IMPROVEMENT OF THE PREDICTIONS OF A TEMPERATURE-BASED SOLAR RADIATION MODEL USING EMPIRICAL ADJUSTMENT FACTORS AT A TROPICAL STATION ILORIN, NIGERIA

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ABSTRACT
Adjustment factors for the predictions of the temperature-based Hargreaves solar radiation model were derived using historical (1996 to 2001) daily weather data for Ilorin, Nigeria. The adjustment factors (ρ) were estimated as ratiosof observed to predicted global solar radiation. The average daily ρwere determined as a Fourier series function of Julian day by fitting the historical average dailyρ to the function. The year was also delineated into three seasons namely, Cool dry Harmattan, Hot dry with Early Rains and Cool Rainy seasons and the average ρ for each season determined. The annual average ρ was also obtained. The periods of the seasons were considered to be November through December to February for the first, March to May for the second and June to October for the third. Their determined ρ-values were 0.869, 0.987 and 0.856 for the Cool dry Harmattan, Hot dry with Early Rains and Cool Rainy respectively. The annual average value was 0.894. The adjustment factors were tested by applying them to the predicted daily solar radiation for the period 2002 to 2005. The daily observed solar radiation for the period were compared with both the adjusted and unadjusted Hargreaves model predictions. The mean and root mean square of the prediction errors were found to be substantially reduced by the application of the adjustment factors. The seasonal factors were therefore recommended for locations with weather conditions similar to Ilorin but with different timings for the seasons.

INTRODUCTION

Knowledge of global solar radiation (R_s) at the earth's surface is important in agricultural applications such as design and operation of solar drying and other solar-powered systems. It is indispensable in the estimation of crop evapotranspiration, and simulation crop growth and yield. Other areas where it is required include hydrology, meteorology and environmental sciences. Due to the cost of acquisition, operation and maintenance of the required instrumentation, measured R_s data is frequently lacking in weather stations. In Nigeria, historical data on directly-measured R_s is usually not available at the weather stations of Nigerian Meteorological Agency (NIMET).

As an alternative to direct R_s measurement, several models of varying complexity and input data requirements have been developed for estimating R_s from other more easily measured weather data. A review of the models has been made by Tolabi *et al.* (2014). Babatunde (1989) based on a review of existing R_s models proposed an empirical model for a tropical station in Nigeria. The model was found to be more suitable than the popular Angstrom-type (Angstrom, 1924) model and this finding was corroborated by Ejieji (2002). However, a major limitation in routine application of the model is the required input data which are sunshine hours, average day-time temperature and day-time visibility. The last two are to be derived from the averages of 3-hourly observations between 6 h and 18h GMT. A more feasible alternative would therefore be the simpler temperature-based models. The most popular of such models is the Hargreaves model (Hargreaves, 1994; Allen et al., 1998) which requires daily maximum and minimum temperature as the only input data. The model has however been found to generally over-predict R_s with the prediction error increasing inversely with observed $R_s$at Ilorin, Nigeria (Ejieji, 2011).

The objectives of this study were therefore to (i) determine empirical factors for adjustment of the predictions of the original Hargreaves (Allen et al., 1998) model; and, (ii) evaluate the performance of the model with and without adjustment. The empirical factors were in the form of ratios of observed to predicted R_s which were obtained using the original Hargreaves model with historical input data.

MATERIALS AND METHOD

Location of the study

The study location Ilorin is approximately on latitude 80 28^{o} N and longitude 4o 40^{o} E at an elevation of about 340 m above mean sea level. It iswithin 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 part of the dry season fromNovember through December to February is the Harmattan period when cool, dry and dusty wind, which generate substantial amounts of aerosols, blows from the Sahara desert.

Meteorological data collection and pre-processing

Observed daily data which included R_s, air temperature (T) and relative humidity (RH) were obtained from Department of Physics (DOP), University of Ilorin for the period of January 1996 to July, 2005 that they were available. The data R_s data were measured with Eppley precision spectral pyranometer while a combined temperature-humidity sensor was used for T and RH. All the data were logged at one-minute intervals.For the purpose of this study, daily maximum (Tmax) and minimum (Tmin) temperatures were respectively determined from themaximum and minimum instantaneous values of the logged data while average day-time temperatures were obtained by numerical integration of over day-time hours. The daily R_s was obtained by numerical integration of the logged data and application of the pyranometer calibration constant. The constantof 8.69×10^{-6}V/ W m^{-2}was applied generally with the exception of Year 2000 data for whichthe constant of 8.22×10^{-6}V/ W m^{-2} used.

In order to aid data quality checks, daily data on Tmax, Tmin and, sunshine hours, as well as those on synoptic 3-hourly T andvisibility (VIS) were obtained for Ilorin from NIMET. In addition, data on Tmax, Tmin, and sunshine hours were obtained from the National Centre for Agricultural Mechanization (NCAM), Idofian, near Ilorin and used to fill the missing records in the NIMET data following the method that has been described by Ejieji (2011). The criteria used for quality assessment of the DOP data on daily basis were as follows. The temporal pattern and values of the T from DOP and NIMET must be comparable. Days having relatively high values of average day-time T, VIS and sunshine hours were not expected to have unreasonably low R_s and vice-versa. All data not meeting the criteria were deemed to be coming from malfunctioning sensors or ancillary equipment and were therefore rejected.

Determination of the adjustment factors

Using the DOP data for the period 1996 to 2001, daily $R_s$was first predicted using the Hargreaves solar radiation equation expressed as follows(Allen et al., 1998)

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

where R_a is extraterrestrial radiation (MJ m^{-2} d^{-1}), T_{max} and T_{min}, are, respectively, maximum and minimum temperatures (^{o}C) and K_R is an empirical coefficient in the range of 0.16 to 0.19. K_R-value of 0.16, recommended for interior locations (Allen *et al*., 1998), was adopted.R_a was computed as described by Ejieji (2011).

The predicted R_s was then used to divide the corresponding observed $R_s$to obtain the adjustment factor. Three categories of adjustment factors were considered namely, daily average, seasonal average and annual average factors. For the seasonal factors the year was considered to be made up of three seasons namely, Cool dry Harmattan, Hot dry with Early Rains and Cool Rainy seasons. The periods of the seasons were considered to be November through December to February for the first, March to May for the second and June to October for the third. The computed adjustment factor of each day was allotted to a particular season depending the date of the year after which the averages of the daily factors allotted to each of the seasons were computed and taken to be the seasonal average adjustment factors. The mean of all the computed adjustment factors was taken as the annual average adjustment factor.

For estimation of the daily average adjustment factor, the means for each of the 365 Julian days of the year were computed and fitted to the following Fourier series expression to obtain the average daily adjustment factor as a function of Julian day.

$$x_t = \mu + \sum_{j=1}^{m}\left(A_j \cos\frac{2\pi jt}{\omega} + B_j \sin\frac{2\pi jt}{\omega}\right) \qquad (1)$$

Where x_t is the average adjustment factor for Julian day t, μ is a constant term equal to the general mean of the series, A_j and B_j are coefficients, m is the number of the significant harmonics and $\omega$the value of which is 365 for this study represents the reciprocal of the fundamental frequency. The least squares estimates of the coefficients were obtained using the following equations (Box et al, 1994)

$$\left.\begin{aligned} A_j &= \frac{2}{N}\sum_{t=1}^{N} x_t \cos\left(\frac{2\pi jt}{\omega}\right) \\ B_j &= \frac{2}{N}\sum_{t=1}^{N} x_t\, sin\left(\frac{2\pi jt}{\omega}\right) \end{aligned}\right\} \quad j = 1, 2, \ . \ . \ ., q \qquad (2)$$

Where N is the number of data in the series (365 in this study) and q = (N – 1)/2. q being even made B_q to be zero (Box et al, 1994). After the estimation of the coefficients the number of significant harmonics was estimated as outlined by Yevjevich (1974).

Testing of the adjustment factors

DOP data on Tmax and Tmin for the period 2002 to 2005 were used with Equation (1) to obtain R_s predictions which were then adjusted using the factors that have been estimated. The adjusted predictions were compared with observed R_s data using as indices the mean error and root mean square error of the predictions. The indices were expressed as follows.

$$ME = \sum_{i=1}^{K} 100\left(\frac{Y_{o,i}-Y_{p,i}}{Y_{o,i}}\right) \quad (3)$$

$$RMSE = \left[\frac{1}{K}\sum_{i=1}^{K}\left(100\,\frac{Y_{o,i}-Y_{p,i}}{Y_{o,i}}\right)^2\right]^{1/2} \quad (4)$$

In Equations (3) and (4), Y_o is the observed R_s, Y_p is the adjusted prediction of Equation (1) and K is the number of pairs of data compared.

RESULTS AND DISCUSSION

The average daily values of some meteorological variables for the months of the year are presented in Table 1. The months of the season denoted as Hot dry with Early Rains had the highest insolation as could be inferred from the their R_s. Their values for VIS, sunshine hours and temperatures were also the highest. The Cool Rainy season months recorded the lowest Tdtime and highest relative humidity while Tmin and VIS were lowest for Cool dry Harmattan.

Table 1. Monthly average daily values of some meteorological data at Ilorin for the period (1996 – 2005) covered by the study

Month	Tmax (°C)	Tmin (°C)	Tdtime (°C)	RH_10h (%)	RH_16h (%)	Vis (km)	Sun (h)	Solar Rad (MJ m^{-2} d^{-1})
Jan	34.2	20.5	27.6	55.4	23.3	6.8	6.8	15.0
Feb	35.9	22.5	29.6	54.6	23.3	8.8	7.6	18.8
Mar	35.9	23.6	30.3	67.6	36.1	12.8	7.9	19.8
Apr	34.0	23.5	29.5	66.9	47.5	14.9	7.6	19.4
May	32.2	22.5	28.2	73.2	59.2	14.5	7.2	18.4
Jun	30.4	21.6	26.3	73.7	63.1	14.1	6.3	15.9
Jul	28.7	21.5	25.1	77.6	68.8	13.2	4.6	13.4
Aug	28.0	21.4	24.6	90.8	76.8	13.2	3.5	12.2
Sep	29.7	21.2	25.2	90.3	74.6	13.2	4.0	14.5
Oct	31.9	21.5	26.6	86.8	65.2	12.8	5.7	16.7
Nov	34.3	20.9	28.1	77.7	39.6	12.4	7.6	17.5
Dec	34.3	19.9	27.7	65.7	29.5	9.4	7.7	15.6

Tmax, Tmin and Tdtime = maximum, minimum and average day-time temperatures respectively; RH_10h and RH_16H = relative humidity at 10 h and 16 h GMT respectively; Vis = average day-time visibility; Sun = sunshine hours; Solar Rad = Global solar radiation.

The plot of the computed average daily adjustment factors is shown Figure 1. It should be noted that although 6-year (1996 to 2001) data were used in computing the daily average, not all the Julian days had 6 individual values of adjustment factor because of the data quality criteria adopted. The actual numbers for the Julian days ranged from 4 to 6. Also shown in Figure 1 is the plot of the fitted Fourier function. Only the first three harmonics were found to be significant at 0.05 level. This finding is consistent with that of Adeyemo (2006) in which the first three harmonics were significant in a Fourier series fit of solar radiation data. The parameters of the fitted Fourier function are presented in Table 2. Theseasonal and annual adjustment factors obtain areshown in Table 3.

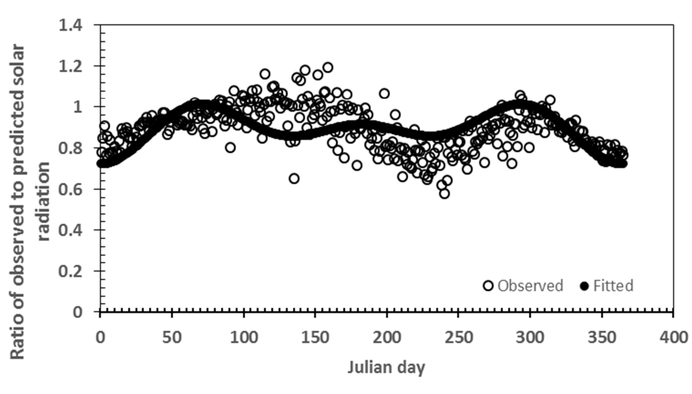

Figure 1 Daily averages of the ratio of observed to predicted solar radiation (The original Hargreaves model (Allen et al., 1998) was used for the prediction).

Table 2. The coefficients and constant terms in the Fourier series representation of ratio of observed to predicted solar radiation as a function of Julian date

	Values of the coefficients for the significant harmonics	
i	A_i	B_i
1	0.010493	-0.010482
2	-0.038353	-0.038332
3	-0.037256	-0.037224
	(μ)	0.8941

i = significant harmonic; A_i = coefficient of the cosine term;
B_i = coefficient of the sine term; μ = constant term

Table 3. Ratio of observed to predicted solar radiation solar radiation (ρ)obtained for the seasons (The original Hargreaves model (Allen et al., 1998) was used for the prediction).

Season	Definition	Period at Ilorin	P
1	Cool dry Harmattan	Nov., Dec., Jan. to Feb.	0.869
2	Hot dry with Early Rains	Mar. to May	0.987
3	Cool Rainy	Jun. to Oct.	0.856
	Annual	Jan. to Dec.	0.894

Table 4. Summary of the performance of the Hargreaves model without and with adjustment of the predictions using the various adjustment factors.

*Statistic	Values for the various adjustment ratios			
	Unadjusted	Daily-based	Seasonal-based	Annual-based
Mean error (%)	-14.77	-1.60	-3.02	-2.62
RMSE (%)	24.53	17.07	17.51	17.71
Maximum error (%)	27.23	34.45	37.68	34.93
Minimum error (%)	-155.10	-129.85	-118.46	-128.09

*For mean, maximum and minimum error, positive and negative values imply under-prediction and over-prediction respectively
RMSE = root mean square error.

The summary of the comparisons of the adjusted and unadjusted model predictions is presented in Table 4.It shows that substantial improvement was achieved in model predictions following the adjustment. The daily-based adjustment factor better results in terms of mean prediction error. It should be noted with respectto the errors that the reported extrema were recorded only once for each. The minimum (that is, maximum negative value) occurred on 12th September 2003 having Tmax, Tmin and Tdtimeof 23.9, 20.1 and 21.9 °C respectively. The RH_10h and RH_16H were 100.0 and 89.2% respectively while the Rs was 4.5 MJ/m2. The sky clearness index (Babatunde and Aro, 1995), that is, the ratio $\frac{R_s}{R_a}$ was 0.12. The day was therefore cool and humidwith overcast sky condition leading to the substantial over-prediction of R_s.

It should be pointed out that the adjustment approach in this study is different from that proposed by Allen(1997). His approach was not followed in this study because availability of near-clear sky ($\frac{R_s}{R_a} \approx 1$) conditionsduring peak insolation seasons is a requirement for its successful outcome. It is therefore not feasible in the generally cloudy skies of tropical regions. For the period of the study, the average values of $\frac{R_s}{R_a}$were 0.51, 0.52 and 0.40 for the Cool dry Harmattan, Hot dry with Early Rains and Cool Rainy seasons respectively. In the approach proposed by this study, the original Hargreaves model (Allen, 1998) is to be applied as-is and the predictions adjusted with the derived adjustment factors.

CONCLUSIONS AND RECOMMENDATIONS

Application of the adjustment factors have been shown to improve the predictions of the Hargreaves solar radiation model. The factors derived in this study should therefore be useful for other locations with conditions similar to Ilorin. The use of the seasonal factors is recommended for such locations where the timing of the seasons are different. Further testing of the factors at other locations is recommended to ascertain the general applicability of the conclusions reached in this study.

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