these flux-profile relationships exist which have been evaluated and validated for the conditions of the mid-latitudes (Denby and Greuell, 2001; Park et al., 2009 Radic *et al.*, 2017; Ishola et al., 2020; Mohan et al., 2020). However, due to the scarcity of experimental data for the tropical locations, Nigeria inclusive, these relationships have not been properly investigated under different weather conditions. Hence, this study aims at evaluating the performance of existing flux-profile relationships in the SL for a tropical site such as Ile-Ife, Nigeria. This will provide empirical data that will improve the understanding, description, and representation of atmospheric boundary layer processes of a tropical condition, for applications in weather forecast and climate modeling.

2.0 Methodology

2.1 Description of Experimental Site

The experimental site (Fig. 1) for this study is located at the Teaching and Research farm (7.5^{o} N, 4.5^{o} E), Obafemi Awolowo University campus, Ile-Ife, Southwestern Nigeria. The measurement area is of dimension 18 m by 18 m and its surface was covered with blow-level grass which is cut periodically. Although, the dimension of the experimental site was not wide enough to allow for the required fetch necessary for effective flow measurement yet the location has the advantage of not being surrounded by trees and buildings thus obstructing surface flow and the surface roughness parameters greatly minimized. The field measurements took place for two months (June and July 2016). The climate of the study area is generally characterized by two seasons: namely the wet and dry seasons with the wet season spanning between March to October and the dry season lasting from November to February. According to (Jegede et al. 2004), the variation of this season is a function

<Insert Fig. 1 **>**

of the meridional movement of the Inter-Tropical Discontinuity (ITD) which demarcates the warm and moist South-Westerly trade wind at the surface from the hot and dry North-Easterly trade winds (Jegede et.al., 2006). During May/June, which is the onset of the wet season at Ile-Ife, it is within weather zone B (which extends 200–400 km south of the surface position of the ITD). The zone is characterized by suppressed convection resulting in cumulus clouds and precipitation is limited to light showers, whereas in August/September, which is at the peak of the wet season in the area, Ile-Ife falls within the weather zone D characterized by stratus cloud and is accompanied by light rains and drizzles with occasional moderate thunderstorm activities (Ayoola et.al., 2014).

2.2 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. The cup anemometers (model A100L2) and air temperature/relative humidity sensors (HMP60) were arranged in a log-linear position at five (5) heights of 1.14 m, 1.88 m, 3.30 m, 6.30 m, and 12.10 m on the same mast (Fig. 2). Simultaneously with the profile measurements, an eddy covariance (EC) system comprising of a 3D ultrasonic anemometer (CSAT3) and an open path infrared gas analyzer (LI-7500) placed on a mast of the height of 1.81 m was co-located to measure the turbulent fluxes of momentum, sensible and latent heat, and stability parameters at the surface. 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 values while the turbulent fluxes were recorded at 10 Hz.

<Insert Fig. 2 **>**

The raw data were reduced to Thirty (30) minutes 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 of air potential temperature, wind speed, and air-specific humidity data using MATLAB.

$$\bar{\theta}\left(z\right)=az+blnz+c$$

1

$$\bar{q}\left(z\right)={a}^{\prime\prime}z+{b}^{\prime\prime}lnz+{c}^{\prime\prime}$$

2

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

$\frac{\partial \bar{\theta}}{\partial z}=a+\frac{b}{z}$ (3) $\frac{\partial \bar{q}}{\partial z}={a}^{\prime}+\frac{{b}^{\prime}}{z}$ (4)

In this study, the widely applied expression of Businger *et al.* (1971) has been used to obtain$\phi_h\left(\xi\right)$, Eq. (5) which is essentially equivalent to$\phi_q\left(\xi\right)$.

The expression is given as:

$$\phi_h=\begin{array}{c}0.74{\left(1-9\xi\right)}^{-\frac{1}{2}}\left(unstablecondition\right)\\ 0.74+4.7\xi\left(stablecondition\right)\end{array}$$

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:

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

6

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

7

where$\bar{\theta}$and$\bar{q}$are mean wind speed, potential temperature, and specific humidity respectively, k 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 (see Högström, 1988). Today, 0.40 is the accepted value for k, 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), andξ=z/L is a stability parameter defined as the ratio of height, z, to the Obukhov length, L, (characteristic height in the surface layer).

With the gradients and the non-dimensional similarity functions of heat and momentum$\phi_h(\xi)$, $\phi_q(\xi)$ obtained;$\theta_*, and q_*$ were then determined from equations 6 and 7 above.

From the estimated θ_*andq_*following the aforementioned steps, the turbulent fluxes of sensible, H_s, and latent heat, H_L, were obtained from expressions given in equations 8 and 9:

$$H_s = -\rho C_p u_* \theta_*$$

8

$$H_L = \rho \lambda q_* u_*$$

9

where $\rho$is the air density, C_p is the specific heat capacity of heat at constant pressure, $\lambda$is the latent heat of vaporization, $u_*$is the friction velocity, $\theta_*$is the scale temperature and$q_*$is the scale humidity as earlier discussed. The computed fluxes were then compared with the direct measurement obtained from the EC system.

3.0 Results And Discussions

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 Figs. 3, 4, and 5.

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

From the figures, the diurnal pattern of sensible heat flux obtained from the flux-profile method was in good agreement 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. Although the values of sensible heat flux obtained by the flux-profile method were not consistent in terms of over or underestimation of the sensible heat flux values throughout the study period, nevertheless, the method identically replicates the daily pattern of directly measured 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 indicated that the flux-profile method overestimated sensible heat flux by about 25%. 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 (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 $(\bar{u}\geq 3m/s)$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 (Arya, 1988; Denby, 2001; Andreas *et al.*, 2010). 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.

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

From the figures, the diurnal course of latent heat flux was satisfactorily produced by the flux-profile method. In comparison to direct measurement, the nighttime simulations of latent heat flux from the flux profile method were near-perfect while there was an obviously large 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 error analysis carried out, 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 (Chen et al., 1996; Yang *et al.*, 2006 Steeneveld *et al.*, 2008). This assumption led to the treatment of the non-dimensional similarity function of water vapor$\left(\phi_q\right)$as an equivalent function of the nondimensional similarity function of heat$\left(\phi_h\right)$. Hence, an accurate determination of the non-dimensional similarity function of water vapor $\left(\phi_q\right)$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.

4.0 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 a 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.

Declarations

5.0 Competing Interest

The authors declare that no conflict of interest exists.

5.1 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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Figures

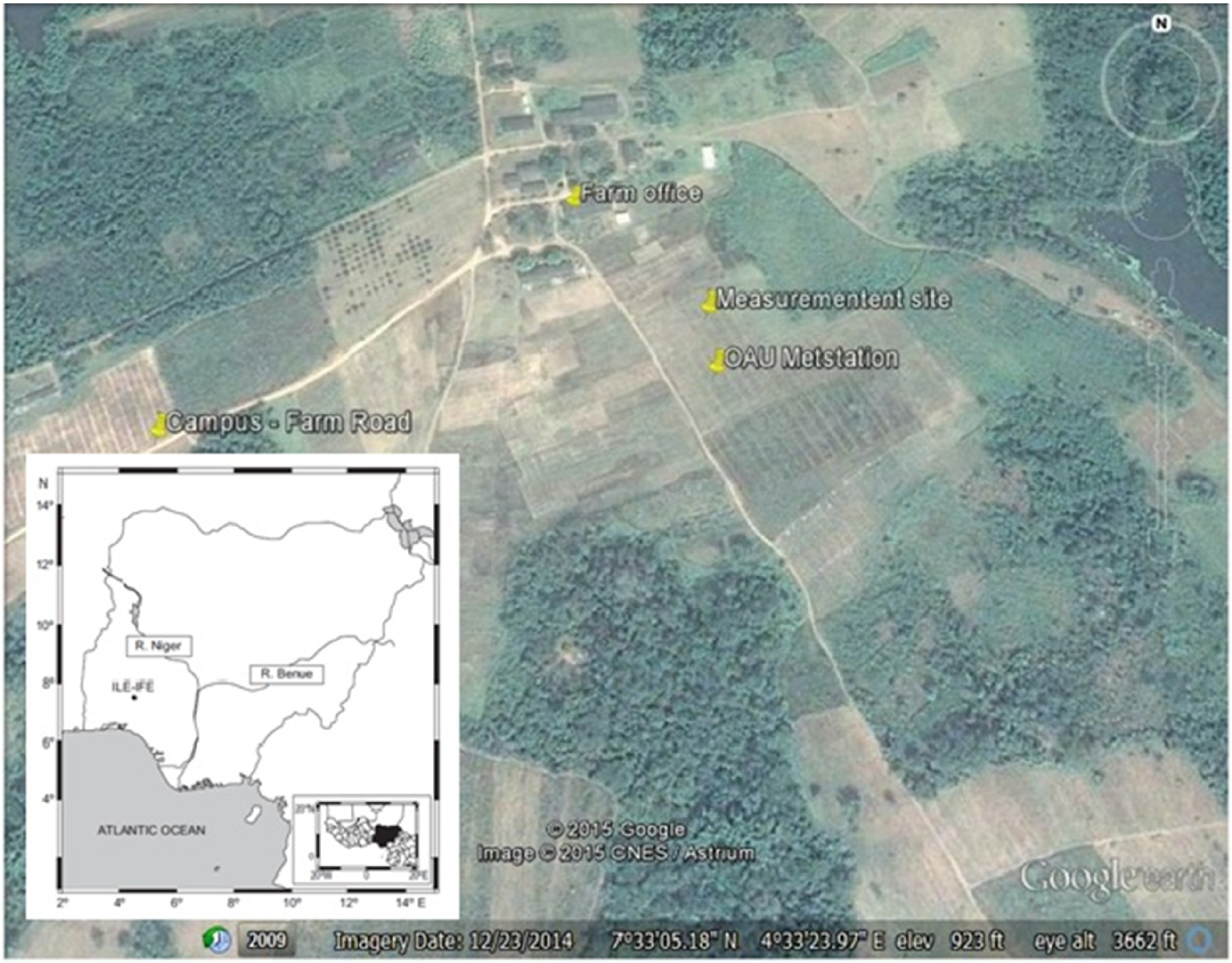

Figure 1

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.

Figure 2

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

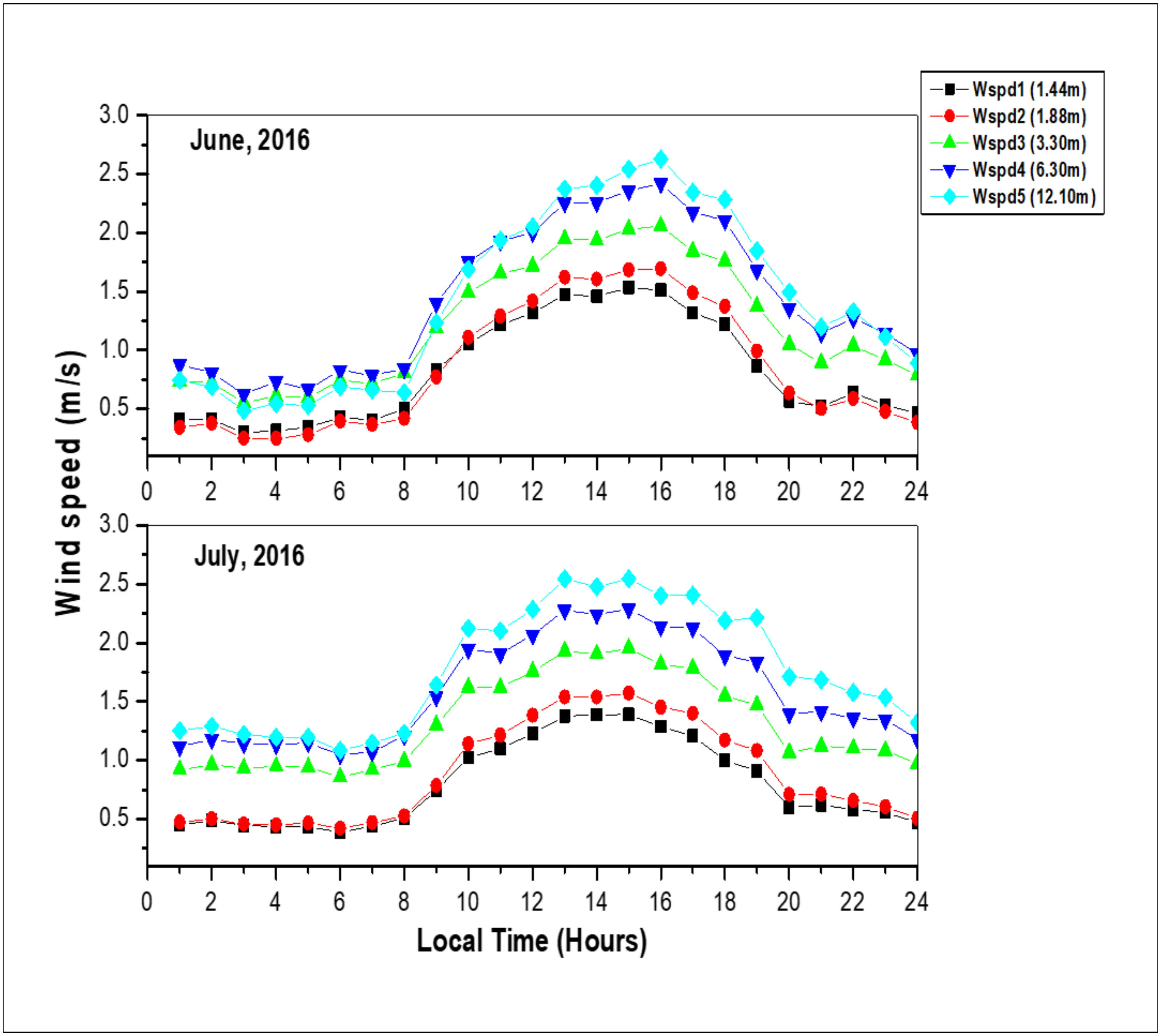

Figure 3

Diurnal Variation of Multilevel measurements of Wind speed at the Teaching and Research Farm, O.A.U., Ile-Ife in June and July, 2016.

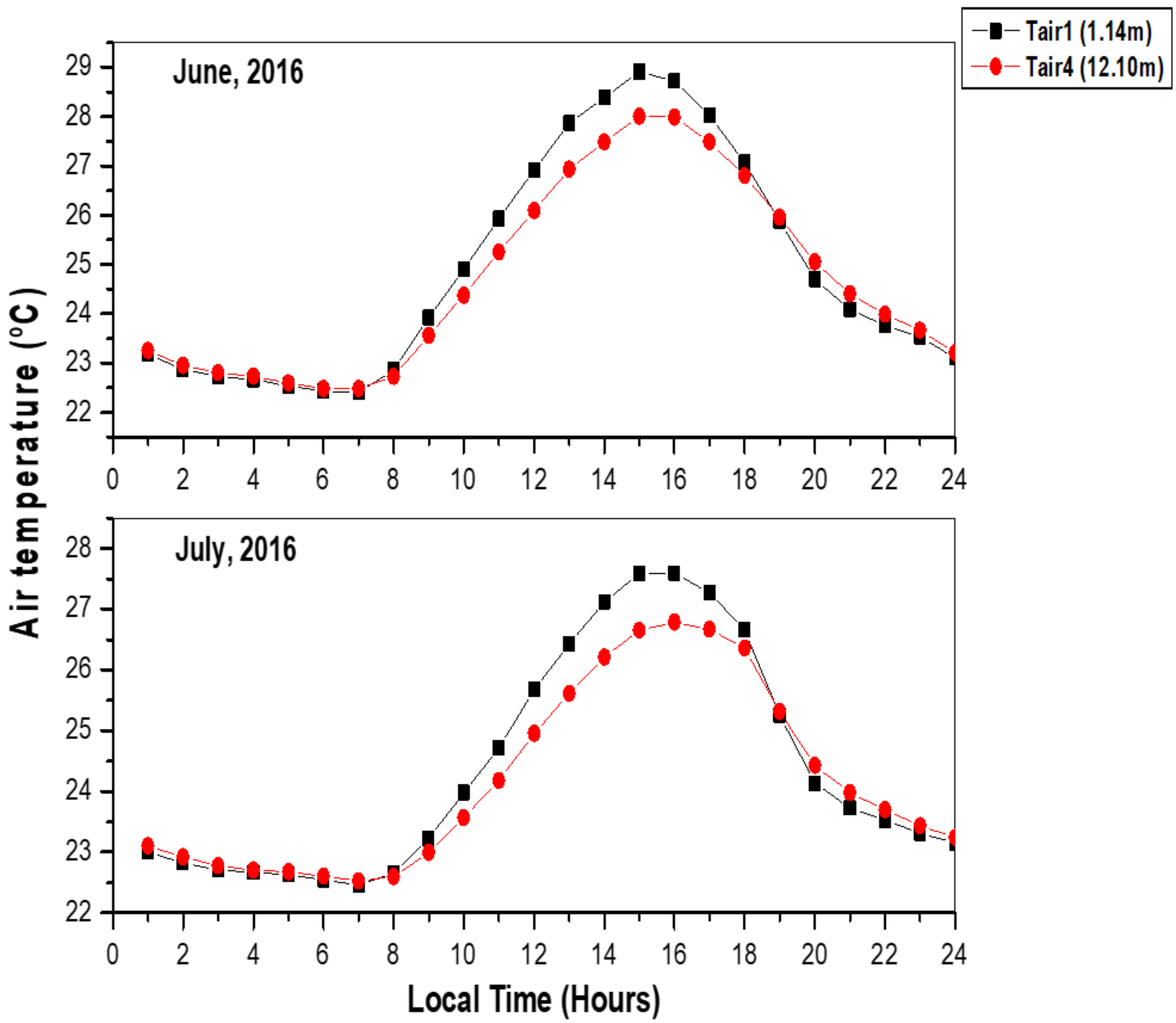

Figure 4

Diurnal Variation of Temperature Profile Measurements at the Teaching and Research Farm, O.A.U., Ile-Ife in June, 2016.

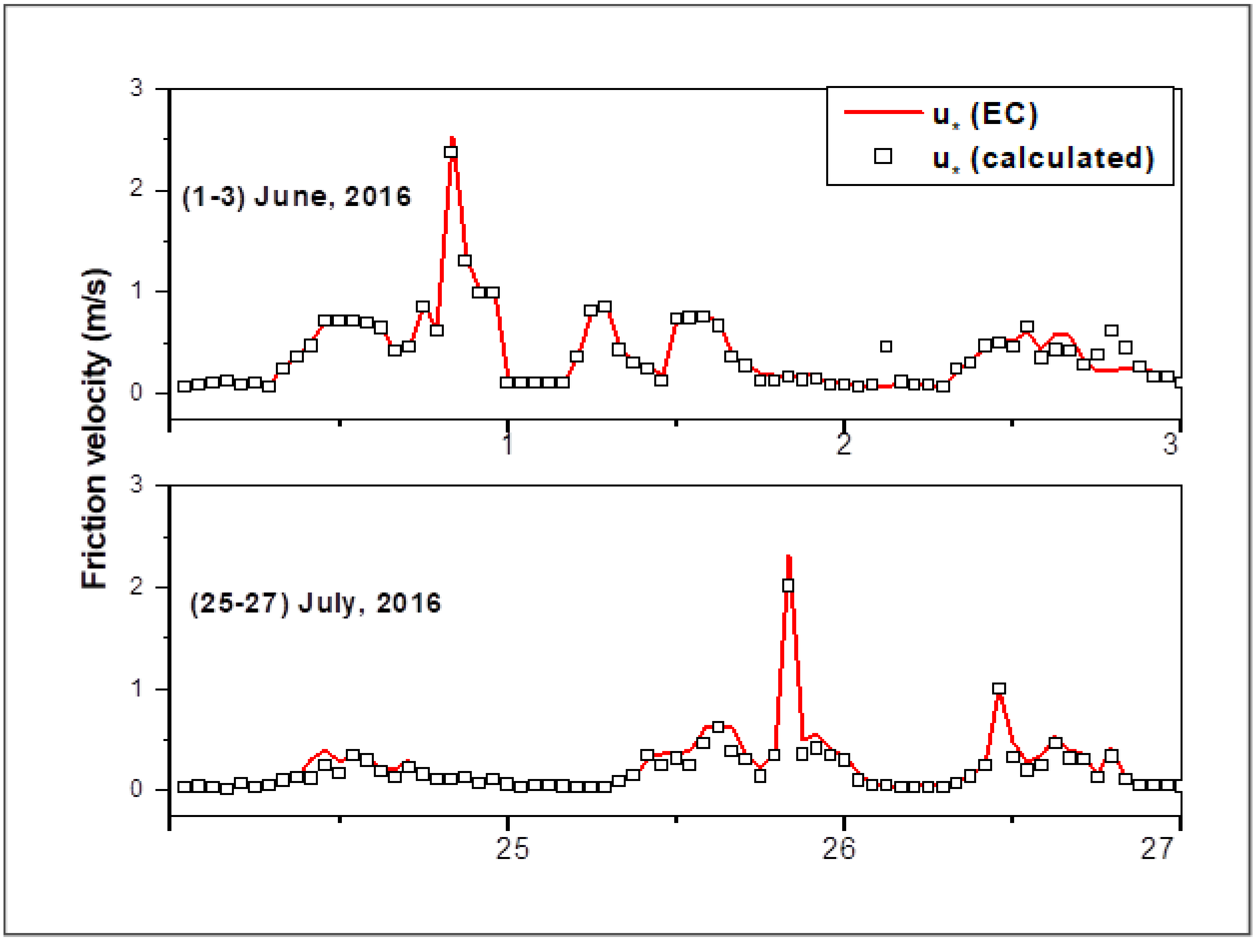

Figure 5

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.

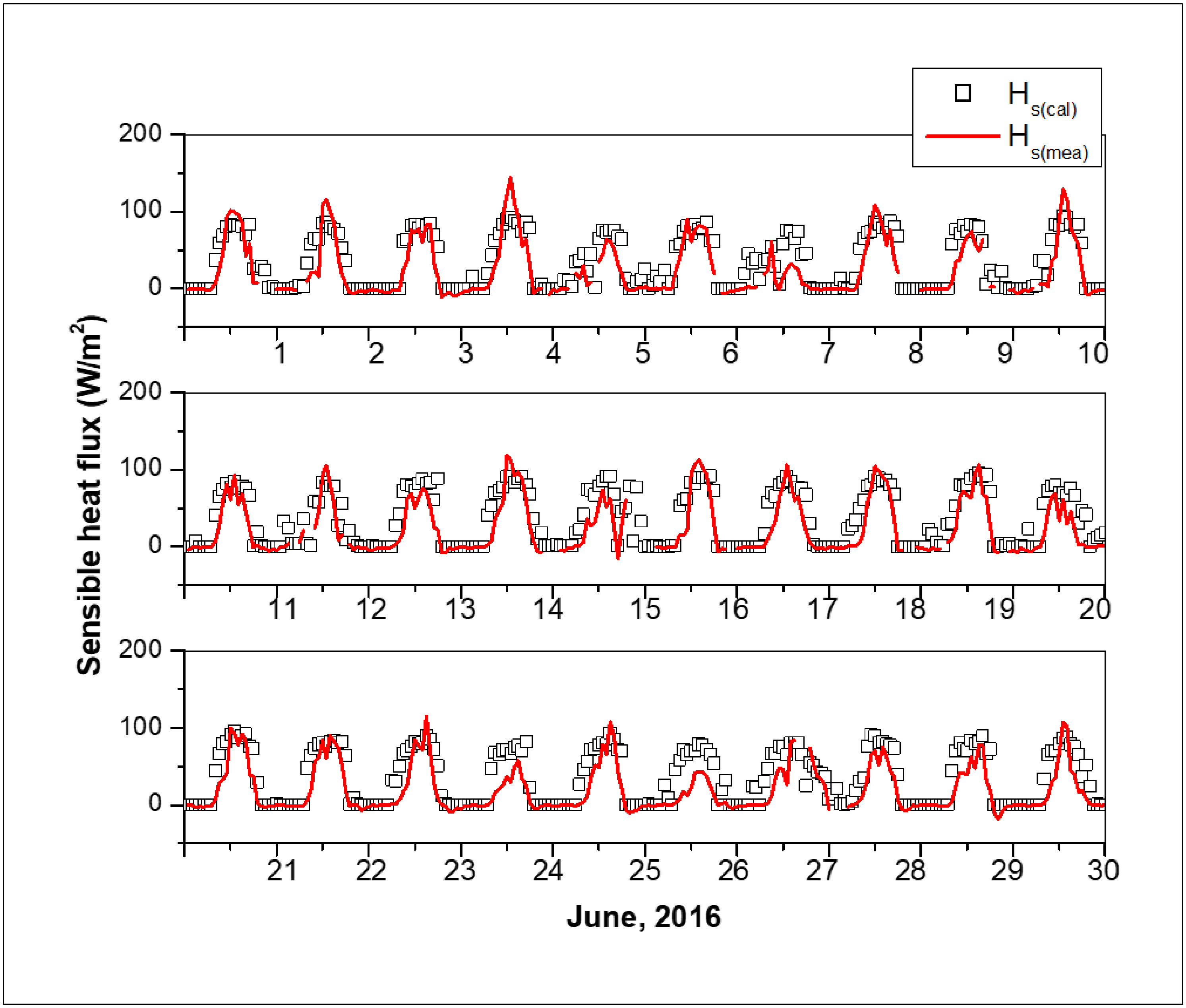

Figure 6

Diurnal Variation of Estimated and Measured Sensible Heat Flux at the Teaching and Research Farm, O.A.U., Ile-Ife in June, 2016.

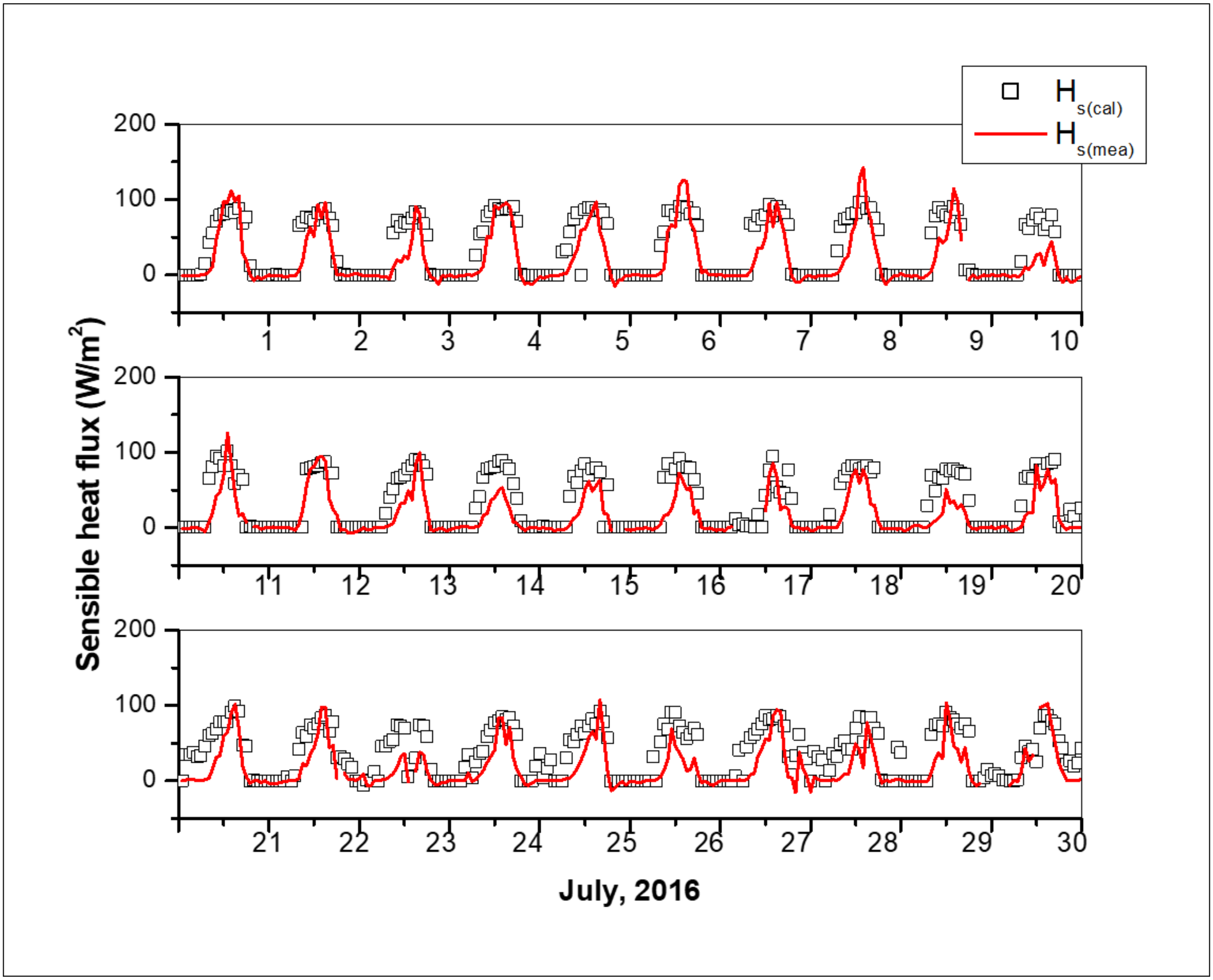

Figure 7

Diurnal Variation of Estimated and Measured Sensible Heat Flux at the Teaching and Research Farm, O.A.U., Ile-Ife in July, 2016.

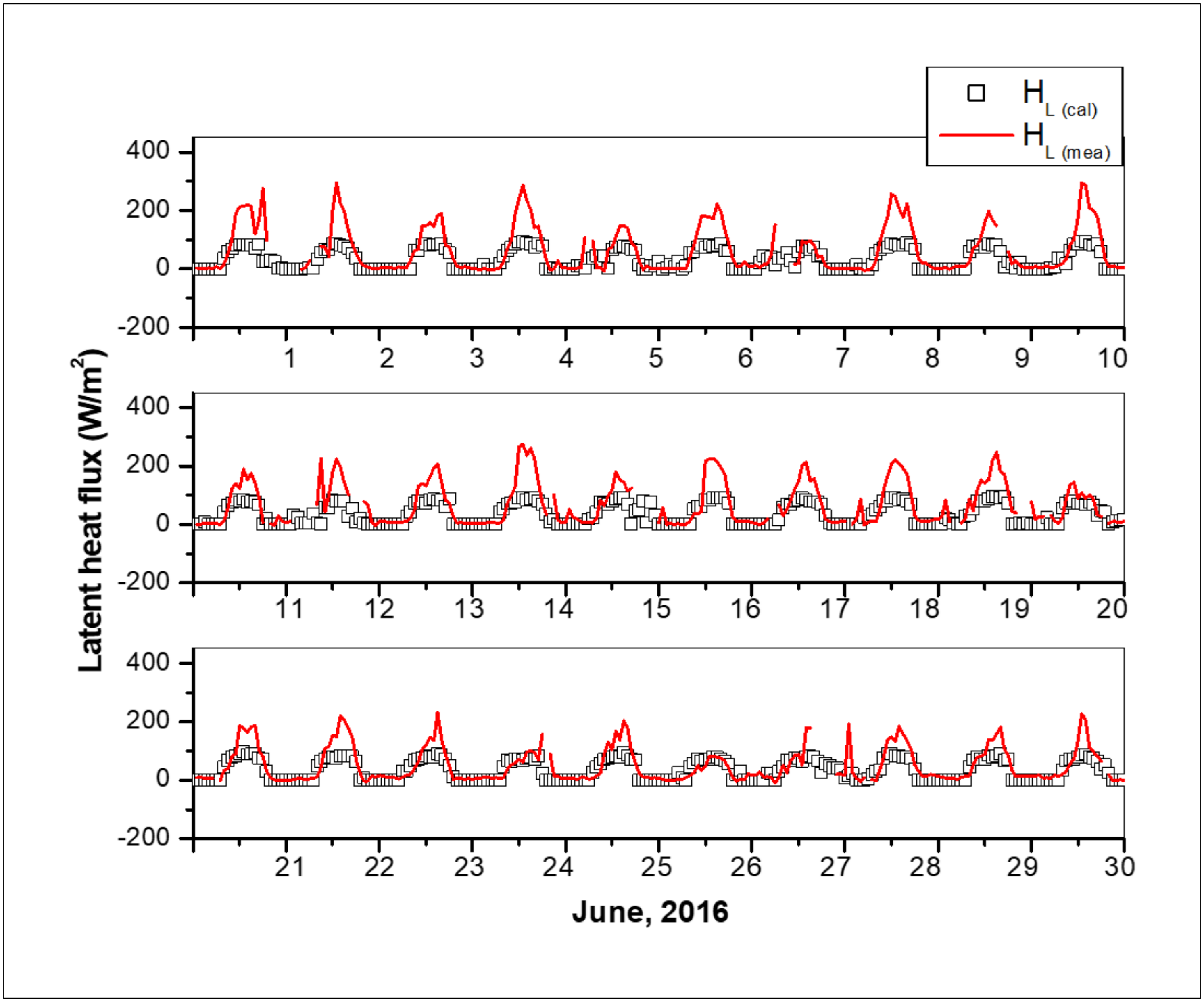

Figure 8

Diurnal Variation of Estimated and Measured Sensible Heat Flux at the Teaching and Research Farm, O.A.U., Ile-Ife in July, 2016.

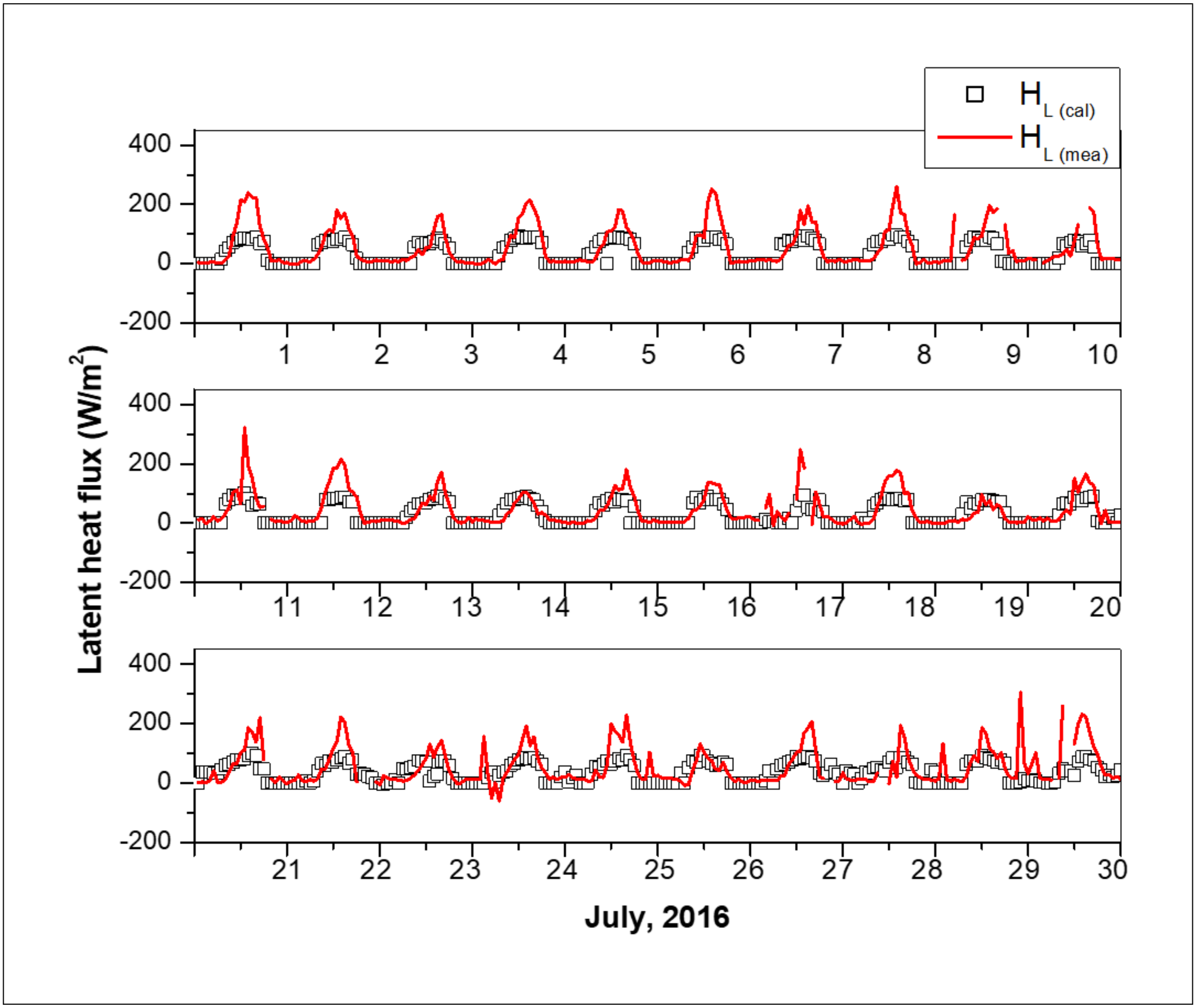

Figure 9

Diurnal Variation of Estimated and Measured Latent Heat Flux at the Teaching and Research Farm, Obafemi Awolowo University, Ile-Ife in July 2016