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RESEARCH ARTICLE

CONTRIBUTION TO THE ESTIMATION OF THE SOLAR POTENTIAL ON THE GROUND BY SEMI-EMPIRICAL METHODS AND BASED ON THE THERMAL ZONING OF BURKINA FASO

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ABSTRACT

In this paper, we evaluate the solar potential of Burkina Faso by a numerical simulation based on four theoretical models most used in the literature. We validate the numerical results obtained using the solar radiation values recorded on the meteorological sites installed in the different zones defined from the determined climatic zoning that we realized. Climate zoning is established using correlations linking air temperature, relative humidity, sunstroke duration, and global solar radiation. It appears that the territory of Burkina Faso is divided into three climatic zones. A comparative study of the results obtained by simulation from the four models and those measured has shown that whatever the climatic zone considered, the model proposed by Ball & Atwater and that of Bird & Hulstrom make it possible to better evaluate the solar potential. The results obtained with these two models for the three climatic zones come close to real values with great precision.

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INTRODUCTION

Burkina Faso, like the countries of Africa south of the Sahara, has a solar field in abundance. Development policies in energy matters are therefore oriented towards this form of energy. In the field of research applied to renewable energies, the knowledge of the solar energy potential in a given site is a paramount parameter for the designers of systems having solar as a source of energy. There are relatively few sites for measuring solar radiation over the entire territory of Burkina Faso (E. Ouedraogo and O. C. A. Ouedraogo,2012). As a result, the necessary complete meteorological data are most often missing. In addition, we found that some semi-empirical formulas often do not allow to evaluate the solar radiation of certain localities of the country. Numerous studies exist in the literature on solar potential estimation models. We can cite the first steps led by Liu and Jordan (B. Y. H. Liu and R. C. Jordan, 1960), which gave a relation between diffuse daily solar irradiation and global one on a horizontal surface. We can also mention the work of (J. F. Orgill and K.G.T. Hollands, 1977) as well as the work of (Beriot NICOLAS, 1985) which correlated the diffuse fraction of solar radiation with the clarity index. Markovian approaches have contributed to the modeling of random fluctuations in solar radiation (S. HARROUNI et A. MAAFI, 2002) and have enabled the development of solar radiation calculation models. More recent studies have focused on modeling the randomness of solar radiation using neural networks (A. MAAFI et S. HARROUNI, 2000) and fractal analysis (A. SFETSOS et A. H. COONICK, 2000, S. BARBARO, G. CANNATA, S. COPPOLINO, C. LEONE and SINAGRA, 1981). Some authors have used insolation (J. Canada, 1988, C. Gueymard, 1993) and others, the daily average of the relative humidity, the maximum and the minimum of the temperature (I. Supit and R.R. Van Kappel, 1998, J. C. Ododo et al, 1995). In this work, we will first map the thermal zones of Burkina Faso. On the basis of this map study the theoretical modeling of solar radiation, then proceed to its validation. Finally , a comparative study of the evolutions of the solar radiation of the climatic zones will be carried out, an approach which has not been realized in the previous works.

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MATERIALS AND METHODS

Model of Lacis & Hansen model: The model proposed by Lacis & Hansen allows the calculation of global solar radiation on a horizontal plane.

$$R_g = I_{se}\cos\theta_z\left[\frac{0.647-\rho_s-\alpha_o}{1-0.0685\rho}+0.353-\alpha_\omega\right] \tag{1}$$

Where,

I_{se} is the extraterrestrial solar constant calculated by :

$$I_{se}(m)=I_o\left[1+0.033\cos\left(\frac{360}{365}(m-3)\right)\right] \tag{2}$$

I_o is the average solar constant $\left(I_o=1367W/m^2\right)$;
m is the number of the day in the year (m equals 1 on January 1 st and 365 on December 31 st) ;
θ_z is the zenith angle, $\theta_z=90^o-h$ where h is the height of the sun given by equation (3) :

$$\sin h=\cos\delta\times\cos\varphi\times\cos\omega+\sin\varphi\times\sin\delta \tag{3}$$

φ is the latitude of the place, δ the declination of the sun given by equation (4), ω is the hour angle given by equation (5).

$$\delta=23.45\times\sin\left[\frac{360}{365}(m+284)\right] \tag{4}$$

$$\omega=15(TSV-12) \tag{5}$$

In equation (1), α_o is the absorption coefficient of direct solar radiation by the ozone layer. The equation (6) allows us to calculate α_o (M. Koussa, A. Malek et M. Haddadi, 2006):

$$\alpha_o=\frac{0.02118U_o}{1+0.042U_o+3.21\times10^{-4}U_o^2}+\frac{1.082U_o}{(1+138.6U_o)^{0.805}}+\frac{0.0658U_o}{1+(103.6U_o)^3} \tag{6}$$

U_o is the thickness of the ozone layer corrected by the optical path of the solar radiation through this layer and defined by (T. K. Van Heuklon, 1979) :

$$U_o=l\times m_r \tag{7}$$

l represents the amount of ozone at the vertical of the site (thickness in cm of the reduced ozone layer) guiven by equation (8) and m_r , the relative optical air mass is given by equation (9) :

$$l=\frac{235+\left[150+40\sin(0.9856(m-30))+20\sin(3L)\right]\left[\sin^2(1.28\varphi)\right]}{1000} \tag{8}$$

$$m_r=\left[\cos\theta_z+0.15(93.885-\theta_z)^{-1.253}\right]^{-1} \tag{9}$$

L and φ are respectively the longitude and the latitude of the site.

α_ω represents the absorption coefficient of direct solar irradiation by water vapor :

$$\alpha_\omega=\frac{2.9X_\omega}{(1+141.5X_\omega)^{0.635}+5.925X_\omega} \tag{10}$$

X_ω is the thickness of condensable water corrected by optical path of the radiation through this layer, given by :

$$X_\omega = m_a \times U_w \tag{11}$$

m_a is the corrected air mass given by equation (12) :

$$m_a = m_r \left(\frac{P}{1013}\right)^{0.75} \times \left(\frac{273}{T}\right)^{0.5} \tag{12}$$

In this equation, P is the atmospheric pressure (mbar) calculated from Equation (13) below (M. Iqbal, 1983), T is the ambient temperature (K).

$$P = P_o \times \exp(-0.0001184z) \tag{13}$$

P_o is the atmospheric pressure at sea level (P_o= 1013 mbar) ; z (m) is the altitude of the place in relation to the sea level.

$$U_w = \frac{0.493}{T} HR \times \exp\left(26.23 - \frac{5416}{T}\right) \tag{14}$$

HR is the relative humidity (%).

Model Bird and Hulstrom

Calculation of direct radiation: The irradiance due to direct radiation on a horizontal plane is given by equation (15) below (M. Mesri-Merad, I. Rougab, A. Cheknane et N.I. Bachari, 2012) :

$$R_{dir} = 0.9751 \times I_{se} \times \tau_r \times \tau_g \times \tau_\omega \times \tau_o \times \tau_a \times \cos(\theta_z) \tag{15}$$

With,

τ_g is the transmission coefficient after absorption by the permanent gases (CO_2 and O_2),

$$\tau_g = \exp\left(-0.0127 \times m_a^{0.26}\right) \tag{16}$$

τ_r is the transmission coefficient after the molecular diffusion or diffusion of Raleigh (D. Saheb-Koussa, M. Koussa et M. Belhamel, 2006) and is also expressed as a function of the air mass m_a by :

$$\tau_r = \exp\left[-0.0903 \times m_a^{0.84}\left(1 + m_a + m_a^{1.01}\right)\right] \tag{17}$$

The absorption coefficient by the ozone layer τ_o is calculated by the relation :

$$\tau_o = 1 - 0.1611 \times U_o \times \left(1 + 139.48 \times U_o\right)^{-0.3035} + 0.002715 \times U_o \times \left(1 + 0.044 \times U_o + 0.0003 \times U_o^2\right)^{-1} \tag{18}$$

The transmission coefficient after absorption of solar radiation by water vapor is given by:

$$\tau_\omega = 1 - 2.4959 U_\omega \left[\left(1 + 79.03 U_\omega\right)^{0.6828} + 6.385 U_\omega\right]^{-1} \tag{19}$$

The transmission coefficient τ_a after aerosol diffusion can be calculated according to equation (20) below,(M. Mächler, 1983) :

$$\tau_a = \exp\left[-k_a^{0.873} \times m_a^{0.9108} \times \left(1 + k_a - k_a^{0.7088}\right)\right] \tag{20}$$

Where,

$$k_a = 0.2758 \times k_{a1} + 0.35 \times k_{a2} \tag{21}$$

k_{a1} and k_{a2} are two attenuation coefficients determined from experimental measurements deduced from equation (22), forthe respective wavelengths $\lambda_1 = 0.38 \mu m$ and $\lambda_2 = 0.5\ \mu m$:

$$k_a(\lambda) = \beta \times \lambda^{-\alpha} \tag{22}$$

α is the particle size distribution coefficient, therefore characterizes the visibility of the sky and β is the atmospheric cloud coefficient established by Angstrom. The value of α varies from 0 (for small particles) to 4 (for large particles). In our work, we consider $\alpha = 1.3$. The coefficient β is 0.02 for a very pure sky (deep blue) and 0.2 for a polluted sky (milky blue), (A. Mefti, 2007).

Calculation of diffuse radiation: The Bird and Hulstrom model calculates the diffuse radiation on a horizontal plane by summing the three diffuse components due to the various types of diffusion of solar radiation by the atmospheric film.

$$R_{dif} = D_a + D_r + Dm \tag{23}$$

D_r is the diffuse radiation from the Raleigh diffusion:

$$D_r = 0.79 \times I_{se} \times \cos(\theta_z) \times \tau_o \times \tau_g \times \tau_w \times \tau_{aa} \times 0.5 \times \frac{1-\tau_r}{1-m_a+m_a^{1.02}} \tag{24}$$

$$\tau_{aa} = 1-(1-\omega_o)(1-m_a+m_a^{1.06})(1-\tau_a) \tag{25}$$

In equation (24), ω_0 is the unit reflection coefficient relative to aerosol diffusion; its recommended value is 0.9,(D. Saheb-Koussa, M. Koussa et M. Belhamel, 2006).

- D_a is the diffuse radiation after the aerosol diffusion:

$$D_a = 0.79 \times I_{se} \times \cos(\theta_z) \times \tau_o \times \tau_g \times \tau_w \times \tau_{aa} \times F_c \times \frac{1-\tau_{as}}{1-m_a+m_a^{1.02}} \tag{26}$$

F_C is the dispersion factor of the atmosphere, we will take it equal to 0.84 ; τ_{as} is given by relation (27):

$$\tau_{as} = \frac{\tau_a}{\tau_{aa}} \tag{27}$$

- D_m is the diffuse radiation due to the multi-reflection phenomenon earth-atmosphere :

$$D_m = \frac{(I+D_a+D_r)\rho \times \rho_a'}{1-\rho_g \times \rho_a'} \tag{28}$$

ρ is the terrestrial albedo, ρ_a' is the albedo of the clear sky given by :

$$\rho_a' = 0.0685 + (1-F_c)(1-\tau_{as}) \tag{29}$$

Table 1. Values of factor F_c as a function of zenith distance, (G. D. Robinson, 1962)

$\theta_z(^o)$	0	10	20	30	40	50	60	70	80	85
F_c	0.92	0.92	0.90	0.90	0.90	0.85	0.78	0.68	0.60	0.50

Table 2. Average values of climatic parameters used for zoning

Parameter	insolation	radiance	Temperature	Relative humidity
Average value	8.267 hours	18967 kJ / m ^{2}.Day	37.389 ° C	49.579%

Table 3. Statistical weights

Climatic parameter	radiance	Temperature	Relative humidity	insolation
Statistical weight	1/2	1/4	1/8	1/8

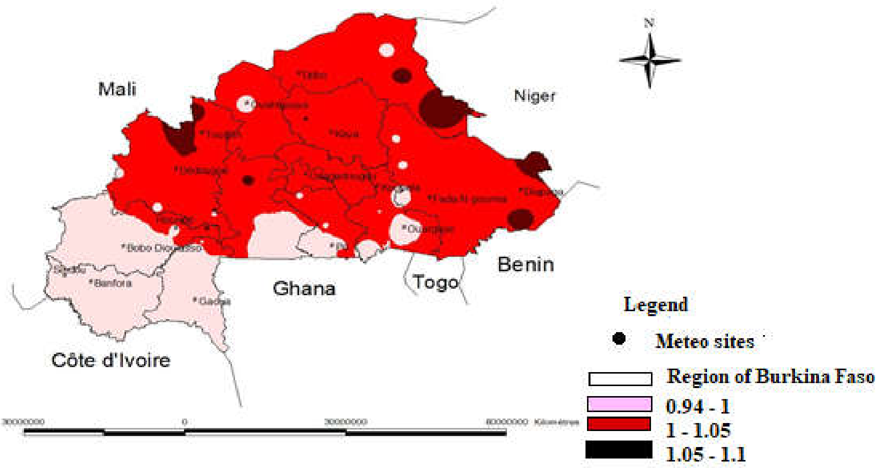

Figure 1. Thermal Zoning Map

Table 4. Geographic coordinates and average values of climatic parameters of the sites considered

	Climate Zone1 (City of Bobo Dioulasso)	Climate zone 2 (City of Ouagadougou)	Climate zone 3 (City of Dori)
Latitude (°)	11	12	14
Longitude (°)	4	1	0
Altitude (m)	432	294	276
Relative average humidity (%) [23]	57.96	48.08	37.91
Temperature average maximum (°C) [23]	34.98	37,60	40.44

Table 5. Year model considered

Year [22]	Month	N° of month	Average day [25]	Day of the year
1994	January	1	17	17
1992	February	2	16	47
2006	March	3	16	75
2002	April	4	15	105
2001	May	5	15	135
1996	June	6	11	162
1994	July	7	17	198
2006	August	8	16	228
2006	September	9	15	258
1999	October	10	15	288
2001	November	11	14	318
1998	December	12	10	344

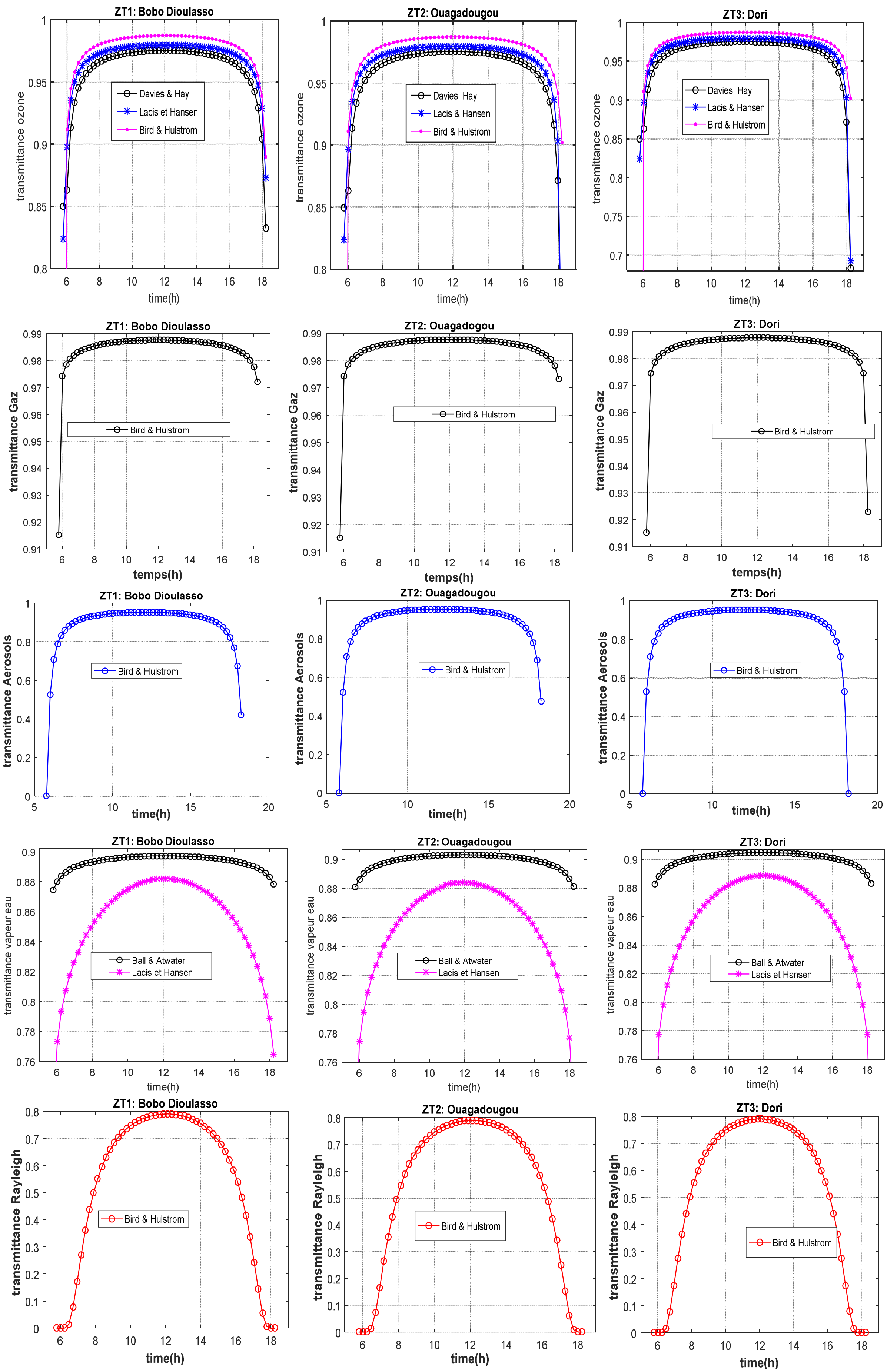

Figure 2 . Evolution of the transmission coefficients of the different atmospheric constituents during a clear sky day

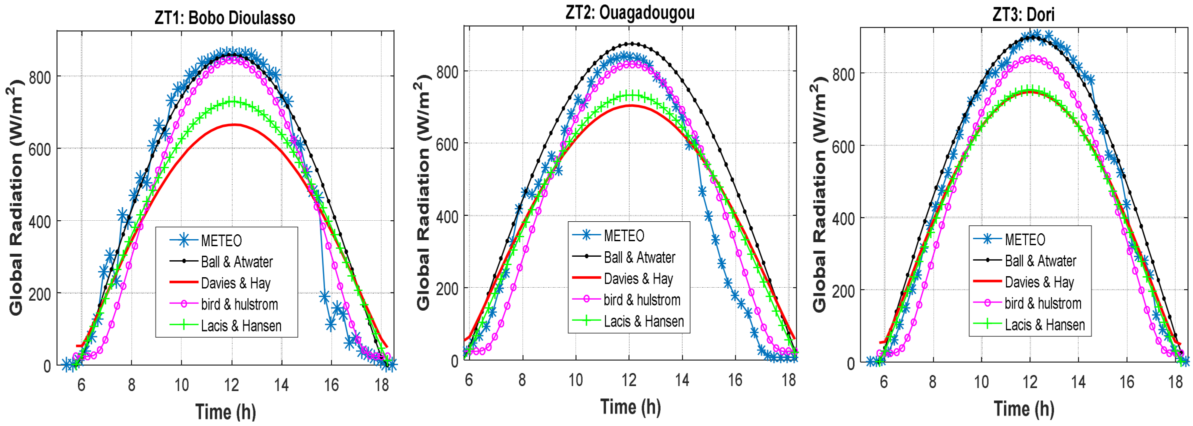

Figure 3. Global insolation curve of the three thermal zones measured and simulated for the average day of July

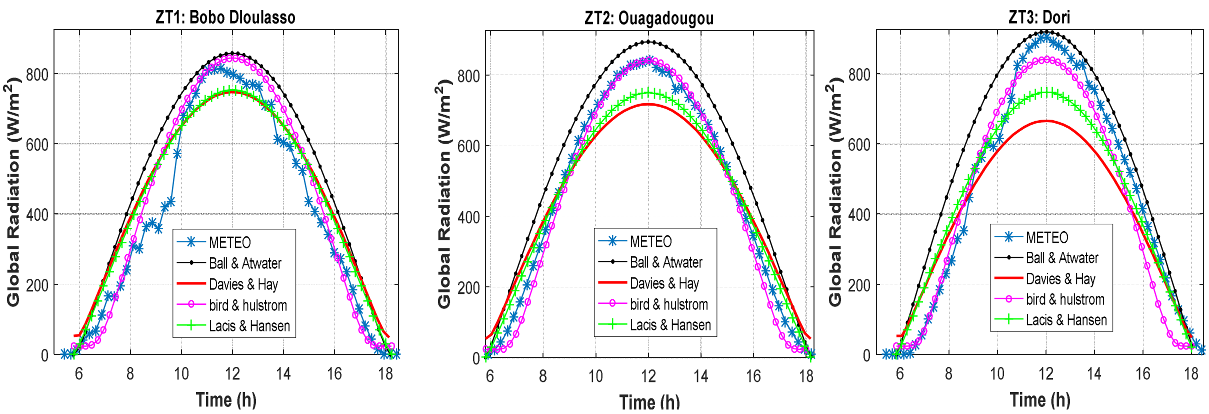

Figure 4 . Global insolation curve of the three thermal zones measured and simulated for the average day of August

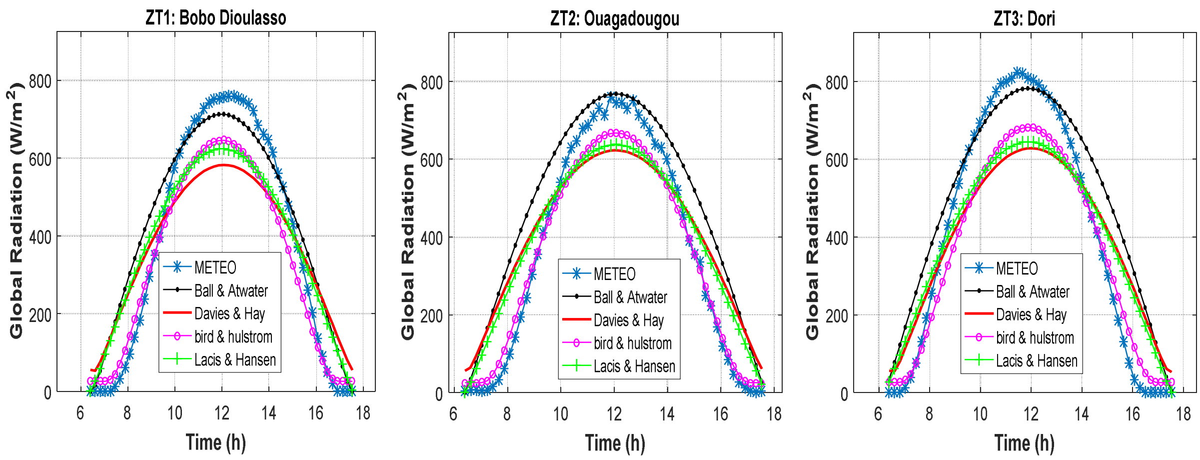

Figure 5 . Global insolation curve of the three thermal zones measured and simulated for the average day of December

Table 6. Mean Relative Error (%) Between Simulated and Measured Sunshine Values

Sites	average day	Ball & Atwater	Davies & H ay	Bird & Hulstrom	Lacis & Hansen
ZT1 Bobo Dioulasso	*July, 17*	16	20	09	20
	August, 16	17	20	04	2 7
	December, 10	26	38	15	30
ZT2 Ouagadougou	*July, 17*	19	26	07	25
	August, 16	09	14	02	13
	December, 10	24	36	08	32
ZT3 Dori	*July, 17*	08	07	02	05
	August, 16	09	10	03	13
	December, 10	11	11	03	14

Calculation of global radiation: The global radiation on a horizontal plane is the sum of the two direct and diffuse solar components:

$$R_g = R_{dir} + R_{dif} \tag{30}$$

Davies and Hay model

Calculation of direct radiation: The equation (31) is proposed by Davies and Hay for the evaluation of direct radiation:

$$R_{dir} = I_{se} \times \tau_a \times \cos(\theta_z) \times \left[(1-\alpha_o) \times \tau_r - \alpha_w\right] \tag{31}$$

- α_o is the absorption coefficient of direct solar radiation by the ozone layer given by equation (6) ;
- τ_r is the transmission coefficient after the molecular diffusion or diffusion of Raleigh. In the model of Davies et al, it is worth:

$$\tau_r = 0.972 - 0.08262 m_a + 0.00933 m_a^2 - 0.00095 m_a^3 + 0.000437 m_a^4 \tag{32}$$

- m_a is the air mass corrected and given by :

$$m_a = \frac{P}{P_o} m_r = \frac{\exp[-0.0001184 \times z]}{\cos(\theta_z) + 0.15 \times \left(93.885 - \theta_z^{-1.253}\right)} \tag{33}$$

- α_ω represents the absorption coefficient of direct solar radiation by water vapor given by equation (10);
- the transmission coefficient τ_a after aerosol diffusion can be calculated according to this model :

$$\tau_a = (0.12445\alpha - 0.0162) + (1.003 - 0.125\alpha)\exp\left[-\beta m_a (1.089\alpha + 0.5123)\right] \tag{34}$$

Where $\beta \prec 0.5$.

Calculation of diffuse radiation

The scattered radiation on a horizontal plane is the sum of the three diffuse components : D_a, D_r and D_m ; such as

$$D_r = 0.5 \times I_{se} \times \tau_o \times \tau_a (1 - \tau_r) \cos(\theta_z) \tag{35}$$

$$D_a = I_{se} \times (\tau_o \times \tau_r - \alpha_w) \times \left[F_c \times \omega_o (1 - \tau_a)\right] \cos(\theta_z) \tag{37}$$

$$D_m = \frac{(I + D_a + D_r)\rho \times \rho_a'}{1 - \rho \times \rho_a'} \tag{38}$$

Where,

$$\tau_o = 1 - \alpha_o \tag{39}$$

ω_o is the albedo of dispersion of the atmosphere. It is usually assigned a value independent of the wavelength. For urban / industrial areas, ω_o worth 0.6, and for rural / agricultural areas it is 0.9,(M. Iqbal, 1983); F_c is the direct dispersion coefficient of the atmosphere. Table 1 gives values for this factor as a function of the zenith angle;

$$\rho_a' = 0.0685 + \omega_o \times (1 - F_c)(1 - \tau_a') \tag{40}$$

The solar radiation transmission coefficient after aerosol diffusion should be calculated for an air mass value equal to $1.66 \times \left(\frac{p}{p_o}\right)$. The factor $(1 - F_c)$ is the backscattering coefficient.

Calculation of global radiation

The global radiation on a horizontal plane is the sum of the two direct and diffuse solar components:

$$R_g = R_{dir} + R_{dif} \tag{40}$$

Atwater and Ball Model

$$R_g = I_{se}\cos\theta_z\left[\frac{T_M - \alpha_w}{1-0.0685\rho}\times\tau_a\right] \tag{41}$$

T_M is given by:

$$T_M = 1.021 - 0.0824\omega_o \times \left[m_o\left(949\times10^{-10}\times P + 0.051\right)\right]^{0.5} \tag{42}$$

m_o is the mass of ozone air given by:

$$m_o = \frac{35}{\left[1224\times\cos^2(\theta_z)+1\right]^{0.5}} \tag{43}$$

THERMAL ZONING OF BURKINA FASO

The construction of the zones was done on the basis of meteorological parameters such as maximum temperature, relative humidity, global radiation and duration of insolation. As a first step, a zoning corresponding to each parameter is established. Subsequently, we made a single climate zoning taking into account all the parameters for the design needs of solar thermal systems. Since meteorological parameters do not have the same dimensions, to connect them, we have sized them using their average value.

The unsized values Rg, Tmax, Hr and N of the parameters were obtained by posing :

$$R_g = \frac{R_{g,i}}{R_{g,moy}},\ T_{\max} = \frac{T_{\max,i}}{T_{\max,moy}},\ N = \frac{N_i}{N_{moy}},\ Hr = \frac{Hr_i}{Hr_{moy}}$$

Where,

R_g : Global radiation, T_{max} : Maximum temperature, N : Insolation duration , Hr : Relative humidity. And α, β, γ and λ are the respective statistical weights of Global Radiation, Maximum Temperature, Relative Humidity and Insolation Duration. These values are linked together using the statistical weights. Equation (46) is obtained :

$$x = \alpha\times R_g + \beta\times T_{\max} + \gamma\times Hr + \lambda\times N \tag{46}$$

To determine the statistical weights, we consider zero weights for wind speed. Drawing on the literature (T. CEBECAUER et M. SURI, 2014, O. COULIBALY, 2011), we determined the weight of the other four climatic parameters. The results obtained are confined in Table 3.

RESULTS AND DISCUSSION

Considering the climatic parameters mentioned above and their weights, the results obtained lead to the country's distribution in three climatic zones as shown in Figure 1. It is noted that Burkina Faso benefits from sunshine. However the south of the country (Banfora, Bobo Dioulasso, Po, Gaoua, Ouargaye) is less radiated than the center and the north. We also note the existence of some pockets of high solar potential mainly in the regions of the Mouhoun (Tougan), the Sahel (Dori) and the East (Diapaga). The low solar potential of the southern part in the center and north of the country can be explained by the high relative humidity of this area. The average annual relative humidity values are given in Table 4. Increasing the relative humidity results in the suspension of water molecules that contribute more to the reflection of direct radiation. For the rest of the work, we consider the climatic parameters of the cities of Bobo Dioulasso, Ouagadougou and Dori respectively to represent climatic zones 1, 2 and 3 established by the map of figure 1. The values of these parameters are confined in the table 1 below. Note also that we consider the months of July, August and December for the study. Indeed, previous work has gone up that in Burkina Faso, these months are the least sunny during the course of a year(A. COMPAORE, 2018).

For the rest of the work, we consider the climatic parameters of the cities of Bobo Dioulasso, Ouagadougou and Dori respectively to represent climatic zones 1, 2 and 3 established by the map of figure 1. The values of these parameters are confined in the table 4 below. Note also that we consider the months of July, August and December for the study. Indeed, previous work has gone up that in Burkina Faso, these months are the least sunny during a year (A. COMPAORE, 2018).The simulation is done using Matlab software. For greater representability, we considered the values of global sunlight provided by E. Ouedraogo et al (E. Ouedraogo and O. C. A. Ouedraogo,2012).They defined a typical year based on a 15-year weather record (1994 to 2008). This year's details are summarized in Table 5. The curves in Figure 2 show the impact of different atmospheric constituents that absorb and diffuse solar radiation. These results are obtained on the basis of the equations of the four models presented above by integrating the geographical and climatic parameters of the three climatic zones. The graphs are drawn for the day of July 17 which corresponds to the average day of July (S. A. Klein, 1977).

For the four models used and for the three climate zones defined in Table 4, it can be seen that the values of the transmission and diffusion coefficients of the solar radiation vary little from sunrise to sunset. In particular, the transmission coefficient after absorption by ozone varies between 0.95 and 0.98 during all the duration of the sunshine but a little less at sunrise and at sunset. The same applies to the transmission coefficient after absorption by gases with values between 0.91 and 0.99. Water vapor has a strong absorption of solar radiation compared to ozone and gases. The values of the transmission coefficient are between 0.76 and 0.9.In addition, aerosols have a high rate of absorption of solar radiation. We have coefficient values lower than 0.4 at sunrise and sunset. This represents a significant diffusion of solar radiation. Note that these values stabilize and remain above 0.9 between 8am and 5pm. The values of the Rayleigh diffusion coefficient are high. This can be explained by the fact that this coefficient depends on the air mass, which is very high at sunrise and sunset. In sum, we believe that aerosols and water vapor contribute much more to attenuate the solar radiation that comes to the ground compared to ozone and gases. In order to validate the four semi-empirical models studied, we compared the values of solar radiation recorded on the meteorological sites of the cities of Bobo Dioulasso, Ouagadougou and Dori during the days of July 17, August 16 and December 10 of the 2017, with the values obtained by simulation under Matlab software. The representative curves of the measured values and those estimated by each of the models were drawn using the same coordinated axes. We then calculated the relative error obtained by equation (47) below:

$$E(\%) = Abs\left(\frac{E_{gm} - E_{gc}}{E_{gm}}\right) \times 100 \tag{47}$$

Where E_{gm} is the measured value of global insolation, E_{gc} is the value calculated from each model. The mean relative error is given by:

$$E_m(\%) = \sum_i \frac{E(\%)}{i} \tag{48}$$

The results of the theoretical and experimental studies are presented in Figures 3, 4 and 5 below. The representative global radiation curves in Figures 3, 4 and 5 reveal that the Davies & Hay and Lacis & Hansen models underestimate global insolation in all three climatic zones represented by the Bobo Dioulasso, Ouagadougou and Dori sites. The values of the average relative errors are summarized in Table 3. Mean relative errors are relatively small for these two models. Indeed, the general expressions of calculation of the global insolation proposed by these two models take into account only the absorption coefficients of the solar radiation by certain atmospheric constituents by neglecting the other extinction coefficients due to other constituents such as air molecules, gases and aerosols. For the Ball & Atwater and Bird & Hulstrom models, we notice for the three zones, the values of the estimated global radiation component are very close to the measured values. The mean relative error is very small and sometimes even negligible. In particular, for the mean days of the months of July and August the two curves simulated by the two curves simulated by these two models are in very good agreement with the curves of the measured values, so that the relative error is very small. However, there is an underestimation of the peak of sunshine by the Bird & Hulstrom model for the average day of December. For the same period, the Ball & Atwater model overestimates the global radiation at sunrise and sunset. These errors are not inherent to the models themselves, but would, in our opinion, be due to probable cloudy periods or fog suspensions that affect the estimate of global radiation. Indeed, these models remain valid for situations of clear sky.

Conclusion

In this paper we modeled and simulated the global radiation on the ground for clear sky days from semi-empirical approaches. The results obtained were compared to the values recorded on the meteorological stations for the sites of Ouagadougou, Bobo Dioulasso and Dori in the typical days for the months of July and August, considered as the least sunny months of the year. These sites were chosen on the basis of the thermal zoning of the territory of Burkina Faso that we have established. We found that the Ball & Atwater and Bird & Hulstrom models give a better estimate of global solar radiation. The results obtained with these two models, for the three climatic zones, are close to real data with great precision. In addition, it should be noted that this work enabled us to answer the questions related to the modeling of global solar radiation in Burkina Faso to affirm that there is no universal theoretical method that matches the experimental results. Moreover, for the case of our country, we can privilege the use of models proposed by Ball & Atwater and Bird & Hulstrom. Also the complementarity of the "ground measurement" and "satellite imagery" approaches is essential as well as the good understanding of the limits of each model for each given situation.

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