



Calibration of Ångström-Prescott Coefficients to Estimate Global Solar Radiation in Côte d'Ivoire

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Abstract

In this study, we used monthly mean daily global radiation data and sunshine durations from nine (9) weather stations in Côte d'Ivoire to determine the annual Ångström-Prescott coefficients. The calibration of the Ångström-Prescott equation has been done through linear regression using the least square method. The empirical coefficients obtained are utilized to predict the global horizontal irradiance over the nine (9) weather stations of interest. Estimated and measured global radiations were compared using the root mean square error (RMSE), the mean bias error (MBE), the mean absolute bias error (MABE), the mean percentage error (MPE), the Nash-Sutcliffe coefficient of efficiency (NSE), and the statistic t-test (**t-statistic**). The low values of the statistic t-test (from 0.10 to 1.07) and MPE (from -0.413 to 0.201) indicate a good performance of the model. The high values of the coefficient of determination R^2 (from 0.9776 to 0.9916) show a remarkable agreement between predicted and measured global solar radiations. This remark is also confirmed by the high values of NSE (from 0.8671 to 0.9819) closer to 1. The obtained values of MBE (from -18.17 to 8.69 kWh/m²), MABE (from 7.16 to 8.52 kWh/m²), and RMSE (69.1 to 167.3 kWh/m²) show a low deviation or bias between the estimate and the measurements. The Ångström-Prescott coefficients determinants are consistent and can be used to efficiently calculate

the global horizontal irradiance. The model established can be recommended to be used in the nine (9) weather stations to accurately estimate global solar radiation on horizontal surfaces.

Keywords: Ångström-Prescott Coefficients, Global Solar Radiation, Global Horizontal Irradiance, Statistic t-Test

1. Introduction

Information on solar radiation on the Earth's surface is required in many applications including agriculture, hydrology, meteorology, climatology, architecture, active and passive solar energy systems, and photovoltaic electricity production systems (Medeiros et al., 2017; Liu et al., 2009; Ishola, 2018; Girma, 2017; Jeong et al., 2018). The amount of global solar radiation received on a surface depends on numerous factors such as the altitude of the sun, the clearness index, the slope and the latitude of an area. Therefore, global solar radiation varies in space and time due to all these factors. A major challenge facing solar energy technologies is the availability of solar radiation data at the area of interest (Asilevi et al., 2019; Krivoshein et al., 2020). The optimization of the solar energy reception in different applications is highly dependent on the ability to measure and understand its spatial-temporal distribution (Ishola, 2018). Thus, adequate assessment of solar radiation data is crucial for planning and designing solar energy based systems (Mbiaké et al., 2018; Govindasamy & Chetty, 2019; Ya'u et al., 2018; Al-Aboosi, 2020). For this reason, the best way to access solar radiation data at any location is to install suitable ground measuring instruments such as pyranometers and pyrhemometers and record its various components at a desired time scale (Al-Aboosi, 2020; Ener Kusen, 2018). In some regions around the world, measured solar radiation data do not exist or are available at a few places due to the cost, maintenance and instrument calibration requirement, while sunshine hours are measured at any locations (Ya'u et al., 2018; Al-Aboosi, 2020). Lack of adequate spatial and temporal resolution data on solar radiation is a worldwide problem especially in many developing countries. Developing methods to accurately estimate global solar radiation from other meteorological parameters is an alternative to overcome this problem. Numerous methods of varying complexity were established by scientists to estimate solar radiation including those based on generation from stochastic weather models (Richardson & Wright, 1984), satellite image (Pinker et al., 1995), linear interpolation (Hay & Suckling, 1979), artificial neural network (Tymvios et al., 2005), empirical relations using other meteorological variables (Angström, 1924; Prescott, 1940; Bristow & Campbell, 1984), and physical transfer processes (Gueymard, 2001). Among these estimation methods, there are robust numerical models requiring too

many inputs parameters. These methods are only suitable for theoretical analysis rather than practical applications (Morcette et al., 2008; Manners et al., 2009). In contrast, simple empirical models remain the main tools for solar radiation estimation (Linacre, 1992) due to their simplicity, low computational costs, and easily accessible input data. These models were proposed worldwide to estimate solar radiation based on different available meteorological data. They are generally classified into four broad categories as follows (Besharat et al., 2013):

- Sunshine-based models (Ångström, 1924; Prescott, 1940);
- Cloud cover-based models (Kasten, 1984);
- Temperature-based models (Bristow & Campbell, 1984);
- Other meteorological parameters-based models (Swartman & Ogunlade, 1967);

Therefore, the availability of meteorological parameters, which are used as the input of solar radiation models, is the important key to choose the proper radiation modes at any location (Ya'u et al., 2018).

The comparison of these different empirical models revealed that those based on sunshine duration give better results than the others in many studies (Trnka et al., 2005; Podesta et al., 2004; Zhou et al., 2005; Chen et al., 2004; Wu et al., 2007), in particular the Ångström-Prescott equation (Ishola, 2018; Liu et al., 2015; Liu et al., 2012).

Ångström (1924) proposed a linear relationship between the ratio of global radiation to the corresponding value on a completely clear sky day and the ratio of daily sunshine hours to the maximum possible sunshine duration. To solve the difficulty introduced by the perfectly clear sky radiation data, Prescott (1940) replaced it by the extraterrestrial radiation and this modification led to the formulation of the Ångström-Prescott equation (1).

The Ångström-Prescott regression coefficients **a** and **b** result essentially from the empirical attenuation coefficients of extraterrestrial radiation that reaches Earth's surface through the atmosphere. The global heterogeneity of atmospheric thickness and its components distribution objectively produce regional differences in the magnitude of global solar radiation reaching the surface (Xia et al., 2019). The coefficients **a** and **b** of Ångström-Prescott equation are site-specific. They depend on physical characteristics of the atmospheric layer and are influenced by local latitude and altitude without missing the seasonal variability of weather conditions (rainfall, wind, humidity and aerosol thickness and concentrations). The empirical coefficients **a** and **b** should be calibrated for a certain region and cannot be used directly for other regions (Ekici, 2019). Since the establishment of the Ångström-Prescott equation, it has undergone many modifications focused on improving its prediction accuracy and its general validity as summarized by Liu et al. (2009). The improvements consisted in relating the

parameters to geographical factors (Glover & McCulloch, 1958) or to meteorological variables to introduce additional variables into the equation (Ododo et al., 1995; Garg & Garg, 1983) or simply to increase the polynomial order of relative sunshine duration. Although some authors claimed that these modified models were better than the conventional Ångström-Prescott model, this is apparently not the case in many comparative studies undertaken by other researchers (Iziomon & Mayer, 2002; Boisvert et al., 1990; Soler, 1990; Ulgen & Hepbasli, 2004; Ertekin & Yaldiz, 2000; Yorukoglu & Celik, 2006; Zho et al., 2005). Since these modifications did not bring any gain in the estimation accuracy, it is questionable whether it is worthy to adopt such complexity at the risk of losing the simplicity and convenience of the original Ångström-Prescott model. In fact, the other meteorological factors were already implicitly incorporated into the information of the Ångström-Prescott coefficients. This is easily explained by the fact that sunshine duration is linked to the variability of the other meteorological parameters. Therefore, the local calibration of the Ångström-Prescott equation is more important than developing new methods or their modification (Liu et al., 2009).

In Côte d'Ivoire, no study on the modeling of Ångström-Prescott equation was undertaken. This study aims to determine the Ångström-Prescott coefficients in nine (9) meteorological stations from global solar radiation data on a horizontal surface and sunshine hours, and the obtained results was used to estimate global horizontal irradiance.

2. Methods and Materials

2.1. Theoretical Aspect

The global solar radiation reaching the earth's surface is the result of complex interactions between solar rays from the top of the earth's atmosphere and the climatic conditions at the site of interest. The Ångström-Prescott equation establishes a functional relationship between clearness index and relative sunshine duration as follow:

$$\frac{H}{H_0} = a + b \frac{S}{S_0} \quad (1)$$

where H and H_0 are, respectively, global and extraterrestrial radiations, S the actual daily sunshine duration and S_0 the theoretical sunshine duration or day length.

To determine H_0 and S_0 , it is necessary to go through theoretical calculations. So the daily mean extraterrestrial radiation on a horizontal surface H_0 can be calculated for a typical day of a month according to the following equation:

$$H_0 = \frac{24}{\pi} I_{sc} E_0 \left(\frac{\pi}{180} \omega_s \sin \delta \sin \varphi + \cos \delta \cos \varphi \sin \omega_s \right) \quad (2)$$

where $I_{sc} = (1367 \pm 4) \text{W.m}^{-2}$ is the solar constant, E_0 the eccentricity correction factor of the Earth's orbit, ω_s the sunset hour angle, δ the solar declination and φ the latitude of the location.

The eccentricity correction factor is determined by the modified Duffie and Beckman's equation :

$$E_0 = 1 + 0.034 \cos \left[\frac{2\pi(n-2)}{365} \right] \quad (3)$$

where n is the number of day of the year, starting from the first of January ($n = 1$) and ended on December 31th ($n = 365$ or 366 depending on the year).

The solar declination can be calculated from the equation:

$$\delta = 23.429 \sin \left(\frac{2\pi n}{370.84} - 1.3616 \right) + 0.242 \sin \left(\frac{4\pi n}{360.15} - 1.93 \right) \quad (4)$$

The sunset hour angle on a horizontal surface can be obtained by the relationship:

$$\omega_s = \cos^{-1}(-\tan \varphi \tan \delta) \quad (5)$$

This expression leads to determine the maximum sunshine duration of a day on a horizontal surface in hours as follows:

$$S_0 = 2\omega_s = \frac{2}{15} \cos^{-1}(-\tan \varphi \tan \delta) \quad (6)$$

2.2. Solar Radiation Data

To carry out the study, we used data from nine (9) radiometric stations in Côte d'Ivoire from 2006 to 2010. Figure 1 shows the geographical locations of the selected weather stations. The data including the sunshine duration and monthly mean daily solar radiation on horizontal surfaces are collected by Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Météorologique (SODEXAM), the company in charge of the meteorological parameters measurement in Côte d'Ivoire.



Figure 1. Geographical Positions of the Selected Weather Stations (SODEXAM)

Table 1 shows the geographical coordinates of each site as well as the measurements periods.

Côte d'Ivoire is a West Africa country located between latitudes 4 °N and 10 ° N. It is between two main climatic zones, i.e., the humid tropical climate in the south and the Sudanese climate in the north. The coefficients of Ångström-Prescott equation **a** and **b** were determined through linear regression analysis by using the ordinary least squares method relating monthly mean daily clearness index to the corresponding relative sunshine duration at each station.

Table 1. Geographical Coordinates of the Sites and the Periods of the Measurements

Station	Latitude (°)	Longitude (°)	Elevation (m)	Period
Abidjan	5.260291	-3.927276	8	2006-2010
Adiaké	5.286841	-3.302014	39	2006-2010
Bondoukou	8.016067	-2.762753	370	2006-2010
Daloa	6.87669	-6.45161	277	2006-2010
Dimbokro	6.649426	-4.704057	92	2006-2010
Gagnoa	6.132974	-5.95177	210	2006-2010
San-Pédro	4.746199	-6.660735	30	2006-2010
Sassandra	4.951934	-6.088562	66	2006-2010
Tabou	4.41397	-7.363371	21	2006-2010

The values **a** and **b** were obtained from 10-days data covering the period 2006 to 2010, collected annually in each weather station.

2.3. Analysis Methods

After calibrating the Ångström-Prescott equation, the model is evaluated by comparing the measured and estimated values of the monthly

mean daily irradiation H . The performance of the model is determined by calculating the root mean square error (RMSE), the mean bias error (MBE), the mean absolute bias error (MABE), the mean percentage error (MPE), the t -statistic (t -stat), and the Nash-Sutcliffe coefficient of efficiency (NSE) which are defined as follows:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (c_i - m_i)^2} \quad (7)$$

$$MBE = \frac{1}{n} \sum_{i=1}^n (c_i - m_i) \quad (8)$$

$$MABE = \frac{1}{n} \sum_{i=1}^n |c_i - m_i| \quad (9)$$

$$MPE = \frac{1}{n} \sum_{i=1}^n \frac{(c_i - m_i)}{m_i} \times 100 \quad (10)$$

$$t\text{-stat} = \sqrt{\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}} \quad (11)$$

$$NSE = 1 - \frac{\sum_{i=1}^n (m_i - c)^2}{\sum_{i=1}^n (m_i - m_a)^2} \quad (12)$$

Where, n is the number of data pairs, c_i the predicted values of H , m_i the measured values of H and m_a the average of measured values of H .

The RMSE and MBE are the most commonly used indicators to compare models for solar radiation estimations. The RMSE provides information on the short term performance of correlations by allowing a term by term comparison of the actual deviation between the estimated and measured values. Meanwhile, the MBE shows the overestimation or underestimation of the computed values. Low values of RMSE and MBE are expected but depending on the data, some fluctuations can be observed. Togrull et al. (2000) demonstrated that the use of RMSE and MBE in isolation is not an adequate method for evaluating the model performance. Thus, it was concluded that the addition of the statistic t -test t -stat gave more reliable and explanatory results for the evaluation and comparison of solar radiation models (Almorox et al., 2005). In the same way, Jacovides (Jacovides & Kontoyiannis, 1995; Jacovides, 2000) demonstrated that the separated use of RMSE and MBE indicators can lead to the incorrect selection of the best model. It was commonly recommended to use the statistic t -test t -stat in conjunction with RMSE and MBE in order to reliably assess a model's performance (Almorox et al., 2005).

The MABE measures the average of the absolute differences between predicted and measured values. Low values of MABE are desired.

The statistic t-test **t-stat** is given as a function of the widely used root mean square error and mean bias error. In this paper, we used the **t-stat** in conjunction with the RMSE and MBE for the evaluation of the model. We assume that the smaller the value of **t-stat**, the better the model's performance. To determine whether a model is statistically significant, the absolute value of the calculated **t-stat** must be less than the critical **t-stat** value obtained from the statistical tables. By referring to the number of data used in this work ($n = 60$) and for a confidence level of 95%, the critical value of statistic t-test is $t_{crit} = 1.671$ for a one-sided test.

MPE is defined as the percentage deviation of the estimated values from the measured ones. For a better model performance, a low value of MPE is desirable and the percentage error between -10% and +10% is considered acceptable (Samanta et al., 2020).

NSE is a simple measure to determine the model precision by plotting observed values against predicted values in a 1:1 line. Generally, NSE ranges from $-\infty$ to 1.0 and the model is more efficient when NSE is closer to 1 (Samanta et al., 2020). So, in regression procedures, NSE is equivalent to the coefficient of determination (R^2).

3. Results and Discussion

The results of the regression analysis for the five (5) years (2006-2010) of monthly mean daily irradiances for each weather station can be seen in Table 2. The different statistical error indicators and tests are also given in Table 4. According to Table 2, coefficient **a** vary from 0.2154 in Gagnoa to 0.2652 in Bondoukou, **b** vary from 0.3808 in Dimbokro to 0.4182 in Abidjan. Parameter **b** is slightly stable with a coefficient of variation (CV) of 3.36% against 9.85% for **a**. Obviously, the Ångström-Prešcott coefficients vary from one site to another. These variations in **a** and **b** values can be explained as a consequence of local atmospheric climatology. This demonstrates the importance of local calibration of the Ångström-Prešcott equation. On the contrary, the sum (**a + b**) is stable with a CV of 1.5% in the study area, indicating that the overall atmospheric transmission under clear sky conditions is the same in each station.

The calibrated coefficients have a physical meaning because their sum always remains less than one throughout the study area. In the literature (Mbiaké et al., 2018; Besharat et al., 2013; Martinez-Lozano et al., 1984; Nwokolo & Ogbulezie, 2018), the different Ångström-Prešcott coefficients determined in several countries on the five continents (308 values) show that **a** varies between -0.1910 and 0.713, while **b** varies between 0.1900 and

0.7874. By comparison, the values of **a** and **b** obtained belong to these respective intervals.

Table 2. Regression Results for Each Site

Cities	a	b	a + b	R ²
Abidjan	0.2168	0.4179	0.6347	0.9838
Adiaké	0.2210	0.4066	0.6276	0.9801
Bondoukou	0.2652	0.3907	0.6559	0.9843
Daloa	0.2156	0.4182	0.6338	0.9828
Dimbokro	0.2707	0.3808	0.6515	0.9886
Gagnoa	0.2154	0.4173	0.6327	0.9776
San-Pédro	0.2176	0.4159	0.6335	0.9834
Sassandra	0.2169	0.4172	0.6341	0.9780
Tabou	0.2165	0.4144	0.6309	0.9916

Table 3 gives a comparative view of the Ångström-Preccott coefficients determined in some places in Africa. From this table, it is seen that the values obtained in this work are of the same order of magnitude as those of the other regions of Africa, especially for Bobo Dioulasso (**a** = 0.21 and **b** = 0.46), Douala (**a** = 0.2530 and **b** = 0.4266), Ibadan (**a** = 0.308 and **b** = 0.358), Kumasi (**a** = 0.22 and **b** = 0.43), and Lome (**a** = 0.263 and **b** = 0.374) which are five regions in West Africa like Côte d'Ivoire.

Table 3. Values of Ångström-Preccott Coefficients in other African Countries

a	b	a + b	Authors	Year	Region	Country
0.22	0.43	0.65	Quansah and Neba	2014	Kumasi	Ghana
0.250	0.470	0.720	Abbas et Elnesr	1977	Giza	Egypt
0.367	0.367	0.734	Chegaar et Chibani	2001	Beni Abbas	Algeria
0.308	0.358	0.666	Fagbeule	1993	Ibadan	Nigeria
0.430	0.320	0.750	Davies	1965	Ford Lamy	Chad
0.230	0.620	0.850	Glover et McCulloch	1958	Kabete	Kenya
0.240	0.513	0.753	Jain et Jain	1988	8 stations	Zambia
0.320	0.400	0.720	Khogali	1983	Port Sudan	Sudan
0.320	0.460	0.780	Lewis	1983	Harare	Zimbabwe
0.210	0.562	0.772	Mabasa et al.	2020	Mthatha	South Africa
0.210	0.520	0.730	Page	1961	Kinshasa	Zaire
0.300	0.480	0.780	Page	1961	Antananarivo	Madagascar
0.240	0.470	0.710	Rijks et Huxley	1964	Kampala	Uganda
0.263	0.374	0.637	Banna and Gnininri	1998	Lome	Togo
0.2530	0.4266	0.6796	Afungchui and Neba	2013	Douala	Cameroon
0.21	0.46	0.67	Coulibaly and Ouedoraogo	2016	Bobo Dioulasso	Burkina Faso

By observing Table 4, the NSE values that range from 0.8671 to 0.9819 are closer to 1 in all sites. This shows that the model have a good performance. This remark is also confirmed by the low values of **t-stat** (varying from 0.10

to 1.07) which are all less than 1.671. Moreover, MBE values (range from -18.17 to 8.69 kWh/m²/day) point out that the model slightly underestimates the solar radiation values in all sites except in Abidjan where the model overestimates them. The MABE values (ranging from 7.16 to 8.52 kWh/m²/day) reveal that the absolute bias between calculated and measured values is low. It is the same for the RMSE values (from 69 to 167kWh/m²/day) which display that the absolute mean deviation between estimated and measured values is also low. In sum, all the results of the statistical indicators and tests support that the estimated values of the global solar radiation are close to the measured ones. The Ångström-Prescott coefficients obtained by the modeling are consistent. They can allow making a good estimate of the global horizontal irradiance in the nine (9) meteorological stations.

Table 4. Statistical Error Indicators of the Model

Cities	MBE (kWh/m ² /day)	MABE (kWh/m ² /day)	RMSE (kWh/m ² /day)	MPE(%)	NSE	t-stat
Abidjan	8.69	6.87	69.1	0.201	0.9819	1.07
Adiaké	-1.14	7.84	84.3	-0.413	0.9774	0.10
Bondoukou	-15.26	8.52	148.6	-0.320	0.8961	0.79
Daloa	-8.54	7.57	100.9	-0.205	0.9522	0.65
Dimbokro	-13.75	7.23	122.7	-0.291	0.9185	0.87
Gagnoa	-12.20	8.01	124.1	-0.278	0.9129	0.76
San-Pédro	-17.04	8.08	156.6	-0.345	0.8994	0.84
Sassandra	-18.17	8.47	167.3	-0.364	0.8671	0.84
Tabou	-8.71	7.16	91.5	-0.204	0.9737	0.73

4. Conclusion

- Angström-Prescott equation is calibrated, for the first time, in Côte d'Ivoire using nine (9) weather stations data, which is sampled in 10-days global radiation and sunshine hours.
- The performance of the resulting annual model was evaluated using some statistical error methods. The results obtained show a strong correlation with a high determination coefficient for each weather station confirmed by NSE closer to 1. The model performed very well due to the low values of t-stat. The RMSE and MBE related to the comparison between measured and estimated monthly mean daily global radiation ranged, respectively, from 69.1 to 167.3 and from -8.71 to 8.69 kWh.m⁻².day⁻¹. Those values are in convenient with those encountered in literature.
- The comparisons made with other values of the Angstrom-Prescott coefficients throughout the world and specifically in certain

regions of Africa confirm that the coefficients obtained have a good consistency.

- Our results reveal that the model proposed in this work may be used satisfactory for the estimation of monthly mean daily global solar radiation in the nine (9) weather stations in Côte d'Ivoire.

Nomenclature

a : Ångström-Prescott regression coefficient

b : Ångström-Prescott regression coefficient

C_i : Predicted values of H

CV: Coefficient of variation

E_0 : Eccentricity correction function of the Earth's orbit

H : Global horizontal radiation (kWh/m²)

H_0 : Extraterrestrial radiation (kWh/m²)

I_{sc} : Solar constant (W/m²)

m_a : Average of measured values of H (kWh/m²)

m_i : Measured values of H (kWh/m²)

S : Sunshine duration (h)

S_0 : Maximum sunshine duration (h)

δ : Solar declination (°)

φ : Latitude (°)

ω_s : Sunset hour angle (°)

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