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EVALUATION OF THREE EMPIRICAL REFERENCE EVAPOTRANSPIRATION MODELS AT A TROPICAL STATION UNDER THREE SKY CONDITIONS USING TWO SOLAR RADIATION ESTIMATION METHODS

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Abstract
An existing solar radiation model developed at Ilorin and found to be more reliable than Angstrom-type and Hargreaves solar radiation equations was used in the FAO Penman-Monteith reference evapotranspiration model (FAOPM) to obtain daily reference crop evapotranspiration (ET_o) for a 32-year (1970 to 2001) period. The number of days having all the required input meteorological data was 9335. The sky conditions of the days were classified as clear, partially cloudy or cloudy depending on the cloudiness index i.e. the ratio of diffuse solar radiation to total solar radiation. The ET_o values obtained with FAOPM were compared with predictions of three simpler empirical ET_o models namely the Hargreaves (HGRV), Jensen and Haise (JHSE) and Blaney-Morin-Nigeria (BMN) models. When the more reliable solar radiation model was used in HGRV and JHSE, their performances were better than when the solar radiation equation of Hargreaves was used. Generally the three simpler models overpredicted ET_o. The bias, root mean square difference (RSMD) and absolute error of prediction deteriorated with sky cloudiness when the solar radiation equation of Hargreaves was used. Linear regression equations with zero intercepts were developed for the estimation of FAOPM predictions from those of the simpler ET_o models. The regression equations relating the predictions of FAOPM to those of HGRV generally yielded the highest coefficients of determination and the lowest standard errors of regression. The predictions of HGRV were also the closest to the corresponding FAOPM predictions under the various sky conditions. Based on the outcome of the regression analysis and the ease of application of HGRV, the FAOPM-versus-HGRV regression equations were recommended for the estimation of FAOPM predictions of daily ET_o when the use of FAOPM is necessary but not feasible because of incomplete input data.

Keywords: Evapotranspiration, solar radiation, Blaney-Morin-Nigeria, modeling

1. Introduction

Knowledge of reference crop evapotranspiration (ET_o) is routinely required for the estimation of crop water use in the planning, design and operation of irrigation and, soil and water conservation systems. Direct measurement of evapotranspiration is usually not feasible in many field situations because it is expensive and time-consuming. The required instrumentation may also be lacking. Several models, which can be categorised into temperature-based, radiation, mass transfer and combination models (Igbadun *et al*., 2006) have therefore been developed for the estimation of evapotranspiration using weather data. Penman-type combination models (Penman, 1948) based on energy balance and mass transfer principles are considered to most accurately describe the evapotranspiration process. Combination models however require more input data compared to the simpler alternatives like the temperature-based models. Igbadun *et al*. (2006) noted that temperature-based models, though less accurate than combination models for periods less than five days, were attractive in many areas especially in sub-Saharan Africa where air temperature data were more readily available than other data required by the other types of models.

At the planning and design stages of irrigation and water conservation schemes, historical average daily values of ET_o for multi-day periods (e.g. weekly, ten-day and monthly) may be satisfactory for estimation of crop water use (Adeniran *et al.,* 2010). At operational stages however, daily information on ET_o may be vital to making real-time decisions especially where biophysical simulation of crop water use (Kra and Ofosu-Anim, 2010) or of crop growth and development (Gowing and Ejieji, 2001) are incorporated into the process. The FAO version of the Penman-Monteith combination model (FAOPM) has been proposed as the standard for the estimation of ET_o (Allen *et al*., 1998). In daily real-time ET_o estimation, simpler models such as the temperature-based ones could be valuable substitutes on days when the use of combination models is not feasible due to incomplete input data. This could arise from absence from duty of personnel or failure of instrumentations required for direct measurement of essential input data. The shortcoming of employing more than one ET_o model in such situation has however been highlighted in the work of Earlsa and Dixon (2008) which indicated that accuracy of ET_o estimates could differ significantly across the models. However, where the predictions of a given simpler model had been calibrated for local conditions, the simpler model can be used for predicting the ET_o for that local condition.

In the tropical environment of the present study, radiation component has been shown to predominate over the aerodynamic component during the cloudy humid season with the contribution of the radiation component to potential evapotranspiration ranging from 50% to 97% (Bashir, 1991). Reliable estimation of solar radiation is therefore essential in such environment for accurate ET_o estimation. Solar radiation estimation using parameterised Angstrom-type empirical equation (Angstrom, 1924) has been found to overpredict daily incoming solar radiation by 38%, 12% and 9 % under cloudy, partially cloudy and, partially clear sky conditions respectively in the locality (Babatunde, 1989). This lead to unreasonably high ET_o predictions by the FAOPM combination model on cloudy days in a study by Ejieji (2002). Babatunde (1989) also reported an 11% underprediction of incoming radiation by the parameterised Angstrom equation under clear sky conditions. He therefore proposed a solar radiation model (BSRM) which improved solar radiation estimation by incorporating visibility and day-time temperature as input data. Among the solar radiation estimation methods recommended by Allen *et al*. (1998), only the Angstrom equation and the Hargreaves equation (Hargreaves and Samani, 1982) incorporated surrogate variables for sky cloudiness condition. The Hargreaves equation is simple and easy to apply requiring daily maximum and minimum temperatures as the only measured input data.

Reliability of solar radiation estimation routines was not considered in past studies which compared the ET_o predictions of some empirical evapotranspiration models (including temperature-based ones) with those of Penman-type combinations models in Nigeria. Furthermore, the studies considered either average monthly total ET_o (Mbagwu, 1988) or monthly average daily ET_o (Fapohunda, 2001; Adeboye *et al*., 2009). The results of such studies may therefore not be suitable for use at daily time steps because of smoothing effect of the averaging process. Local information applicable to daily time steps is therefore lacking for calibrating the predictions of the simpler ET_o models against those of the standard combination model.

The objectives of this study were therefore to (a) compare the reliability of the solar radiation models of Hargreaves (Allen et al., 1998) (HSRM) and Babatunde (1989) as basis for determining the more suitable one for use in the standard FAOPM, (b) compare, under three sky conditions, the daily ET_o predictions of FAOPM with the predictions of three simpler empirical ET_o models in order to determine the relative accuracies of the simpler models under the sky conditions and (c) to develop regression relationships for estimating the predictions of FAOPM from the ET_o predictions of three simpler empirical models.

Two of the simpler ET_o models were the temperature-based models of Hargreaves (Allen *et al*., 1998; Hargreaves, 1994) (HGRV) and, Jensen and Haise (1963) (JHSE). The third is the Blaney-Morin-Nigeria model of Duru (1984) (BMN) which considers both temperature and relative humidity. The sky conditions considered in this study were cloudy, partially cloudy and clear skies. The focus of this study was the facilitation of the use of simpler temperature-based models to obtain daily ET_o estimates which are sufficiently close to those of the standard FAOPM when complete input data for the latter are unavailable in the stated area. This was addressed through the development of regression equations with relating FAOPM predictions to those of the respective simpler models. Since the radiation component over-predominates the aerodynamic component of ET_o in the study area, it was vital that a reliable solar radiation model be employed in FAOPM for meaningful result. Angstrom-type equations have been shown to perform poorly under the sky cloud conditions of the area (Babatunde, 1989); therefore the suitability of BSRM and HSRM for use in FAOPM was also investigated.

2. Materials and methods

2.1 Location of the study

The study location Ilorin is approximately on latitude 8^0 28′ N and longitude 4^o 40′ E at an elevation of about 340 m above mean sea level. It is the capital of Kwara State, Nigeria and is within the Southern Guinea Savannah ecological zone of Nigeria (Agboola, 1979) which corresponds to the tropical hinterland zone described by Fapohunda (2001). The wet season begins towards the end of March and ends in October. The dry season which starts in November and ends about the middle of March is generally hotter than the wet season. The exception for the dry period is November to January when the cool, dry and dusty Harmattan wind blows from the Sahara desert.

2.2 Meteorological data collection and estimation of some missing data

Meteorological data from the Ilorin airport for the years 1970 to 2001 were obtained from the Nigerian Meteorological Agency, Oshodi, Lagos. They consisted of daily records of maximum and minimum temperatures, wind run (at 2 m height), sunshine hours and rainfall. The data also included three-hourly records of wet and dry bulb temperatures, relative humidity, wind speed (at 5.78 m height), visibility and rainfall.

For the purpose of filling missing records, daily records of sunshine hours and, maximum and minimum temperatures for the years 1992 to 2001 were also obtained from National Centre for Agricultural Mechanisation (NCAM), Idofian located about 25 km southeast of the airport. The inception of records at the NCAM weather station was year 1992. Both meteorological stations were not irrigated so the ground surface was covered by dry grass in the dry season. The fetch in the prevailing wind directions were greater than 200 m.

Daily wind run was used to estimate average daily wind speed. In case of missing record, the average of the 3-hourly wind speeds for the day was computed and used to estimate the average wind speed at 2 m height by the application of the power law relationship (Jensen, 1974). Corresponding records of maximum temperature from the airport and NCAM respectively were used to develop a linear regression equation forced through the origin. The airport daily maximum temperature was the dependent variable. For any day, within 1992 to 2001, that the maximum temperature record for the airport was missing, the regression equation used to estimate the missing record provided the corresponding NCAM record was available. The same process was carried out in estimating missing airport records of minimum temperature and sunshine hours from corresponding NCAM records for the period 1992 to 2001. The approach adopted for estimating missing records was predicated on a prior analysis of the plots of corresponding data sets of the two stations. The plots of corresponding data sets generally yielded slopes not significantly different from unity and intercepts not significantly different from zero.

2.3 Description of the solar radiation models

The Hargreaves equation for estimation of solar radiation is given as (Allen et al., 1998)

$$R_s = K_R\left(T_{\max} - T_{\min}\right)^{0.5} R_a \tag{1}$$

where R_a is extraterrestrial radiation (MJ m^{-2} d^{-1}), T_{max} and T_{min}, are, respectively, maximum and minimum temperatures (^oC) and K_R is an empirical adjustment coefficient in the range of 0.16 to 0.19.

The model of Babatunde (1989) is given as

$$\frac{H}{H_O} = 0.0189 + 0.2599\frac{S}{S_m} + 0.0027V + 0.0101T \tag{2}$$

where H_o is the radiation at the top of the atmosphere (W h m^{-2}), H is the incoming solar radiation (W h m^{-2}), S is the hours of bright sunshine, S_m is the maximum possible hours of sunshine, V is visibility (km) and T is average day-time temperature (^oC).

2.4 The reference evapotranspiration models and adaptations employed

The main equations of the FAO-Penman-Monteith, Blaney-Morin-Nigeria, Hargreaves, and Jensen-Haise models; and specific adaptations for their application for this work are presented in this subsection. The detailed equations of the sub-units of the models may be found in the related references.

The FAO Penman-Monteith model (FAOPM) as described by Allen *et al*. (1988) is stated as

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma[900/(T+273)]U_2(e_a - e_d)}{\Delta + \gamma(1+0.34U_2)} \quad (3)$$

where ET_o is the reference crop evapotranspiration (mm/d), R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}), G is the soil heat flux (MJ m^{-2} d^{-1}), T is the average air temperature (^oC), U_2 is the wind speed measured at 2m height (m/s), (e_a – e_d) is the vapour pressure deficit (kPa) i.e. the difference between saturation vapour pressure, e_a and the actual vapour pressure, e_d. γ is the psychrometric constant (kPa/ ^oC) and Δ is the slope of the vapour pressure curve (kPa/ ^oC) .

Further references on the standard computations for R_n and other parameters used in the FAOPM equation are given Allen *et al.* (1988) and were mainly employed in this study.

The Blaney-Morin-Nigeria model (BMN) of Duru (1984) could be stated as follows for the estimation of daily potential evapotranspiration over monthly periods:

$$ETp = r_f\left(0.45T + 8\right)\left(520 - R^{1.31}\right)/100 \quad (4)$$

where ETp is the potential evapotranspiration (mm/d), T is the mean daily temperature for the month (^oC) estimated as the average of the daily maximum and mimimum temperatures, R is the mean daily relative humidity (%) obtained by averaging the daily relative humidities at 09.00 h and 15.00 h GMT, and r_f is the radiation factor evaluated as the ratio of the radiation at the top of the atmosphere in the month to that for the whole year.

In order to adapt the model for ET_p estimation over one-day periods, actual daily values of T and R were used in place of their average daily values for the month. To obtain the r_f -value for each day, the H_o for the day and those of 29 preceding days were summed and divided by the total H_o for the year. Computation of H_o for each day of the year was carried out as described by Babatunde (1989).

The Hargreaves model (HGRV) as presented by Allen *et al.* (1998) is given as

$$ET_o = 0.0023\left(T_{mean} + 17.8\right)\left(T_{\max} - T_{\min}\right)^{0.5} R_a \quad (5)$$

where ET_o is reference crop evapotranspiration (MJ m^{-2} d^{-1}), R_a is extraterrestrial radiation (MJ m^{-2} d^{-1}) and, T_{mean}, T_{max} and T_{min}, are, respectively, average, maximum and minimum temperatures (^oC). T_{mean} is evaluated as half the sum of T_{max} and T_{min}.

The Jensen-Haise model (JHSE) for calculating grass reference evapotranspiration (Jensen and Haise, 1963) was stated as follows by Burman and Pochop (1994)

$$\lambda ET_o = C_T\left(T_{mean} - T_x\right)R_s \quad (6)$$

where ET_o is reference evapotranspiration (mm d^{-1}), λ is the latent heat of vaporisation kJ kg^{-1}, R_s is solar radiation (MJ m^{-2} d^{-1}) and, T_{mean} is as previously defined while C_T and T_x are station constants obtained as follows

$$C_T = \left[\left(38 - \frac{z}{152.5}\right) + 7.3\left(\frac{5.0}{es_{\max} - es_{\min}}\right)\right]^{-1} \quad (7)$$

$$T_x = -2.5 - 1.4\left(es_{\max} - es_{\min}\right) - \frac{z}{550} \quad (8)$$

where ‘z’ is altitude of the location (m); es_{max} and es_{min} are saturation vapour pressures (kPa) at the average monthly maximum air temperature and monthly minimum temperature (^oC), respectively, for the warmest of the month of the year based on long-term weather data.

The Jensen-Haise model has been recommended for estimating ET_o for periods of five days to one month (Burman *et al*., 1980). The use of the model for periods ranging from one day to a month has however been reported (Burman and Popchop, 1994). It was therefore applied in this work to one-day periods without further adaptations. However, for the purpose of converting, in Equations (5) and (6), the energy values of ET_o to mm/d, both sides of the equations were divided by the latent of vaporisation value at the average daily temperature as outlined by Burman and Popchop (1994).

2.5 Estimation of solar radiation

In all the ET_o models except BMN, solar radiation was estimated with Hargreaves formula i.e. Equation (1) and also with the equation of Babatunde i.e. Equation (2) for comparison. In the application of Equation (1), consideration was given to the fact that the location of study was inland, therefore, a K_R-value of 0.16, recommended for interior locations (Allen *et al*., 1998), was adopted. Explicit estimation of solar radiation is not required in BMN.

In the case of Equation (2), the computation of H_o and S_m were carried out as outlined by Babatunde (1989). For conversion of the units from W h m^{-2} to MJ m^{-2} d^{-1}, the computed H was multiplied by 3600 s and divided by 10^6. R_a (in Equations (1) and (5)) was evaluated from H_o converted from W h m^{-2} to MJ m^{-2} d^{-1} as already described. The values of T and V required in Equation (2) obtained from the averages of 3-hourly records from 6 h to 18 h GMT.

2.6 Correction for aridity

Because the weather station of the study location was not irrigated, non-ideal conditions for ET_o computation prevailed in the dry season. The ET_o estimates of the models were therefore corrected for aridity by applying a correction for bias to daily mean temperature. The temperature bias was estimated as follows (Jensen *et al*., 1997)

$$T_{bias} = K\left(1 - \frac{P}{\sqrt{ETH}}\right) \tag{9}$$

where T_{bias} is the bias in temperature relative to a well-watered environment (^oC), K is a coefficient ranging from 0 to 4 depending of degree of site aridity, P is total precipitation for 10-day period (mm) and ETH is the uncorrected ET_o estimates of HGRV for 10-day period (mm). A K-value of 3 was used for this study.

In the application of Equation (9), the year was divided into 10-day time periods with the last (i.e. 37^{th}) period being five days (or six days for a leap year). For each of the time periods, the value of T_{bias} was calculated. Each day of the year was thereafter assigned to the appropriate time period for the purpose determining the T_{bias}-value applicable to the particular day.

In the case of FAOPM, estimation of vapour pressure deficit ($e_a - e_d$) using daily maximum and minimum temperatures was employed in order to address the nonstandard conditions (Jensen *et al*., 1997).

2.7 Estimation of sky cloudiness condition

Following Babatunde and Aro (2001), cloudiness index, i.e. the ratio of diffuse solar radiation (H_d) to total solar radiation (H) was used for estimating the sky condition. They established the following as thresholds for delineating the states of sky cloudiness referred to as “clear”, “partially cloudy” and “cloudy” conditions respectively:

$$0 < \frac{H_d}{H} \leq 0.4 \quad \Rightarrow \quad \text{Clear sky} \tag{10a}$$

$$0.4 < \frac{H_d}{H} \leq 0.5 \quad \Rightarrow \quad \text{Partially cloudy sky} \tag{10b}$$

$$\frac{H_d}{H} > 0.5 \quad \Rightarrow \quad \text{Cloudy or turbid sky} \tag{10c}$$

where $\frac{H_d}{H}$ is the cloudiness index.

The estimation of cloudiness index was carried out using the following empirical relationship (Babatunde and Aro, 1995)

$$\frac{H_d}{H} = 0.945 - 0.971\frac{H}{H_o} \tag{11}$$

where $\frac{H}{H_o}$ is referred to as the clearness index and was obtained as explained for Equation (2).

2.8 Evaluation of the models

The ET_o predictions of each of the three simpler models were compared with the corresponding outputs of FAOPM. The performances of the simpler models were evaluated using bias, root mean square difference (RSMD) and mean absolute prediction error as indices. The regression equations developed for the purpose of estimating FAOPM predictions from those of the simpler models were also evaluated on the basis of the coefficients of determination and standard errors of regression. The bias of each of the simpler models was obtained with the expression

$$B = \frac{1}{n}\sum_{i=1}^{n}(EM_i - EPM_i) \tag{12}$$

where B is the bias (mm d^{-1}) , EM_i and EPM_i are, respectively, the corresponding ET_o predictions of the simpler model and FAOPM (mm d^{-1}) while n is the number of paired comparisons. The root mean square difference was estimated from

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(EM_i - EPM_i)^2} \tag{13}$$

where RMSD is root mean square difference (mm d^{-1}). The mean absolute prediction error was estimated using the following equation

$$Err = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{100(EM_i - EPM_i)}{EPM_i}\right| \quad (14)$$

where Err is mean absolute prediction error (%) and all other terms are as previously defined.

In order to evaluate the reliability of Equations (1) and (2) for estimating solar radiation, their daily predictions were compared with measured solar radiation data for year 2000. The measured daily solar radiation data, i.e. incoming shortwave radiation, were collected from Department of Physics, University of Ilorin. The data which were measured with an Eppley precision spectral pyranometer, with a calibration constant of 8.2×10^{-6} V/ W m^{-2}, were logged at one-minute intervals. The daily total incoming short wave radiation values used for this study were obtained from the logged data by numerical integration.

3. Results and discussion

The warmest month was March (Table 1). The maximum value of temperature bias was 3 ^{o}C and it occurred in the first and in the last decades (i.e. 10-day periods) of the year. Temperature bias was negligible in the decades falling within the time when the rainy season was well-established (Figure 1.).

Table 1: Monthly means of some daily weather data at Ilorin (1976 – 2001)

Month	Max. Temp (^{o}C)	Min. Temp (^{o}C)	Max. Rel. humidity (%)	Min. Rel. humidity (%)	Wind speed (m/s)	Sunshine (hr)
Jan.	33.8	19.0	73.5	26.4	1.0	6.6
Feb.	35.7	21.8	78.5	27.3	1.2	7.3
Mar.	35.9	23.4	85.3	36.0	1.5	6.8
Apr.	34.5	23.5	89.8	48.3	1.7	6.9
May	32.4	22.5	93.1	58.4	1.6	7.0
Jun.	30.6	21.7	94.6	64.0	1.4	6.2
Jul.	29.0	21.4	94.5	66.8	1.5	4.4
Aug.	28.7	21.3	94.9	68.9	1.5	3.6
Sep.	29.7	21.1	95.9	66.7	1.2	4.4
Oct.	31.3	21.4	95.5	59.2	1.1	6.1
Nov.	33.8	20.5	91.7	37.1	1.0	7.5
Dec.	33.6	19.1	83.9	30.0	0.9	7.3

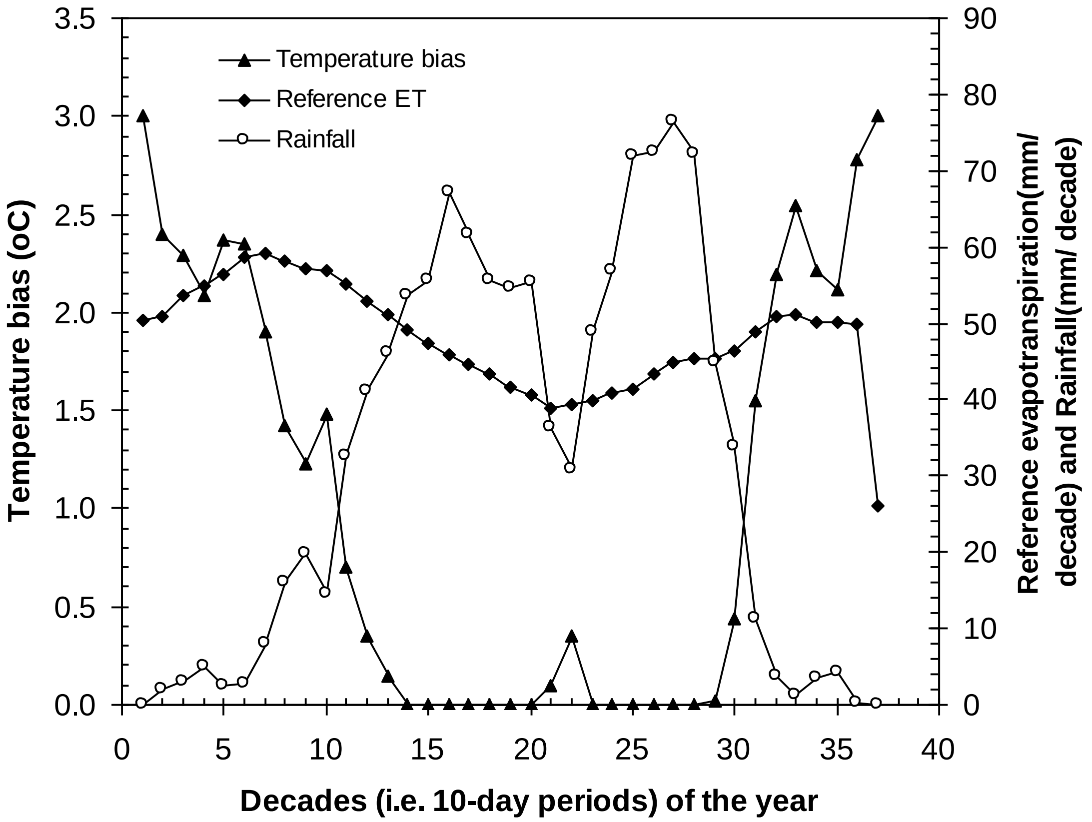

Figure 1: Estimated temperature bias relative to well-watered environment, reference evapotranspiration and rainfall at the various decades (i.e. 10-day periods) of the year (plotted reference evaporation values were estimated using the Hargreaves model of Allen *et. al*. (1998) without correction for aridity; the last period is five days or six days in a leap year).

Out of the 11688 days in the years 1970 to 2001, required weather data for simultaneous comparison of all the ET_o models were available for 9335 days. More recent (i.e. post 2001) data had more missing records especially of sunshine hours and NCAM records were not available for their estimation. The relative frequencies of clear, partially cloudy and cloudy sky conditions were 0.159, 0.522 and 0.319 respectively, indicating that the sky was not clear 84.1% of the time. The relatively low relative frequency of clear sky conditions agrees with the finding of Akpabio *et al*. (2005) in a similar environment that only four months of the year which excludes the hazy dusty Harmattan period and the rainy season experienced clear sky conditions. The values of daily ET_o computed with FAOPM using BSRM averaged 5.00 ± 0.61 mm, 4.43 ± 0.56 mm and 3.48 0 ± 0.50 mm for clear, partially cloudy and cloudy sky conditions respectively.

A comparison of observed year 2000 daily solar radiation with the predictions of the models of Hargreaves (Allen et al., 1998), Equation 1 (HSRM) and Babatunde (1989), Equation 2 (BSRM) is presented in Figure 2 as a plot of the absolute values of the prediction errors against the actual values of observed daily solar radiation. Generally, the prediction errors of both models increased as daily solar radiation decreased indicating reduced reliability with increasing sky cloudiness.

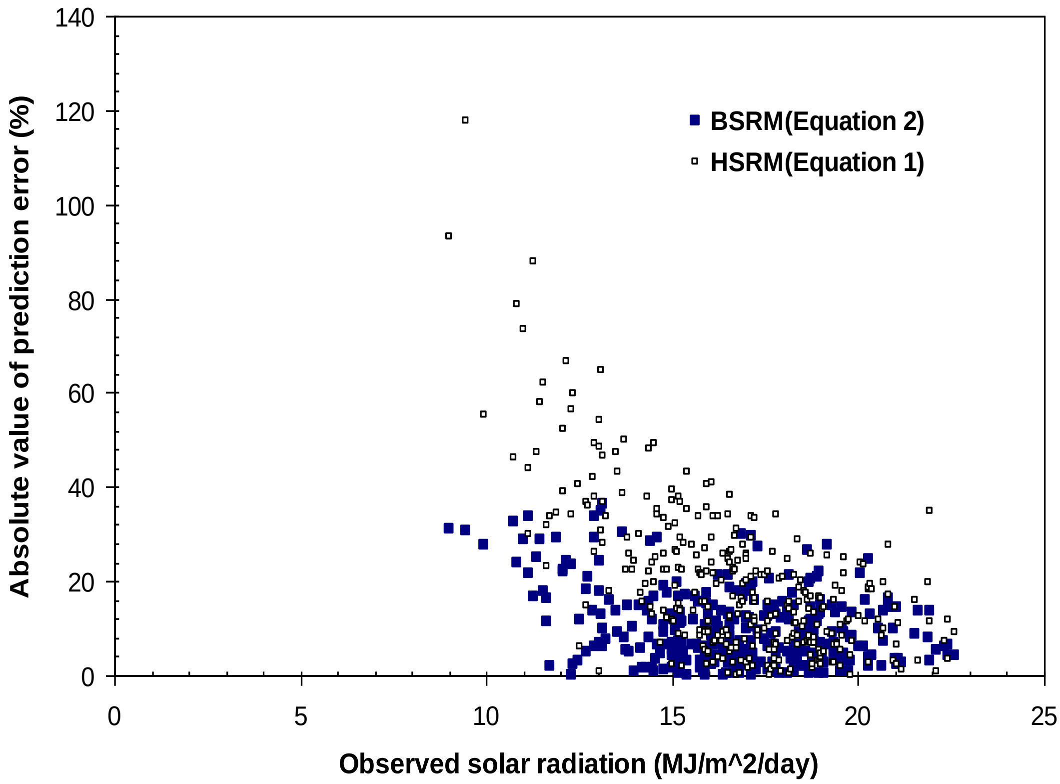

Figure 2: Absolute values of prediction errors of solar radiation estimation models of Babatunde (1989), BSRM, and Hargreaves (Allen et al 1998), HSRM, at the observed daily solar radiation values in the year 2000.

However, BSRM performed better than HSRM over the entire range of observed values. The bias, RMSD and mean absolute prediction error for BSRM were 0.007 MJ m^{-2} d^{-1}, 1.967 MJ m^{-2} d^{-1} and 9.84 % respectively. In the case of HSRM, the corresponding values were 2.282 MJ m^{-2} d^{-1}, 3.599 MJ m^{-2} d^{-1} and 19.51 % for bias, RMSD and mean absolute prediction error respectively. When expressed in kW h m^{-2} d^{-1} the bias and RMSD for BSRM become 1.944 × 10^{-3} kW h m^{-2} d^{-1} and 0.546 kW h m^{-2} d^{-1} respectively. The absolute value of the bias for BSRM and was less than the 2.30 × 10^{-3} to 42.9 × 10^{-3} kW h kW reported for a temperature-based radiation model proposed for Nigerian conditions by Okundamiya and Nzeako (2001). However, RMSD for BSRM was on the average double of their reported values. This is to be expected since their model considered monthly average daily radiation which has smoother observed data set than actual daily values considered in BSRM. Strictly considered, their model may not be appropriate for application at daily time-steps since individual daily data were not used in their derivation. This also applies to a proposed solar radiation model by Akpabio *et. al*. (2004) for which prediction errors ranging from 3.85% to 3.91%.were reported. Another limitation of the model of Akpabio *et. al*. (2004) is that it requires eight meteorological input parameters, is not parsimonious and would be difficult to use with limited data.

When daily ET_o values obtained for year 2000 with FAOPM using measured solar radiation were linearly regressed against those obtained using FAOPM with solar radiation estimated with BSRM, a slope of 1.014 statistically not different from unity and an intercept of 0.009 statistically zero (at .05 level of significance) were obtained. The standard error of regression was 0.45 mm d^{-1}. When the regression was forced through the origin, the standard error was virtually unchanged, the slope increased insignificantly to 1.016 while the coefficient of determination improved from 72.90 % to 98.99 %. When solar radiation estimated with HSRM was used, and the linear regression carried out, the corresponding values for slope, intercept and standard error were 0.732, 1.457 and 0.47 mm/day respectively. The slope was however statistically less than unity and the intercept greater than zero at 0.05 level of significance. The coefficient of determination was also lower at 65.01 %. In the light of the results of the comparisons it was concluded that using BSRM with FAPOM better reproduced the results obtainable from FAOPM when all the input data were actual observed values. BSRM is therefore to be preferred for ET_o computation with FAOPM in the study area when the required input data except observed solar radiation are available.

The result of the comparisons of the daily ET_o estimations of the three simpler models with those of FAOPM when BSRM was used in solar radiation estimation in FAOPM, HGRV and JHSE is presented in Table 2. That of when BSRM was used in FAOPM and HSRM in HGRV and JHSE is presented in Table 3. The performance of BMN deteriorated consistently with sky cloudiness. This behaviour did not change between the two cases because BMN which does not require explicit estimation of solar radiation. In the case of HGRV and JHSE their performance deteriorated in all the indices of performance when HSRM was used (Table 3) except under clear sky condition indicating the importance of improved solar radiation estimation under cloudy and partially cloudy sky conditions which are more prevalent in the locality.

For the case presented in Table 3, all the performance indices, i.e. bias, root mean square difference and mean absolute prediction error generally deteriorated with cloudiness with their magnitudes increasing under partially cloudy and cloudy conditions compared with clear sky condition. The positive bias exhibited by all the simpler models under all the sky conditions (Tables 2 and 3) indicate that they generally overpredicted daily ETo relative to FAOPM. For HGRV the overprediction is consistent with the findings of Smith *et al*. (1996) for humid regions although they compared the model predictions with lysimeter-determined ET_o. Underprediction was however reported for JHSE in their own case. Underprediction by HGRV has been reported by Wang et al. (2007) for a less humid tropical environment. Adeboye *et al*. (2009) compared simpler ET_o models with FAOPM for three locations in a similar tropical environment. They reported that when the parameterised Angstrom equation was employed for solar radiation in FAOPM and JHSE but HSRM in HGRV the RSMD were 1.03 mm d^{-1} and 1.79 mm d^{-1} for JHSE and HGRV respectively for one of the stations having required meteorological data.

Table 2: Bias, root mean square difference and mean absolute error of reference evapotranspiration predictions of the simpler three models under three sky conditions. (The models were compared with the FAO Penman-Monteith model. The model of Babatunde (1989) was used in solar radiation estimation in the FAO Penman-Monteith, Hargreaves and Jensen-Haise models).

Models and Sky conditions	*Bias (mm/d)	Root mean square difference (mm/d)	Mean absolute prediction error (%)
Cloudy sky			
Blaney-Morin-Nigeria	0. 61	1.20	23.69
Hargreaves	0. 00	0.35	7.48
Jensen-Haise	0. 35	0.52	13.73
Partly cloudy sky			
Blaney-Morin-Nigeria	0.47	0.91	15.57
Hargreaves	0.13	0.40	7.86
Jensen-Haise	0.64	0.77	16.12
Clear sky			
Blaney-Morin-Nigeria	0.34	0.74	11.82
Hargreaves	0.40	0.55	9.93
Jensen-Haise	1.08	1.15	22.23
Pooled data for the three sky conditions			
Blaney-Morin-Nigeria	0.49	0.99	17.57
Hargreaves	0.13	0.41	8.07
Jensen-Haise	0.62	0.78	16.33

* Positive bias-value denotes over-prediction

Table 3: Bias, root mean square difference and mean absolute error of reference evapotranspiration predictions of the simpler three models under three sky conditions. (The models were compared with the FAO Penman-Monteith model. The model of Babatunde (1989) was used in solar radiation estimation in the FAO Penman-Monteith model and that of Hargreaves (Allen et al., 1998) in the Hargreaves and Jensen-Haise models).

Models and Sky conditions	*Bias (mm/d)	Root mean square difference (mm/d)	Mean absolute prediction error (%)
Cloudy sky			
Blaney-Morin-Nigeria	0.61	1.20	23.69
Hargreaves	0.73	0.90	21.93
Jensen-Haise	1.15	1.29	33.85
Partly cloudy sky			
Blaney-Morin-Nigeria	0.47	0.91	15.57
Hargreaves	0.42	0.67	11.90
Jensen-Haise	0.96	1.10	22.59
Clear sky			
Blaney-Morin-Nigeria	0.34	0.74	11.82
Hargreaves	0.06	0.47	7.34
Jensen-Haise	0.70	0.86	15.01
Pooled data for the three sky conditions			
Blaney-Morin-Nigeria	0.49	0.99	17.57
Hargreaves	0.46	0.72	14.38
Jensen-Haise	0.98	1.13	24.98

* Positive bias-value denotes over-prediction

When HSRM was employed in the all the models, the corresponding values of RMSD were 2.51 mm d^{-1} and 2.50 mm d^{-1} for JHSE, and 2.50 mm d^{-1} and 0.89 mm d^{-1} for HGRV for the remaining two stations having limited meteorological data. Their results therefore showed that the comparison outcomes were dependent on the method of estimation of solar radiation.

Linear regression of the daily ET_o predictions of FAOPM against those of the simpler models assuming non-zero intercept yielded lower coefficients of determination than when the regression line was forced through the origin. The proposed regression model for estimating the ET_o predictions of FAOPM from those of the simpler models is therefore as follows:

$$ETo_{PM} = \alpha ET_{SM} \quad (15)$$

where ETo_{PM} is the estimated prediction of FAOPM (mm d^{-1}), ET_{SM} is the prediction of the simpler model (mm d^{-1}), and α is the slope of the regression line forced through the origin. .

The results of the linear regression including the slope (α), coefficient of determination and standard error of regression are presented in Table 4 for the case where BSRM was used for solar radiation estimation in FAOPM, HGRV and JHSE. The corresponding result for the case where BSRM was used in FAOPM with HSRM used in HGRV and JHSE are presented in Table 5. In both cases, the coefficients of determination and standard errors of regression were comparable. The differences in standard errors of prediction in the two cases were, at most, 0.11 mm d^{-1} under the various sky conditions and 0.16 mm d^{-1} for the pooled data. The relatively high coefficients of determination for all the models and sky conditions in both cases reflect the adequacy of Equation (15) as a predictive tool. The closer the slope is (i.e. α) to unity, the better the fit manifesting in reduction in the standard error of prediction. It can therefore be inferred from the α-values in Tables 4 and 5 that the FAOPM-versus-HGRV regression equations constitute the best estimation tools under the conditions studied because, generally, their α-values are the ones closest to unity.

In the light of the results of the regression analysis and in view of the relatively easier availability of input data for HSRM it should be more practically expedient to be estimating the ET_o predictions of FAOPM from the simpler models using Equation (15) with the α-values (i.e. slopes) presented in Table 5 when any of the required input data for using FAOPM with BRSM is unavailable. In effect, the α-values could be regarded as calibration constants. The preferred simpler ET_o model for the purpose of estimating FAOPM predictions should however be HGRV because it performed best of the three simpler models (Table 3). Although nearly similar prediction errors could be achieved using JHSE (Table 5), HGRV is easier to apply than JHSE.

Table 4: Results of linear regression of FAO Penman-Monteith model predictions against those of the three models for the various sky conditions with the regression lines forced through the origin.(The model of Babatunde (1989) was used in solar radiation estimation in the FAO Penman-Monteith, Hargreaves and Jensen-Haise models)

Models and Sky conditions	Slope	Coefficient of determination	Standard error of regression (mm/d)
Cloudy sky			
Blaney-Morin-Nigeria	0.803	0.939	0.87
Hargreaves	0.995	0.990	0.35
Jensen-Haise	0.902	0.990	0.36
Partly cloudy sky			
Blaney-Morin-Nigeria	0.885	0.975	0.71
Hargreaves	0.969	0.993	0.38
Jensen-Haise	0.870	0.992	0.40
Clear sky			
Blaney-Morin-Nigeria	0.927	0.985	0.63
Hargreaves	0.926	0.995	0.37
Jensen-Haise	0.823	0.995	0.37
Pooled data for the three sky conditions			
Blaney-Morin-Nigeria	0.873	0.948	0.78
Hargreaves	0.964	0.978	0.38
Jensen-Haise	0.865	0.980	0.41

Table 5: Results of linear regression of FAO Penman-Monteith model predictions against those of the three models for the various sky conditions with the regression lines forced through the origin.(The model of Babatunde (1989) was used in solar radiation estimation in the FAO Penman-Monteith model and that of Hargreaves (Allen et al., 1998) in the Hargreaves and Jensen-Haise models)

Models and Sky conditions	Slope	Coefficient of determination (%)	Standard error of regression (mm/d)
Cloudy sky			
Blaney-Morin-Nigeria	0.803	0.939	0.87
Hargreaves	0.817	0.984	0.45
Jensen-Haise	0.742	0.984	0.45
Partly cloudy sky			
Blaney-Morin-Nigeria	0.885	0.975	0.71
Hargreaves	0.908	0.988	0.49
Jensen-Haise	0.817	0.988	0.48
Clear sky			
Blaney-Morin-Nigeria	0.927	0.985	0.63
Hargreaves	0.984	0.992	0.46
Jensen-Haise	0.874	0.991	0.47
Pooled data for the three sky conditions			
Blaney-Morin-Nigeria	0.873	0.968	0.78
Hargreaves	0.898	0.984	0.54
Jensen-Haise	0.807	0.985	0.52

4. Conclusions

The solar radiation model BSRM has been shown to be more reliable than HSRM in predicting solar radiation at Ilorin. The model has also been shown to be the better one to use in FAOPM because it yield practically identical daily ET_o estimates with the case when measured solar radiation data was used. This was not the case with HSRM. Furthermore the reported performances of recently proposed models in literature for estimating solar radiation under Nigerian conditions were not clearly superior to that of BSRM despite the fact that the models considered monthly average daily solar radiation which comprises less noisy data set than actual daily values considered by BSRM.

The comparisons of the predictions of the simpler ET_o models with those of FAOPM highlighted influence of the solar radiation estimation methods on the quality of outcomes. Generally the performances of HGRV and JHSE improved with the reliability of the solar radiation method. The reliability of the solar radiation models decreased with increasing sky cloudiness, As a consequence, the performance of the simpler models were generally better under clear than partly cloudy or cloudy sky conditions when the less reliable HSRM was used to estimate solar radiation in HGRV and JHSE.

On the basis of the relative performance of the simpler models and ease of application, HGRV was recommended for use in the regression equation (i.e. Equation (15)) for estimating FAOPM predictions when the application of FAOPM is necessary but not feasible. Provided the appropriate value of α is selected (see Tables 4 and 5), ET_o obtained with HGRV using HSRM or BSRM could be used with practically the same outcome. Employing ET_o obtained with HGRV using HSRM and the appropriate α-value may however be more expedient. The α-values specific to sky conditions are to be preferred to those for pooled data since the former would yield lower standard errors of estimation. Penman-type combination equations are wind-sensitive (Fischer *et al*., 2005; Schneider *et al*., 2007). It should therefore be noted that the calibration results reported in this study may be limited in application to tropical environments where the radiation component predominates over the aerodynamic component of the evapotranspiration process.

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