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ORIGINAL ARTICLE

Modeling of diurnal pattern of air temperature in a tropical environment: Ile-Ife and Ibadan, Nigeria

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Abstract Modeling of diurnal pattern of air temperature (T_a) is essential in the parameterization of turbulent heat fluxes in climate models. However, climate models still simulate the nocturnal stable boundary layer surface T_a with biases across the globe. This paper therefore validated five different diurnal T_a models (Ephrath, Hirotaka, de Wit, Parton and Fourier series models) used for estimating hourly T_a from daily maximum, daily minimum, and daily mean air temperature. It also developed an improved fourier series parameterization approach for T_a using surface layer observations from Nigerian micrometeorological experimental (NIMEX) site. The overall performance of the Ephrath, Hirotaka, de Wit and Parton models revealed a large deviation from the measured data during the early hours of the morning and late hours of the nighttime. The original fourier series model showed better performance for unstable air temperature parameterizations while the stable T_a was strongly overestimated. The performance of the model was improved with the inclusion of the atmospheric cooling rate that accounts for the temperature inversion which occurs during the nocturnal boundary layer condition. The mean bias error and root mean square error in estimated T_a by the modified fourier series model reduced by 4.13 and 3.01 °C, respectively during the transition period from dry to wet stable atmospheric conditions. The existing models simulated night time T_a with high biases and could not accurately capture the strong cooling inversion associated with a humid tropical region. The modified Fourier series model that incorporated the night time inversion variables gave the best estimation of the diurnal weather patterns of T_a when compared with other existing models for a tropical environment.

Keywords Air temperature · Surface energy balance · Fourier series analysis · Mean bias error · Cooling inversion

List of symbols

t	Current time
T_a	Current air temperature
T_{amax}	Maximum daily air temperature °C
T_{amin}	Minimum daily air temperature °C
$T_{amax(j+1)}$	Maximum daily air temperature °C of next day
$T_{amin(j+1)}$	Minimum daily air temperature °C of next day
t_s	Sunset time
T_{sun}	Sunset temperature °C
L	Night length
τ	Time coefficient
LSH	Time of maximum solar height
DL	Day length
N	Hour after sunset
b	Slope of exponential curve

Introduction

Surface energy balance (SEB) describes the energy exchange between the earth's surface and the atmosphere. The equation of SEB finds application at local scales from point measurement to synoptic scale (models), and most importantly in climate models (CMs) (Pandey and Vanita 2016; Prasanta et al. 2016; Shiferaw et al. 2016). The way this energy exchange affect the climate is not well understood

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especially in West Africa where studies on land–atmospere interactions are still scarce (Mauder et al. 2006; Foken et al. 2006). One of such interaction whose poor parmeterizations in CMs has affected weather and climate change predictions is the nocturnal inversion process during stable atmospheric boundary layer condition at calm nighttime (Stull 1988; Foken et al. 2006). The energy balance of the soil–atmosphere interface is expressed as

$$Q_S - Q_H - Q_E - Q_G = 0, \tag{1}$$

where Q_S is the net radiation (Wm^{-2}), Q_H is the sensible heat flux density (Wm^{-2}), Q_E is the latent heat flux density (Wm^{-2}), Q_G is the ground heat flux density (Wm^{-2}). Here Q_S and Q_G are positive downward, Q_H and Q_E are positive upward. To solve Eq. (1) numerically at any time interval of interest in CMs, the values of some climate variables such as air temperature, wind speed and surface temperature are needed since they are the fundamental parameters for estimating the turbulent sensible and latent heat fluxes in the CMs. Several diurnal temperature cycle (DTC) meteorological models generate diurnal data of climatic variables from their mean daily values using the analogy between their cycles during the day and trigonometric functions (Jury and Horton 2003; Saito and Šimůnek 2009). Once the values of climate variables are obtained at any given time, they can be further used in parameterization formulae to calculate the turbulent heat fluxes (Saito et al. 2006). Nevertheless, standard data at time intervals of interest required for most sophisticated studies and simulations are not readily available and even when available they are very expensive, thereby constituting a restraint on research at micro-scale levels. Thus, diurnal changes in these variables need to be calculated from available daily average values using meteorological models (Ephrath et al. 1996; Balyani et al. 2017).

The shape of the diurnal temperature curve has been modeled with a variety of method with varying degrees of complexity. These methods include linear models (Parton and Logon 1981), simple curve fitting models based on sine or exponential analysis (Isikwue et al. 2011) and more complex energy budget models (Goudrian and Waggoner 1972; Lemon et al. 1972). Studies revealed that some of these models had been modified to account for the decay of air temperature at nighttime, while others are yet to be corrected (Ephrath et al. 1996; Parton and Logon 1981). The linear and simple curve models have an advantage in that they are easy to use and often require only daily minimum and maximum temperature. Reicosky et al. (1989) examined five such existing methods, three of which are used in an existing soybean growth model for calculating hourly air temperature from daily extremes. John and Schroll (1997) also developed an empirical model based on normalized T_Q using beta function distribution analysis and compared with other existing methods. In addition, Julia et al. (2001) examined different T_a models for different synoptic stations over the Mediterranean belt. They concluded that all methods worked well for daytime, but had limited success on nighttime stable atmospheric condition. In West Africa, Isikwue et al. (2011) only employed Fourier series analysis in modeling the hourly air temperature variation over Lagos and Abuja, but no intercomparison with other existing models was carried out and the diurnal behavior of the simulated T_a was not properly investigated. They concluded that the variation in hourly air temperature in the two stations was dominated by the first harmonics, thus it fluctuates by one cycle with a period of 24 h (Lidija 2007; Atsu and David 2000).

The above mentioned works developed and compared models for modeling air temperature values on hourly basis. However, there is dearth of information on studies that compare the performance of different air temperature models in order to obtain the best models for this region. The aim of this paper is to evaluate the performance of different air temperature models along with the modified Fourier series model under stable nighttime and unstable daytime atmospheric conditions, based on the NIMEX (Nigeria Micrometeorological Experiment) dataset in order to select the one(s) most suited to fit parameters of harmonics for the finite period at a specific location using hourly air temperature data.

Materials and methods

Experimental sites

Nigeria Micrometeorological Experiment (NIMEX) (Jegede et al. 2004) was conducted at Ile Ife (Latitude 7°33′N and longitude 4°33′E) in Nigeria during the transition period from dry to wet season (Fig. 1). The period of intensive observation was from February 19th through to March 9th [day of the year (DOY) 55 through DOY 68, using Julian days notation] in 2004. This site is located in the humid equatorial region of West Africa and the climatic region is Aw class according to Köppen classification (Essenwanger 2001). This site is at an attitude of 288 m above sea level and its vegetation can be characterized as fallow bush-land. The ground surface of the site is flat and homogenous. The soil is loamy sand and it is at its permanent wilting condition at the beginning of the experiment (Jegede et al. 2004; Mauder et al. 2006). The maximum and minimum air temperatures during the period of the experiment were 46.33 and 20.04 °C, respectively and the mean annual rainfall amount is 1225 mm (Otunla and Oladiran 2013).

Another phase of NIMEX-experiment was carried out at Ibadan at the experimental field of lower atmospheric physics unit (7°25′N, 3°53′E), University of Ibadan, Ibadan in Nigeria. The period of intensive observation was from

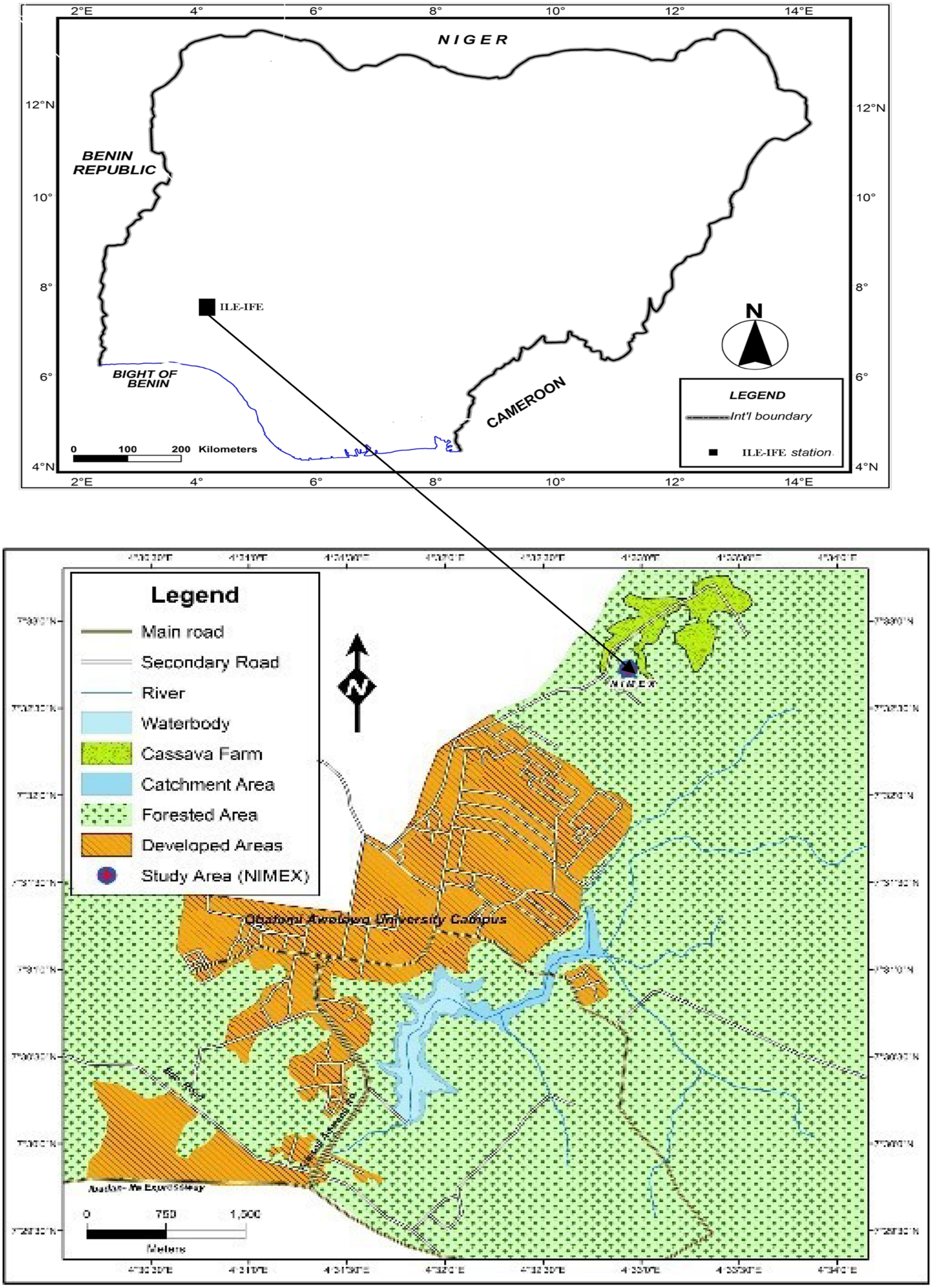


Fig. 1 *Sketch* showing the position of the measurement site (Ile-Ife) in Nigeria

February 22nd through to March 31th (DOY 54–DOY 90) in 2006 (Fig. 2). The site is located at about 78 km from Ile-Ife. The site comprises of an area of 850 m^2 of flat terrain at an elevation of 220 m above sea level. The soil type is loamy sand with bulk density of 1600 kgm^{-3} at 0.05 m depth (Adeniyi et al. 2012a). The ground surface of the target area was bare during the measurement period. The topography of the terrain surrounding the site can be classified as undulating low land with few high places which are easily sighted from the site (Otunla and Oladiran 2013). The maximum and the minimum air temperature during the period of the experiment were 38.07 and 24.02 °C, respectively and the annual rainfall amount is 1280 mm (calculated over 50 years) (Otunla and Oladiran 2013). Simple visual test according to Foken (2003) was used on daily basis to check the quality of the basic meteorology variables (slow response) (Mauder and Foken 2004). In this research work, we are only concerned with air temperature measured during the transition period from dry to wet season.

Modeling of the diurnal pattern of air temperature

Existing air temperature models

The models selected for this study meet the following criteria: Firstly, all input data required for the parameterization approach are available in our data set and other weather stations. Secondly, the parameterization approach are widely used (Julia et al. 2001), and they gave good results for daily to diurnal air temperature conversion. And lastly, few input parameters are required for the implementation of the models, which makes them simple. Basically, all existing models stated in Table 1 below, were developed for high latitude climatic regions (Julia et al. 2001), and not for humid tropical region. For this reason, a new diurnal air temperature model based on the concept of Fourier series is therefore, corrected to account for the strong cooling inversion associated with equatorial climatic region.

However, application of some existing models requires that some parameters are recalculated to accurately reflect the diurnal trends of climatic variables for this region. And some adjustments were made to rise and fall time during the daylight hours. The nighttime temperature coefficient (b) that reflects the steepness of the exponential decline in temperature after sunset for Parton and Logan model (1981) was estimated as 3.2 for the two locations in this region. The value is slightly higher than ones obtained by Parton and Logan (1981) and Wann et al. (1985). The argument of the sinusoidal model of Saito and Šimůnek (2009) shows that the highest temperature is assumed to occur at 1 pm and the lowest at 1am, but for this region, the time of highest temperature for Ife and Ibadan was 2.00 pm during NIMEX period (Akinnubi and Adeniyi 2010). Moreover, in a study on earlier period (1997–2001) than NIMEX at Ibadan, the time of maximum air temperature value extends beyond 2.00 pm (Adeniyi et al. 2012b; Adeniyi and Ogunsola 2012).

Modified fourier series model

In this research work, the fourier series model was employed to estimate the diurnal trends of air temperature using available maximum and minimum air temperature. Fourier series model is represented by the following equation (Panofsky and Brier 1960; Isikwue et al. 2011)

$$T_a = \overline{T_a} + \sum_{i=1}^{N} C_i \cos\left[\frac{2\pi}{24}(t - t_m) - \phi\right], \tag{2}$$

$$t_m = \frac{p}{360}\text{arc sin}\left(\frac{A}{C}\right), \tag{3}$$

C_i is the amplitude of the ith harmonic; $C_i = \sqrt{A_i^2 + B_i^2}$, t_m is the time at which its ith harmonic is at maximum is the phase angle and P is the period of observation. $\overline{T_a}$ is mean air temperature given by

$$\overline{T_a} = \frac{T_{a\min} + T_{a\max}}{2}, \tag{4}$$

T_{amin} = daily minimum air temperature, T_{amax} = daily maximum air temperature.

The fourier coefficients and phase angle are expressed as

$$A_i = \frac{2}{N}\sum_{i=1}^{N/2} \overline{T_a} \sin\left(\frac{2\pi}{p}it\right), \tag{5}$$

$$B_i = \frac{2}{N}\sum_{i=1}^{N/2} \overline{T_a} \cos\left(\frac{2\pi}{p}it\right), \tag{6}$$

$$\phi = \text{arc tan}\left[\frac{b_i}{a_i}\right]. \tag{7}$$

The preliminary investigation of the original fourier series analysis using the NIMEX data revealed that the strong cooling inversion associated with a tropical environment at nighttimes (stable atmospheric condition) could not be captured by the model. After sunset, a strong cooling inversion profile is expected to occur, in which temperature of the atmosphere increases with height (Fritz et al. 2008). The overnight radiative cooling of the surface air results in a nocturnal temperature inversion that leads to thermally stable condition near the earth surface. So, the original Fourier series model was modified by introducing an exponential height dependent function [$\exp(-z/H)$] and atmospheric cooling rate (γ)

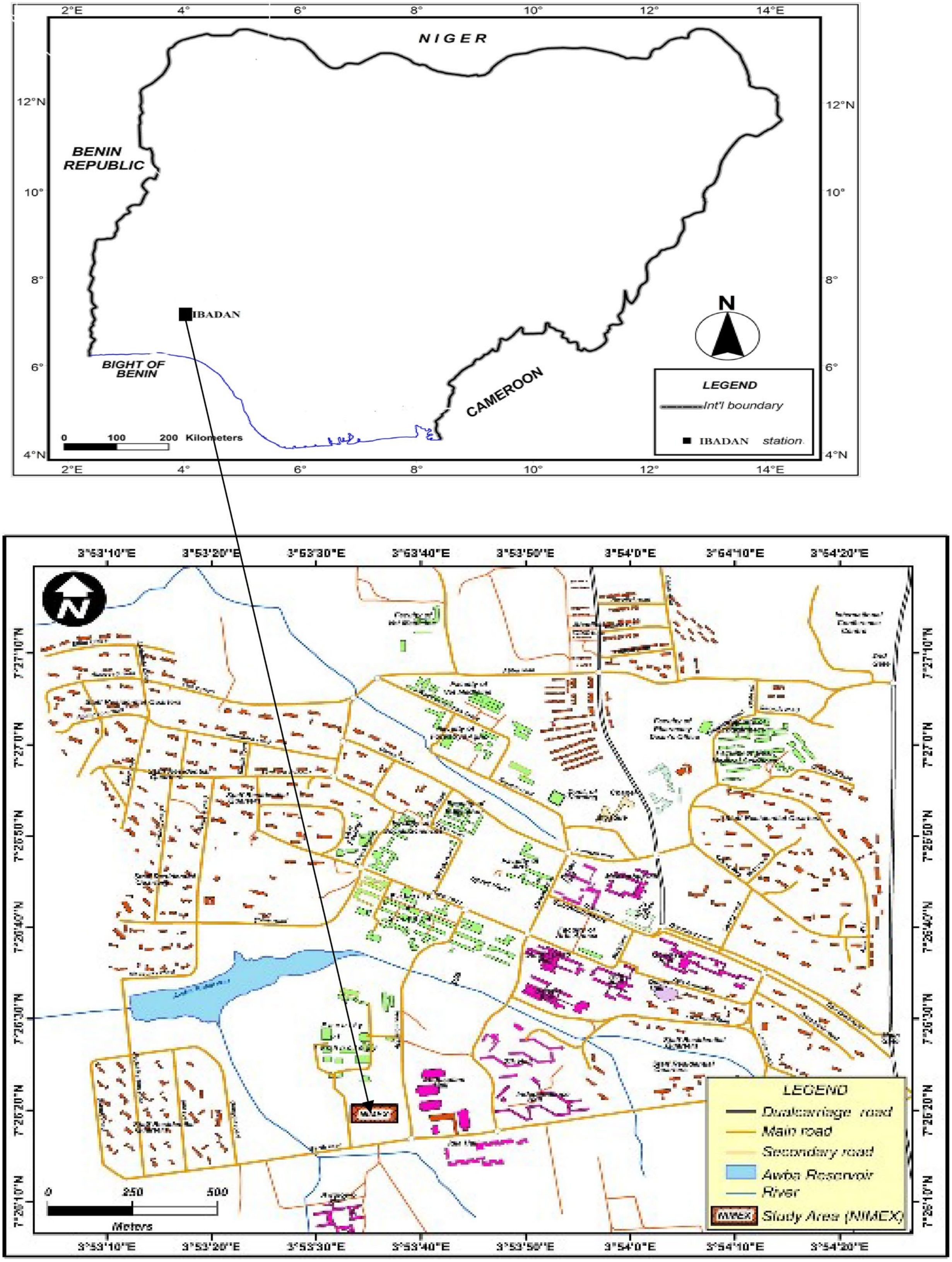


Fig. 2 *Sketch* showing the position of the measurement site (Ibadan site) in Nigeria

Table 1 Existing diurnal air temperature models

Models	Expressions	Reference(s)
Parton model	$T_a(\text{daytime}) = T_{min} + \left(T_{max} - T_{min}\right) \times \sin\left[\frac{\pi}{2}\left(\frac{t-t_1}{t_n-t_1}\right)\right]$	Parton and Logan (1981)
	$T_a(\text{nighttime}) = T_{min} + \left(T_{sun} - T_{min}\right) \times e^{-b\frac{N}{L}}$	
Ephrath model	$T_a(\text{daytime}) = T_{min} + \left(T_{max} - T_{min}\right) \sin\left(\pi \frac{\left(t-LSH+\frac{DL}{2}\right)}{\text{DL+2P}}\right)$	Ephrath et al. (1995)
	$T_a(\text{nighttime}) = \frac{T_{min(J+1)} - T_{sun} \times \exp\left(-\frac{l}{\tau}\right) + \left(T_s - T_{min(J+1)}\right) \times \exp\left(\frac{-t_a - t_s}{\tau}\right)}{1-\exp\left(-\frac{l}{\tau}\right)}$	
De wit model	$T_a(\text{daytime}) = \frac{\left(T_{max}+T_{min}\right)}{2} - \frac{\left(T_{max}-T_{min}\right)}{2} \cos\left[\pi\left(\frac{t-t_s}{t_{max}-t_1}\right)\right]$	De Wit et al. (1978)
	$T_a(\text{nighttime}) = \frac{\left(T_{max}+T_{min}\right)}{2} + \frac{\left(T_{max}-T_{min}\right)}{2} \cos\left[\pi\left(\frac{t-t_n}{t_1-t_n}\right)\right]$	
Hirotaka model	$T_a = \bar{T} + A_t \cos\left[2\pi\left(\frac{t-13}{24}\right)\right]$	Saito and Šimůnek (2009)

which account for the temperature inversion at nighttime in humid tropical region as shown in Eq. (8). The [exp$(-z/H)$] explains the variation of temperature with height during the stable condition. This term is also analogous to the variation of atmospheric pressure with height according to the Barotropic Law of hydrostatic equilibrium (Berberan-Santos et al. 1996). The barometric formula relates the pressure p (z) of ideal gas of molecular mass m at some height z to its pressure $p(0)$ at height $z=0$. Since pressure and temperature have a direct relationship (Berberan-Santos et al. 1996), the variation of atmospheric temperature with height is assumed to be equal to variation of atmospheric pressure with height during stable nighttime condition so that

$$T_a = \overline{T_a} + \sum_{i=1}^{N} C_i \cos\left[\frac{2\pi}{24}(t - t_m) - \phi\right] e^{\left(-\frac{z}{M}\right)^{\gamma}}. \tag{8}$$

The atmospheric scale height (H) represents the vertical distance above the soil surface at which the density or pressure of the atmosphere decreases by exactly 1/e or $(2.718)^{-1}$ (Stull 1988; Rummalls and Oke 2000). And it can be calculated as

$$H = \frac{KT_a}{Mg}, \tag{9}$$

where M is the mean molecular mass of dry air (4.80×10^{-29} kg), $g = 9.80\ \text{ms}^{-2}$, T_a is the mean air temperature in Kelvin (K) for stable period and K is the Boltzmann's constant ($1.38 \times 10^{-23}\ \text{JK}^{-1}$).

The atmospheric cooling rate (γ) is computed using (Varghese et al. 2003).

$$\gamma = \frac{\Delta\theta}{\Delta \text{t}} = \frac{\text{g}}{\text{C}_\text{v}} \frac{\Delta \text{Q}_\text{s}}{\Delta \text{p}}, \tag{10}$$

where g is gravitational acceleration, C_v is the specific heat of air at constant pressure, and Δp is change in atmospheric pressure during the night time, ΔQ_S = change in net radiation during nighttime. The net flux at any level is calculated as the algebraic sum of both the downward and upward components of shortwave and long wave radiation flux density (Foken et al. 2006). The divergence of the net flux at atmospheric level (z) represents the rate of energy loss per unit volume of the atmosphere, or the cooling rate.

Data analysis

To evaluate the efficiency of the models, their results are compared to the measured dataset using statistical means namely the mean bias error (MBE) (average deviation between parameterized and measured data) and the RMSE (average positive distance between parameterized and measured data) (Evans et al. 1993; de Miguel et al. 2001). The MBE and root mean square error (RMSE) were calculated as follows

$$MBE = \sum \frac{(T_a(\text{Estimated}) - T_a(\text{Observed})}{n}, \tag{11}$$

$$RMSE = \sqrt{\sum \frac{(T_a(\text{Estimated}) - T_a(\text{Observed})^2}{n}}, \tag{12}$$

where n is the number of observation.

Results and discussion

Diurnal variation of the atmospheric scale height

Figures 3 and 4 represent the diurnal variations of atmospheric scale height for Ile-Ife and Ibadan study sites, respectively. The diurnal value of H slightly varies for different

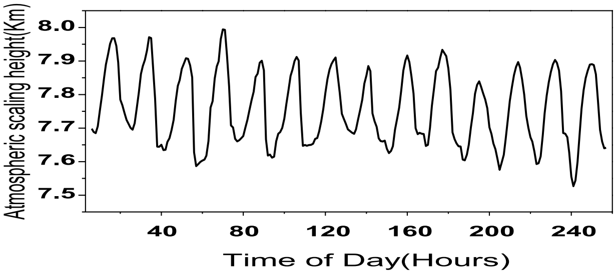


Fig. 3 Diurnal variation of atmospheric scale height for Ile-Ife site, DOY 55–DOY 70, 2004

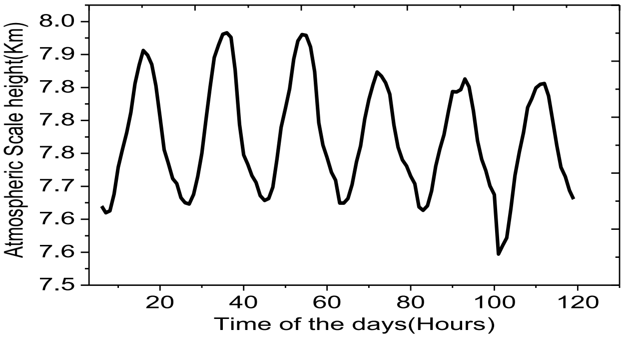


Fig. 4 Diurnal variation of atmospheric scale height for Ibadan site, DOY 54–DOY 60, 2004

atmospheric conditions. This diurnal variation is understandable from the classical definition of the scale height which is positively correlated to temperature. In Fig. 3, the diurnal variation of the scale height is also clear, suggesting its relation to the boundary-layer processes. It was found that the scale height moved upward in the morning to arrive at the maximum height around 1200 h LT. The magnitude of *H* was found to be higher during the unstable atmospheric condition, with corresponding mean value of 7.8 km at mean air temperature of 27 °C. During the stable condition (Ta > Ts), the value of *H* (6.6 km) was not as high as that of the daytime value. For both Ile Ife and Ibadan sites, the mean daily value of *H* ranged from 7.7 to 7.8 km. This implies that the estimated value of *H* for different DOYs was almost constant. The mean value for both sites was 7.8 km (Tables 2, 3).

Diurnal variation of the atmospheric cooling rate

Figures 5 and 6 represent atmospheric cooling rate for stable case for Ile Ife and Ibadan, respectively. The diurnal trend of atmospheric cooling rate was best represented by a polynomial of order 8, which is of the form (Figs. 5, 6).

Table 2 Atmospheric scaling depth (km) and Atmospheric cooling rate estimated for NIMEX site, Ile-Ife

DOY	Atmospheric scaling depth (Km)	Atmospheric cooling rate (Kday^{-1})
55	7.80	0.206
56	7.80	0.226
57	7.70	0.335
58	7.80	0.318
59	7.70	0.425
60	7.70	0.403
61	7.80	0.042
62	7.70	0.055
63	7.80	0.094
64	7.70	0.110
65	7.70	0.082
66	7.70	0.093
67	7.70	0.063
68	7.70	0.055
69	7.70	0.031
70	7.70	0.026

Table 3 Atmospheric scaling depth (km) and atmospheric cooling rate estimated for NIMEX site, Ibadan

DOY	Atmospheric scaling depth (Km)	Atmospheric cooling rate (Kday^{-1})
54	7.70	0.048
55	7.70	0.167
56	7.70	0.070
80	7.80	0.075
81	7.70	0.182
82	7.70	0.036
83	7.80	0.088
84	7.70	0.050
85	7.80	0.083
86	7.80	0.071
87	7.80	−0.002
88	7.70	0.108
89	7.70	0.096
90	7.70	0.076

$$Y = A + B_1X_i^1 + B_2X_i^2 + B_3X_i^3 + B_4X_i^4 + B_5X_i^5 + B_6X_i^6 + B_7X_i^7 + B_8X_i^8, \tag{13}$$

where $i = 1, 2, \ldots.. 24$, having 1 h interval through the whole day.

For Ile Ife site, the values of coefficients were—9.4228E7, 1.22208E7, −691223.67, 22336.18,−450.56, 5.80983, −0.00477, 2.1489E-4 and −4.3132E-7, respectively, the

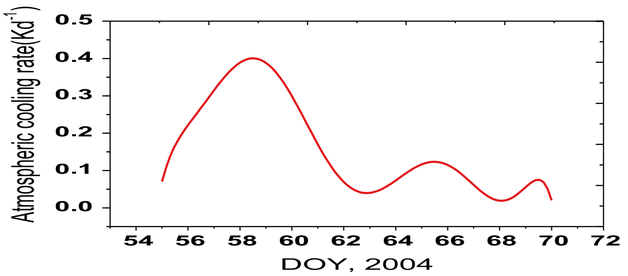


Fig. 5 Atmospheric cooling rate variations for night-time case at Ile-Ife from DOY 55 to DOY 70, 2004

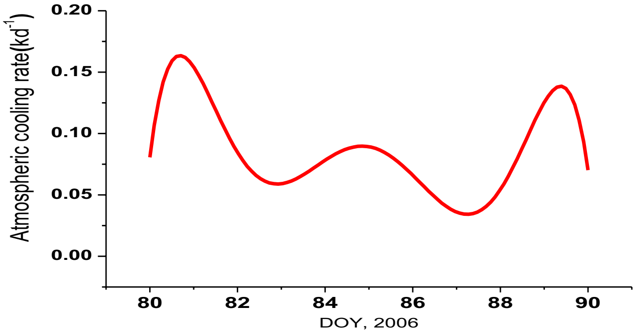


Fig. 6 Atmospheric cooling rate variations for nighttime case at Ibadan site from DOY 55 to DOY 56 and DOY 80–DOY 90, 2006

polynomial has R^2 value of 0.72 and residual sum of square of 0.0425.

For Ibadan site, the values of the coefficients were −564953.036, 63334.8032, −3090.84556, 85.7743, −148,067, and 0.01628, −1.1145E-4, 4.33751E-7 and −7.3555E-10, respectively, the R^2 value was 0.70 and residual sum of square was 0.0162.

In Fig. 5, the magnitude of the radiation cooling rate in wet period varied from 0.017 kday^{-1} (DOY 55) to maximum value of 0.450 kday^{-1} (DOY 58), after which it decreases to 0.001 kday^{-1} for DOY 68 (dry day). This was due to the low soil moisture content observed during the stable condition for dry days (Foken et al. 2006). In Fig. 6, the magnitude of γ drastically reduced for days without rainfall. The least value was obtained for DOY 87 (0.035 kday^{-1})while higher value of 0.163 kday^{-1} was obtained for DOY 81(wet day).The mean cooling rate for Ile-Ife site was 0.161 kday^{-1}, while that of Ibadan was 0.138 kday^{-1} (Tables 2, 3). The mean γ for wet days was 0.250 kday^{-1}, while days without rainfall had a value of 0.0128 kday^{-1} for Ile-Ife site. For Ibadan site, days with rain had a mean value of 0.078 kday^{-1} while days without rain had a value of 0.025 kday^{-1} The mean daily values of γ for Ile-Ife site for DOY 55, DOY 56 and DOY 57 were 0.206, 0.226 and 0.335 kday^{-1}, respectively, while DOY 61, DOY 62 and DOY 63 were 0.042, 0.055 and 0.094 kday^{-1}, respectively. For Ibadan site, DOY 54, DOY 55 and DOY 56 had daily mean values of 0.048, 0.167 and 0.070 kday^{-1}, respectively, while DOY 56, DOY 84 and DOY 88 had daily mean values of 0.071, −0.002 and 0.108 kday^{-1}, respectively. These results reveal that the strongest radiation cooling occurs during wet stable atmospheric condition than dry stable period. The value of cooling rate for nighttime condition obtained for Ibadan was slightly higher than the value obtained for Ile-Ife site. This implies that the atmospheric cooling rate is affected by elevation above sea level, solar elevation and geographical location. High elevation sites are associated with low diurnal solar elevation (giving rise to a shadow effect), which caused low radiative cooling at nocturnal boundary layer condition (Rummalls and Oke 2000). Ibadan site elevation (220 m) is lower than that of Ile-Ife (288 m), while its solar elevation is higher when compare to Ile-Ife site (Jegede et al. 2004; Mauder et al. 2006; Rummalls and Oke 2000). This assertion supports the reason why the nocturnal cooling rate of Ibadan was higher than that of Ile-Ife site.

Comparison of the fourier series and modified fourier series models for stable atmospheric condition

The simulated stable air temperature from the original Fourier series model and modified Fourier series model were compared with the observations for wet and dry days for Ile-Ife and Ibadan study sites in Figs. 7(a, b) and 8(a, b), respectively. The stable conditions of the nocturnal boundary layer for these sites start from 1800 Hr LT to 2359 Hr LT. The T_a was strongly overestimated by the original Fourier series during the stable atmospheric condition for DOYs 55, 56 and 57 in 2004 for Ile-Ife study site. The overestimated values ranged from 10 to 15 °C (Fig. 7a). The large deviation was also observed for DOY 62. This was due to the heavy rainfall that drastically reduced the night-time T_a value. The inclusion of cooling rate constant estimated using Eq. 10 affected the diurnal variation of the air temperature during the stable nighttime condition for the two locations. The modified Fourier series model showed a better agreement for stable nighttime conditions for both wet and dry days (Fig. 7b). For Ibadan site in 2006, the results of the modified Fourier model is approximately the same as the measured data, but a slight overestimation of T_a of about 2–3 °C was observed for DOY 83 and DOY 84, respectively. The cooling term had slight effect on the diurnal variation of T_a for DOY 85 (Fig. 8b) due to the slight increase in wind speed. It was also observed from the figures that the performance of the modified model was better during wet days at Ile-Ife than Ibadan site. This can be attributed to the slight diurnal variations of the inversion height observed across the tropics (Liu 1990).

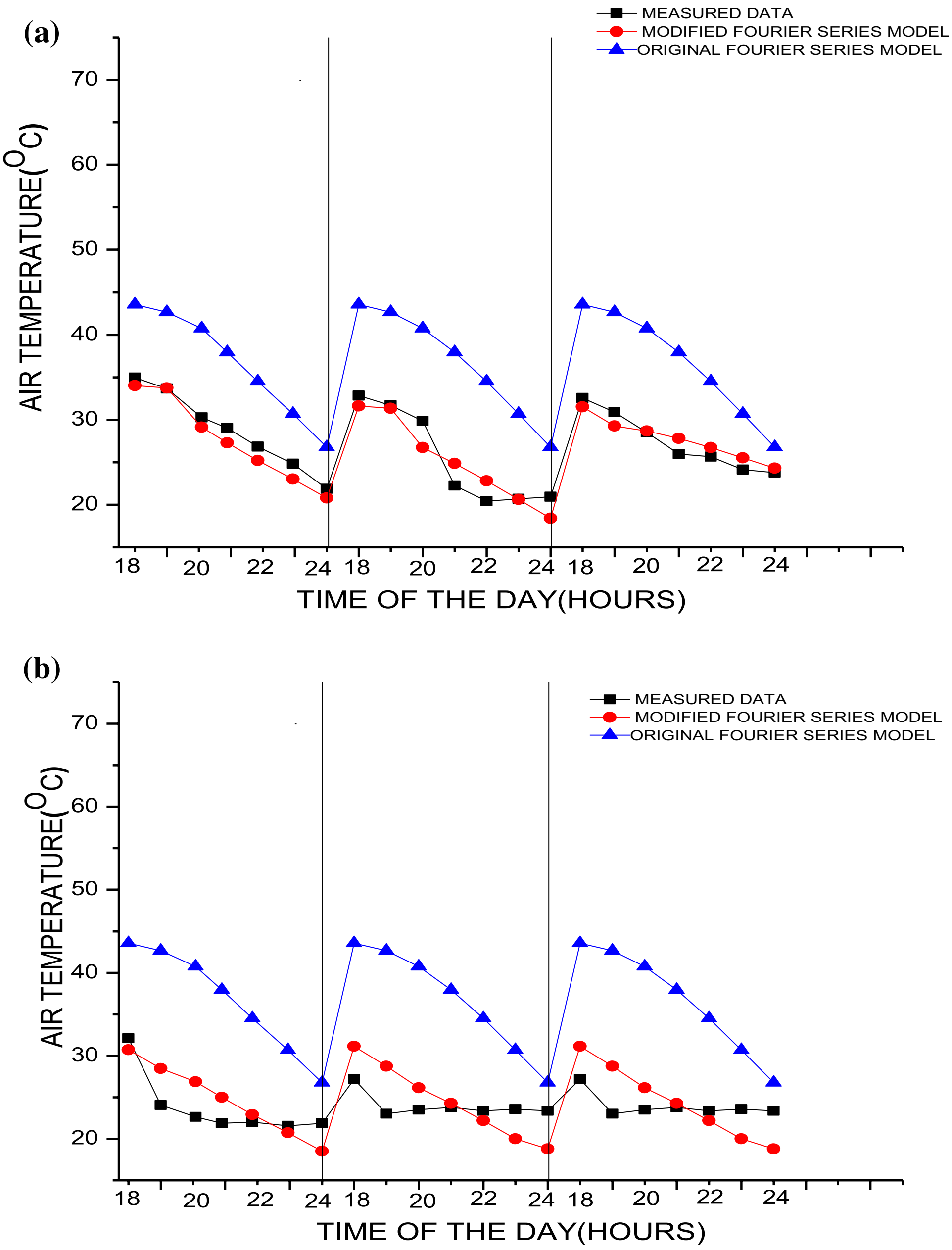
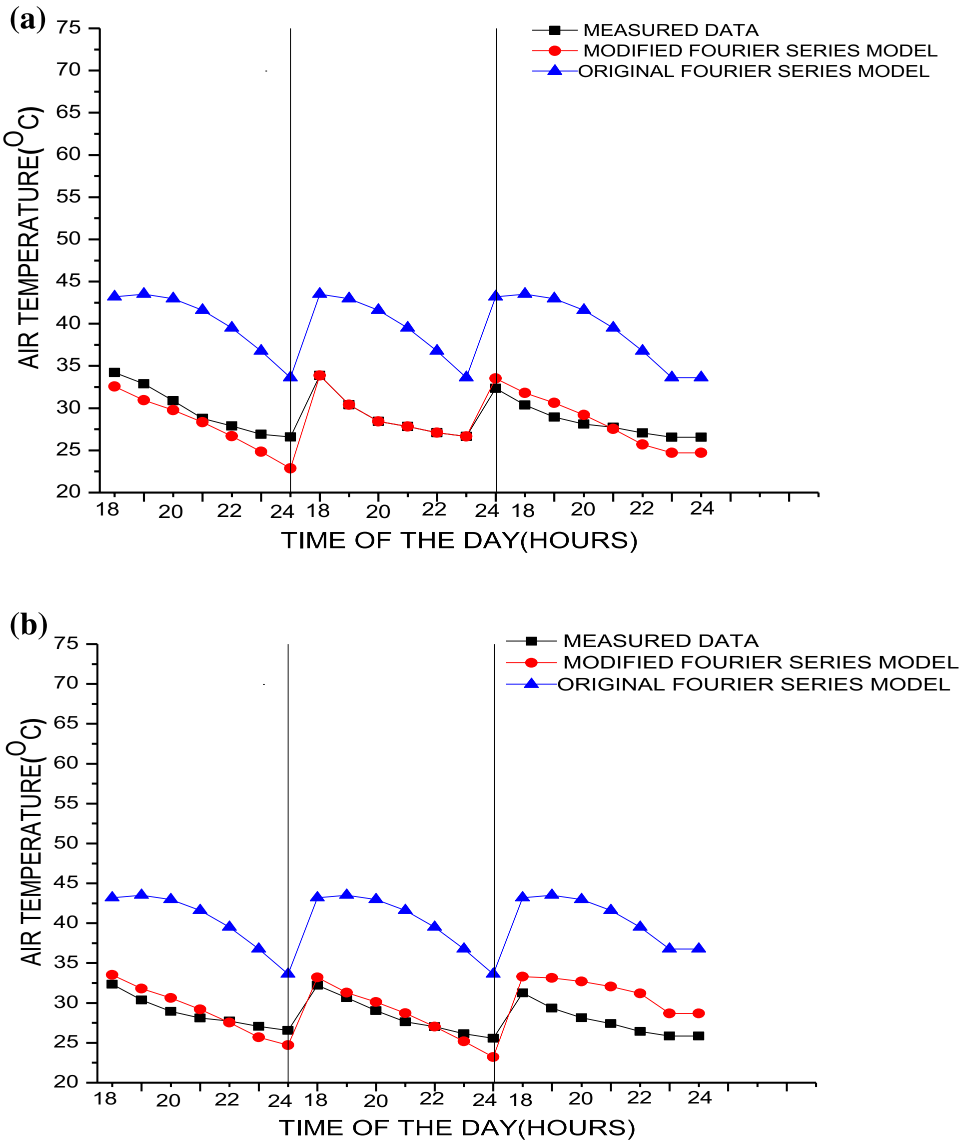


Fig. 7 **a** Comparisons of measured air temperature with modeled air temperature for stable nighttime atmospheric condition using fourier series and modified fourier series models at Ife site for DOYs 55–57(wet days), 2004. **b** Comparisons of measured air temperature with modeled air temperature for stable nighttime atmospheric condition using fourier series and modified fourier series models at Ife site for DOYs 60–62 (dry days), 2004

Figures 9 and 10 show the scatter plots of the measured and estimated T_a from original fourier series and modified fourier series models during stable nighttime condition. The scatter in the graphs was reduced drastically, especially for small values of T_a simulated by the modified fourier series model. This was due to the inclusion of the cooling rate constant to the original model for nighttime conditions. The original fourier series model had a good performance for daytime conditions, with high r^2 values and low MBE and RMSE values, whereas the performance of the model was poor during the stable nighttime conditions, with low r^2 values and high MBE and RMSE values (Table 4). The ranges of r^2, MBE and RMSE for daytime conditions (original fourier series model)at Ile-Ife site were 0.69–0.81, 1.67–3.76 and 2.41–5.23 °C, respectively, while that of nighttime conditions were 0.34–0.52, 2.14–4.76 and 4.14–7.45 °C, respectively (Tables 4, 5). Also, the ranges of r^2, MBE and RMSE for daytime conditions (original fourier series model) at Ibadan site were 0.67–0.80, 1.59–3.68 and 2.33–5.17 °C, respectively, while that of nighttime conditions were 0.37–0.48, 2.06–4.68 and 4.06–7.37 °C, respectively (Tables 4, 5). The modified Fourier series model for nighttime conditions had low MBE and RMSE values, ranging from −0.07 to 0.78 and 0.65–2.73 °C respectively, with high r^2 values, ranging from 0.92 to 0.99 (Tables 4, 5) at both sites. The mean r^2 value of the modified Fourier model

Fig. 8 **a** Comparisons of measured air temperature with modeled air temperature for stable nighttime atmospheric condition using Fourier series and modified Fourier series models at Ibadan site for DOYs 55–57 (wet days), 2006, **b** comparisons of measured air temperature with modeled air temperature for stable nighttime atmospheric condition using fourier series and modified fourier series models at Ibadan site for DOYs 83–85 (dry days), 2006



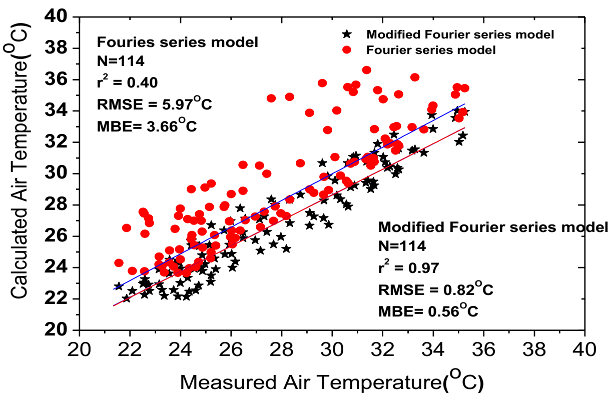


Fig. 9 *Scatter plot* showing the stable measured Air Temperature and estimated Air temperature for Ile-Ife, 2004

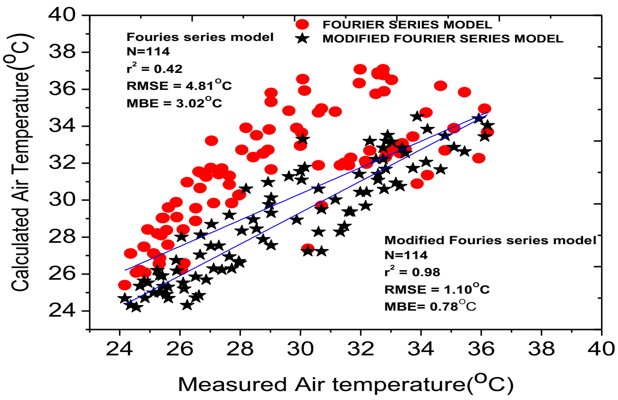


Fig. 10 *Scatter plot* showing the stable measured air temperature and estimated air temperature for Ibadan Site, 2006

were 0.97 (Ile-Ife) and 0.96 (Ibadan Site), respectively for stable condition. In addition, the overall night-time MBE and RMSE for the modified fourier series model reduced from 3.50 to 0.50 and 5.93–1.80 °C, respectively during the transition period from dry to wet stable (nighttime) atmospheric conditions for both sites (Figs. 9, 10). This impies that the modified fourier series model favoured stable condition.

Comparison of the modified fourier series and other existing air temperature models

Figures 11(a, b) and 12(a, b) depict the comparison of the measured air temperature with the modeled air temperature using different models for wet and dry days for Ile-Ife and Ibadan sites, respectively. The T_a modeled using modified fourier series model showed better agreement with the

Table 4 Daytime and nighttime estimated root mean square error (RMSE) and mean bias error (MBE) of modeled air temperature using original and modified fourier series model for Ile-Ife

DOY(s)	Fourier series model						Modified fourier series model		
	Daytime			Nighttime			Nighttime		
	MBE	RMSE	r^2	MBE	RMSE	r^2	MBE	RMSE	r^2
55	1.98	3.51	0.73	3.25	7.16	0.45	0.78	1.73	0.97
56	2.32	3.61	0.70	3.13	4.71	0.50	0.34	2.11	0.92
57	2.47	3.83	0.70	4.17	6.91	0.46	0.01	1.76	0.97
60	2.32	3.85	0.70	3.78	5.32	0.51	1.01	1.96	0.95
61	2.61	4.10	0.72	4.27	6.19	0.41	1.17	2.12	0.96
62	1.67	2.41	0.80	3.76	6.10	0.47	0.08	1.96	0.99
63	2.47	3.14	0.80	3.31	5.95	0.43	0.61	1.83	0.96
64	3.76	4.00	0.71	3.14	5.02	0.34	1.78	2.73	0.93
65	2.11	3.09	0.81	2.14	4.14	0.52	0.78	1.73	0.97
66	2.01	3.45	0.72	4.76	7.45	0.47	0.03	1.81	0.98
67	2.24	3.68	0.77	3.81	6.28	0.48	0.28	1.63	0.97
68	2.01	4.01	0.72	3.11	6.11	0.47	0.02	0.73	0.99
70	2.04	5.23	0.69	3.34	6.23	0.44	0.08	1.83	0.97
Mean	2.31	3.69	0.74	3.54	5.97	0.46	0.54	1.84	0.97

Table 5 Daytime and nighttime estimated root mean square error (RMSE) and mean bias error (MBE) of modeled air temperature using original and modified fourier series model for Ibadan

DOY(s)	Fourier series model						Modified fourier series model		
	Daytime			Nighttime			Nighttime		
	MBE	RMSE	r^2	MBE	RMSE	r^2	MBE	RMSE	r^2
54	1.90	3.43	0.71	3.17	7.08	0.41	0.70	1.65	0.96
55	2.24	3.53	0.68	3.05	4.63	0.46	0.26	2.03	0.97
56	2.39	3.75	0.68	4.09	6.83	0.42	−0.07	1.68	0.96
57	2.24	3.77	0.68	3.70	5.24	0.47	0.93	1.88	0.94
80	2.53	4.02	0.70	4.19	6.11	0.37	1.09	2.04	0.95
81	1.59	2.33	0.78	3.68	6.02	0.43	0.07	1.88	0.98
82	2.39	3.06	0.78	3.23	5.87	0.39	0.53	1.75	0.95
83	3.68	3.92	0.69	3.06	4.94	0.39	1.70	2.65	0.92
84	2.03	3.01	0.79	2.06	4.06	0.48	0.70	1.65	0.96
85	1.93	3.37	0.70	4.68	7.37	0.43	−0.05	1.73	0.97
86	2.16	3.61	0.75	3.73	6.24	0.44	0.23	1.55	0.96
87	1.93	3.93	0.70	3.03	6.03	0.43	−0.06	0.65	0.98
88	1.96	5.15	0.67	3.26	6.15	0.40	0.02	1.75	0.96
89	1.94	3.95	0.80	3.08	6.09	0.43	−0.09	0.69	0.98
90	1.98	5.17	0.69	3.28	6.11	0.43	0.05	1.79	0.96
Mean	2.22	3.60	0.71	3.45	5.88	0.41	0.45	1.76	0.96

measured data for both wet and dry days (Fig. 11a). The modified fourier series model was relatively close to the measured value during the stable period than the unstable period although, the model showed an overestimation (4–6 °C) of T_a during the early hour of the night for DOY 55 for Ibadan site (Fig. 12a). It was also observed from Table 6 that the first harmonic dominates the periodic component in the hourly average air temperature of all the sites since it has the highest contribution of 93 and 92% for Ile-Ife and Ibadan sites, respectively. This implies that the contribution of the second and third harmonics for each site is negligible, thus the information about them is discarded. The bulk of the total variance is contained in the first harmonic term. This result is in agreement with the work of Kothandaraman (2007) in which the application of harmonic analysis to daily mean air, water temperature records indicated that the first harmonic accounted for a major portion of the total variance in the record.

The sinusoidal Hirotaka model proposed by Saito and Šimůnek (2009) overestimated T_a by 5–6 °C during the late hour of the night (DOY 56) for Ile-Ife. The modeled T_a by Hirotaka model was close to the observed data in the morning (800Hr LT) on DOY 55 (Ile-Ife). The performance of the Hirotaka model was very poor for DOY 56 (Fig. 11a). This is due to the drastic drop in the observed maximum and minimum air temperature. The peak of the modeled T_a was out of phase with the observed at midday on DOY 60, though the modeled T_a was strongly underestimated in the morning. The overall result revealed that Hirotaka model underestimated T_a by 6–8 °C during the unstable atmosphere condition at Ile-Ife. For Ibadan site, the Hirotaka model overestimated T_a by about 5–6 °C in the morning on DOY 55, and during the mid-day, the peak of the maximum T_a was underestimated by about 3–4 °C. However, the model performed relatively better during the nighttime for DOY 83, although a slight overestimation of Hirotaka modeled T_a by about 3–4 °C still

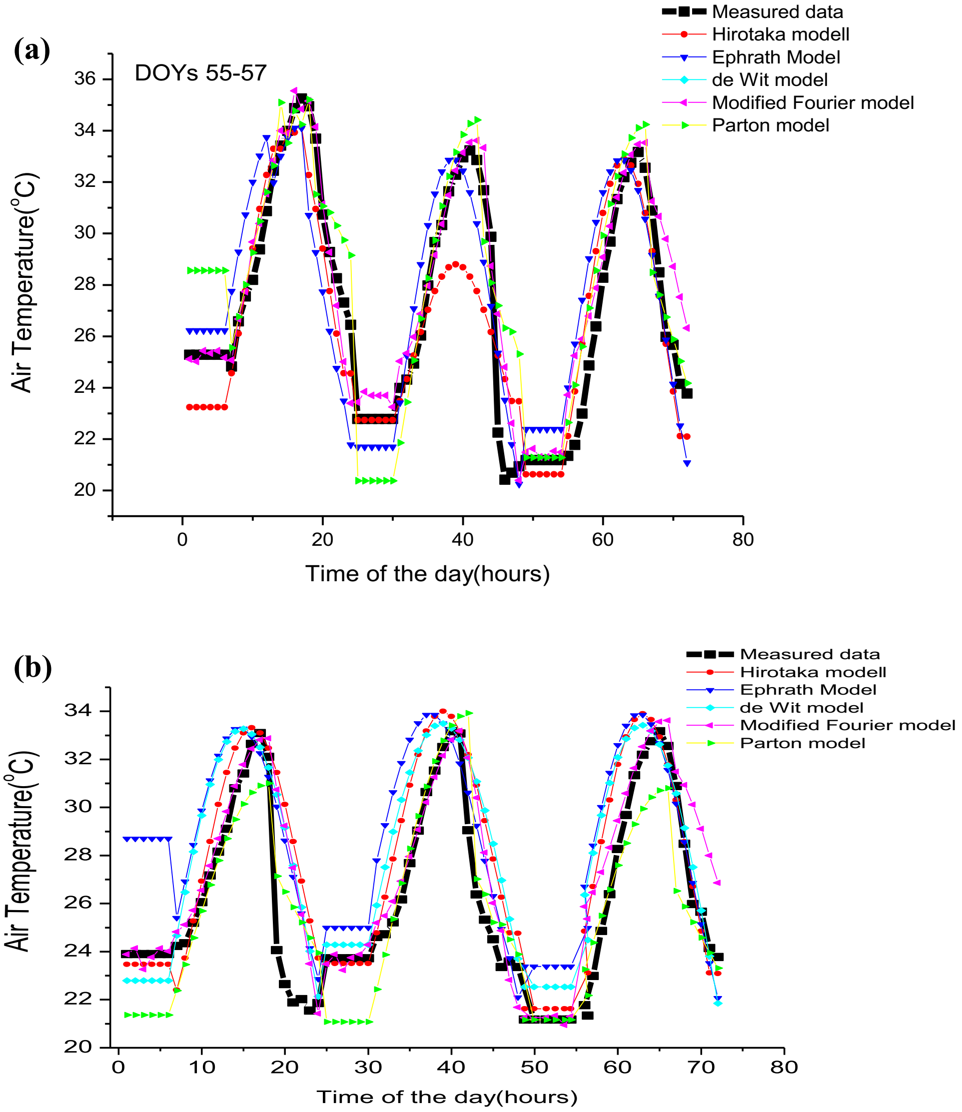


Fig. 11 **a** Wet days comparisons of measured air temperature with modeled air temperature using different models at Ile-Ife site for DOYs 55–57, 2004. **b** Dry day comparisons of measured air temperature with modeled air temperature using different models at Ile-Ife site for DOYs 60–63, 2004

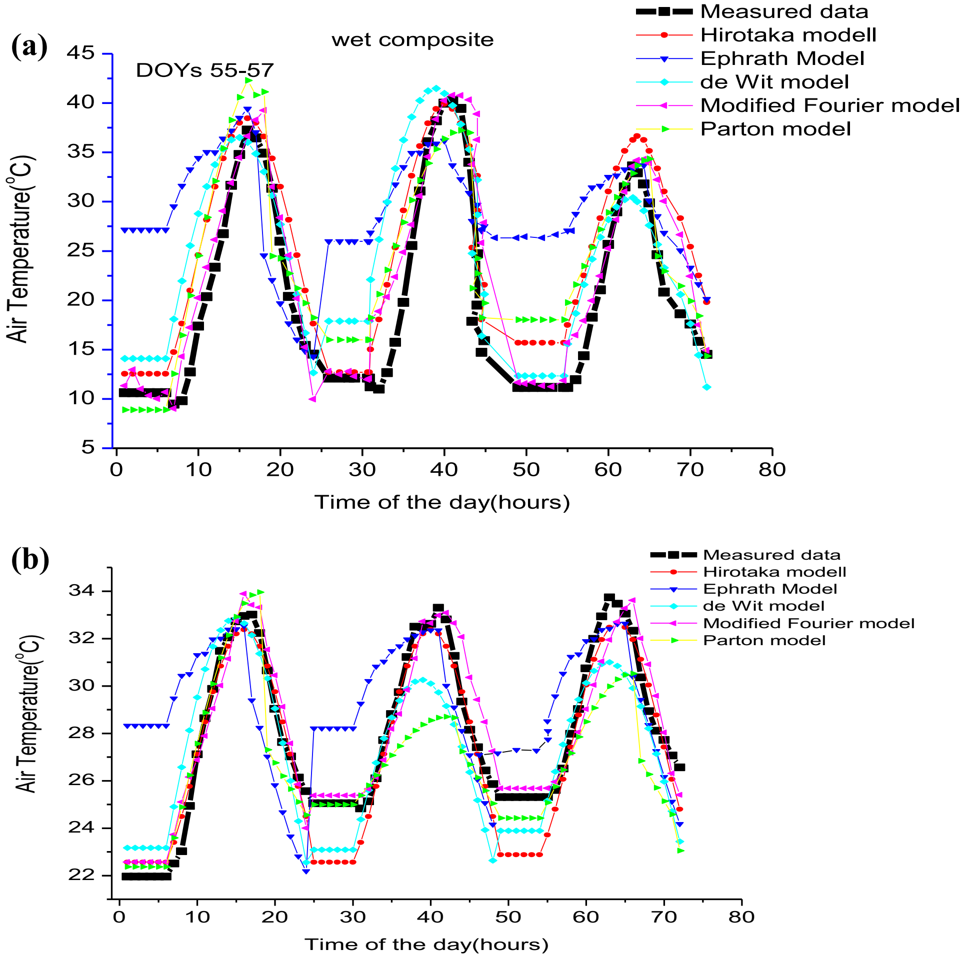


Fig. 12 **a** Wet days comparison of measured air temperature with modeled air temperature using different models at Ibadan site on DOYs 55–57, 2006. **b** Dry days comparison of measured air temperature with modeled air temperature using different models at Ibadan site on DOYs 83–85, 2006

Table 6 Parameters of the first three harmonic functions for Ile-Ife and Ibadan study sites using the fourier series model

Location(s)	Term(s)	Amplitude	Phase	a	b	%variance
Ile-Ife	1	2.89	0.95	1.86	2.28	93
	2	2.82	0.06	1.11	−1.56	20
	3	8.20	017	−0.17	0.12	10
Ibadan	1	2.83	0.09	1.05	2.20	91
	2	2.80	−0.21	−0.65	−0.77	23
	3	2.80	−0.49	0.14	−1.32	5

occurred during the evening hours. For DOY 82, the modeled T_a was very close to the measured data for both the unstable and stable atmospheric conditions. Similar behaviour was observed for DOY 84, though with slight underestimation during the morning hours (600–1000Hr LT). The performance of the model was better during the dry days than wet days for unstable atmospheric condition.

At Ile-Ife site, the de Wit model strongly overestimated measured T_a for both stable and unstable conditions by about 5–7 and 4–5 °C, respectively during the dry period (Fig. 11b). The modeled T_a was slightly overestimated by 2 °C during the midday for DOY 60 and other days followed the same pattern. At Ibadan site, the performance of the model was very poor for both unstable and stable atmospheric condition for DOY 85. For DOY 84 (dry day), the modeled T_a was strongly overestimated by about 6–7 °C during the unstable period, while it was overestimated by about 4–5 °C for stable period (Fig. 12b). But during the wet days (DOY 56 and DOY 57), the nighttime values of the modeled T_a almost approximated the measured value, while the daytime modeled T_a was still overestimated by about 3–4 °C in the morning. It is obvious from Figs. 11 and 12, that the performance of this model was better during wet period than dry period.

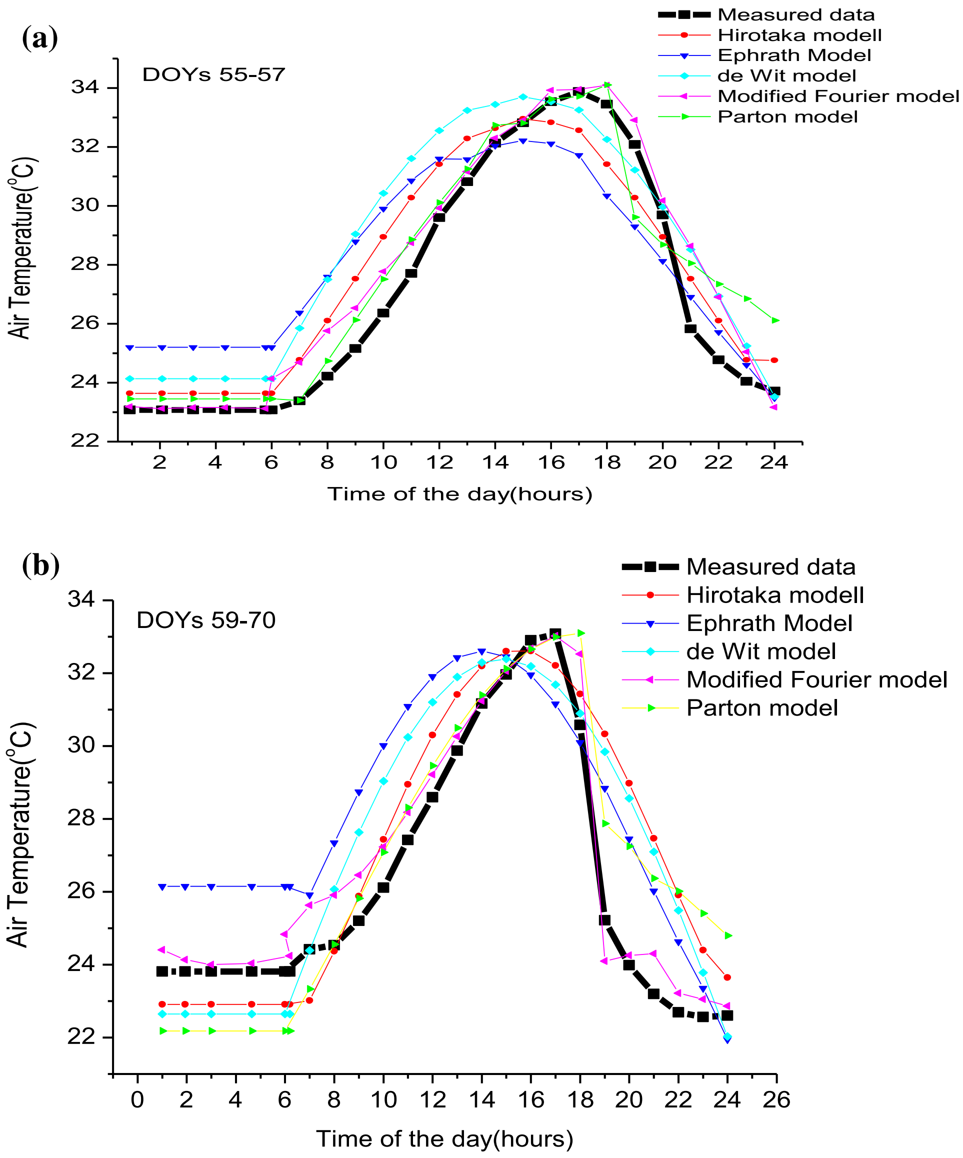


Fig. 13 **a** Wet composite comparisons of measured air temperature with modeled air temperature using different models at Ile-Ife site for DOYs 55–57, 2004. **b** Dry composite comparisons of measured air temperature with modeled air temperature using different models at Ile-Ife site for DOYs 59–70, 2004

The Ephrath model strongly overestimated T_a by about 4–6 °C during the daytime, especially in the morning (Fig. 11a). The peak of the estimated T_a was generally out of phase with the observed value for all the selected days. For DOY 56 at Ile-Ife site, the model performed better for night-time situation, while for DOY 62, the model showed a strong underestimation during the early hours of the day by about 10–15 °C. At Ibadan site, the modeled T_a was relatively close to the measured value for DOY 55, DOY 83 and DOY 85 during the nighttime, though a slight underestimation by about 2–3 °C was observed for dry days (Fig. 11a, b). The performance of the model during daytime situation was generally poor, especially for early hours in dry days for Ephrath model. This model simulated T_a well on dry days for nighttime only.

The modeled T_a by the Parton model was relatively close to the observed data for nighttime situation, except for the strong overestimation observed in the morning hours on DOYs 55 and 57 for Ile-Ife site. The peak of the maximum T_a was almost in phase with measure data (Fig. 11a). At Ibadan site, Parton model slightly underestimated T_a by 2–3 °C during the late hours of the day for DOY 56 (Fig. 12b). The Parton model seems to model T_a better at midday for wet periods (Fig. 12b). For DOY 84, the model showed an unusual behaviour with the measured T_a during the midday, with strong underestimated of about 10–12 °C. This implies that the Parton modeled T_a was affected by atmospheric conditions. Generally, the model performance was good for unstable condition during dry days than wet days at Ibadan site.

Figure 13 represents the composite of diurnal variations of T_a simulated by different models for wet and dry days,

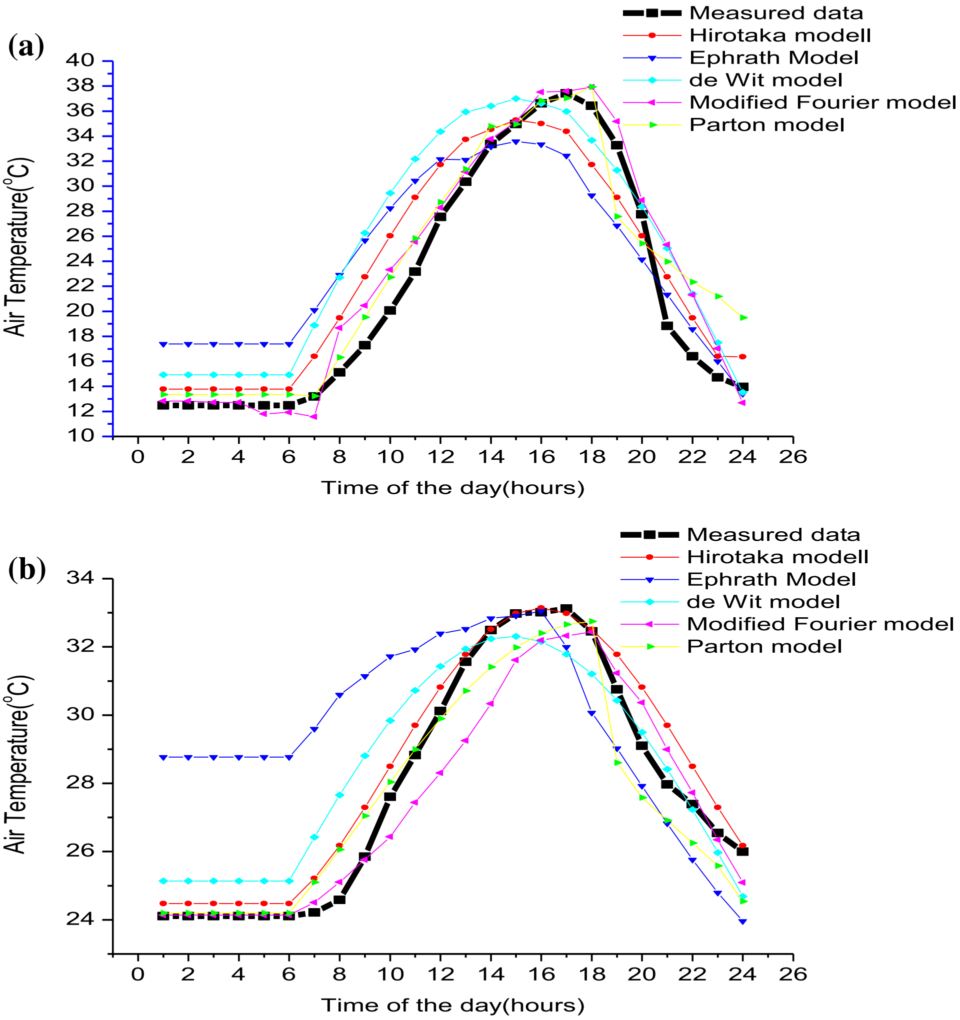


Fig. 14 **a** Wet days composite comparison of measured air temperature with modeled air temperature using different models at Ibadan site for DOYs 55–57, 2006. **b** Dry days composite comparison of measured air temperature with modeled air temperature using different models at Ile-Ife site for DOYs 80–92, 2006

respectively for Ile-Ife site while, Fig. 14 represents similar variations at Ibadan. The working principles of Parton, Ephrath, Hirotaka and de Wit models are similar to the Fourier series model; which according to the modification is now a physically-based model. The performance of these models are better for daytime T_a parameterization on dry days than wet days. Although, some large deviations were still simulated by de Wit and Parton models during the morning and early night-time on wet and dry days, respectively. The Hirotaka model performs better at midday but accumulated large overestimates in the late afternoon and early night-time. In general, the performance of some existing models revealed large deviations from the measured data in the morning and late hours of the night-time. Therefore, it can be concluded that these existing models could not accurately capture the strong cooling inversion associated with a humid tropical region. The performances of the models are good on some specific days however, on the average the existing models simulated T_a with high bias during stable condition. The biggest cause of error in these models is the occurrence of temperature extreme at time far removed from the time assumed by the models. In other word, the assumed fixed T_{min} and T_{max} for this region violated some assumptions of some existing models. Another potential error encountered by some models is the inability to capture properly the strong tropical cooling inversion at night. The modified Fourier series model which accounted for cooling inversion in the tropics showed a better result for dry and wet composite diurnal variations for the two sites.

The comparisons of scatter plots of hourly estimated T_a versus measured T_a are shown in Figs. 15 and 16 for Ile-Ife and Ibadan sites, respectively. The diagonal line on the figures represents the ideal match between the estimated and measured values of T_a. The modified fourier series model estimated better values of T_a than the other models because the model parameters of the fourier series are more dependent on the location. The modified fourier series model had small scatter (Fig. 15) and the mean values of r^2 were 0.97 and 0.98 for Ile-Ife and Ibadan sites, respectively. The linear fit gave slopes close to 1.00 of 0.82 (Ibadan) and 0.79

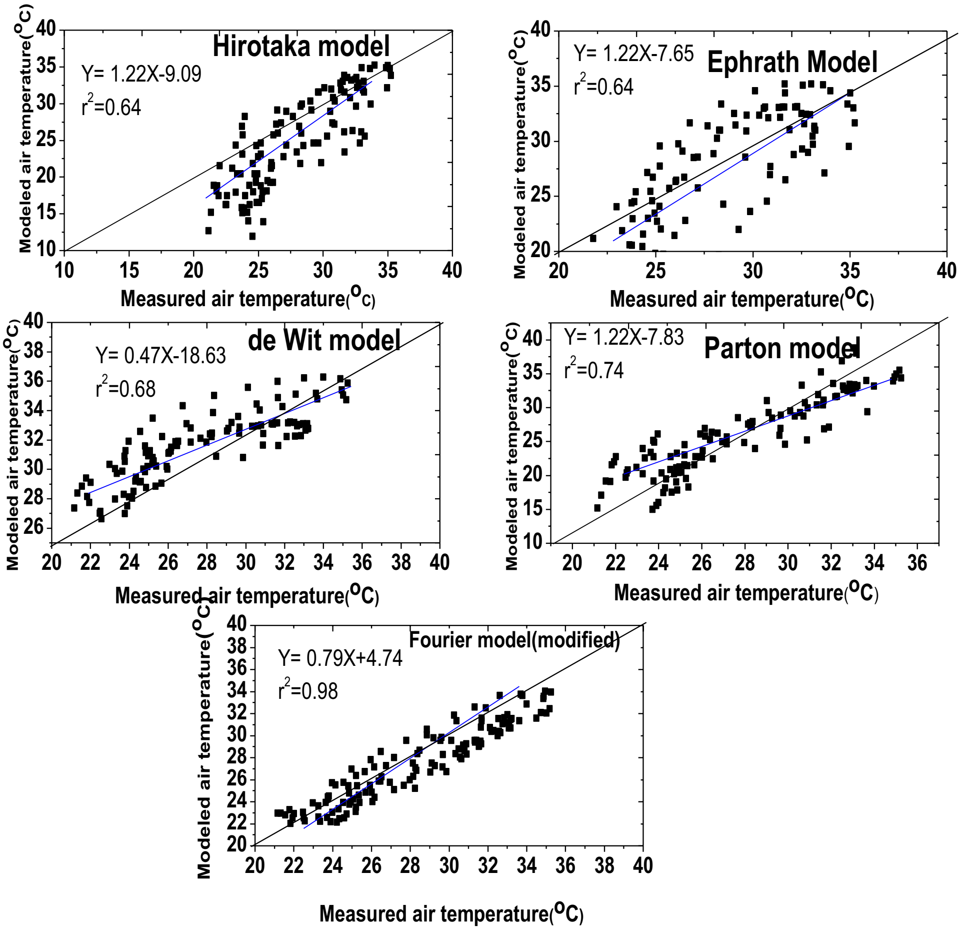


Fig. 15 *Scatter plots* showing the comparisons of measured air temperature with modeled air temperature using different models at Ile- Ife site, 2004

(Ile-Ife), respectively, while the values of the intercept (4.94) were almost the same for the two sites. The Ephrath model had a large scatter with high RMSEs of 4.76 °C (Ile-Ife) and 3.76 °C (Ibadan) for wet days, respectively, and almost the same large errors were also obtained for dry days for two sites. The r^2 value obtained for Ibadan site was 0.33 while that of Ile-Ife was 0.53. So, it can be seen that the performance of the Ephrath model at Ibadan site was very poor (Table 3). The linear fit gave slopes ranging from 0.78 to 1.22 and intercept ranging from −7.66 to −5.93, respectively. The scatter plots reveal partly strong underestimation for small values of T_a. Furthermore, for Hirotaka model, the graphs revealed small scatter, with r^2 value of 0.88 obtained at Ile-Ife study site. For Ibadan, the scatter was moderate with r^2 value of 0.68 for dry periods. The average slopes for the two sites were 1.56 and 1.22, respectively. de Wit model had r^2 value of 0.82 with the slope less than one for dry days at Ibadan site (Fig. 15). The linear regression of the de Wit model showed tendency towards underestimation during the night-time for both sites. The Parton model had a small scatter as well as high r^2 value of 0.82 (Fig. 16) with intercepts ranging from −7.83 to −17.00 °C for dry days at Ibadan site, its performance during wet days was also better.

Table 7 shows the overall statistical estimates of T_a (mean bias error and relative RMSE) obtained for Ibadan and Ile-Ife study sites, respectively. Comparing the RMSE and MBE of T_a, small errors were observed for modified fourier series model (which varied from −0.01 to −1.79 °C for MBE; 1.23 to 1.76 °C for RMSE for wet and dry days for both sites). Ephrath and de Wit models gave high RMSE values of 3.76–4.76 °C for wet days; 4.27–4.87 °C for dry days and 2.98–5.92 °C for wet days; 2.98–4.95 °C for dry days, respectively for both sites. The modified Fourier series model gave high coefficient of determination (r^2) ranging from 0.95 to 0.98 at Ile-Ife site. The Parton model also showed a good performance for both sites, with average RMSE values of 2.54 and 2.08 in Ile-Ife and Ibadan sites, respectively, and corresponding r^2 value ranging from 0.75 to 0.82. The modified fourier series model gave the best result with respect to the existing models considered. This is because it gave the least error values at both sites and parameterized the air temperature value better. The more substantial decrease in error term of original fourier series model resulted from the incorporation of the atmosphere scaling height and cooling rate estimated for the locations, which affect the diurnal variation of the air temperature.

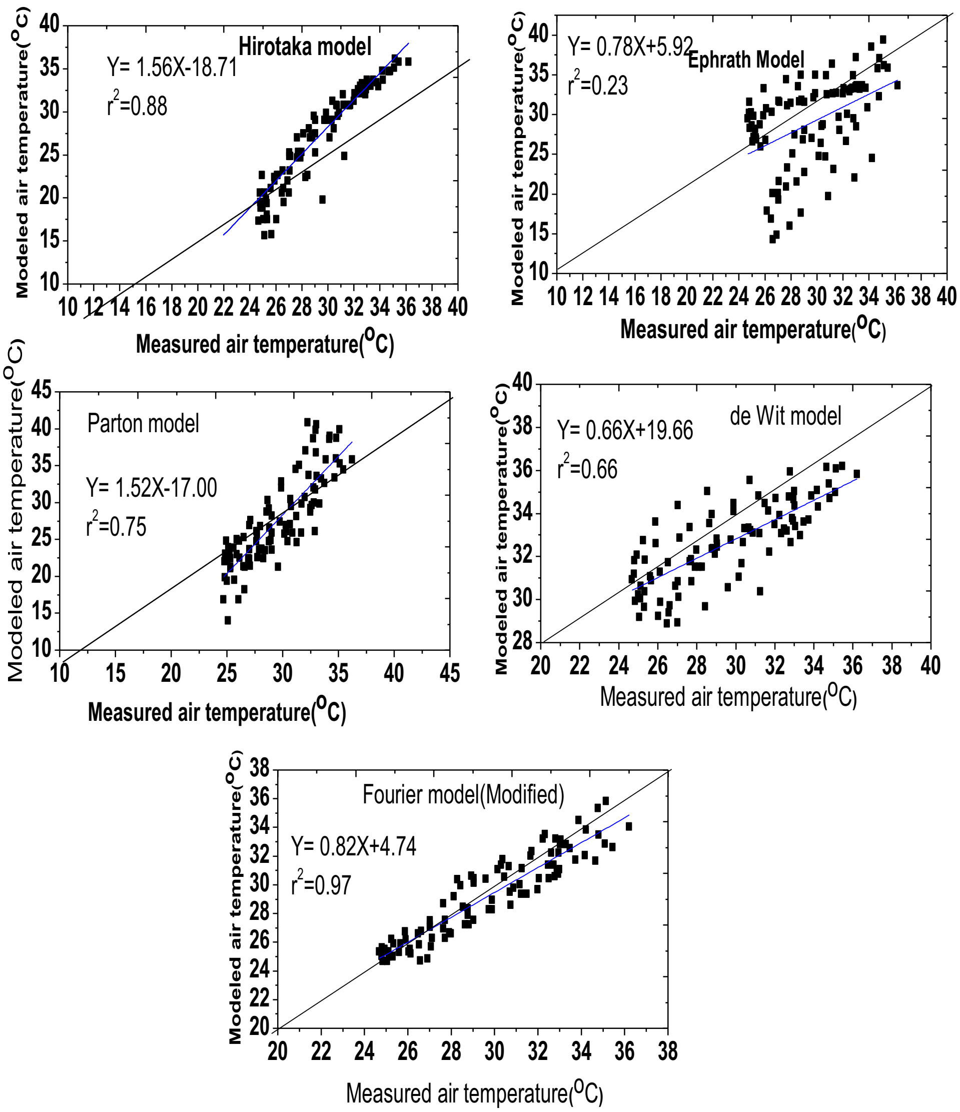


Fig. 16 *Scatter plots* showing the comparisons of measured air temperature with modeled air temperature using different models at Ibadan site, 2006

Conclusion

The existing models for estimating hourly air temperature from daily data have been tested over a bare soil sites at Ibadan and Ile-Ife sites to determine the best model (s) for application in a tropical region where low wind speed is prevalent. The Ephrath, Hirotaka, de Wit and Parton models simulated T_a with large deviation from the measured data in the morning and late hours of the nighttime. These existing models could not accurately capture the strong cooling inversion associated with a humid tropical region. Though, the models yielded better results on some specific days, on the average a high bias was found in the simulated T_a for stable conditions. The modified fourier series model which accounted for cooling inversion in the tropics showed better results for dry and wet composite diurnal variations at the two sites. The modified fourier series model proposed to estimate the diurnal air temperature at microscale level during the transition period from dry to wet season in the tropics had some limitations. Firstly, the proposed model is best for regions around globe where low wind speed, typically of magnitudes less than 3 ms^{-1}, is prevalent. Secondly, the atmospheric scale height of the region should not exceed 8.8 km in troposphere and, thirdly, the value of cooling rate during stable condition should range between −0.002 and 0.182 $Kday^{-1}$, the values obtained were very small compared with what were obtainable in Polar Regions and high wind speed environment (Varghese et al. 2003). Lastly, these models have been evaluated for bare ground. Application of the models in other ecosystems like forest and crop land requires evaluation in such ecosystems. The performance of some of the existing models such as Parton Hirotaka and fourier series models was relatively good for the tested sites except with little success during night-time.

Table 7 Summary of the Overall Root Mean Square Error (RMSE) and Mean Bias Error (MBE) of modeled air temperature using different models for Ile-Ife and Ibadan

Location(s)						
Models	Wet period			Dry period		
	MBE (ºC)	RMSE (ºC)	r^2	MBE (ºC)	RMSE (ºC)	r^2
Ile-Ife						
Hirotaka model	0.24	1.15	0.64	−2.07	4.29	0.88
Epthrath model	−4.97	4.76	0.67	3.26	4.87	0.33
de Wit model	−3.76	4.92	0.68	−3.31	2.98	0.68
Fourier series model (modified)	−0.04	1.23	0.97	0.71	1.76	0.97
Parton model	1.12	2.54	0.74	−1.57	4.08	0.72
Ibadan						
Hirotaka model	−1.24	2.15	0.68	−4.23	4.79	0.68
Epthrath model	−2.97	3.76	0.71	0.26	1.87	0.56
de Wit model	3.76	5.92	0.66	−3.31	4.98	0.82
Fourier series model (modified)	−0.24	0.94	0.96	−1.36	1.61	0.95
Parton model	0.76	1.54	0.82	−2.57	3.08	0.82

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