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RESEARCH PAPER

ESTIMATION OF SURFACE ENERGY FLUXES FROM BARE GROUND IN A TROPICAL STATION USING PRIESTLEY TAYLOR METHOD

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ABSTRACT

This investigation was designed to test the performance of Priestley Taylor method in the partitioning of the available energy into sensible and latent heat fluxes in a tropical site. Compared to eddy covariance measured fluxes, the conventional Priestley Taylor constant (α_{PT}) of 1.25 gave low coefficient of determination and high bias error for both sensible and latent heat fluxes. It overestimated latent heat flux in the noon and afternoon but underestimated sensible heat flux. The bias error reduced and the coefficient of determination increased for sensible heat flux when α_{PT} value was reduced to 1.0. The bias error for latent heat also reduced but the coefficient of determination did not change with the reduction in α_{PT} value. The root mean square error reduced with the reduction in the α_{PT} value. Compared to measured fluxes, coefficient of determination of sensible heat flux ranged from 0.82 to 0.90 while that of latent heat flux ranged from 0.78 to 0.9. Priestley Taylor method is recommended for partitioning of available energy into its component sensible and latent heat fluxes.

Keywords: *α_{PT} value, energy, latent heat ,flux*

INTRODUCTION

The monitoring of atmospheric turbulent fluxes (sensible and latent heat) at the land surface is crucial to the determination and modeling of the land –atmosphere energy and mass exchange processes that are applicable in weather, climate, agricultural and hydrological studies, Priestley and Taylor (1972). The fluxes can be measured or estimated. The Eddy covariance (EC) method is a standard technique that is widely used to monitor turbulent fluxes of sensible and latent heat.

Unfortunately the equipment is not available in many stations in West Africa due to the expenses and expertise involved. Profile measurements are done in most stations since they are less expensive. From the profile measurement of temperature, wind speed, relative humidity and vapour pressure, various estimation methods can be used to find the fluxes of sensible and latent heats. The Bowen ratio energy balance (BREB) method is a widely used estimation method that enforces closure on the energy balance equation (Jegede et al., 2001; Balogun et al., 2002; Jegede et al., 2004; Kim et al., 1989; Heilman et al., 1989; Gutierre and Meinzer, 1994; Fritschen and Simpson 1989).

The Priestley Taylor parameterization has not been widely applied in West Africa, though it has been proved reliable in various parts of the globe (Sumner and Jacobs, 2005; Gardelin and Lindstrom, 1996; Agam et al., 2010). There is the need to validate all the available estimation methods using standard measurement system.

The Nigerian Micrometeorological Experiment (Nimex) group started measurement in 2004 during which eddy covariance measurement of turbulent fluxes and profile measurement of meteorological parameters were done.

This investigation is based on the assessment of the performance of Priestley Taylor model in partitioning of surface energy flux into sensible and latent heat portions.

STUDY AREA

The Nimex-1 experimental field was located on a farm land at Obafemi Awolowo University, Ile-Ife ($7^0 33'$ N, $4^0 33'$ E) Nigeria. The site is a level terrain of about 100000 m^2 with an elevation of 288 m above sea level. Generally in Nigeria there are two seasons: wet (April to October) and dry (November to March). These seasons are influenced by two air masses namely south-westerlies coming from the Atlantic Ocean and north-easterlies from the Sahara desert respectively. The position of the Inter -tropical convergence zone (ITCZ) across West Africa affects the seasons (Figure 1). The ITCZ is at its minimum position in January and it reaches its maximum position in August. There is rainfall at the region below the ITCZ and dryness at the region above it (Adedokun, 1978 and Balogun, 1981). The investigation was conducted during the transition period from dry to wet season, precisely from 19 February to 9 March, 2004.

METHODS

Measurement

Slow Response Measurements

During the course of the experiment, profile measurements of the following parameters were done: wind speed at eight levels; wind direction at 14.8 m; wet and dry bulb temperatures at three levels; soil surface temperature; soil temperature at three depths; and soil heat flux at three depths. Complete description of the equipment used in this investigation is given in Table 1. Jegede et al., (2004) and Mauder et al., (2007) reported the preliminary results of this experiment.

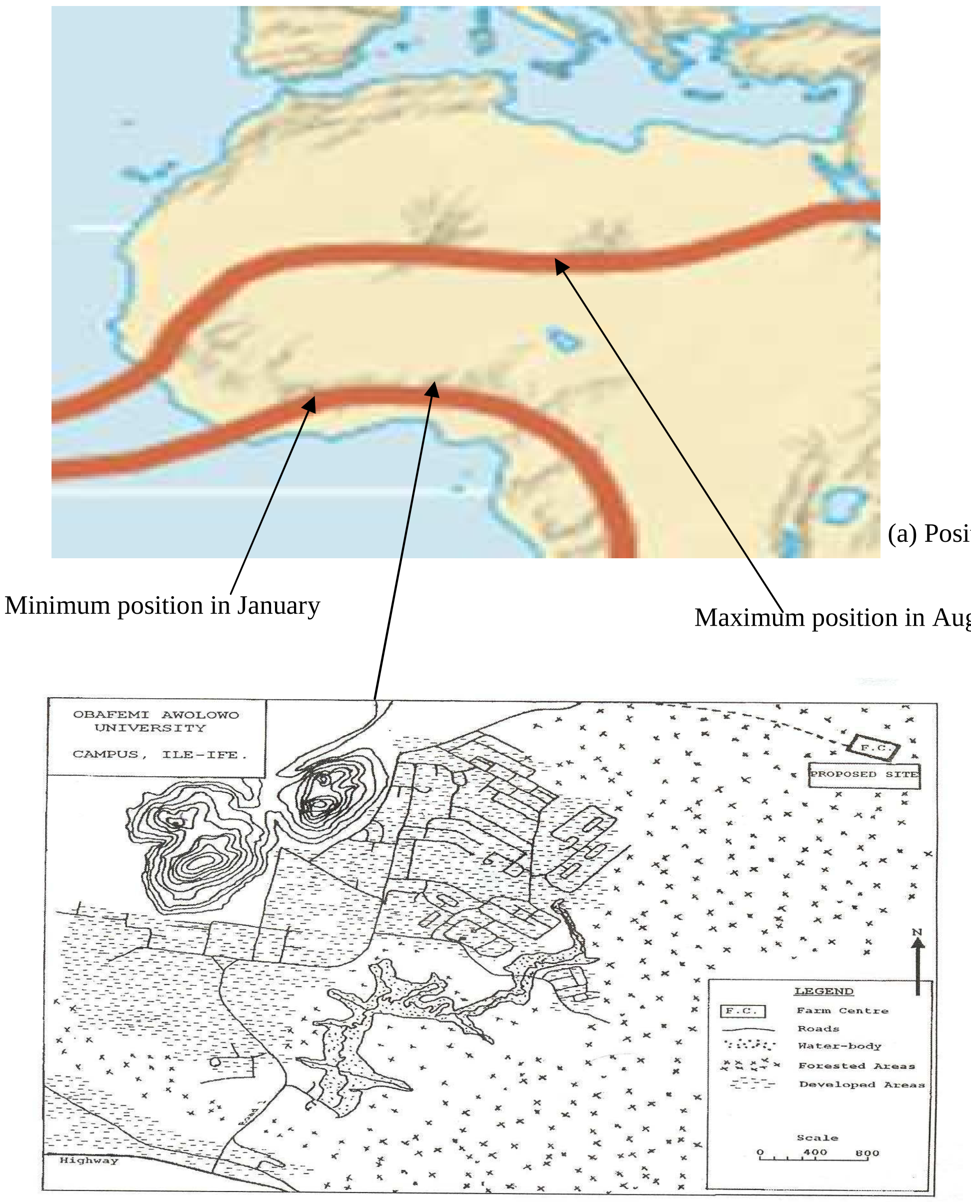
Day of year (DOY)s 61, 63, 66 and 67 were selected for this investigation based on their completion or closeness to completion of the profile and EC data. The experimental field was almost bare soil, since it was cleared just before the commencement of the experiment and soil heat flux at 2cm depth was used, so leaf area index and energy storage in the soil can be neglected in the treatment of data.

Fast Response Measurements

The eddy covariance system used on Nimex-1 field comprised of a three dimensional Metek USA-1 sonic anemometer used to measure high frequency wind velocity components (u, v and w) and air temperature (T) and a Campbell Scientific krypton hygrometer (KH2O) used to measure high frequency signals of water vapour density. The sensors were installed on a 2.5 m mast. The sonic anemometer was sampled at 16 Hz while the krypton hygrometer was sampled at 8 Hz.

Visual test was carried out on daily basis to check the quality of the data from the slow response equipment (Foken, 2003). A software package written by Mauder and Foken (2004) was used to check the quality and to analyze the fast response data. The software package was employed to carry out the following processes:

- Removal of physically impossible values following the spike detection method of Vickers and Mahrt(1997) based on Hojstrup (1993).



(a) Position of ITCZ

(b) Nimex-1 station

Fig 1: (a) Position of ITCZ over West Africa in January and August (b) Nimex- 1 Station

- The difference in the sampling frequency of sonic anemometer and krypton hygrometer necessitated the application of cross correlation analysis for each averaging interval of both sensors for the determination of the time delay between them. This was done.

Table 1: List of Equipment deployed during Nimex-1

Parameter	Sensor	Accuracy	Levels of measurement (m)
Data acquisition	Campbell Scientific Data-logger CR10X	Not applicable	Not applicable
Wind speed	Vector Instruments Cup anemometer A101ML/A100L2	1%	0.7, 1.2, 2.2, 3.3, 5.2, 7.2, 10.2 and 14.8
Wind direction	Vector Instruments Wind vane W200P	$\pm 2^0$	14.8
Wet and dry bulb air temperature	Theodor Friedrichs Frakenberger Psychrometer	$\pm .05\ ^0$C	0.9, 4.9 and 10.0
Soil surface temperature	Heitronics Infrared Pyrometer KT1582D	$\pm 0.5^0$C	1.8
Soil temperature	Campbell Scientific Thermistor Thermocouple	$\pm 1^0$C	0.05, 0.10 and 0.30 (depth)
Soil heat flux	Hukseflux HFP01SC self calibrating Heat flux plate	±3%	0.02, 0.05, 0.10 and 0.30 (depth)
Net radiation	Kipp and Zonen CNR1 net radiometer	±10% (daily total)	1.9
3D wind speed	Metek USA-1 3-D ultrasonic anemometer	0.01 ms^{-1}	2.48
Water vapour content	Campbell Scientific KH20 krypton Hygrometer	0.15 $m^3g^{-1}cm^{-1}$ (sensitivity)	2.43
Volumetric soil moisture (%)	Campbell Scientific CS616 water content reflectometer	± 3% of water content	0.05(depth)

- Sonic temperature was corrected using Liu et al. (2001) method.
- Planar fit method of Wikzak et al. (2001) was applied for coordinate transformation.
- Following Moore (1986), the spectral models of Kaimal et al. (1972) and Hojstrup (1981) were used for spectral correction.
- Schotanus et al. (1983) method was applied in the conversion of buoyancy flux into sensible heat flux.

- Webb et al. (1980) method was applied in the corrections for fluctuations for density fluctuation in calculating the water vapour.

- The methods of Foken and Wichura (1996) and Foken et al. (2004) were applied to test for steady state conditions and well- developed turbulence.

Theory and Calculation

Priestly Taylor Parameterization

The Priestley-Taylor parameterization of the sensible heat flux, Q_H and the latent heat flux, Q_E are respectively given by DeBruin (1983):

$$Q_H = \frac{\left[(1-\alpha_{PT})S_{cc}+\gamma\right](Q_N-Q_G)}{S_{cc}+\gamma} \quad (1)$$

$$Q_E = \frac{\alpha_{PT} S_{cc} (Q_N - Q_G)}{S_{cc} + \gamma} \quad (2)$$

where S_{cc} is the change of specific humidity with temperature, at saturation it is given by :

$$\frac{dq_{sat}}{dT} = \frac{\varepsilon L_v \overline{q}_{sat}}{R\overline{T}^2} \equiv S_{cc}(\overline{T})$$

Q_N = net radiation

Q_G = ground heat flux

γ = 0.667 KhPa^{-1} is the psychometric constant for p = 1000 hPa and T = 20^0C.

The Priestley Taylor constant, α_{PT} is used to make the equation applicable to unsaturated conditions.

Q_N - Q_G in equation (2) is the available energy that controls the exchange processes at the surface.
q = specific humidity (If the air is saturated, $q = q_{sat}$).

The latent heat of evaporation Lv was computed from L_v (*J/kg*) = [12.501-0.00237.T(^0C)] 10^6

The universal gas constant, R = 287.04 J/(kg K),T = temperature

The value of α_{PT} is generally 1.25 or 1.26 for well watered surfaces.

ε = 0.622 (g_{water}/g_{air}) is the ratio of gas constants for air and water vapour. The value of q_{sat} can be obtained as a function of temperature (T) by using a variation of Tenten's formula (Bolton 1980) as:

$$q_{sat} = 0.622 \frac{e_{sat}}{P} \quad (3)$$

where

$$e_{sat} = (0.6112\,kPa)\cdot \exp\left[\frac{17.67\cdot(T-273.16)}{T-29.66}\right] \quad (4)$$

Determination of α_{PT} value for unsaturated surface

The period of Nimex-1 was the transition between dry and wet seasons which is always characterized by unsaturated soil surface due to little or no precipitation. The α_{PT} values during Nimex- 1 were computed according to Eichinger et al. (1996).

$$\alpha_{PT} = \frac{1+[\gamma C/(\Delta+\gamma)]}{1-[\gamma C/(\Delta+\gamma)]^2}$$

where

$$\Delta = \left.\frac{de_{sat}}{dT}\right|_T \approx \frac{e_{sat}(T_g)-e_{sat}a}{T_g-T_a}$$

$$C = \frac{(e_{sat}a - e_a)}{(e_{sat}(T_g) - e_a)} \quad \text{and}$$

$$C = \frac{(1-RH_a)e_{sat}a-(1-RH_g)e_{sat}(Tg)}{(RH_g e_{sat}(T_g)-e_a)} \quad \text{for unsaturated}$$

Surfaces.

T_g= surface temperature, T_a = air temperature, $e(T_g)$ = water vapour pressure at the surface temperature, e_a = water vapour pressure in the air, $e_{sat}(T_g)$ and $e_{sat}a$ are the saturation vapour pressure at temperature T_g and T_a respectively. RH_a and RH_g are the relative humidity of the air and the surface respectively.

RESULTS AND DISCUSSION

Result for DOY 66

Sensible and latent heat fluxes estimated using Priestley Taylor parameterization versus measured values for DOY 66 are shown in Fig. 2a.The effect of the varying Priestley Taylor constant on the estimated fluxes was examined by plotting the bias between the measured and the estimated sensible and latent heat fluxes (Fig.3) Table 2 shows the statistics coefficient of determination (R^2) and root mean square error (RMSE) between estimated and measured fluxes for the period of investigation.

Figs 2 and 3 clearly show the overestimation of sensible heat flux in the morning and evenings and its underestimation at about noon to afternoon. There was also a general underestimation of latent heat flux in the morning and evenings but it was overestimated in the afternoon.

Sensible and latent heat fluxes biases were high in the afternoon but low in the morning and evening probably because that was the time of maximum fluxes and the deviation at that time can be high as well. The biases reduced with the reduction in the α_{PT} value.

Sensible heat flux had lower bias and higher R^2 than latent heat flux.(Figs. 3a, 4, 5 and Table 2). The bias value of sensible heat flux reduced from maximum value of 66.9 to less than 40 Wm^{-2} with most points between -10 and + 20 W m^{-2} while the bias value of latent heat flux varied mostly between -2.2 and -60 W m^{-2} with a few (2)points higher than -60W m^{-2} in the improved estimation. In general there was a better representation of Q_E flux with reduced α_{PT}, though there was no change in R^2 value throughout.

The α_{PT} value for DOY 66 was computed to be 1.0 using Eichinger *et al.* (1996) formulation for α_{PT}. With Priestley Taylor constant of 1.25 the coefficient of determination (R^2) for senble heat flux was low (0.74) but with the reduction to 1.0, the R^2 value increased to 0.83 (Fig 4). Fig. 2a also show a better representation of sensible heat flux with reduced Priestley Taylor constant. Comparing Fig. 2a-d, it can be noticed that the reduction in the α_{PT} value adjusted the fluxes such that the sensible heat flux was increased in the afternoon while the latent heat flux was reduced. Considering the RMSE, α_{PT} =1(calculated value) gave the least RMSE values for both fluxes.

Result of DOY 67

The diurnal variations of the estimated and measured sensible and latent heat fluxes for varying α_{PT} of 1.25 and 1.0 for DOY 67 are shown in Fig. 2b. Figure 3b presents the biases between the estimated and measured sensible and latent heat fluxes for DOY 67. The estimated fluxes were approaching measured fluxes with the reduction of Prietley Taylor constant. The α_{PT} value for DOY 67 was computed to be 1.0 using Eichinger et al., (1996) formulation for α_{PT}.

The Q_E bias value reduced from between -70.9 and 110.4 to between -70.9 and 46.7 W m^{-2}. The Q_H bias moved from between -105.2 and 35.2 to between -41.9 and 35.2 W m^{-2}.

Result for DOY 61 and 63

Measured fluxes on DOY 61 and 63 did not extend to 24 hours, however the available points were used. The reduction in the α_{PT} value brought the estimated fluxes closer to the measured ones for DOYs 61 and 63 like the other DOYs (Figures 2c and d; Figures 3 c and d). The R^2 value increased while the RMSE value reduced with α_{PT} value of 1.0 for sensible heat flux. The R^2 value remained constant for latent heat flux but the RMSE value reduced (Table 2, Figs 4 and 5).

Table 2: Statistics between the estimated and observed surface fluxes using varying α_{PT}

	DOY 61		DOY 63		DOY66		DOY 67	
	Q_H	Q_E	Q_H	Q_E	Q_H	Q_E	Q_H	Q_E
Coefficient of determination (R^2) (Trend line through the origin)								
α_{PT} =1.25	0.55	0.80	0.81	0.91	0.74	0.83	0.78	0.85
α_{PT}= 1.00	0.84	0.80	0.94	0.91	0.83	0.83	0.88	0.85
RMSE (W m^{-2})								
α_{PT} =1.25	42.24	76.53	33.83	57.18	30.25	41.94	40.07	49.89
α_{PT} =1.00	13.41	44.64	10.22	31.89	16.01	43.44	19.16	36.50

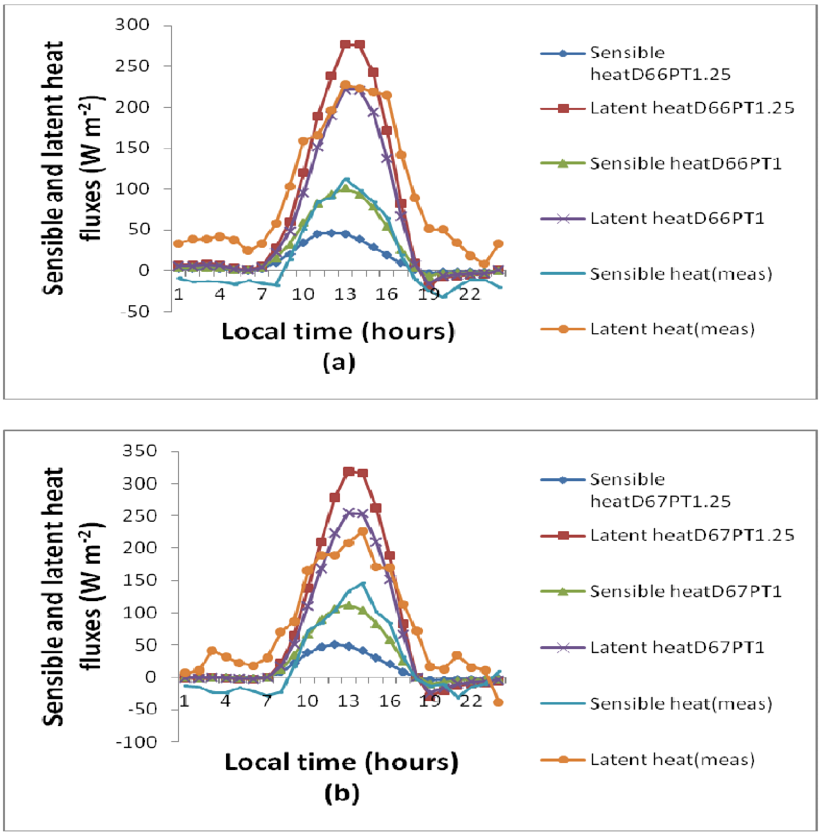


Fig 2a, b : Sensible and latent heat fluxes with Priestley Taylor constant of 1 and 1.25 for DOYs(a) 66, (b) 67

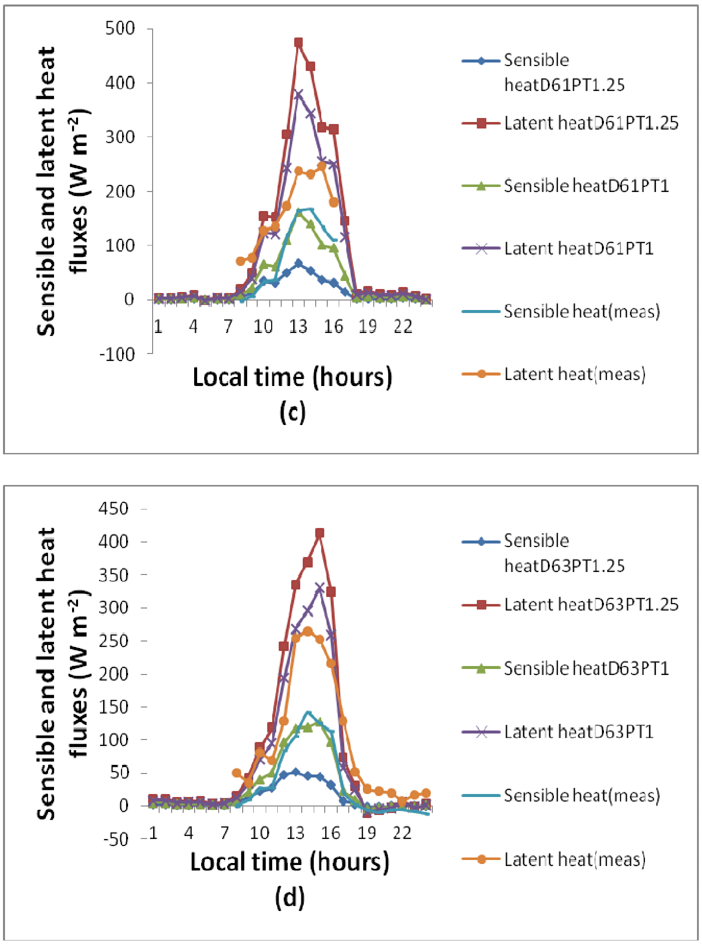
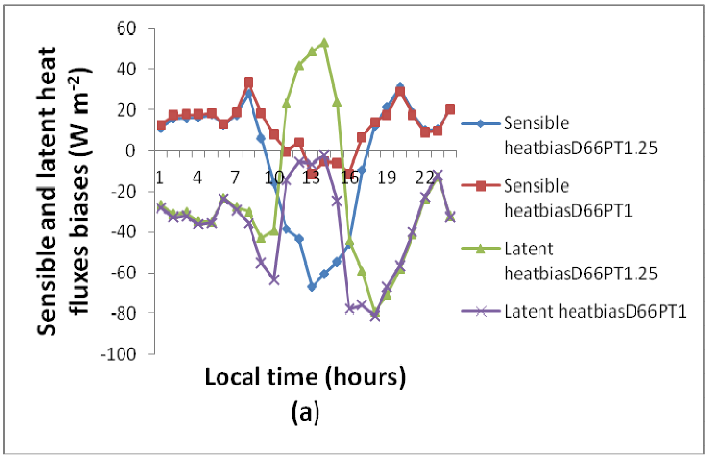


Fig 2c, d: Same as Fig 2a, b except for DOYs (c) 61 and (d) 63



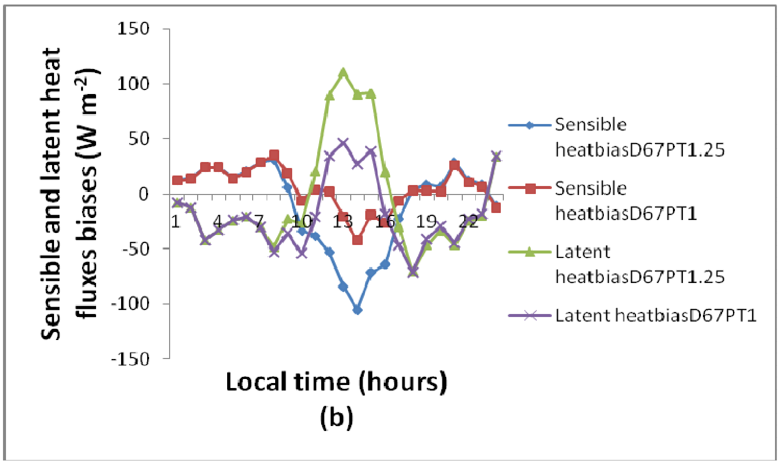
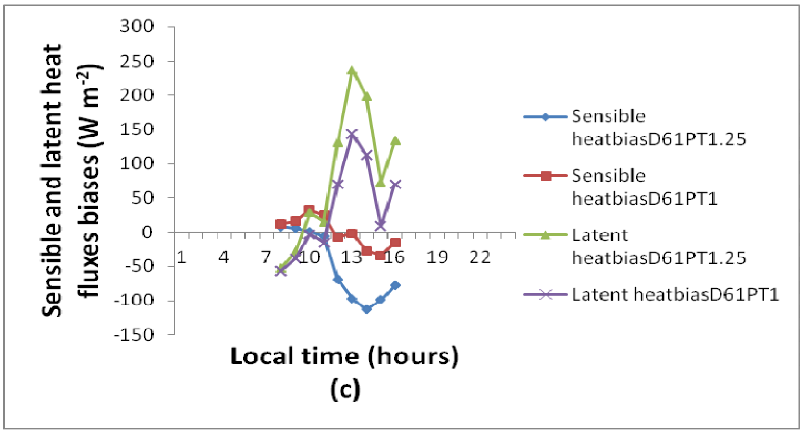


Fig 3a, b: Biases for sensible and latent heat fluxes for DOYs (a) 66, (b) 67



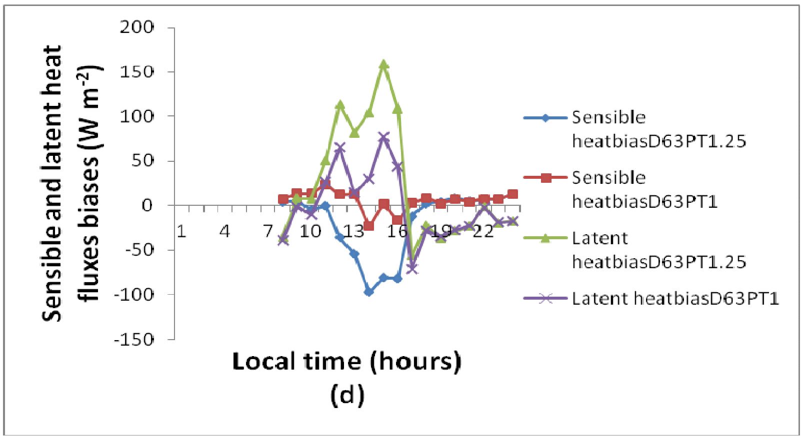


Fig: 3c,d: Same as Fig 3a, b except for (c) DOY 61 and (d) DOY 63

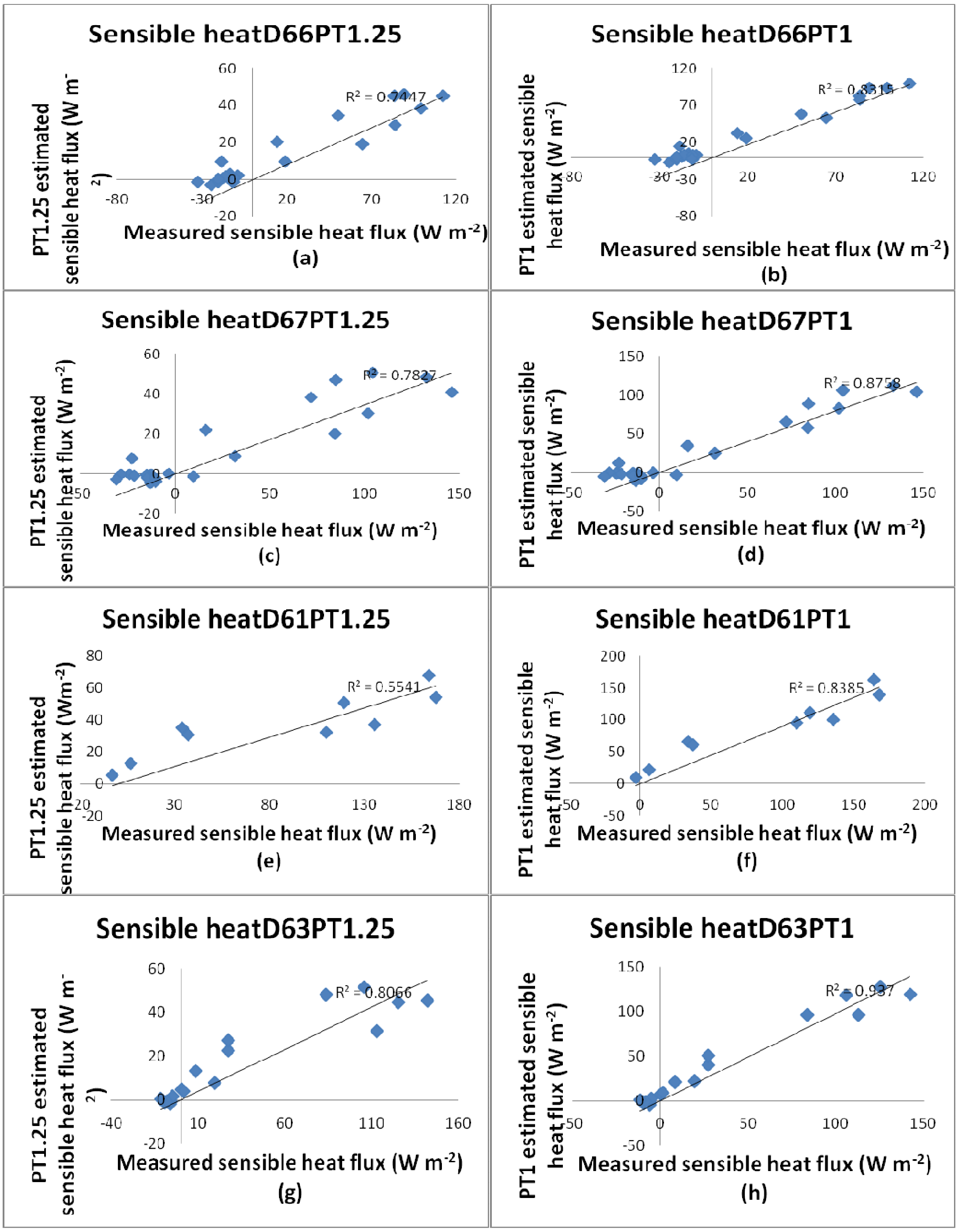


Fig 4: Scatter plots of measured and estimate sensible heat flux

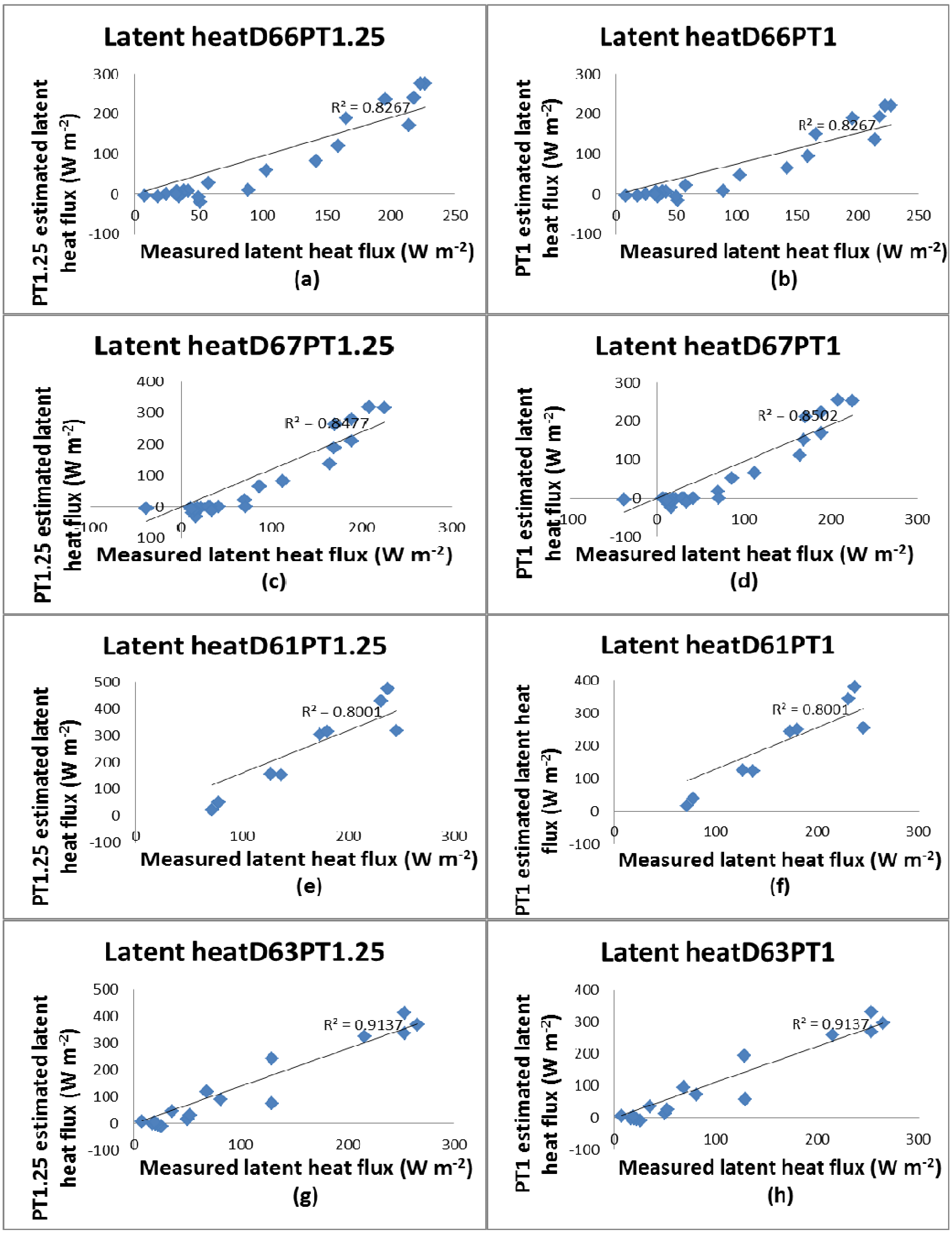


Fig 5: Scatter plots of measured and estimated latent heat flux

Overall Performance of Priestley Taylor Parameterization

The soil moisture was very low during the period of the experiment since the rainy season was just starting and there were gaps in the rain days. In particular there was no rain in all the days considered in this investigation. Generally soil moisture was decreasing (negative trend) through the DOYs considered. Daily average soil moisture of 14, 11, 9 and 8 % were recorded for DOYs 61, 63, 66 and 67 respectively.

The average daily bias error in sensible heat flux (excluding DOY 61due to its few hourly values) was between 3.5 and 23.1 W m^{-2} with α_{PT} of 1, this is very small. The average daily bias error for latent heat flux was between 0.9 and 37.0 Wm^{-2}, which is also between acceptable limit. The RMSE values reduced with reduction in the α_{PT} value.

The adjustment in the α_{PT} value did not affect the R^2 value of latent heat but increased that of sensible heat. High R^2 values of 0.83 to 0.94 were obtained for sensible heat flux and 0.80 to 0.91 for latent heat flux (Table 2 and Figs 4 and 5) with α_{PT} value of 1.0. The R^2 values obtained were comparable with those obtained by Su (2002) who estimated sensible and latent heat fluxes using surface energy balance system, he obtained R^2 values ranging from 0.81-0.88 and 0.43-0.87 for sensible and latent heat flux respectively. Summer and Jacobs (2005) got R^2 value of 0.81 for evapotranspiration using Penmman Monteith parameterization. Gardelin and Lindstrom (1996) got R^2 value ranging between 0.79 and 0.94 using Priestley Taylor method. Albertson *et al*. (1995) used flux variance method to estimate sensible heat flux that has R^2 value of 0.88.

In this investigation, the fluctuation in sensible heat flux with varying α_{PT} was such that sensible heat flux and its R^2 value increased as α_{PT} reduced. Latent heat flux reduced with reduction in α_{PT} value while its R^2 value remained constant. This is contrary to the report by Pereira and Nova (1992) that α_{PT} value is linearly related to sensible heat in a positive way. This is probably due to the site of the experiments.

CONCLUSION

Priestley Taylor parameterization was used to partition the available energy from a bare surface in a tropical station into its sensible and latent heat parts. The parameterization was verified by eddy covariance measurements during the transition period from dry to wet season of 2004. In general the diurnal values of the estimated sensible and latent heat fluxes compared well with measurements. When the Priestley Taylor constant of 1.25 was used, the estimated sensible and latent heat fluxes had higher bias error values but the use of Eichinger et al., (1996) formulated α_{PT} values gave reliable estimates of the sensible and latent heat fluxes. Acceptable coefficient of determinations and root mean square errors were obtained for both fluxes when compared with previous estimation works. This method can be successfully applied in this area.

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