Estimation of daily solar radiation at equatorial region of West Africa using a more generalized #ngström-based broadband hybrid model

T. A. Otunla

Meteorology and Atmospheric Physics

ISSN 0177-7971
Volume 132
Number 3

Meteorol Atmos Phys (2020)
132:341-351
DOI 10.1007/s00703-019-00691-8

Springer

Meteorology and Atmospheric Physics (2020) 132:341–351
https://doi.org/10.1007/s00703-019-00691-8

ORIGINAL PAPER

Estimation of daily solar radiation at equatorial region of West Africa using a more generalized Ångström-based broadband hybrid model

T. A. Otunla[1]

Received: 3 May 2018 / Accepted: 19 August 2019 / Published online: 7 September 2019

Abstract
A well-calibrated simple and economical viable Ångström–Prescott model has long been accepted to be more accurate than other surface meteorological data-based models. The major limitation is that it is site dependent. This study exploited the appropriateness of a more generalized Ångström-based broadband hybrid model in the estimation of solar radiation at seven stations in equatorial region of West Africa. This model features parametric equations that explicitly and accurately account for clear-sky damping processes in the atmosphere. It empirically estimates cloudy sky radiation extinctions using relative sunshine duration. A new cloud transmittance calibration curve that followed the cloud cover patterns of the region of study was also tried. The result indicated that the new cloud transmittance could be unique to equatorial region of West Africa. The performance of the hybrid model, after modification using the new cloud transmittance equation, was tested using mean bias error and root mean squared error. The performance was found to be comparable to the site-dependent, locally calibrated, Ångström–Prescott model at the calibration stations, and even better at validation stations. The same performance test comparisons with the original version of the hybrid model, and four other site-independent models: globally calibrated, FAO-recommended Ångström–Prescott models, Hay and Gopinathan models indicated the modified version of the hybrid model as better

1 Introduction

Daily solar radiation is an important parameter required in the fields of agriculture, hydrology and meteorology. It provides energy for processes that drive photosynthesis and evapotranspiration in the crop growth models, and it is also a necessary requirement in the calculation of water requirements for irrigation schedules (Hoogenboom 2000; Pohlert 2004). In spite of its importance, solar radiation measurements are sparsely deployed in both developing and developed countries (Hunt et al. 1998; Liu and Scott 2001). There are about just 40 weather stations in UK which collect solar radiation data (Miller et al 2008). There are 122 solar radiation stations built in Mainland China (Tang et al. 2010). Developing regions of the world like West Africa even fair worse. The possible reasons for paucity in radiation measurements all over the world as compared to other meteorological parameters are possibly due to high cost, maintenance, and calibration requirements of the measuring equipment (Thornton and Running 1999). The limited coverage of radiation measuring networks, therefore, dictates the need for developing solar radiation models. There are complex spectral models, broadband single and multi-layer radiative transfer models, and surface meteorological data-based empirical models. In hydrological and crop growth models, empirical solar radiation models are, however, the most popular because of the accessibility of requisite meteorological data and computational cost. The empirical models are either sunshine duration-based (Ångström 1924; Prescott 1940), air temperature-based (Bristow and Campbell 1984; Thornton and Running 1999; Meza and Varas 2000; Weiss and Hays 2004) or cloud-based (Nielsen et al. 1981; Supit and van Kappel 1998; Ehnberg and Bollen 2005). A sunshine-based Ångström–Prescott equation (Ångström 1924; Prescott 1940):

$$E/E_{\mathrm{o}} = a + bn/N, \tag{1}$$

where E is the solar radiation, E_0 the extraterrestrial solar radiation, n the sunshine duration, N the maximum possible

Responsible Editor: M. Telisman Prtenjak.

✉ T. A. Otunla
biodunotunla@gmail.com

[1] Atmospheric Physics Research Unit, Department of Physics, University of Ibadan, Ibadan, Nigeria

sunshine duration, parameters a and b are regression coefficients and its higher order polynomial equivalents have been widely used by various workers (Adedokun 1978; Bamiro 1983; Balogun 1991; Thornton and Running 1999; Akpabio 2002; Falayi et al. 2008; Ogolo 2010; Adaramola 2012) and have been shown to be better than either temperature-based or cloud-based models when they are well calibrated (Iziomon and Mayer 2001; Pohlert 2004; Almorox et al. 2011).

The need to calibrate the parameters of Eq. 1 and its higher order polynomials to reflect the climate of the region where it is used, for its estimates to be reliable is a major limitation of these empirical models (Wong and Chow 2001; Liu et al. 2009). This limitation is intrinsically embedded in bulk nature of the transmittance of Ångström–Prescott models, that is, a and b (Tang et al 2010). There had been some attempt at generalization to build site-independent models by relating a and b to other parameters like altitude, latitude, cloud-cover, albedo, and air mass. For instance, Gopinathan (1988) relates a and b to latitude, altitude, and percentage of possible sunshine while Chen et al. 2018, in a recent study, relate them to altitudes for Yangtze river basin. Yang et al. (2001) exploited a more generalized hybrid model that retains the original version of Ångström model (Ångström 1924) and calculates solar radiation transmittances in the clear sky by explicitly accounting for radiation damping processes due to air mass, aerosols, water vapor, and ozone. A later improvement to all-sky empirically relates solar radiation transmittance for cloudy sky to relative sunshine duration (n/N) (Yang and Koike 2005; Yang et al. 2001, 2006a, b). In Yang and Koike (2005) and Yang et al. (2006a, b), the model was calibrated with data from Japan (i.e., a sub-tropical to temperate climate region: 24–45°N) and was validated with data from USA (a sub-tropical to temperate climate region: 26.2–36.28°N), Japan, Saudi Arabia (arid climate region: 16.9–28.32°N), and China (a sub-tropical to temperate climate region:18.32–39.47°N) under varying elevations, from lowland areas to highland areas against Japanese and globally calibrated Ångström–Prescott models and others with proven higher performances especially for hourly, daily, and highland areas. Also, Tang et al. (2010) evaluated the performance of this model in estimating daily and monthly global solar radiation against observations at 97 China stations after quality control and obtained satisfactory results. This current work attempts to exploit this more generalized solar radiation model in equatorial region (0–9.28°N) of Nigeria in West Africa, and to demonstrate and justify the need for a separate solar radiation transmittance for cloud in the region.

2 Data

Data of global solar radiation, air temperature, air pressure, and relative humidity measured at 5 min intervals for seven stations covering different climates zones in Nigeria were obtained from TRODAN data sets situated in Centre for Atmospheric Research, National Space Research and Development Agency (CAR-NSRDA) in Nigeria. Data of actual sunshine duration were not measured directly at these stations. Their values were estimated based on the definition of sunshine duration by WMO as the length of time for which direct solar radiation exceeds a threshold (T) of 120 W/m^2. Gueymard 1993 examined T values of 5, 60, 120, 180, and 240 W/m^2 for both direct and global solar radiation. His work indicated that coefficient of correlation between clearness index and relative sunshine duration is highest at $T = 120$ W/m^2 for direct solar radiation and only increases slightly at $120 \leq T \leq 240$ W/m^2 (i.e., $0.959 \leq R \leq 0.970$) for global radiation. In this work, the actual sunshine duration was extracted from global solar radiation using $T = 210$ W/m^2. The Ångström turbidity data are produced by the GADS (Global Aerosol Data Set 2.2a; see Koepke et al. 1997 and Hess et al. 1998) model. The thickness of ozone layer is obtained from TOMS (Total Ozone Mapping Spectrometer) zonal means provided by NASA/GSFC Ozone Processing Team (see https://toms.gsfc.nasa.gov/ozone/ozone_v8.html). Geographical information and annual-mean climatological data for the stations used in the study are listed in Table 1.

3 Description of the broadband all-sky model

The solar radiative transfer model used in this study is an all-sky radiation model (hereafter known as hybrid model) that combined parameterization of broadband transmittances for clear sky and empirical transmittance for cloudy sky (Yang et al. 2001, 2006a, b; Yang and Koike 2005). The transmittances that were used to quantify the five notable damping processes under clear sky had been adjudged to be high performers (Gueymard 2003a, b; Paulescu and Schlett 2004; Madkour et al. 2006). The model for daily radiation is described by the following mathematical equations:

$$E = E_{\text{clear}}\tau_{\text{c}}, \tag{2}$$

$$E_{\text{clear}} = E_{\text{b clear}} + E_{\text{d clear}}, \tag{3}$$

where E (MJ/m^2) is the all-sky daily global radiation (hereafter known simply as solar radiation), E_{clear} (MJ/m^2) is clear-sky daily global radiation, and τ_{c}, is the daily mean global transmittance due to cloud absorption and scattering. Yang and Koike (2005) empirically relate τ_{c} to relative sunshine duration (n/N_{clear}) as:

$$\tau_{\text{c}} = 0.2505 + 1.1468\,(n/N_{\text{clear}}) - 0.3974(n/N_{\text{clear}})^2, \tag{4}$$

Using data from 12 stations located in the lowland, humid region of Japan (i.e. the stations have humidity ranging between 55 and 75%, and altitude ranging between 0 and

Table 1 Geographical and annual-mean climatological data at calibration and validation stations

Climate zone	Site	Acronyms	Latitude (°N)	Longitude (°E)	Altitude (m)	Period	Air. temperature (°C)	Relative humidity (%)	Global radiation (MJ/m^2/day)
Monsoon (Am)									
	Yola	YO	9.28	12.38	260	2009–2012	29.4	40.3	18
	Abuja	AB	9.07	7.48	536	2007–2010	27.8	65.2	14.4
	+Lapai	LA	9.03	6.82	242	2010–2012	27.5	62.1	15.8
	+Anyigba	AN	7.25	7.18	420	2010–2013	25.7	68.3	13.4
	+Akure	AK	6.96	4.6	131	2010–2011	25	78.1	13.3
	Nsuka	NS	6.85	7.4	359	2007–2013	26.1	69.6	11.5
Tropical savannah (Aw)									
	Lagos	LAG	6.6	3.34	39	2007–2008	27.8	76.6	10.2
	Port Harcourt	PH	4.78	6.98	7	2008–2011	27.1	78.8	10.7

Annual rad. is the annual mean daily solar radiation. The stations are classified into climate zone based on Koppen climate classifications. + Represent the calibration stations

610 m). Where n is the sunshine duration and N_{clear} is the maximum possible sunshine duration. $E_{\text{b,clear}}$ (MJ/m^2) and $E_{\text{d,clear}}$ (MJ/m^2) are the daily direct radiation and diffuse solar radiation received at the ground level under clear skies, respectively. They are calculated as follows:

$$E_{\text{b,clear}} = \int_{t1}^{t2} E_0 \bar{\tau}_{\text{b}} \mathrm{d}t, \tag{5a}$$

$$E_{\text{d,clear}} = \int_{t1}^{t2} E_0 \bar{\tau}_{\text{d}} \mathrm{d}t, \tag{5b}$$

where E_0 (W/m^2) is the solar constant and t_1, t_2, $\bar{\tau}_{\text{b}}$, and $\bar{\tau}_{\text{d}}$ are the sunrise (s), sunset (s), broadband normal radiative transmittance and diffuse radiative transmittance, respectively. The transmittance are approximated as given in Yang et al. (2006a, b) by

$$\bar{\tau}_{\text{b}} \approx \max(0, \vec{\tau}_{\text{oz}}\vec{\tau}_{\text{w}}\vec{\tau}_{\text{g}}\bar{\tau}_{\text{r}}\bar{\tau}_{\text{a}} - 0.013), \tag{6a}$$

$$\vec{\tau}_{\text{d}} \approx \max\{0, 0.5[\vec{\tau}_{\text{oz}}\vec{\tau}_{\text{w}}\vec{\tau}_{\text{g}}(1 - \vec{\tau}_{\text{r}}\vec{\tau}_{\text{a}}) + 0.013]\}, \tag{6b}$$

where $\vec{\tau}_{\text{r}}$, $\vec{\tau}_{\text{a}}$, $\vec{\tau}_{\text{oz}}$, $\vec{\tau}_{\text{w}}$ and $\vec{\tau}_{\text{g}}$ are the solar transmittances of five radiative extinction processes in the atmospheric layer for Rayleigh scattering, aerosol extinction, ozone absorption, water vapor absorption, and permanent gases absorption, respectively. The input parameters for calculating these transmittances are the precipitable water w (g/cm^2), Ångström turbidity, ozone layer thickness, surface elevation, and surface air pressure.

In the model, the precipitable water w (cm) is estimated from surface relative humidity h_{r} (%) and air temperature T_{a} (K) by a semi-empirical formula:

$$w = 0.00493 h_{\text{r}} T_{\text{a}}^{-1} \exp[26.23 - 5416 T_{\text{a}}^{-1}] \tag{7}$$

Yang and Koike (2005) combined Eqs. 2 and 4 to obtain a parametric model for estimating daily all-sky solar radiation (hereafter known as hybrid model) as:

$$E = \tau_{\text{c}} E_{\text{clear}} = (0.2505 + 1.1468(n/N_{\text{clear}}) - 0.3974(n/N_{\text{clear}})^2) E_{\text{clear}}. \tag{8}$$

4 A new radiative transmittance for cloud

The effects of cloud extinction on solar radiation were investigated by developing a new radiative transmittance for cloud using the pool of data at the calibration stations. The transmittance is defined as the ratio of solar radiation E (W/m^2) to that under clear sky E_{clear} (W/m^2). That is,

$$\tau_{\text{c}} = E/E_{\text{clear}}. \tag{9}$$

Excluding the damping processes that characterized the clear-sky solar radiation, τ_{c}, according to Ångström (1924) is linearly related to the daily average of relative sunshine duration as

$$E/E_{\text{clear}} = a + bn/N, \tag{10a}$$

Recent studies had shown that polynomial function such as

$$\tau_{\text{c}} = b_1 + b_2 n/N_{\text{clear}} + b_3 (n/N_{\text{clear}})^2, \tag{10b}$$

are much more accurate (Suehrcke et al. 2013), where N_{clear} is the modified day length. Figure 1 gives the calibration curve for Eq. (10b) and hence, a new radiative transmittance for cloud was obtained as

$$\tau_{\text{c}} = 0.1397 + 0.5572 n/N_{\text{clear}} + 0.4414 (n/N_{\text{clear}})^2 \tag{11}$$

Equation 11 was used to replace Eq. 4 in the original version of hybrid model (Eq. 8) to derive a modified version

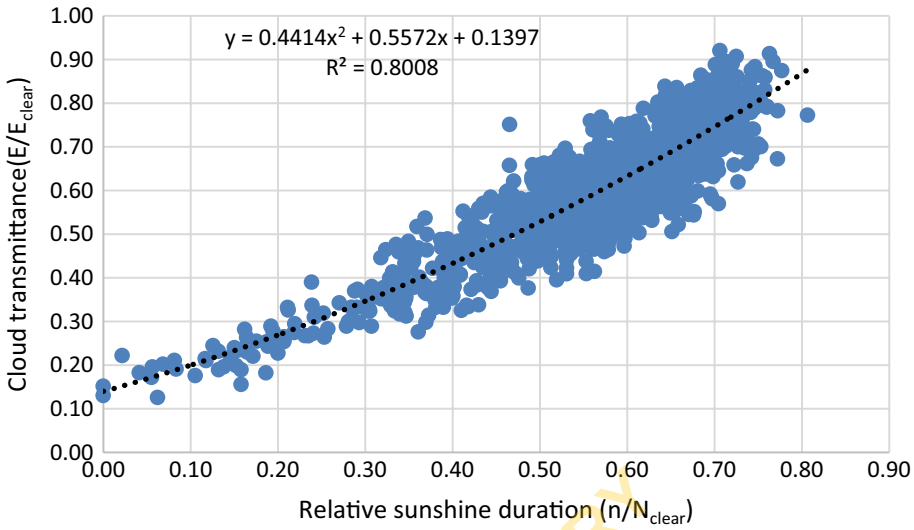

Fig. 1 Calibration curve for solar radiation transmittance for cloud using the pool of data from all the calibration stations in Table 1

of hybrid which should be more appropriate for equatorial region of West Africa.

5 Solar radiation models for comparisons

The FAO (Allen et al 1998) recommended the values of 0.25 and 0.5 for a and b in Eq. (1), respectively, for locations where actual solar radiation data are not available and no calibration has been carried out to derive regression coefficients a and b.

Gopinathan (1988) (hereafter known as GOP model) suggested the regression coefficients a and b in Eq. (1) in terms of the latitude, elevation, and percentage of possible sunshine for any location around the world as:

$$a = -0.309 + 0.539\cos\varphi - 0.0693h + 0.29n/N, \tag{12}$$

$$b = 1.527 - 1.027\cos\varphi + 0.0926h - 0.359n/N, \tag{13}$$

where ϕ is the latitude and h is the altitude above the sea level.

Hay (1979) (hereafter known as Hay model) considered the effects of cloud cover, ground reflectivity, and average air mass on the coefficients and proposed a site-independent correlation using data collected from western Canada as

$$\frac{E}{E_0} = \frac{0.1572 + 0.556(n/N)}{1 - \rho_g\left[\rho_a(n/N) + \rho_c(1 - (n/N)\right]} \tag{14}$$

where ρ_g, ρ_a,and ρ_c are ground, clear sky, and cloud albedo, respectively. Constant values of 0.25 and 0.6 are provided for clear sky and cloud albedo, respectively.

Yang and Koike (2005) used a pool of data from 12 stations in Japan (humid climate), 4 stations in the USA, and 4 stations in Saudi Arabia (dry climate) to derive a global Ångström–Prescott model (hereafter known as global model) of the form

$$E/E_0 = a_1 + a_2 n/N + a_3(n/N)^2, \tag{15}$$

where E_0 is the extraterrestrial solar radiation at the horizontal level at the top of the atmosphere and a_1, a_2, and a_3 are Ångström–Prescott's regression coefficients from the calibrations with the values 0.1715, 0.8419, and − 0.3206, respectively.

New coefficients were also obtained for Eq. 15 using the data at the calibration stations (Table 1) to develop a locally calibrated Angstrom–Prescott model (hereafter known as Nigerian A–P) at $R^2 = 0.81$ (Fig. 2) as:

$$E/E_0 = 0.0965 + 0.3815(n/N) + 0.3098(n/N)^2. \tag{16}$$

6 Models comparisons

The above listed models (Eqs. 1, 8, 12–16, with the various and appropriate coefficients) were used to estimate the daily mean solar radiation at all the stations listed in Table 1 excluding Akure because of the shortness in the duration of measurements at the station.

Model performances were evaluated using mean bias error (MBE) and root mean square error (RMSE).

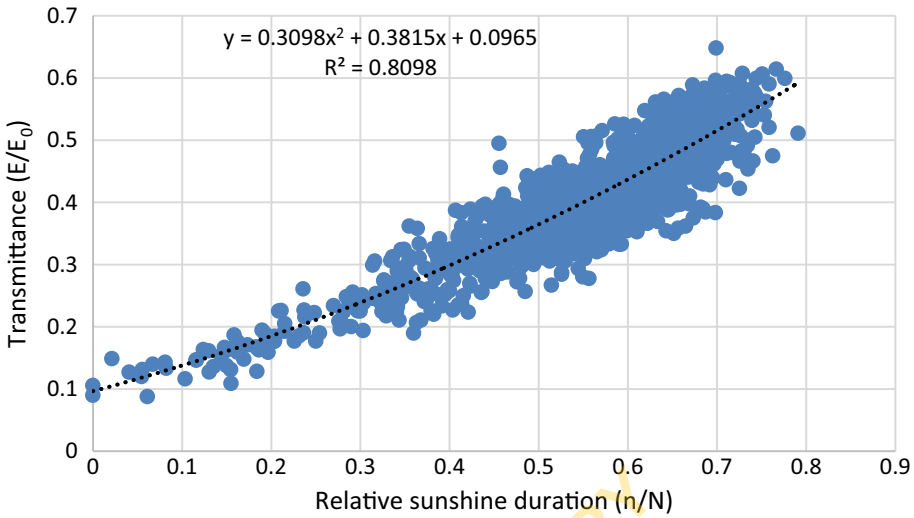

Fig. 2 A new Ångström–Prescott model (A–P model) developed from the pool of data in all the calibration stations in Table 1

Table 2 Monthly variation of Clearness Index (E/E_{clear}) and relative sunshine duration (n/N) at the calibration stations

Month	n (h)	E (MJ/m^2)	n/N_{clear}	E/E_{clear}
January	6.8	13.4	0.6	0.6
February	6.8	14.8	0.6	0.6
March	6.8	14.6	0.5	0.6
April	7.3	16.7	0.6	0.6
May	6.7	15.3	0.5	0.6
June	6.8	14.6	0.5	0.6
July	6.3	13.6	0.5	0.5
August	5.2	11.6	0.4	0.4
September	6.1	13.6	0.5	0.5
October	6.5	14.1	0.6	0.6
November	6.5	14.7	0.6	0.7
December	6.8	14.2	0.6	0.7

7 Results

7.1 Weather conditions and transmittance for cloud at the calibration stations

The monthly mean daily global solar radiation, actual sunshine duration, relative sunshine duration, and Clearness Index from the pool of data at the calibration stations are given in Table 2. The rainy season months (April–October) have lower values of both relative sunshine duration (n/N) and Clearness Index ($\tau_c = E/E_{clear}$) compared with the dry season months (November–March). These low values of Clearness Index were indicated by Suehrcke et al. (2013) to be latitude dependent as values ranging from 0.66 at sites located in equatorial humid region to 0.77 for sites at low humidity, and higher latitudes were observed by using monthly data. August has the lowest values of both n/N and τ_c. Using the weather condition classification proposed by Igbal (1980), which are (1) heavily overcast weather for $\tau_c \leq 0.4$, (2) partly overcast weather for $0.4 \leq \tau_c \leq 0.6$, and (3) clear weather $\tau_c \geq 0.7$, the likelihood of cloudy weather event is given in Fig. 3a. It was shown that the prevailing weather condition for all the months is partly overcast. Month of April through to October that corresponds to the rainy season is heavily overcast. August is the cloudiest month even though September has the highest number of rainy events (61.8%). Based on relative sunshine duration classification scheme reported by WMO (2008), that is, (1) cloudy sky ($0 \leq n/N \leq 0.3$), (2) scattered clouds sky ($0.3 \leq n/N < 0.7$), and (3) clear sky ($0.7 \leq n/N < 1.0$), the prevailing weather condition at the calibration stations is scattered clouds sky (Fig. 3b).

Figure 4 gives various comparisons of transmittances using Eqs. 11 and 16 developed from all the data at the calibration stations and those developed elsewhere (Eqs. 1, 4, and 15). Equation 1 utilized the recommended coefficient of FAO model. The values of transmittances generated based on Angstrom–Prescott model (Eq. 16) using Nigeria data are indicated to be lowest for all n/N values considered. The Nigerian-based cloud transmittances generated from Eq. 11 have slightly lower values for cloudy condition (i.e., $0 \leq n/N \leq 0.4$) when compared with Japan-based cloud transmittances (Eq. 4) and global-based Angstrom–Prescott transmittance (Eq. 15). However, the Nigerian-based cloud transmittance Eq. 11 is indicated in Fig. 4 to generate the highest values of transmittance for a range of weather events starting from scattered cloudy to clear sky ($n/N > 0.4$). The FAO-based, Japan-based, and global-based transmittances generated from Eqs. 1, 4, and 15, respectively, are indicated to converge to almost a single curve for $0.2 \leq n/N < 0.8$. The values of FAO-based

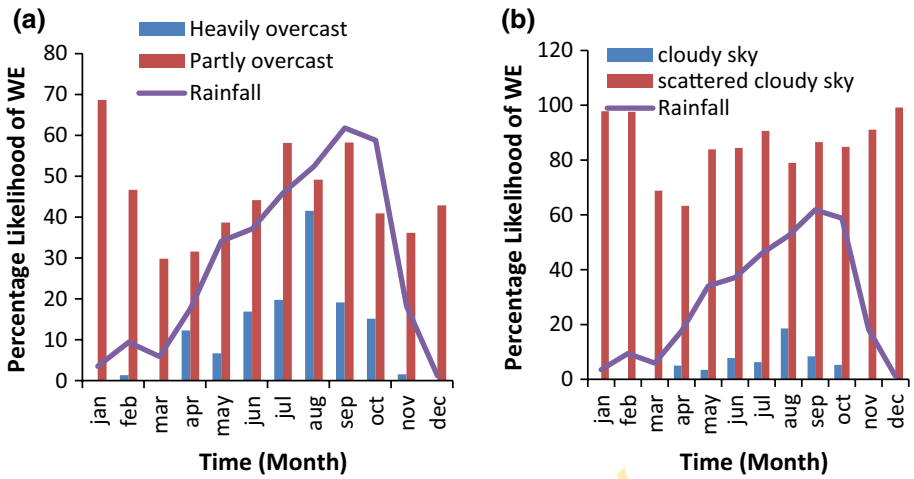

Fig. 3 Monthly variations of the percentage likelihood of weather events (WE), **a** heavily overcast, partly overcast, and rainfall and **b** cloudy sky, scattered cloudy sky, and rainfall from the pool of data at all the calibration stations in Table 1

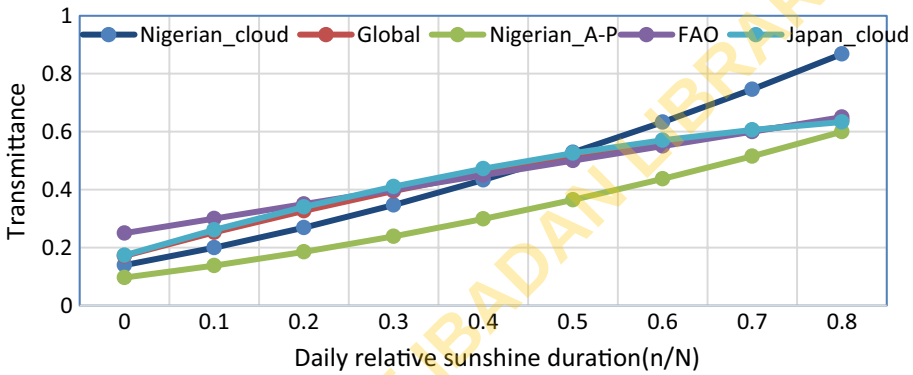

Fig. 4 Relationship between relative sunshine duration (greater than 0) and solar radiative transmittance for cloud and other Ångström–Prescott-based transmittances. Curves labeled "Global" represent the calibrated curve for the 12 Japan Meteorological Agency stations, 4 United States stations, and 4 Saudi Arabia stations. The "Nigerian A–P," curve represents the calibrated curve for Lapai, Anyigba, and Akure data in Nigeria (Table 1). The "FAO" curve represents FAO-recommended parameters. The "Japan_cloud" is the cloud transmittance curve of data from the 12 Japan Meteorological Agency stations. The "Nigerian_cloud" is the cloud transmittance curve representing the calibrated curve for all the data at the calibration stations in Table 1

transmittances are indicated highest for cloudy sky or heavily overcast weather condition.

7.2 Comparisons of solar radiation models

The annual and seasonal comparisons of the performances of five site-independent models, namely, FAO, global, GOP, Hay, hybrid and two new models developed for equatorial region of West Africa were compared using MBE and RMSE (Figs. 5, 6, 7). The new models are: (1) a modified version of hybrid model using a new cloud transmittance developed for equatorial region of West Africa and (2) a second ordered Angstrom–Prescott model developed using the same data in (1) above.

On the annual scale (Fig. 5), the magnitude of MBE and RMSE values for all the site-independent models (i.e., global, GOP, FAO, Hay, and hybrid models) decreased from Port Harcourt (PH: MBE values ranged from − 6.4 to − 5.86 MJ/m^2 and RMSE values ranged from 6.01 to 8.28 MJ/m^2) in tropical savannah to Yola (YO: MBE values ranged from − 1.16 to − 1.12 MJ/m^2 and RMSE values ranged from 2.22 to 2.33 MJ/m^2) in monsoon region with exception of Abuja (AB) where GOP, FAO, and Hay models generated the highest MBE values and Yola where GOP deviated from the normal trend. The performance of the Hay model is comparatively the best at five of the seven locations (PH to AN) of all the site-independent models with MBE values ranging between − 5.86 and − 2.35 MJ/m^2 and RMSE values ranging between 3.04 and 6.01 MJ/m^2 and the statistics are almost equal to that global and FAO at YO. hybrid and FAO models ranked best at Abuja which are the only two excepted station. The GOP model is comparatively the worst of all.

Figure 5 further indicates that the locally calibrated Angstrom–Prescott (A–P) and the modified hybrid model were the best on the annual scales in all the locations considered.

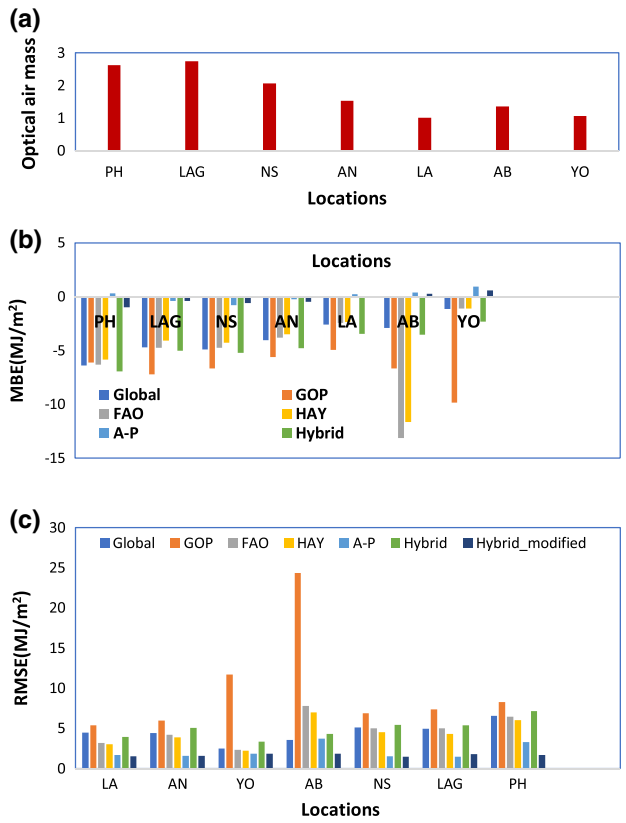

Fig. 5 Annual performances using **a** annual estimates of optical air mass at all stations in Table 1 except Akure in order of increasing latitudes **b** mean bias error (MBE) and **c** root mean squared error (RMSE) of the globally calibrated Ångström–Prescott model (global), Gopinathan model (GOP), FAO-recommended model (FAO), Hay model (Hay), locally calibrated Ångström–Prescott model (A–P), all-sky parametric model (hybrid), and modified all-sky parametric model (Hybrid_modified) in estimating daily solar radiation

For A–P model, the MBE values ranged from − 0.79 to 0.94 MJ/m^2 and RMSE values ranged from 1.46 to 3.69 MJ/m^2 while for modified hybrid model, the MBE values ranged from − 1.0 to 0.57 MJ/m^2 and RMSE values ranged from 1.47 to 1.84 MJ/m^2.

For dry season, the values of MBE (ranging from − 7.59 to − 0.77 MJ/m^2) and RMSE (ranging from 0.8 to 8.89 MJ/m^2) for all the site-independent models showed a more or less decreasing trend from PH to YO with exception of GOP at LA (Fig. 6). Hay model again, was indicated as the best of all the site-independent models from locations PH to LA. It was only out-performed by global model at AB and YO. The performance of the locally calibrated Angstrom–Prescott (A–P) and the modified hybrid models were comparatively better than all the site-independent models in the dry season in all the locations considered (Fig. 6). For A–P model, the MBE values ranged from − 2.65 to 0.96 MJ/m^2 and RMSE values ranged from 1.44 to 2.98 MJ/m^2 while for modified hybrid model, the MBE values ranged from − 1.98 to 0.82 MJ/m^2 and RMSE values ranged from 0.79 to 1.82 MJ/m^2.

The MBE and RMSE values of all the site-independent models in the wet season have similar magnitudes with those of dry season, with roughly the same trend of decreasing in values from PA to YO with the exception of LA (Fig. 7). The performance of the locally calibrated Angstrom–Prescott (A–P) and the modified hybrid models was comparatively better than all the site-independent models during the wet season in all the locations considered (Fig. 7). For A–P model, the MBE values ranged from − 2.28 to 0.01 MJ/m^2 and RMSE values ranged from 1.47 to 2.68 MJ/m^2 while for modified hybrid model, the MBE values ranged from − 2.18 to 0.3 MJ/m^2 and RMSE values ranged from 1.44 to 2.67 MJ/m^2.

8 Discussion

All the site-independent models considered in this study underestimated the daily solar radiation with decreasing magnitudes which are latitude dependent as indicated by the MBE values that decreased with latitudes (i.e., from PH: Port Harcourt to YO: Yola) in Figs. 5, 6, 7. This latitudinal influence was further investigated by calculating the absolute optical air mass using the formula of Kasten and Young (1989) at solar noon (12 p.m.) in each location of study on the annual scale. Absolute air mass is a parameter that combined zenith angle (a factor influenced by latitude), altitude, and air temperature. Figure 5 clearly indicates that both mean bias error (index for underestimation) and root mean squared error (a measured of accuracy) decreased with decrease in optical air mass. It therefore confirmed that all the site-independent models were developed using data at latitudes higher than those in equatorial regions and with possibility of lower optical air mass at the solar noon on the annual scale. Hence, to improve the performance of the site-independent global models, more data from the equatorial region should be infused into their calibrations. Hay model that included albedos of ground, clear sky, and cloud at relatively low altitude perform best of all site-independent models. The performance of hybrid model during the dry season is much better than wet season indicating the influence of explicit parameterization of aerosol by this model in clear-sky condition. Otunla (2019) had shown that aerosol and water vapor are the principal attenuators of solar radiation under clear-sky condition in Nigeria. The overall performance of hybrid in the region of study is, however, poor compared with its modified version and locally calibrated A–P model unlike other regions where performance tests were indicated to be good (Yang and Koike 2005; Yang et al. 2001, 2006a, b; Tang et al. 2010).

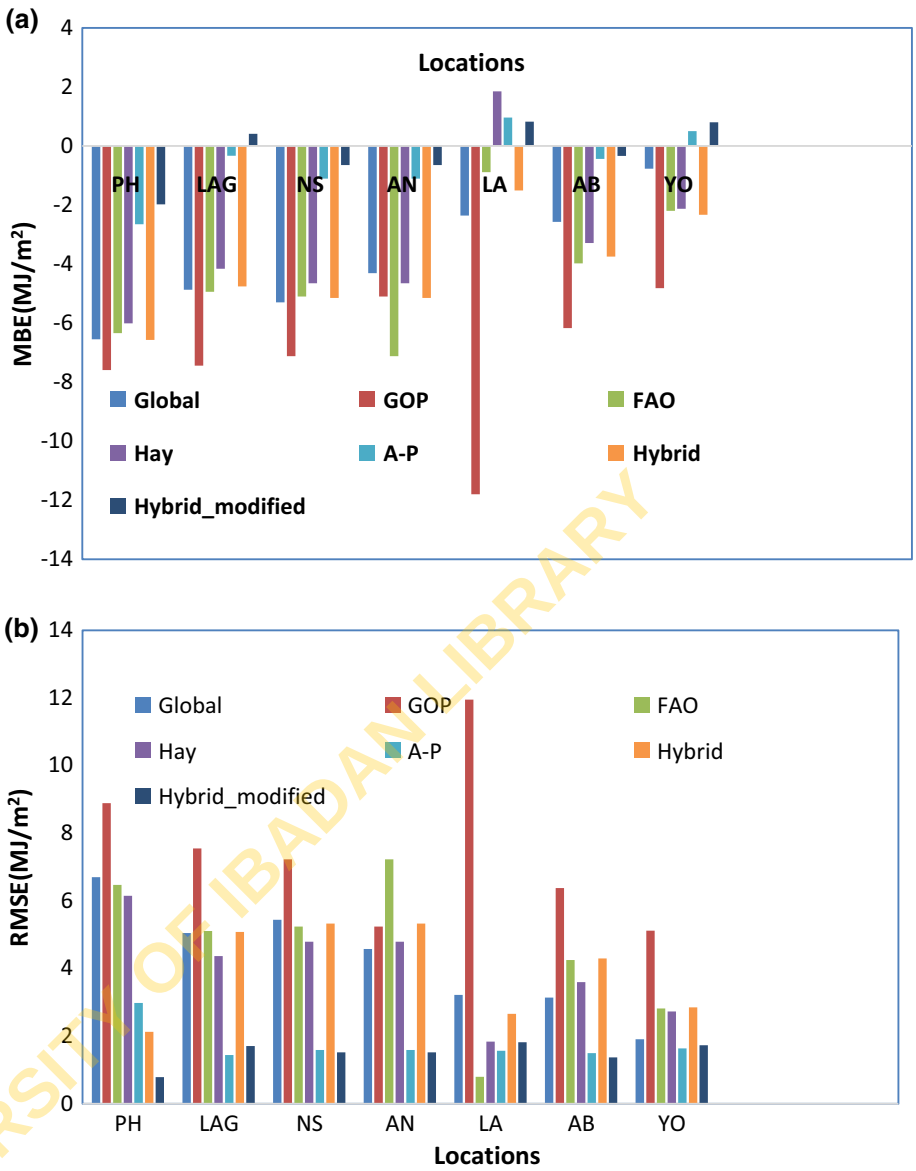

Fig. 6 Dry season performances using **a** mean bias error(MBE) and **b** root mean squared error (RMSE) of the globally calibrated Ångström–Prescott model (global), Gopinathan model (GOP), FAO-recommended model (FAO), Hay model (Hay), locally calibrated Ångström–Prescott model (A–P), all-sky parametric model (hybrid), and modified all-sky parametric model (modified hybrid) in estimating daily solar radiation in all the stations in Table 1 except Akure in order of increasing latitudes

The patterns of cloud cover observed at the stations used in this study (Fig. 3) are characteristics of the monsoon climate of equatorial region of West Africa. Weather pattern in the region usually follows the meridional shift of Intertropical Convergence Zone (ITCZ). Highly moist, rain-laden air masses and clouds have been observed south of the ITCZ during the rainy season while the air masses north of ITCZ are dry and dust laden (Odekunle 2004; Adeniyi 2014). A phenomenon usually characterized with high gust of wind, overcast or nearly overcast skies, and cessation or lesser rainfall in the coastal areas had been observed in month of August when the ITCZ reached its northmost position (Adejuwon and Odekunle 2006). This weather pattern is characteristic of monsoon climate of West Africa with a consequence of a distinct solar radiation cloud transmittance pattern different from other regions of the world (Fig. 4). Thus, a new solar radiation cloud transmittance is required (Eq. 11) for parametric broadband solar radiation models (hybrid model) that separately parameterized clear and cloudy sky solar radiation damping processes in equatorial region of West Africa. Investigation of the performances (based on MBE and RMSE) of the modified broadband all-sky solar radiation model using the new cloud transmittance indicated that the modified model produced daily solar radiation estimates that were better than the original all-sky broadband solar radiation model (hybrid model) and slightly better than the locally calibrated Ångström–Prescott model (A–P model). The modified broadband solar radiation model performances were clearly better than FAO, global, Gopinathan and Hay site-independent solar radiation models.

The slight superiority of the modified version all-sky broadband solar radiation model (modified hybrid

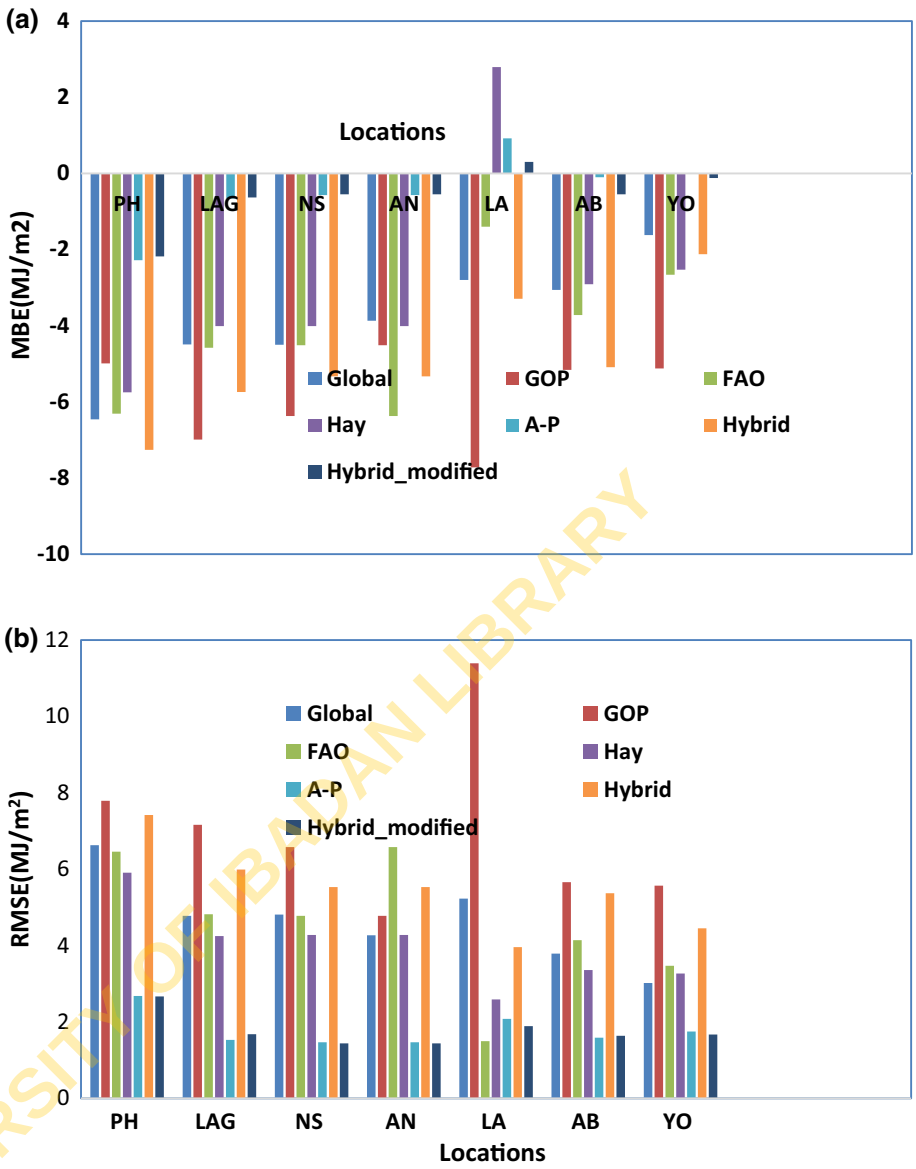

Fig. 7 Wet season performances using **a** mean bias error(MBE) and **b** root mean squared error (RMSE) of the globally calibrated Ångström–Prescott model (global), Gopinathan model (GOP), FAO-recommended model (FAO), Hay model (Hay), locally calibrated Ångström–Prescott model (A–P), all-sky parametric model (hybrid), and modified all-sky parametric model (modified hybrid) in estimating daily solar radiation in Table 1 except Akure in order of increasing latitudes

model) over the locally calibrated, site-dependent Ångström–Prescott model (A–P model) is traceable to its spectra model-based explicit and accurate parameterization of clear-sky solar radiation (Gueymard 2003a, b).

9 Conclusions

A broadband solar radiation model that explicitly and separately parameterized clear and cloudy sky radiation (hybrid model) damping processes had been examined. Solar radiation transmittance for cloud which was empirically formulated as a function of relative sunshine duration had also been examined for equatorial region of West Africa. A distinct cloud transmittance pattern which is appropriate for the weather pattern of the region of study was obtained. The new solar radiation transmittance for cloud was implemented as a modification of hybrid model and was tested at seven locations in the equatorial region. The modified version of the hybrid model was found to generally perform better than either locally calibrated Ångström–Prescott model or four other site-independent models.

Acknowledgements Prof. Kun Yang of Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, China provided the code for hybrid model and the two auxiliary data through personal communications. Centre for Atmospheric Research, National Space Research and Development Agency (CAR-NSRDA) Anyigba, Nigeria provided meteorological data through its TRODAN project.

References

Adaramola MS (2018) Estimating global solar radiation using common meteorological data in Akure, Nigeria. Renew Energy 47:38–44. https://doi.org/10.1016/j.renene.2012.04.005

Adedokun JA (1978) West African precipitation and dominant mechanisms. Arch Meterol Geophys Bioclimatol Ser A 27:289–310

Adejuwon JO, Odekunle TO (2006) Variability and severity of the little dry season in southwestern Nigeria. J Clim 19:1–8

Adeniyi MO (2014) Variability of daily precipitation over Nigeria. Meteorol Atmos Phys 126:161–176. https://doi.org/10.1007/s00703-014-0340-6

Akpabio LE (2019) Modeling global solar radiation for a tropical location: Onne, Nigeria. Turk J Phys 29:63–68

Allen Richard G, Pereira Luis S, Raes Dirk, Smith M (1998) Crop evapotranspiration-guidelines for computing crop water requirement. FAO Irrig Drain Pap 56:281p

Almorox J, Hontoria CBM (2011) Models for obtaining daily global radiation with measured air temperature data in Madrid (Spain). Appl Energy 88:1703–1709

Angstrom A (1924) Solar and terrestrial radiation. Q J R Meteorol Soc 50:121–125

Balogun EE (1991) Convective activity over Nigeria during the monsoon. Proc Int Conf Early Results FGGE Large Scale Asp Monsoon Exp Tallahassee Fla 12:22–27

Bamiro OA (1983) Empirical relations for the determination of solar radiation in ibadan, Nigeria. Sol Energy 31:85–94

Bristow KL, Campbell GS (1984) on the relationship between incoming solar radiation and daily maximum and minimum temperature. Agric For Meteorol 31:159–166

Chen JL, He L, Wen ZF, Lv MQ, Yi XX, Wu SJ (2018) a general empirical model for estimation of solar radiation in Yangtze river basin. Appl Ecol Environ Res 16(2):1471–1482

Ehnberg JSG, Bollen MHJ (2005) Simulation of global solar radiation based on cloud observations. Sol Energy 78:157–162

Falayi EO, Adepitan JO, Rabiu AB (2008) Empirical models for the correlation of global solar radiation with meteorological data for Iseyin, Nigeria. Niger Int J Phys Sci 3:210–216

Gopinathan KK (1988) A general formula for computing the coefficients of the correlation connecting global solar radiation to sunshine duration. Sol Energy 41:499–502

Gueymard C (1993) Analysis of monthly average solar radiation and bright sunshine for different thresholds at Cape Canaveral, Florida. Sol Energy 51:139–145. https://doi.org/10.1016/0038-092X(93)90075-Y

Gueymard CA (2003) Direct solar transmittance and irradiance predictions with broadband models. Part II: validation with high-quality measurements. Sol Energy 74:381–395. https://doi.org/10.1016/S0038-092X(03)00196-8

Gueymard AC (2003) Direct solar transmittance and irradiance with broadband models. Part I: detailed theoretical performance assessment. Sol Energy 74:355–379. https://doi.org/10.1016/j.solener.2003.11.002

Hay JE (1979) Calculation of monthly mean solar radiation for horizontal and inclined surfaces. Sol Energy 23:301–307

Hess M, Koepke P, Schult I (1998) Optical properties of aerosol and clouds: the software package OPAC. Bull Am Meteorol Soc 79:831–844

Hoogenboom G (2000) Contribution of agrometeorology to the simulation of crop production and its applications. Agric For Meteorol 103:137–157

Hunt LA, Kuchar L, Swanton CJ (1998) Estimation of solar radiation for use in crop modeling. Agric For Meteorol 91:293–300

Igbal M (1980) Prediction of hourly diffuse solar radiation from measured hourly global radiation on a horizontal surface. Sol Energy 24:491–503

Iziomon MG, Mayer H (2001) Performance of solar radiation models—a case study. Agric For Meteorol 110:1–11

Kasten F, Young AT (1989) Revised optical air mass tables and approximation formula. Appl Opt 28:4735–4738

Koepke P, Hess M, Schult I, Shettle E (1997) Global aerosol data set. Max-Planck Institut fu¨r Meteorologie. Rep No 243

Liu DL, Scott BJ (2001) Estimation of solar radiation in Australia from rainfall and temperature observation. Agric For Meteorol 106:41–59

Liu XY, Mei XR, Li YZ, Zhang YQ (2009) Calibration of the Angstrom–Prescott coefficients (a, b) under different time scales and their impacts in estimating global solar radiation in the yellow river basin. Agric For Meteorol 149:697–710

Madkour MA, El-Metwally M, Hamed AB (2006) Comparative study on different models for estimation of direct normal irradiance (DNI) over Egypt atmosphere. Renew Energy 31:361–382. https://doi.org/10.1016/j.renene.2005.03.009

Meza F, Varas E (2000) Estimation of mean monthly solar global radiation as a function of temperature. Agric For Meteorol 100:231–241

Miller DG, Rivington M, Matthews KB, Buchan K, Bellocchi G (2008) Testing the spatial applicability of the Johnson–Woodward method for estimating solar radiation from sunshine duration data. Agric For Meteorol 148:466–480

Nielsen L, Berkowicz R, Conradsen K (1981) Net incomng radiation estimated from hourly global radiation and/or cloud observations. J Clim 1:255–272

Odekunle TO (2004) Determination of rainfall onset and retreat dates. J Hum Ecol 16:239–247

Ogolo EO (2010) Evaluating the performance of some predictive models for estimating global solar radiation across the varying climatic conditions in Nigeria. Pac J Sci Technol 11:60–72

Otunla TA (2019) Estimates of clear-sky solar irradiances over Nigeria. Renew Energy 131:778–787

Paulescu M, Schlett Z (2004) Performance assessment of global solar irradiation models under Romanian climate. Renew Energy 29:767–777

Pohlert T (2004) Use of empirical global radiation models for maize growth simulation. Agric For Meteorol 126:47–58

Prescott JA (1940) Evaporation from water surface in relation to solar radiation. Trans R Soc Aust 641:114–125

Suehrcke H, Bowden RS, Hollands KGT (2013) Relationship between sunshine duration and solar radiation. Sol Energy 92:160–171

Supit I, van Kappel RR (1998) A simple method to estimate global radiation. Sol Energy 63:147–160

Tang W, Yang K, He J, Qin J (2010) Quality control and estimation of global solar radiation in China. Sol Energy 84:466–475. https://doi.org/10.1016/j.solener.2010.01.006

Thornton PE, Running SW (1999) An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity, and precipitation. Agric For Meteorol 93:211–228

Weiss A, Hays CJ (2004) Simulation of daily solar irradiance. Agric For Meteorol 123:187–199

WMO (2008) Guide to meteorological instruments and methods of observation. Seventh edition, WMO-NO. 8, Geneva

Wong LT, Chow WK (2001) Solar radiation model. Appl Energy 69:191–224. https://doi.org/10.1016/S0306-2619(01)00012-5

Yang K, Koike T (2005) A general model to estimate hourly and daily solar radiation for hydrological studies. Water Resour Res 41:1–13. https://doi.org/10.1029/2005WR003976

Yang K, Huang GW, Tamai N (2001) A hybrid model for estimating global solar radiation. Sol Energy 70:13–22. https://doi.org/10.1016/S0038-092X(00)00121-3

Yang K, Koike T, Stackhouse P et al (2006a) An assessment of satellite surface radiation products for highlands with Tibet instrumental data. Geophys Res Lett 33:3. https://doi.org/10.1029/2006GL027640

Yang K, Koike T, Ye B (2006b) Improving estimation of hourly, daily, and monthly solar radiation by importing global data sets. Agric For Meteorol 137:43–55. https://doi.org/10.1016/j.agrformet.2006.02.001