An Evaluation of the Performances and Subsequent Calibration of Three Solar Radiation Estimation Models for Semi Arid Climates in Midlands Zimbabwe

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Abstract

The Hargreaves, Bristow – Campbell (B-C) and Donatelli – Campbell (C-D) solar radiation estimation models were evaluated to establish their performances in the semi arid climate of Midlands Zimbabwe. The models were also calibrated to attain the site specific empirical coefficients so as to improve in terms of prediction accuracy. To achieve this evaluation, daily incoming solar radiation, minimum temperature and maximum temperature were measured for a year (July 2013 to June 2014) at two sites (Mlezu and Mvuma) in Midlands Zimbabwe. The temperatures were used to calculate daily solar radiation for the Hargreaves, B-C and C-D models. The measured solar radiation at both sites was used to evaluate the performances of the models using the Mean Absolute Prediction error (Err), Model Efficiency (EF), Root Mean Square Error (RMSE), Bias and coefficient of determination (R^2). All models were calibrated using linear regression equations. The B-C model performed better than the other models overall. The least performer was the C-D model. The B-C model had the lowest Err (17.85 % and 16.31 %), RMSE (3.725 $MJm^{-2}day^{-1}$ and 3.486 $MJm^{-2}day^{-1}$) and Bias (2.501 $MJm^{-2}day^{-1}$ and 1.281 $MJm^{-2}day^{-1}$) values at both sites. The Hargreaves and C-D models' performances were almost similar at both sites. The Bias levels were between 3 $MJm^{-2}day^{-1}$ and 4 $MJm^{-2}day^{-1}$, and the RMSE values were slightly above 4 $MJm^{-2}day^{-1}$. The EFs of all the models were acceptable since they were > 0. Calibration improved the performances of all the models. The EF values of all the models ranged between 0.55 and 0.7, the Err reduced to between 11 % and 16 % and the Bias was reduced to < 0.5 $MJ\ m^{-2}\ day^{-1}$ for the Hargreaves and B-C models. The Bias was however still higher for the C-D model (~ 2 $MJ\ m^{-2}\ day^{-1}$). The average site specific "K" coefficient of the Hargreaves model, the "a" coefficient of the B-C model and the CD_b coefficient of the C-D model were found to be 0.1361, 6.274 and 0.1895. Solar radiation estimation models are supposed to be calibrated before use for improved prediction accuracy.

Key words: Solar radiation, Bristow – Campbell, Donatelli – Campbell, Hargreaves, Model Evaluation

Introduction

Solar radiation is an important climatic variable which affects many chemical, biological and physical processes (Ji – Long and Guo – Sheng, 2012; Castellví, 2008) like plant growth and photosynthesis, irrigation water requirements and estimation of evaporation (Almorox, 2013; Castellví, 2008; Abtew, 1996; Turc, 1961). Applications of solar radiation are common in hydrology, agronomy, ecology and in the design and evaluation of solar energy devices (Huashan et al., 2014; Bhardwaj, 2013; Ituen et al., 2012). Solar radiation is also an integral aspect in hydrological models and crop yield models (Castellví, 2008; Yang et al., 2006). Quantification of solar radiation can be done through direct measurement or

through estimation using established models / equations. The direct measurement of solar radiationin developing countries including Zimbabwe is limited with only few meteorological stations measuring daily solar radiation consistently. Thus solar radiation is mainly not recorded at sites of interest (Rivington et al., 2005). Direct measurement of solar radiation is further complicated by the requirement of regular calibration of sensors, a process many people are not able to perform. (Ji − Long and Guo − Sheng, 2012). The use of empirical relationships from measured meteorological variables is very common because of low computational costs and readily available inputs (Ji − Long and Guo − Sheng, 2012; Yang et al., 2006). Meteorological data most commonly used for estimation of solar radiation are sunshine duration, maximum and minimum air temperatures, relative humidity and precipitation. There are many methods (models) that can be used for solar radiation estimation. These empirical models can be classified into three categories as outlined by Yang et al (2006) in Table 1.

Table 1: Classification of solar radiation estimation models

Category	Examples
Sunshine based models	Angstrom, 1924; Prescott, 1940
Temperature based models	Bristow and Campbell, 1984; Hargreaves, 1994; Donatelli and Campbell, 1998; Thornton and Running, 1999; Meza and Varas, 2000; Weiss and Hays, 2004
Cloud based models	Nielsen et al., 1981; Supit and van Kappel, 1998; Ehnberg and Bollen, 2005

Sunshine based estimation models were found to be more accurate than temperature and cloud based models (Castellví, 2008; Yang et al., 2006) but their applicability is limited due to the scarcity of sunshine data. Temperature based estimation models are the ones that are widely used because temperature records are easily available (Huashan et al., 2014; Almorox et al., 2013; Yang et al., 2006).

The use of these empirical models however, must be treated with caution because they are usually less accurate and the results may be misleading mainly because the models were developed for specific regions and hence have no universal application (Sheikh and Mohammadi, 2013). Empirical models are, most fittingly, used after local calibrations for them to be reliable (Sheikh and Mohammadi, 2013; ElNesr et al., 2011 and Kra, 2010). It is therefore very critical to know the quality of the estimates that are made by the empirical models before using them (Rivington et al., 2005). The main objective of this study was to evaluate the performances the Hargreaves, Bristow Campbell and Donatelli Campbell radiation estimation models and to calibrate these models to suit semi arid conditions in Midlands Zimbabwe.

Methodology

Study Area and data used

Measurements of incoming solar radiation were made at two sites i.e. Mlezu (19.15⁰S, 29.88⁰E and 1280 m above sea level) and Mvuma (19.28⁰S, 30.53⁰E and 1300 m above sea level). Both sites have a warm temperate climate with a dry winter and warm summer i.e. CWb Koeppen climate class (Grieser, 2006). Mlezu's climate is classified as steppe (Budyko classification) having a radiational index of dryness of 2.214 and an evaporation ratio of 91.5 %. Mlezu has an average precipitation deficit of 819 mm/yr (Grieser, 2006). Mvuma's climate is semi arid (Budyko classification) with a radiational index of dryness of 2.338, an evaporation ratio of 92.5 % and an average precipitation deficit of 766 mm/yr (Grieser, 2006).

Daily measurements of incoming solar radiation and temperatures were made at each site. A silicon pyranometer with fixed daylight calibration (model LI200X-L, LI-COR) was used to measure the incoming solar radiation. Air temperature (maximum and minimum) was measured together with humidity using a temperature and relative humidity probe equipped with a capacitive relative humidity chip and a platinum resistance thermometer (model HMP 60-L, Vaisala) inserted in a 12-plate Gill radiation shield at screen height approximately 1.5 m above the surface. The sensors were connected to a CR200X data logger (Campbell Scientific Limited, UK) programmed with a scan interval of 5 seconds and all signals averaged every hour. Data used for this study consisted of measured daily incoming solar radiation values for a year (July 2013 to June 2014) at both sites.

Procedure

Three empirical (temperature based) solar radiation estimation models were evaluated in terms of their accuracy for solar radiation estimation on a daily basis. These empirical methods are the Hargreaves model, the Bristow and Campbell (B-C) model and the Donatelli and Campbell (C-D) model. The measured temperature data was used to compute daily solar radiation for each model. The Hargreaves (1994) equation that was modified by Allen (1997) is outlined in equation

$$1. R_s = K\left(\sqrt{T_{max} - T_{min}}\right)R_a \qquad \textbf{Equation 1}$$

Where:

R_s is the solar radiation (MJ m^{-2} day^{-1}), K is a site specific coefficient and is calculated using equation 2. T_{max} is the mean daily maximum air temperature (°C), T_{min} is the mean daily minimum air temperature (°C) and R_a is the extraterrestrial radiation (MJ m^{-2} day^{-1}).

$$K = 0.17\left(e^{-0.0001184\ h}\right)^{0.5}$$
$$\textbf{Equation 2}$$

h is the altitude of the site (m)
The Bristow and Campbell (1984) estimation model is outlined in equation 3.

$$R_s = a\left[\left(1 - e^{-b\Delta T^c}\right)\right]R_a \qquad \textbf{Equation 3}$$

Where:

R_s and R_a are as previously defined. *a, b* and *c* are empirical constants with the following default values 0.7, 0.004 – 0.01 and 2.4 respectively. "*T* is the difference between maximum temperature and minimum temperature.

The Donatelli and Campbell (1998) model, C-D model (equation 4) was solved using equations 5 – 8.

$$Radn \_ CD = \tau \left[1 - \exp \left(- CD \_ b \times fT_{ave} \times \Delta T^2 \times fT_{min} \right) \right] R_a \qquad \textbf{Equation 4}$$

$$T_{ave} = \frac{T_{max} + T_{min}}{2} \qquad \textbf{Equation 5}$$

$$fT_{ave} = 0017 \times \exp \left[\exp \left(- 0.053 \times T_{ave} \right) \right] \qquad \textbf{Equation 6}$$

$$\Delta T = T_{max} - \frac{\left(T_{min} + T_{min} 1 \right)}{2} \qquad \textbf{Equation 7}$$

$$fT_{min} = \exp \frac{\left(T_{min} \right)}{CD \_ T_{nc}} \qquad \textbf{Equation 8}$$

Where:

T_{max} is the maximum air temperature, T_{min} is the minimum air temperature τ is clear sky transmissivity (=0.75), CD_b is the CD empirical parameter b (=0.463), $CD\_T\text{-}_{nc}$ is the CD empirical parameter T_{nc} – summer night time temperature factor (=85.6) and R_a is as previously defined.

The extra terrestrial radiation for the 2 sites was determined using equation 9 i.e. according to Duffie and Beckman (1991).

$$R_a = \frac{1.440}{\pi} \left(G_{sc} \times d_r \right) \left[\psi_s \sin(\varphi) \sin(\sigma) + \cos(\varphi) \cos(\sigma) \sin(\psi_s) \right] \qquad \textbf{Equation 9}$$

Where G_{sc} is the solar constant (0.0820 MJm^{-2}min^{-1}), d_r is the inverse relative Earth-Sun distance (Equation 10), $\emptyset_s$ is the sunset hour angle (rad) given by equation 11, σ is the solar declination angle (rad) given by equation 12, φ is the latitude of the location (rad) and JD is the Julian day of year.

$$d_r = 1 + 0.033 \cos \left[\frac{2\pi (JD)}{365} \right] \qquad \textbf{Equation 10}$$

$$\psi_s = ar \cos \left[- \tan(\varphi) \tan(\sigma) \right] \qquad \textbf{Equation 11}$$

$$\sigma = 0.409 \sin \left(2\pi \times \frac{JD}{365} - 1.39 \right) \qquad \textbf{Equation 12}$$

Evaluation of the solar radiation estimation methods
The performances of the Hargreaves, B-C and C-D models were evaluated using the Model Efficiency (EF), Bias (B) in MJm^{-2} day^{-1}, Root Mean Square Error (RMSE) in MJm^{-2} day^{-1},

Mean Absolute Prediction Error (Err) as a percentage and the coefficient of determination (R^2). These tests were calculated using equation 13 to equation 16.

$$EF = 1 - \frac{\sum_{i=1}^{n}\left(RMeasured_i - RModel_i\right)^2}{\sum_{i=1}^{n}(RMeasured_i - \overline{RMeasured_i})^2} \qquad \textbf{Equation 13}$$

$$B = \frac{1}{n}\sum_{i=1}^{n}\left(RModel_i - RMeasured_i\right) \qquad \textbf{Equation 14}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(RModel_i - RMeasured_i\right)^2} \qquad \textbf{Equation 15}$$

$$Err = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{100\left(RModel_i - RMeasured_i\right)}{RMeasured_i}\right| \qquad \textbf{Equation 16}$$

Where:

RModel_i and *RMeasured_i* are the corresponding incoming solar radiation predictions of either the Hargreaves, B-C or C-D models and the measured incoming solar radiation (MJm^{-2} day^{-1}) respectively. *n* is the number of paired comparisons.

An error of $\pm 5\%$ is usually regarded as acceptable by other researchers (Noori Mohammadieh et al., 2009; Irmark et al., 2003). The Mean Absolute Prediction Error was interpreted using Lewis (1982) guidelines (Table 1) in Gundalia and Dholakia (2013). *EF* values between 0 and 1 were regarded as acceptable but values closer to 1 are highly acceptable (Gundalia and Dholakia, 2013). *EF* values less than 0 were unacceptable. Model calibration was done to ensure that the prediction errors would be within acceptable limits.

Table 1: Interpretation of the mean Absolute prediction error values

Err (%)	Judgement of prediction accuracy
< 10	Highly accurate
11 – 20	Good
21 – 50	Reasonable
51$^+$	Inaccurate

All the three models were calibrated using linear regression equations. The Hargreaves model was calibrated by plotting R_s/R_a on the y axis and "$T^{0.5}$" on the x axis. The slope of the graph gave the value of the "K" coefficient of the model (figure 1). To calibrate the B-C model, Rs/R_a was plotted on the y axis and $exp(-b"T^c)$ was plotted on the x axis. The y intercept of the graph gave the "*a*" coefficient of the model (figure 2). The C-D_b empirical coefficient of the C-D model was determined as the slope of the plot of $ln(1-Rs/Ra*\partial)$ against "$T^2*fTave*fTmin$ (Figure 3).

Results and discussion

Based on the performance evaluation tests results, the B-C model performed better than the other models at both sites. The B-C model had lower Err values 17.85 % and 16.32 % at Mlezu and Mvuma respectively (Tables 2 and 4). The Hargreaves model and the C-D model had larger Err values (20 – 26 %) at both sites (Tables 2 and 4). According to the Lewis (1982) guidelines (Table 1), the performance of the B-C model is classified as good at both sites. The Hargreaves' model performance is classified as being reasonable at both sites while the C-D model was reasonable at Mlezu and good at Mvuma.

After calibration of the models, the Err values were significantly reduced (Tables 3 and 5). The B-C's model performance remained in the good category but the error values were reduced in size and were closer to the boundary of being highly accurate. The Hargreaves and C-D models' performances improved from being reasonable to being good in terms of prediction accuracy at both sites after calibration (Tables 3 and 5). The Err values of the B-C model were in agreement with the performances of 12 models that were tested in China – average values of 11.37 % (Ji – Long and Guo – Sheng, 2012) and 15 % for tests done by Samani (2000).

The RMSE and bias values of the B-C model were lower compared to the other models at both sites (Tables 2 and 4). The C-D and Hargreaves' models RMSE values are a cause for concern (RMSE values > 4 MJ m^{-2} day^{-1}) because it is an indication of compromised prediction accuracy. After calibration of the models, the RMSE values were reduced to values < 4 MJ m^{-2} day^{-1} for all models (Tables 3 and 5). This showed a marked improvement in terms of the prediction accuracy of the models.

All the three models generally over estimated solar radiation as indicated by the positive bias values (Tables 2 and 4). The bias levels of the B-C model were lower (2.5MJm^{-2}day^{-1} and 1.3 MJm^{-2}day^{-1} at Mlezu and Mvuma respectively) and indicates better prediction accuracy compared to other models (bias values between 3 and 4 MJm^{-2}day^{-1}). Calibration of the models was able to reduce the bias levels of all models to acceptable limits (Tables 3 and 5). Calibration however led to some slight under prediction of solar radiation by all models.

The efficiencies of all models were acceptable according to Gundalia and Dholakia (2013) because they were between 0 and 1. The B-C model had higher efficiencies compared to other models at both sites. Hargreaves was second in terms of model efficiency and the C-D model was the least performer at both sites (Tables 2 and 4). The prediction accuracies of all the models improved through calibration (Tables 3 and 5). The efficiencies improved from values closer to 0 to values above 0.5 for all models at both sites. The highest performance was again exhibited by the B-C model (EF of 0.7). The R^2 values for all models were generally good with values ranging between 0.6 and 0.72. These R^2

values are slightly higher than those determined by Ji – Long and Guo – Sheng (2012) for the temperature based estimation models they tested. Their R^2 values averaged 0.595 to 0.599.

The performance evaluation results (Err, Bias, RMSE, R^2) for each model at both sites were almost similar giving the impression that each model performed similarly at both sites. This made it easier for the models to be ranked. The overall best performer was the B-C model and the least performer was the C-D model. The overall performances of these temperature based solar radiation estimation models are in agreement with other researchers' findings that temperature based models have lower prediction accuracy than sunshine based models (Castellvi, 2008; Yang et al., 2006).

This reduced prediction accuracy can be corrected through site specific calibrations of the models. These models are supposed to be used after local calibrations have been done for improved prediction accuracy. The site specific empirical coefficients of the models are shown in Figures 1 – 3 for both sites and summarized in Table 6. The recommended value of the "K" coefficient of the Hargreaves model of 0.162 for interior regions (Hargreaves, 1994) proved to be too large for the conditions under investigation. The assumption that all interior regions can have the same "K" value leads to substantial errors in the estimation of solar radiation using the Hargreaves model. The proposed adjustment of "K" values by Allen (1997) using altitude of a place led to the over prediction of solar radiation by the Hargreaves model.

The site specific "K" value of the Hargreaves model established in this study is almost similar to that of Portland (0.13) as given by Samani and Pessarakli (1986) and 0.127 that was determined by Thanoon (2013). The default empirical coefficients of the B-C and C-D models were responsible for the over prediction of the models in semi arid conditions. The CD_b coefficient was reduced from the default 0.463 to between 0.177 and 0.202. The "a" coefficient of the B-C model was reduced from 0.7 to between 0.608 and 0.646.

Table 2: Performance evaluation results for the Hargreaves, Bristow – Campbell (B-C) and Campbell – Donatelli (C-D) models before calibration for Mlezu

	Hargreaves	B-C	C-D
Err (%)	22.696	17.850	25.643
RMSE (MJ m^{-2} day^{-1})	4.252	3.725	4.911
EF	0.156	0.353	0.125
Bias (MJ m^{-2} day^{-1})	3.222	2.501	4.133
R^2	0.641	0.705	0.679

Table 3: Performance evaluation results for the Hargreaves, Bristow – Campbell (B-C) and Campbell – Donatelli (C-D) models after calibration for Mlezu

	Hargreaves	B-C	C-D
Err (%)	13.885	11.599	15.854
RMSE (MJ m^{-2} day^{-1})	2.822	2.581	3.663
EF	0.622	0.689	0.374
Bias (MJ m^{-2} day^{-1})	-0.006	-0.310	-1.8415
R^2	0.641	0.705	0.595

Table 4: Performance evaluation results for the Hargreaves, Bristow – Campbell (B-C) and Campbell – Donatelli (C-D) models before calibration for Mvuma

	Hargreaves	B-C	C-D
Err (%)	21.153	16.321	20.985
RMSE (MJ m^{-2} day^{-1})	3.896	3.486	4.380
EF	0.490	0.6337	0.391
Bias (MJ m^{-2} day^{-1})	2.111	1.284	3.115
R^2	0.647	0.712	0.699

Table 5: Performance evaluation results for the Hargreaves, Bristow – Campbell (B-C) and Campbell – Donatelli (C-D) models after calibration for Mvuma

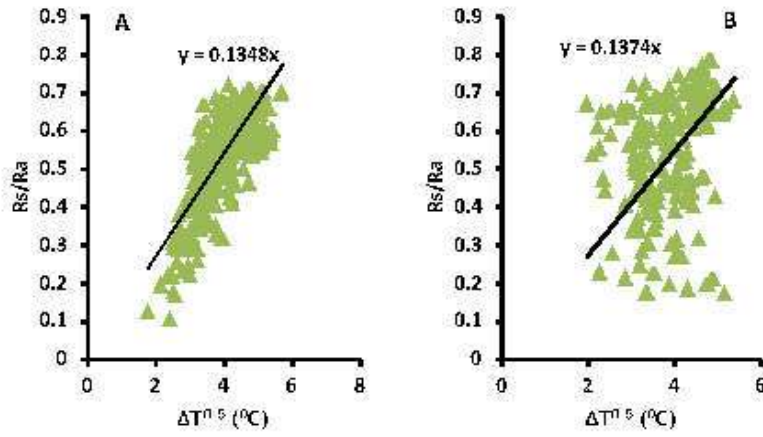|	Hargreaves	B-C	C-D
Err (%)	16.055	14.388	16.129
RMSE (MJ m^{-2} day^{-1})	3.473	3.155	3.969
EF	0.618	0.700	0.545
Bias (MJ m^{-2} day^{-1})	-0.573	-0.355	-2.286
R^2	0.647	0.713	0.685

Figure 1 : Calibration of the Hargreaves model for (A) Mlezu and (B) Mvuma
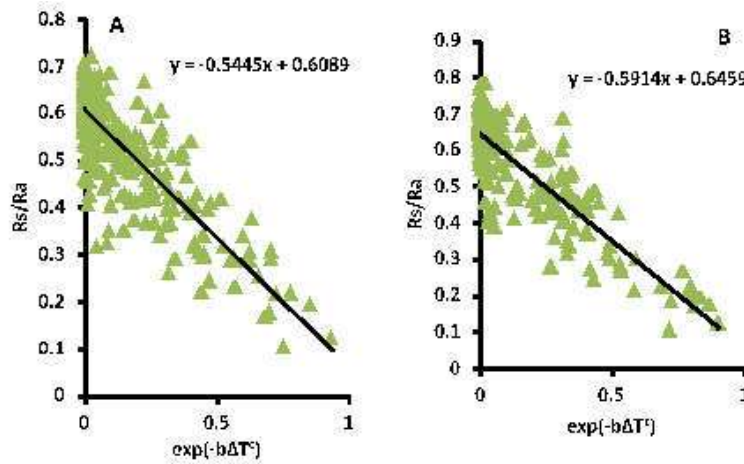

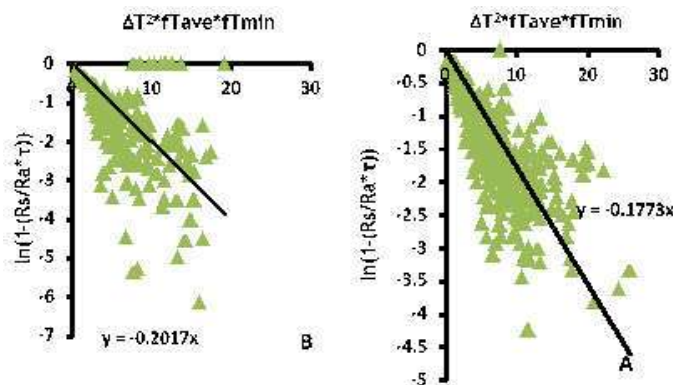**Figure 2 :** Calibration of the B-C model for (A) Mlezu and (B) Mvuma

Figure 3 : Calibration of the C-D model for (A) Mlezu and (B) Mvuma

Table 6: Site specific parameters / coefficients for the three models

Model / parameter	Mlezu	Mvuma
Hargreaves / K	0.1348	0.1374
B-C / a	0.6089	0.6459
C-D / CD-b	0.1773	0.2017

Conclusion

The performances of the three models (Hargreaves, B-C and C-D) in semi arid climates were generally good and acceptable even though the prediction accuracy was not highly accurate. The B-C models proved to be a better predictor of solar radiation compared to the other models. The performances of the Hargreaves and C-D models were almost similar although the former was better than the later. The site specific empirical coefficients of the models were found to be 0.135 -0.137 for the "K" value of the Hargreaves model, 0.608 – 0.646 for the "a" value of the B-C model and 0.177 – 0.202 for the "CD_b" value of the C-D model. All empirical solar radiation estimation models are supposed to be calibrated before being used for better prediction accuracy.

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