GLOBAL JOURNAL OF ENGINEERING RESEARCH VOL 7. NO. 1, 2008: 21 28
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A METHOD FOR ESTIMATING SOLAR RADIATION FROM AIR TEMPERATURE DATA IN SAMARU, NORTHERN GUINEA SAVANNA OF NIGERIA

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(Received 19, November 2007; Revision Accepted 26, March 2008)

ABSTRACT

A major limitation to the application of weather data in engineering designs and agricultural engineering is the lack of solar radiation data, while temperature and rainfall data are relatively available. Four empirical model methods (Bristow-Campbell (BC model), Campbell- Donatelli (CD model), Donatelli- Bellocchi (DB model) and Donatelli-Campbell-Bristow-Bellocchi (Modular DCBB)) were tested by comparing their estimated global radiation values with measured solar radiation data obtained for several years from the meteorological station at Samaru, northern Nigeria with the aim of determining which model estimate correlates more with measured values. The CD model had the best slope of the regression estimated vs measured of 0.87 with the DB and BC models having a slope of 0.65. The CD model also had the lowest RMSE of 2.7 while the DB model had the highest value of 4.5. From the coefficient of residual mass (CRM), BC, CD, and DB models overestimates the global solar radiation while the DCBB model gave underestimated values. The CD model which accounts for situations in which the night air temperature cooling is less than the corresponding clear day and also accounts for the date by using the average air temperature proved to be a reasonably accurate method for estimating global solar radiation for Samaru.

KEYWORDS: Solar radiation, air temperature, model, northern Nigeria

INTRODUCTION

A growing number of applications require weather data in engineering designs such as in solar energy systems design and agricultural engineering as a requirement in agricultural systems simulation modeling. For proper systems design a good knowledge of global solar radiation is required in the prediction and study of the economical viability of such designs.

In the management of artificial and natural ecosystems, the first challenge of a decision support system is to ensure the availability of accurate input data on a timely basis. Apart from actual measurements; interpolation schemes, algorithms to predict meteorological parameters and remotely sensed data can be used to complete necessary meteorological data set. The number of meteorological stations recording global solar radiation is limited compared to the number recording sunshine hours, air temperature and precipitation (Jagtap and Mavromatis, 2003). This dearth of solar radiation data limits to a large extent solar energy research studies. In Nigeria, for example, most weather stations may have long-term records of rainfall and temperatures, but only very few have sunshine hours records and much fewer with solar radiation data records.

A number of models have been developed for the estimation of global solar radiation at instrumental sites where it is not measured using other commonly measured meteorological variables. These models however contain empirical parameters which are usually site-specific. To use these models, these site-specific parameters must be determined. This is usually done by using appropriate location-specific measured meteorological data for model calibration. Calibrations using non-representative data will result in unsuitable parameters for the location of model application.

This paper investigates the quality of four models in estimating daily global solar radiation from air temperature data in Samaru (11^0 09'N, 07^0 38' E; 686 m above sea level), Nigeria by using measured variables to determine site-specific parameters with a view to determining which model estimate correlates more with measured values.

METHODOLOGY

Data Sets

One year (2001) of observed maximum and minimum air temperature (^{o}C) and global solar radiation (MJm^{-2}day^{-1}) as obtained from daily weather records collected from the Automatic Weather Station (Minimet, Eijkelkamp, The Netherlands) of Institute of Agricultural Research (IAR) Meteorological Station, Samaru-Zaria, Nigeria. Daily manual records of weather parameters such as rainfall, maximum and minimum temperatures were also observed and recorded at the same IAR weather station using the convention weather equipment.

Solar Radiation Estimation

Global Solar Radiation (MJm^{-2}day^{-1}) were estimated using four radiation models as contained in the software RadEst v 3.00 (Donatelli et al., 2003). These models are

- Bristow-Campbell (BC model) (Bristow and Campbell, 1984)
- Campbell- Donatelli (CD model) (Campbell and

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Donatelli, 1998)

- Donatelli- Bellocchi (DB model) (Donatelli and Bellocchi, 2001)
- Donatelli-Campbell-Bristow-Bellocchi (Modular DCBB)

All four models give estimated solar radiation as a product of extraterrestrial radiation and the atmospheric solar radiation transmissivity coefficient.

$$He_i = \tau_i\ Ho_i \quad \ldots\ldots\ldots\ldots (1)$$

Extraterrestrial radiation is not a function of the model used. The difference ,in the estimated values of solar radiation is as a result of transmissivity as determined by the individual model.

BC Model

$$H_i = \tau\left[1 - \exp\left(\frac{-b\Delta T_i^c}{month\,\Delta T}\right)\right] \quad \ldots\ldots\ldots\ldots (2)$$

CD Model

$$H_i = \tau\left[1 - \exp\left(-b\,f(T_{avg})\Delta T_i^2 f(T_{min})\right)\right] \ldots\ldots (3)$$

DB Model

$$H_i = \tau\left[1 + f(i)\right]\left[1 - \exp\left(\frac{-b\Delta T_i^2}{\Delta T_{week}}\right)\right] \quad \ldots\ldots (4)$$

$$\Delta T = T_{max_i} - \left(\frac{T_{min_i} + T_{min_{i+1}}}{2}\right) \quad \ldots\ldots\ldots\ldots (5)$$

month ΔT – monthly ΔT ; ΔT_{week} is mobile average daily temperature range over 7days.

$$f(T_{avg}) = 0.017 \times \exp(\exp(-0.053T_{avg})) \ldots\ldots\ldots\ldots (6)$$

$$T_{avg} = \frac{T_{max_i} + T_{min_i}}{2} \quad \ldots\ldots\ldots\ldots (7)$$

$$f(T_{min}) = \exp\left(\frac{T_{min_i}}{T_{nc}}\right) \ldots\ldots\ldots\ldots (8)$$

$$f(i) = c_1\left[\sin\left(i\frac{\pi}{180}c_2\right)\right] + \cos\left(i\,f(c_2)\frac{\pi}{180}\right) \ldots\ldots\ldots (9)$$

$$f(c_2) = 1 - 1.90c_3 + 3.83c_3^2 \ldots\ldots\ldots\ldots (10)$$

$$c_3 = c_2 - \mathrm{integer}(c_2) \ldots\ldots\ldots\ldots (11)$$

The RadEst software (Donatelli et al., 2003) was used to produce and optimize the site specific parameters in all the models by using all available data (air temperature and global solar radiation) in the calibration sets.

The b parameter used by all the models which is responsible for overall mode residual is automatically fitted by minimizing the Root Mean Square Error (RMSE) between measured and estimated solar irradiance. The T_{nc} controls patterns of residual against minimum temperature and is fitted automatically by minimizing the PI_{Tmin}. c_1 and c_2 control the across-year patterns of residuals and they are automatically fitted by minimizing the PI_{doy}.

$$PI = \max_{l,m=1,\ldots,4\ l\neq m}\left|\frac{1}{q_l}\cdot\sum_{i_l=1}^{q_l} r_{i_l} - \frac{1}{q_m}\cdot\sum_{i_m=1}^{q_m} r_{i_m}\right| \ldots\ldots (13)$$

r = residual = (estimated – measured) radiation
l, m = quarters
q_l, q_m = numerosity in the quarters
i_l, i_m = value in the quarter

The quarters are created over the range of day of year (PI_{doy}) and Tmin (PI_{Tmin}).

Model Testing

The performances of the four models were tested using the fuzzy-rule based procedure of Bellocchi et al. (2002) which allows individual indices to be combined into an aggregated index. This is achieved first by integrating indices into a first-level aggregated index, designated as a module, then more modules into a second-level aggregated index, designated as an indicator. The indices used are as shown in Table 1.

Table 1: Multiple-indices assessment method modules and statistical index content

Module	Index	Abbreviation	Value range and purpose
Accuracy (magnitude of residuals)	Coefficient of variability	CV	opt.=0
	Modelling Efficiency	MI	opt.= 1. Negative value of ME indicate that the average value of all measured values is a better estimator than the model
	Probability of the paired t-test	P (t)	0 to 1. opt. = 1 and worst is 1
Correlation(between estimates and measurements)	Correlation coefficient of the estimates versus measurements	r^2	-1 (full negative correlation) to 1 (full positive correlation). opt.= 1
Pattern (presence or absence of pattern in residuals)	Pattern Index by day of year	PI_{doy}	0 to infinity. opt. = 0
	Pattern Index by minimum air temperature	PI_{Tmin}	0 to infinity. opt. = 0

These three defined modules are aggregated to give the indicator of radiation model evaluation, designated as integrated index (Irad) whose optimum value is zero.

The models were evaluated and compared using descriptive statistics to obtain the degree of consistency between results based on daily observed and estimated solar irradiance. The goodness of fit of the regression line between estimated and measured values of solar irradiance were assessed by the RadEst v 3.00 software through the slope of the regression line, intercept and coefficient of determination (R^2). The root mean square error (RMSE) values summarizes the mean difference in the units of observed and predicted values and serves as a good overall measure of model performance.

RESULTS

The clear sky transmissivity (τ) as determined by the model(s) for Zaria is 0.7. The following site-specific parameters for the four models were determined by optimization of their values are shown in Table 2.

Table 2: Site-specific parameters for the models

Model	b	C	C_1	C_2	T_{nc}
BC	0.22	2	-	-	-
CD	0.434	-	-	-	26.4
DB	0.292	-	0.186	0.008	-
DCBB	0.093	-	0.1	0.841	64.1

Tables 3-6 shows the average ten-day meteorological data as estimated by the four models evaluated. From statistics shown in Table 7, the CD model had the best slope of the regression estimated vs measured of 0.871 with the DB and BC models having a slope of 0.65. The CD model also had the lowest RMSE of 2.727 and the DB model had the highest value of 4.452. DB model showed the lowest value of R^2 (0.404), with the highest value of 0.626 given by the CD model. The CD model also performed better in terms of the modeling efficiency (ME) with the DB model recording a negative value showing that the average of measurements is a better estimator than this model. From the coefficient of residual mass (CRM), BC, CD, and DB models overestimates the global solar radiation while the DCBB model underestimates it, but the CD model showed the lowest value of 0.064.

The best overall model performance is given by the CD model as indicated by an Irad value of 0.348. this is followed by the DCBB model (0.622), BC model (0.623) and DB model with an Irad value of 0.639.

Table 3 Relationship between measured and estimated global radiation using the BC Model

MetDataTenDays

Day of the Year	Global Solar Radiation Measured (MJ m^{-2})	Global Solar Radiation Estimated (MJ m^{-2})	RadMea-RadEst
1	19.85	20.2702	-0.4201984
2	20.81	21.24799	-0.4379921
3	20.73	20.95247	-0.2224655
4	20.41	21.827	-1.416992
5	20.34	21.77175	-1.431751
6	21.22001	23.68676	-2.466743
7	22.70002	24.06661	-1.36659
8	23.91	24.58802	-0.6780262
9	22.23999	24.33082	-2.090832
10	23.50997	24.22975	-0.7197742
11	21.65	24.05276	-2.40276
12	18.87996	20.65545	-1.77549

MetDataTenDays

Day of the Year	Global Solar Radiation Measured (MJ m^{-2})	Global Solar Radiation Estimated (MJ m^{-2})	RadMea-RadEst
13	22.3	22.84077	-0.5407715
14	20.66999	22.17046	-1.500465
15	21.05999	23.59875	-2.538769
16	19.87998	20.9687	-1.08872
17	21.12002	21.59412	-0.4740963
18	17.08001	19.00679	-1.926781
19	20.01999	21.65515	-1.635157
20	17.5	19.98364	-2.483643
21	14.92007	18.60957	-3.689501
22	16.1001	19.33843	-3.238331
23	14.93999	17.78608	-2.846093
24	13.62993	19.88179	-6.251855
25	16.34995	19.32344	-2.973486
26	18.51011	21.72632	-3.216211
27	16.41006	20.82886	-4.418798
28	20.95	21.01055	-6.054688E-02
29	19.8	22.32139	-2.521387
30	20.63999	23.46094	-2.820948
31	20.11006	22.00713	-1.897072
32	21.14995	22.24351	-1.093554
33	20.14995	21.04648	-0.8965321
34	19.81997	20.69609	-0.8761234
35	18.53008	19.88535	-1.355272
36	19.02993	20.31045	-1.280518

Table 4: Relationship between measured and estimated global radiation using the CD Model

MetDataTenDays

Day of the Year	Global Solar Radiation Measured (MJ m^{-2})	Global Solar Radiation Estimated (MJ m^{-2})	RadMea-RadEst
1	19.85	20.70963	-0.8596306
2	20.81	21.50507	-0.6950665
3	20.73	21.47901	-0.7490082
4	20.41	22.1616	-1.751593
5	20.34	22.2674	-1.927399
6	21.22001	24.06953	-2.849518
7	22.70002	24.69702	-1.996998
8	23.91	25.22493	-1.314928
9	22.23999	25.36066	-3.120667
10	23.50997	24.60823	-1.098253
11	21.65	24.39558	-2.745581
12	18.87996	21.32397	-2.444019
13	22.3	22.95925	-0.6592541
14	20.66999	22.1249	-1.454908
15	21.05999	23.3791	-2.319115
16	19.87998	19.18445	0.6955318
17	21.12002	19.65759	1.462427
18	17.08001	16.8822	0.1978035
19	20.01999	19.31013	0.7098637
20	17.5	17.37812	0.1218758
21	14.92007	15.43398	-0.513916
22	16.1001	15.31479	0.7853031
23	14.93999	13.63965	1.300342
24	13.62993	16.31499	-2.68506
25	16.34995	17.05708	-0.7071285
26	18.51011	19.82061	-1.310499
27	16.41006	18.91113	-2.501074
28	20.95	22.06314	-1.113134
29	19.8	22.84917	-3.049171
30	20.63999	23.54097	-2.900976
31	20.11006	22.71563	-2.605568
32	21.14995	22.48828	-1.338329
33	20.14995	21.59985	-1.449902

MetDataTenDays

Day of the Year	Global Solar Radiation Measured (MJ m^{-2})	Global Solar Radiation Estimated (MJ m^{-2})	RadMea-RadEst
34	19.81997	21.07612	-1.256151
35	18.53008	20.40132	-1.871239
36	19.02993	20.70156	-1.671631

Table 5: Relationship between measured and estimated global radiation using the DB Model

MetDataTenDays

Day of the Year	Global Solar Radiation Measured (MJ m^{-2})	Global Solar Radiation Estimated (MJ m^{-2})	RadMea-RadEst
1	19.85	24.9221	-5.0721
2	20.81	25.46222	-4.652224
3	20.73	25.56904	-4.839043
4	20.41	26.01882	-5.60882
5	20.34	26.15109	-5.811096
6	21.22001	26.7828	-5.562788
7	22.70002	26.71533	-4.015308
8	23.91	26.45967	-2.549669
9	22.23999	25.99817	-3.758179
10	23.50997	24.78926	-1.279284
11	21.65	23.87554	-2.225538
12	18.87996	21.90466	-3.024708
13	22.3	22.21247	8.752441E-02
14	20.66999	21.09961	-0.429615
15	21.05999	21.02205	3.794098E-02
16	19.87998	18.78303	1.096949
17	21.12002	19.12664	1.993383
18	17.08001	17.32248	-0.2424793
19	20.01999	18.67651	1.343481
20	17.5	18.18799	-0.6879883
21	14.92007	18.00996	-3.089891
22	16.1001	18.00308	-1.902979
23	14.93999	18.18999	-3.250001
24	13.62993	19.28359	-5.653663
25	16.34995	20.15962	-3.809668
26	18.51011	21.74946	-3.239355
27	16.41006	22.41035	-6.000292
28	20.95	24.02539	-3.07539
29	19.8	24.67261	-4.872608
30	20.63999	25.45825	-4.818262
31	20.11006	25.28643	-5.176369
32	21.14995	25.39692	-4.246971
33	20.14995	25.00982	-4.859863
34	19.81997	24.87554	-5.055567
35	18.53008	24.56909	-6.039013
36	19.02993	24.82969	-5.799755

Table 6: Relationship between measured and estimated global radiation using the DCBB Model

MetDataTenDays

Day of the Year	Global Solar Radiation Measured (MJ m^{-2})	Global Solar Radiation Estimated (MJ m^{-2})	RadMea-RadEst
1	19.85	19.01046	0.8395348
2	20.81	20.4136	0.3963985
3	20.73	19.57143	1.158569
4	20.41	19.8832	0.5268002
5	20.34	19.12957	1.21043
6	21.22001	21.1766	4.341316E-02
7	22.70002	21.185	1.515026
8	23.91	21.4366	2.473402
9	22.23999	21.36632	0.8736687
10	23.50997	20.48677	3.023207
11	21.65	21.02451	0.6254883
12	18.87996	18.66682	0.2131348
13	22.3	20.749	1.551001
14	20.66999	20.68723	-1.723671E-02
15	21.05999	22.35286	-1.29287
16	19.87998	19.40271	0.4772701
17	21.12002	19.45974	1.660278
18	17.08001	17.32197	-0.2419662
19	20.01999	19.11641	0.9035892
20	17.5	17.13794	0.3620605
21	14.92007	14.98904	-6.896973E-02
22	16.1001	14.3981	1.702002
23	14.93999	12.83774	2.102246
24	13.62993	13.81997	-0.1900396
25	16.34995	13.06216	3.287792
26	18.51011	14.42749	4.082617
27	16.41006	13.54844	2.861622
28	20.95	15.45063	5.499366
29	19.8	16.2415	3.558495
30	20.63999	18.06206	2.577929
31	20.11006	17.61162	2.498436
32	21.14995	18.87671	2.273243
33	20.14995	17.84287	2.307081
34	19.81997	17.85117	1.9688
35	18.53008	16.98657	1.543507
36	19.02993	17.39492	1.63501

Table 7: Spatial performance of the four models on daily basis for Zaria, Nigeria

Model	No of Days	Slope	Intercept	RMSE	CV	R^2	ME	CRM	PI_{doy}	PI_{Tn}	Irad	Avg Rad M	Avg Rad E
BC	365	0.65	8.719	3.05	15.524	0.545	0.254	-0.094	2.247	3.464	0.623	19.65	21.48
CD	365	0.871	3.789	2.727	13.88	0.626	0.403	-0.064	1.406	1.314	0.348	19.65	20.9
DB	365	0.65	10.141	4.452	22.664	0.404	-0.591	-0.165	4.693	3.486	0.639	19.65	22.89
DCBB	365	0.832	1.778	3.025	15.398	0.571	0.266	0.077	2.819	2.802	0.622	19.65	18.13

CONCLUSION

Four models for estimating global solar radiation from air temperature data were evaluated for Zaria, Nigeria. The Campbell and Donatelli (1998) model which accounts for situations in which the night air temperature cooling is less than the corresponding clear day and also accounts for the date by using the average air temperature proved to be a reasonably accurate method for estimating global solar radiation for Samaru in the absence of sun duration data. The empirical parameters for this model were found by optimization to be b=0.434 and T_{nc}=26.4.

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APPENDIX

Nomenclature

He - Estimated radiation (MJ m^{-2})
Ho – Extraterrestrial radiation (MJ m^{-2})
i – day of the year
tt – transmissivity
τ - clear sky transmissivity
T_{max} – daily maximum air temperature (°C)
T_{min} – daily minimum air temperature (°C)
$f(T_{avg})$ - function of average air temperature.
$f(T_{min})$ - function of daily minimum air temperature.
T_{nc} - Summer night air temperature factor.
$f(i)$ - Seasonality function
B, c, T_{nc} are empirical parameters
c_1 – parameter for seasonal variation magnitude
c_2 – parameter for seasonal variation profile