Assessment of Hourly Solar Direct Normal Irradiance using Eight Broadband Clear Sky Models: Study of Four Moroccan Arid Sites


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Abstract- This paper presents a statistical comparative study of eight important parametric broadband clear sky models, against Meteosat-derived data, to estimate solar hourly direct normal irradiance (DNI) for four Moroccan arid zone sites. To achieve this aim, four sites well spread across this climatic zone were selected, and four references days were chosen. The statistical parameters such as relative mean bias error (rMBE), the relative root mean square error (rRMSE), and the determination coefficient $R^2$ are calculated. According to these results, the Bird model produces acceptable estimates with 62.5% of good results of rMBE ranging between 0 and 6%; 25% of average results of rRMSE ranging between 11% and 14%, and 62.5% of good results of $R^2$ ranging between 0.90 and 0.96. The comparison of both means of DNI, calculated and measured for a given site and day of reference, using the paired t-test, states that for a level of significance of 1%, the Bird model and the REST2 model give in the quarter of the studied cases conforming means of hourly DNI. For a level of significance of 0.1%, the Bird model is more proficient and gives conforming means in almost half of the cases studied. Despite all these performances displayed by the Bird Model, it remains average and does not reach the required level in some sites at certain times. The elaboration of a new simpler DNI estimation model giving higher performances for this zone of high solar potential is of great interest.

Keywords: Clear sky model, direct normal irradiance (DNI), Moroccan arid zone, modeling, solar energy, statistical comparison.

1. Introduction

Morocco has a very great solar potential with incident solar energy averaging 4.7 to 5.7 kWh/m² per day [1]. Thus, it has established a solar program "Noor", estimated at 9 billion dollars, with the aim of producing 2,000 MW of solar power by 2020[2]. This program is characterized by the construction of thermodynamic concentrated solar power (CSP) and photovoltaic plants all located in the arid and
(desert zone of the country. Since the direct normal irradiance (DNI) is the component of global solar coming from the solid angle of the sun's disk[3] and mainly focused by CSP [4], the modeling of this component of solar radiation in this zone characterized by an annual DNI potential higher than 2,000 kWh/m² [5] is of a great interest. Thus, the determination of the mathematical model describing the DNI by giving more accurate estimates will help in the planning of this solar power plants, their conception and optimal utilization [4]-[6].

Recently, many studies have been devoted to the validation of the Meteosat Second Generation MSG derived data. Marchand et al [7] validated the Copernicus Atmosphere Monitoring Service (CAMS-rad) version 3.2 databases by comparing them to coincident ground measurements made at five stations in Morocco. The five compared stations are all located in Moroccan arid or semi-arid zone. Given the scarcity of data concerning this zone, one can consider that the fewer uncertainties observed will not influence the comparative study of broadband models to estimate hourly DNI against data generated using CAMS-rad version 3.2. Table I regroup the selected sites for this study. All are well spread over the Moroccan arid zone. The Bird, Atwater & Ball, Paltridge & Platt, Linke-Kasten, Hoyt, Ineichen & Perez, Molineaux, and REST2 models are the Broadband parametric models selected to achieve this study. All are simpler parametric models and are the most recommended in literature to estimate DNI. Note that using these models the estimation of the DNI is possible using only meteorological parameters as inputs [8].

The main objective of this work is to study and apply these broadband models to Morocco's arid climate zone. Four sites well distributed in this climatic zone of very high solar potential were selected and four reference days equitably distributed over time, which are the two solstices and the two equinoxes, were considered.

**Table 1. Geographical coordinates of the four studied sites having arid zone[5].**

<table>
<thead>
<tr>
<th></th>
<th>Latitude (\phi)</th>
<th>Longitude</th>
<th>Altitude</th>
<th>Annual DNI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ouazarzate</td>
<td>30.92°</td>
<td>-6.89°</td>
<td>1120</td>
<td>2,458</td>
</tr>
<tr>
<td>Errachidia</td>
<td>31.92°</td>
<td>-4.44°</td>
<td>1033</td>
<td>2,270</td>
</tr>
<tr>
<td>Guelmim</td>
<td>28.99°</td>
<td>-10.04°</td>
<td>313</td>
<td>2,098</td>
</tr>
<tr>
<td>Tendrara</td>
<td>33.05°</td>
<td>-2.00°</td>
<td>1443</td>
<td>2,246</td>
</tr>
</tbody>
</table>

2. Models, data used and Methods

2.1. Tested models

- **Bird model**

The direct normal irradiance \(I_{bn}\) in this model is given by[9]:

\[
I_{bn} = 0.9662 \times I_{cn} \times \tau_R \times \tau_a \times \tau_{\phi} \times \tau_{\lambda} \tag{1}
\]

In our calculations we used in Eq.1 factor 0.9751 instead of 0.9662 as adjusted by Bird. Iqbal et al used this modified formulation in his model of estimation of the global irradiance[10].

\(I_{cn}\) stands for extraterrestrial solar radiation in eq.1. It is estimated using the following equation:

\[
I_{cn} = I_0 \left[ 1 + 0.033 \times \cos \left( 360 \left( \frac{\eta_j - 2.7206}{365.25} \right) \right) \right] \tag{2}
\]

\(I_0\) denotes the solar constant, which is equal to 1367 W/m², and \(\eta_j\) denotes the day number of the year, ranging from 1 on 1 January to 365 on December 31.

\(\tau_R\) is the transmittance functions for Rayleigh scattering and is given by [11]:

\[
\tau_R = \exp \left( -0.0903 \left( M' \right)^{0.84} \times \left[ 1 + M' - (M')^{0.11} \right] \right) \tag{3}
\]

In the model formulation, the air mass is expressed as follows:

\[
M' = M \times e^{-0.0001148 \times z} \tag{4}
\]

\(z\) is the altitude in (m) of the location studied, \(M\) is the air mass and is given by Kasten [12]-[13]:

\[
M = \frac{1}{\sin(h) + 0.15 \times (3.885 + h)^{1.253}} \tag{5}
\]

Where \(h\) is the solar altitude in (rad).

\(\tau_{\phi}\) is the absorption by the uniformly mixed gases (oxygen and carbon dioxide). It is expressed as follows [11]:

\[
\tau_{\phi} = \exp \left( -0.0127 \times M'^{0.26} \right) \tag{6}
\]

\(\tau_{\phi}\) is the ozone absorption and given by [11]:

\[
\tau_{\phi} = 1 - 0.1611 X_0 \times \left( 1 + 139.48 X_0 \right)^{-0.3035} \times 0.002715 X_0 \left( 1 + 0.0444 X_0 + 0.0003 X_0^2 \right) \tag{7}
\]

Where, \(X_0\) is the total amount of ozone in a slanted path (atm.cm)

\[
X_0 = U_0 \times M \tag{8}
\]

\(U_0\) is the Amount of ozone in a vertical column from surface in (matm – cm) for any
location in the earth’s northern hemisphere is given by\[14\]:

\[
U_0 = 235 + \sin^2(1.28\varphi) \times \left[ 150 + 40\sin\left(0.9865(n_j - 30)\right) + 20\sin(3L + I) \right]
\]

(9)

Where, \( \varphi \) and \( L \) are the latitude and the longitude of the site in (rad), respectively. And \( I = 0 \) if the longitude of the location is “West”, and \( I = 20 \) if it is “East”.

\( \tau_w \) is the water vapor absorption. It is given by \[11\]:

\[
\tau_w = 1 - 2.4959 \times \frac{X_W}{(1 + 79.03 \times X_w)0.6828 + 6.385 \times X_w}^{-1}
\]

(10)

Where, \( X_W \) is the total of precipitable water in a slanted path (cm,H₂O), it is expressed as:

\[
X_W = w \times M
\]

(11)

\( w \) in (cm) is the Amount of precipitable water in a vertical column from surface is given by\[15\]

\[
w = \frac{49.953}{T} \times \frac{HR}{10^4} \times (17.443 - 2.795 \times -1.868 \times \log(T))
\]

(12)

\( T \) is the ambient temperature in (K). \( HR \) is the relative humidity.

\( \tau_A \) is the aerosol extinction and given by \[11\]:

\[
\tau_A = \exp\left[-K_A \times \left(1 + K_A - K_\alpha\times 0.0088\times M^{0.9108}\right)\right]
\]

(13)

Where,

\[
K_A = 0.2758 \times K_{A,0.38} + 0.351 \times K_{A,0.5}
\]

(14)

\( K_{A,0.38} \) is the Aerosol optical depth from surface in a vertical path at \( \lambda = 0.38 \mu m \)

\( K_{A,0.5} \) is the Aerosol optical depth from surface in a vertical path at \( \lambda = 0.5 \mu m \)

The two latest dimensionless coefficients are determined using the formula proposed by Angstrom\[9\]:

\[
K_A(\lambda) = \beta \times \left[\frac{\lambda}{(\mu m)}\right]^{-\alpha}
\]

(15)

\( \beta \) is the Angstrom’s turbidity coefficient and \( \alpha \) is the wavelength exponent.

For \( \lambda = 0.38 \mu m \) we took \( \alpha = 1.0274 \)

For \( \lambda = 0.5 \mu m \) we take \( \alpha = 1.2060 \)

- **Atwater and Ball model**

  The direct normal irradiance \( I_{dn} \) given by Atwater and Ball model is represented as \[16\]:

\[
I_{dn} = I_{sc} \times (\tau_M - a) \times \tau_A
\]

(16)

Where, \( \tau_M \) is the transmittance for all molecular effects except water vapor absorption and given by:

\[
\tau_M = 1.041 - 0.15\left[M \times (949.10^{-8} P + 0.051)\right]^{0.5}
\]

(17)

\( P \) is the atmospheric pressure in (Pa), \( M \) is calculated using the expression given in the Eq.5. The absorptivity by water vapor \( a_w \) is given as:

\[
a_w = 0.077\left(w \times M\right)^{0.3}
\]

(18)

We note that we used the expression of \( w \) already defined in the Eq.12 in the calculation of \( a_w \). The transmittance \( \tau_A \) after aerosol attenuation is given as:

\[
\tau_A = \exp(-M' \times K_A)
\]

(19)

\( K_A \) is defined by the Eq.14 previously given in the Bird model.

- **Paltridge & Platt model**

  The direct normal irradiance \( I_{dn} \) of the Paltridge & Platt model is given by\[17\]:

\[
I_{dn} = I_{sc} \times (\tau_M - a) \times \tau_A
\]

(20)

Hay and Davies have used this expression in their global solar irradiance model\[18\]. A number of authors have contributed to the development of this model\[10\]. Paltridge and Platt recommended the formalism of the transmittance function of ozone absorption \( \tau_o \), and the absorptivity by water vapor \( \tau_w \), given by Lacis and Hansen in their model for the global irradiance. Therefore,

\[
\tau_0 = 1 - \left[\frac{0.02118X_0}{1 + 0.042X_0 + 0.003232X_0^2}\right]
\]

(21)

\[
\left[\frac{1.082X_0}{1 + 138.7X_0^{0.805}} + \frac{0.0658X_0}{1 + 103.5X_0}\right]
\]

\[
a_w = 2.9X_w/(1 + 141.3X_w)^{0.635} + 5.925X_w
\]

(22)

Where the expression of \( X_0 \) and \( X_w \) are given by the Eq.8 and Eq.11, respectively.

The attenuation due to Rayleigh scattering \( \tau_R \) can be evaluated through the Eq.3 given by Bird. The transmission after the aerosol extinction \( \tau_A \) can be evaluated for \( \beta < 0.5 \) through the Maŭčcher equation\[10\]:

\[
\tau_A = (0.12445\alpha - 0.0162) + (1.003 - 0.125\alpha) \times \exp\left[-\beta M'(1.089\alpha + 0.5123)\right]
\]

(23)

The coefficient \( \alpha \) was fixed at the value of 1.3\[10\].

- **Linke - Kasten model**

  This Model is very often called Kasten model. In fact, the expression of direct normal irradiance is given by Linke \[19\]-\[20\]:

\[
I_{dn} = I_{sc} \times \exp(-\delta R \times M' \times T_L)
\]

(24)
The expression of $\delta_R$ used in this model is defined by [21] as follows:

$$
\delta_R = \frac{1}{0.9 \times M' + 9.4}
$$

(25)

Therefore, we preferred to name this model with the association of these two names.

- **Hoyt model**
  From this model the direct normal irradiance is given by [22]:

$$
I_{ba} = I_{sc} \times \left( \sum_{i=1}^{5} a_i \right) \tau_R \tau_A
$$

(26)

Where the parameters $a_1, a_2, a_3, a_4, a_5$ are the absorbance parameters defined by Hoyt as follows:

$$
a_i = 0.110 \times (0.75U_i M + 6.31 \times 10^{-3})^{0.3} - 0.0121
$$

(27)

$$
a_2 = 0.00235 \times (136 M' + 0.0129)^{0.26} - 7.5 \times 10^{-4}
$$

(28)

$$
a_3 = 0.045 \times (U_6 M + 8.34 \times 10^{-4})^{0.38} - 3.1 \times 10^{-3}
$$

(29)

$$
a_4 = 7.5 \times 10^{-3} \times (M' 0.875)
$$

(30)

$$
a_5 = 0.05 \times T_d
$$

(31)

The transmittance due to Rayleigh scattering $\tau_R$ is calculated here by the following equation instead of the tabulated form used by Hoyt[10]:

$$
\tau_R = 0.6175975 + 0.375666 \exp(-0.2211875 M')
$$

(32)

The transmittance of aerosol scattering is given by:

$$
\tau_A = \left[ g(\beta) \right]^{M'}
$$

(33)

Where:

$$
g(\beta) = -0.914000 + 1.909267 \exp(-0.667023 \beta)
$$

with $0 < \beta < 0.5$

(34)

- **Inechen and Perez model**
  This model was developed by Inechen and Perez[19] in 2002 and is given by the expression:

$$
I_{ba} = b \times I_{sc} \times \exp(-0.09 \times M' \times (T_L - 1))
$$

(35)

Where $b$ is a multiplicative coefficient depending on the altitude of the location and is given by:

$$
b = 0.664 + \left( 0.163 \times \exp(z / 8,000) \right)
$$

(36)

- **Molineux model**
  In this model the direct normal irradiance is given by Molineux et al [23] as follows:

$$
I_{ba} = I_{sc} \times \exp(-\Delta_{cda} \times T_L \times M')
$$

(37)

Where $\Delta_{cda}$ is the integrated optical thickness of a clean and dry atmosphere, and is given by:

$$
\Delta_{cda} = 0.124 - 0.0285 \times \log(M')
$$

(38)

- **REST2 Model**
  In this Model, the solar spectrum is subdivided into two bands. The first is of ultraviolet and visible and the second is of the infrared. The direct normal irradiance $I_{ba}$ is the sum of two-band components: $I_{ba1}$ and $I_{ba2}$. Each of these is calculated using the following expression [24]:

$$
I_{ba1} = I_{sc1} \times \tau_{R1} \times \tau_{w1} \times \tau_{G1} \times \tau_{N1} \times \tau_{W1} \times \tau_{A1}
$$

(39)

Where $\tau_{R1}$, $\tau_{w1}$, $\tau_{G1}$, $\tau_{N1}$, $\tau_{W1}$, and $\tau_{A1}$ are the band transmittances for Rayleigh scattering, uniformly mixed gas absorption, ozone absorption, nitrogen dioxide absorption, water vapor absorption and aerosol extinction, respectively. The energies contained in bands Band 1 and Band 2 are respectively:

$$
I_{sc1} = 0.4604 \times I_{sc} \quad \text{and} \quad I_{sc2} = 0.5057 \times I_{sc}
$$

(40)

The following equations give the formulation of different transmittances in the two bands[24]:

**In band 1:**

$$
\tau_{R1} = \frac{(1 + 1.8169 M' - 0.033454 M'^2)}{(1 + 0.063M' + 0.31978 M'^2)}
$$

(41)

$$
\tau_{G1} = \frac{(1 + 0.95885 M' + 0.012871 M'^2)}{(1 + 0.9632 M' + 0.015444 M'^2)}
$$

(42)

$$
\tau_{N1} = (1 + f_1 m_w + f_2 m_o)/\left(1 + f_3 m_w\right)
$$

(43)

$$
\tau_{w1} = \min[1,(1 + g_1 m_o + g_2 m_w)/(1 + g_3 m_o)]
$$

(44)

$$
\tau_{A1} = (1 + h_1 m_w) / (1 + h_2 m_o)
$$

(45)

$$
\tau_{A1} = \exp\left(-m_w \times \beta_1 \times \delta_{A1}\right)
$$

(46)

**In band 2 :**

$$
\tau_{R2} = \frac{(1 - 0.010394 M')}{(1 - 0.00011042 M')}
$$

(47)

$$
\tau_{G2} = \frac{(1 + 0.27284 M' - 0.00063699 M'^2)}{(1 + 0.30306 M')}
$$

(48)

$$
\tau_{N2} = (1 + c_1 m_o + c_2 m_w^2) / (1 + c_3 m_o + c_4 m_w^2)
$$

(49)

$$
\tau_{w2} = \exp\left(-m_o \times \beta_2 \times \delta_{w2}\right)
$$

(50)

$$
m_o, \text{ is the ozone optical mass, } m_w \text{ is the water vapor optical mass, and } m_o \text{ is the aerosol optical mass are given by[25]:}
$$

$$
m_o = 13.5 / \sqrt{181.25 \sin^2(h) + 1}
$$

(52)

$$
m_w = \left[\sin(h) + 0.0548(5^{h} + 2.65)^{1.452}\right]^{-1}
$$

(53)

$$
m_o = m_w
$$

(54)

$f_1$, $f_2$, and $f_3$ are parameters depending on $U_0$, the Ozone column amount[24]. $g_1$, $g_2$, and $g_3$ are parameters depending on the $U_0$ [24], the total column amount of NO2. Here we took $U_0 = 0.002 \text{ atm} \cdot \text{cm}$ [26]. $c_1$, $c_2$, $c_3$, $h_1$ and $h_2$ are parameters depending on the total column amount
precipitate water \( U_w \) with \( U_w = m_w \) [25]. \( \lambda_{c1} \) and \( \lambda_{c2} \) are the effective aerosol wavelength in each band[24]. Concerning the turbidity data, we considered \( \alpha_1 = \alpha_2 = 1.3 \) and \( \beta_1 = \beta_2 = \beta \).

2.2. The data used

The satellite-derived data of hourly direct normal radiation considered in this work were generated using CAMS-rad service from 2004 up to December 2018. This data has been constructed for the actual weather conditions as well as for clear-sky conditions from images acquired by the Meteosat series of satellites. The coverage area is Europe, Africa, the Atlantic Ocean and the Middle East. The resolution distance is 3 km at Nadir and is 4 to 5 km in latitude 45°. The data are freely available from the web site Soda service. The turbidity data, namely the Angstrom’s coefficient and Linke turbidity, for reference days in this work were considered approximatively to the mean monthly values shown in Table.2 and also available at the SoDa Service [27]. The hourly ambient temperature and relative humidity were extracted for each reference days and sites from the Soda service. A polynomial fit was used to obtain correlations describing their variations for the sunny period of the day versus true solar time (TST). The overall of the correlations is tabulated in Appendix I.

Table 2. Monthly mean values of Angstrom’s coefficient \( \beta \) and factor turbidity of Linke \( T_{L} \) [27]

<table>
<thead>
<tr>
<th>Locations</th>
<th>Months</th>
<th>( \beta )</th>
<th>( T_{L} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Errachidia</td>
<td>June</td>
<td>0.12</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>December</td>
<td>0.06</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>March</td>
<td>0.03</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>0.15</td>
<td>5.2</td>
</tr>
<tr>
<td>Ouazarzate</td>
<td>June</td>
<td>0.12</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>December</td>
<td>0.07</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>March</td>
<td>0.07</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>0.13</td>
<td>4.8</td>
</tr>
<tr>
<td>Guelmine</td>
<td>June</td>
<td>0.08</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>December</td>
<td>0.05</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>March</td>
<td>0.06</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>0.08</td>
<td>3.9</td>
</tr>
<tr>
<td>Tendrara</td>
<td>June</td>
<td>0.08</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>December</td>
<td>0.03</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Mars</td>
<td>0.01</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>0.10</td>
<td>4.3</td>
</tr>
</tbody>
</table>

2.3. Statistical comparison method

The Model’s performances are analyzed using the most common error metrics used in the literature, mainly the Relative Mean Bias Error (rMBE), the Relative Root Mean Square Error (rRMSE) and the determination coefficient \( R^2 \). They are defined as follows [28]-[29]-[30]:

\[
\text{rMBE} = \left( \frac{1}{n} \sum_{i=1}^{n} \left( c_i - m_i \right) \right) 
\]

\[
\text{rRMSE} = \frac{1}{n} \left( \sum_{i=1}^{n} (c_i - m_i)^2 \right)^{1/2} 
\]

\[
R^2 = 1 - \frac{\sum_{i=1}^{n} (m_i - \bar{m})(c_i - \bar{c})^2}{\sum_{i=1}^{n} (m_i - \bar{m})^2 (c_i - \bar{c})^2} 
\]

Where \( c_i \) is a calculated value by a given model, \( m_i \) is the measured value at time \( i \), \( n \) is the total number of observations, \( \bar{m} \) and \( \bar{c} \) are the means of the total measured and the calculated data points, respectively.

A model designed to compute hourly normal solar irradiance provides a good performance if the rMBE, rRMSE have as low values as possible and \( R^2 \) near at 1.

In addition to the error metrics, the paired t-test is also used to make a decision for a given level of significance \( \alpha \), whether the means of the two dependents groups of results are different. The observed value \( t_{ob} \) of the t-test is calculated using the following formula [31]:

\[
t_{ob} = \frac{\bar{d}}{S_d / \sqrt{n}} 
\]

Where \( \bar{d} = m - \bar{c} \) and \( \bar{c} \) is the mean over all calculated data points for a given model and \( S_d \) the standard deviation estimated from a sample of the differences: \( d_i = m_i - c_i \). It is expressed as:

\[
S_d = \frac{1}{n-1} \sum_{i=1}^{n} (d_i - \bar{d})^2 
\]

The two-sided hypothesis tested are \( H_0 \) (the two samples of data are conform; \( \bar{d} = 0 \) ) against the opposite hypothesis \( H_1 \) (the two samples of data are different; \( \bar{d} \neq 0 \) ). The p-value is the lowest level of significance required to reject a null hypothesis using the data provided. [31]. We computed the p-value using statistical software. The decision about the null hypothesis is made by comparison of the p-value and \( \alpha \). If the p-value is more than \( \alpha \), we accept the hypothesis null, and we judged that the difference between calculated values and measured ones is statistically insignificant for a level of significance \( \alpha \). Here, we used the usual values of level of significance 0.1%; 1%; and 5%. The p-value is computed using the free statistical software “R”. Table.3 shows categories of models used in the work. This classification method was used by Badescu et al [32] and then adopted by Engerer and Mills[33].

Finally, to facilitate the distinction between the different models, we assigned a weighting factor to
each category, +3 for "excellent", +2 for "good", +1 for "average", and 0 for "poor". Then we calculated a score for each model. Thus, an excellent model will have a score of 36, a good model will have a score of 24, and average will have a score of 12. Intermediate scores are obviously possible.

Table 3. The three performances categories for the statistical parameters used

| Model    | |rMBE| | rRMSE | | R² |
|----------|------------------|------------------|------------------|
| Poor     | ≥10%             | ≥15%             | ≤0.80            |
| Average  | ≥5%              | ≥10%             | ≤0.90            |
| Good     | ≥2%              | ≥5%              | ≤0.97            |
| Excellent| <2%              | <5%              | >0.97            |

3. Results and discussion

By simply looking at the curves in Fig.1 and Fig.2 and Fig.3 and Fig.4, it appears that some models show fewer discrepancies from the mean measured values than others. This statement depends on the reference day and the studied site. For Ouarzazate site, as shown in Fig.1, the Molineaux and the REST2 models, for March 20, give closer estimates. In contrast to September 23 and June 21, the Bird and the Linke-Kasten models are the closest ones. For December 21, the Hoyt model and the Paltridge model give results that are more convincing.

In the case of Errachidia site, as seen in Fig.2 the Bird model and the Molineaux are more accurate for June 21. In contrast, for December 21, the Atwater & Ball and the Hoyt models are more accurate. For March 20, the REST2 and the Molineaux models coincide very well with the measured values. For September 23, the Ineichen & Perez Model, the bird Model, and the Linke-Kasten Models are more performant.

Figure 3 shows that the REST2 and Molineaux models give very good estimates for Guelmime site and for June 21. The same models give relatively acceptable results for September 23. On the contrary, for December 21, Bird Model, Ineichen & Perez model, and Linke-Kasten give values in very good agreements with measured ones. For March 20, no parametric model gives calculation results showing acceptable discrepancies with CAMS-rad values.

For the site of Tendrara and for June 21, we note as shown in Fig.4 that the Molineaux and REST2 models give results that perfectly match the measured values. For September 23, the Bird and Ineichen & Perez models are producing very convincing results. On the other hand, for 20 March all models give results of calculations more distinguished from the measured values.

Fig. 1. Direct normal irradiance estimated for the two equinoxes and the two solstices using eight parametric models and derived – Satellite data for Ouarzazate.
Fig. 2. Direct normal irradiance estimated for the two equinoxes and the two solstices using eight parametric models and derived – Satellite data for Errachidia.

Fig. 3. Direct normal irradiance estimated for the two equinoxes and the two solstices using eight parametric models and derived – Satellite data for Guelmim.
Fig. 4. Direct normal irradiance estimated for the two equinoxes and the two solstices using eight parametric models and derived – Satellite data for Tendrara.

Fig. 5. Evaluation of performance score of different models by locations.
Fig. 6. Percentage of statistically significant cases with $\alpha = 0.1\%$ (a) and $\alpha = 1\%$ (b) for different models

4. Conclusion

The performance of each model at each site and for each reference day was first calculated by determining the overall relative mean bias error, the relative root mean square error and the determination coefficient. The models were classified according to their performance into four categories: "excellent", "good", "average" and "poor". Finally, with the intention of generalizing to the entire Moroccan arid zone, we have determined the most robust model or models giving better estimates in the four selected sites.

Relatively satisfactory results have been obtained for the Bird model followed by Ineichen & Perez, Molineaux, and REST2 Models. The calculated statistical parameters state that the Bird model gives good estimates results against other models. 62.5% of satisfactory values of rMSE ranging between 0 and 6%; 25% of average values of $r$RMSE ranging between 11% and 14%, and 62.5% of good values of $R^{2}$ ranging between 0.90 and 0.96 are obtained for this model. Our comparison of conformity of means, calculated and measured, using the paired t-test, achieves that the Bird model displays for a level of significance $\alpha = 0.1\%$ the highest Percentage of cases with conforming means, almost the half of tested cases. This percentage decreases to the quarter cases when $\alpha = 1\%$. One note that for a level of significance most serious, $\alpha = 5\%$ for example, value usually used for this type of comparison, no Model produce conforming means to the measured one. Finally, we note that the percentages achieved remains below the attempted results. The elaboration of a new simpler broadband model for arid Moroccan zone seems to be of great importance.

APPENDIX I:

Ambient temperature and relative humidity correlations versus Time solar true $t$ in (h) determined for of the corresponding sites and for the sunny period of the day on the basis of the data from 01/10/2004 To 01/10/2018[34]. $R^{2}$ is the coefficient of determination of the polynomial fit realized.

<table>
<thead>
<tr>
<th>Locations</th>
<th>Days</th>
<th>T(K)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ouarzazate</td>
<td>21-Jun</td>
<td>$T = 0.0021t^{2} - 0.1175t + 2.1294t^{2} - 13.503t + 291.58; \ R^{2} = 0.9945$</td>
<td>$RH = -0.0351t^{2} + 1.8219t - 29.72t + 166.32; \ R^{2} = 0.9892$</td>
</tr>
<tr>
<td></td>
<td>21-Dec</td>
<td>$T = 0.0046t^{2} - 0.2513t + 4.6553t^{2} - 33.506t + 357.2; \ R^{2} = 0.9923$</td>
<td>$RH = -0.0182t^{2} + 0.9711t - 17.781t^{2} + 127.68t - 240.9; \ R^{2} = 0.9905$</td>
</tr>
<tr>
<td></td>
<td>20-Mar</td>
<td>$T = 0.003t^{2} - 0.1618t + 2.8799t^{2} - 18.545t + 316.46; \ R^{2} = 0.9905$</td>
<td>$RH = -0.0079t^{2} + 0.4207t - 7.1078t^{2} + 39.232t + 8.8964; \ R^{2} = 0.9741$</td>
</tr>
<tr>
<td></td>
<td>23-Sept</td>
<td>$T = 0.0023t^{2} - 0.1206t^{2} + 2.0678t^{2} - 12.003t + 309.16; \ R^{2} = 0.9826$</td>
<td>$RH = 0.0228t^{2} - 0.319t^{2} - 4.5405t + 82.727$</td>
</tr>
<tr>
<td></td>
<td>21-Jun</td>
<td>$T = -0.237t^{2} + 6.7807t + 258.7; \ R^{2} = 0.9913$</td>
<td>$RH = -0.0098t^{2} + 0.9116t - 20.199t + 142.67; \ R^{2} = 0.9868$</td>
</tr>
<tr>
<td></td>
<td>21-Dec</td>
<td>$T = 0.0049t^{2} - 0.2586t + 4.681t - 32.792t + 351.71; \ R^{2} = 0.9906$</td>
<td>$RH = -0.0158t^{2} + 0.8201t^{2} - 14.447t^{2} + 97.074t - 136.58; \ R^{2} = 0.9842$</td>
</tr>
<tr>
<td>Date</td>
<td>$T$</td>
<td>$R^2$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>------------</td>
<td>---------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>20-Mar</td>
<td>$-0.2585t^2 + 7.2733t + 241.48$; $R^2 = 0.991$</td>
<td>$R^2 = 0.9754t^2 - 27.374t + 211.36$; $R^2 = 0.9842$</td>
<td></td>
</tr>
<tr>
<td>23-Sept</td>
<td>$-0.2552t^2 + 7.1755t + 252.11$; $R^2 = 0.9929$</td>
<td>$R^2 = 0.6624t^2 - 18.367t + 149.82$; $R^2 = 0.9852$</td>
<td></td>
</tr>
<tr>
<td>21-Jun</td>
<td>$-0.0046t^2 - 0.0301t + 3.4825t + 272.77$; $R^2 = 0.9892$</td>
<td>$R^2 = 0.7955t^2 - 21.651t + 180.59$; $R^2 = 0.9908$</td>
<td></td>
</tr>
<tr>
<td>21-Dec</td>
<td>$-0.0042t^2 - 0.2309t^2 + 4.3228t - 31.866t + 363.19$; $R^2 = 0.9894$</td>
<td>$R^2 = -0.0106t^2 + 0.5814t^2 - 10.675t^2 + 74.439t - 103.73$; $R^2 = 0.9877$</td>
<td></td>
</tr>
<tr>
<td>20-Mar</td>
<td>$-0.0089t^2 + 0.1243t + 1.8042t + 270.9$; $R^2 = 0.9894$</td>
<td>$R^2 = -0.0075t^2 + 0.4254t^2 - 7.7911t^2 + 51.277t - 35.745$; $R^2 = 0.9905$</td>
<td></td>
</tr>
<tr>
<td>23-Sept</td>
<td>$0.0026t^2 - 0.1445t^2 + 2.6354t^2 - 18.014t + 333.49$; $R^2 = 0.9925$</td>
<td>$R^2 = -0.0086t^2 + 0.4861t^2 - 8.7674t^2 + 57.062t - 41.678$; $R^2 = 0.9915$</td>
<td></td>
</tr>
<tr>
<td>21-Jun</td>
<td>$-0.3013t^2 + 8.4437t + 246.78$; $R^2 = 0.9903$</td>
<td>$R^2 = 0.0126t^2 - 0.6841t^2 + 14.016t^2 - 131.43t + 494.87$; $R^2 = 0.9952$</td>
<td></td>
</tr>
<tr>
<td>21-Dec</td>
<td>$-0.0086t^2 - 0.4548t^2 + 8.4762t^2 - 64.849t + 449.26$; $R^2 = 0.984$</td>
<td>$R^2 = -0.0321t^2 + 1.676t^2 - 30.827t^2 + 231.84t - 527.99$; $R^2 = 0.986$</td>
<td></td>
</tr>
<tr>
<td>20-Mar</td>
<td>$-0.2776t^2 + 7.526t + 238.73$; $R^2 = 0.9804$</td>
<td>$R^2 = 1.0739t^2 - 29.826t + 236.66$; $R^2 = 0.9893$</td>
<td></td>
</tr>
<tr>
<td>23-Sept</td>
<td>$-0.3076t^2 + 8.4377t + 243.28$; $R^2 = 0.9825$</td>
<td>$R^2 = 0.9463t^2 - 25.913t + 200.23$; $R^2 = 0.9885$</td>
<td></td>
</tr>
</tbody>
</table>

**APPENDIX II**: Evaluation of the clear sky direct normal irradiance models for Ouarzazate, Errachidia, Guelmime and Tendrara, respectively, with $rMBE$, $rRMSE$, $R^2$ and paired $t$-test calculated in each instance.
| Errachidia | Date         | $|rMBE| \%$ | $|rRMSE| \%$ | $R^2$ | $t_{obs}$ | $p$-value |
|------------|--------------|--------|--------|------|----------|----------|
| **Bird Model** | March20th | 4 | 39 | 0.851 | 16.05 | 0.000 |
| | September23th | 5 | 19 | 0.904 | 3.38 | 0.001 |
| | June 21th | 5 | 14 | 0.953 | 6.08 | 0.000 |
| | December21th | 13 | 17 | 0.943 | 12.89 | 0.000 |
| **Atwater & Ball model** | March20th | 47 | 49 | 0.846 | 21.86 | 0.000 |
| | September23th | 5 | 20 | 0.904 | 3.11 | 0.002 |
| | June 21th | 16 | 21 | 0.951 | 17.58 | 0.000 |
| | December21th | 4 | 12 | 0.943 | 3.86 | 0.000 |
| **Paltridge & Platt model** | March20th | 53 | 53 | 0.849 | 24.35 | 0.000 |
| | September23th | 33 | 38 | 0.897 | 22.07 | 0.000 |
| | June 21th | 37 | 40 | 0.943 | 38.48 | 0.000 |
| | December21th | 9 | 15 | 0.943 | 8.47 | 0.000 |
| **Linke-Kasten model** | March20th | 37 | 41 | 0.855 | 17.87 | 0.000 |
| | September23th | 3 | 19 | 0.902 | 1.82 | 0.070 |
| | June 21th | 9 | 16 | 0.955 | 10.95 | 0.000 |
| | December21th | 12 | 17 | 0.939 | 12.18 | 0.000 |
| **Hoyt** | March20th | 56 | 55 | 0.846 | 25.63 | 0.000 |
| | September23th | 15 | 25 | 0.902 | 10.25 | 0.000 |
| | June 21th | 25 | 28 | 0.948 | 27.23 | 0.000 |
| | December21th | 4 | 12 | 0.943 | 4.37 | 0.000 |
| **Ineichen & Perez** | March20th | 4 | 39 | 0.844 | 15.60 | 0.000 |
| | September23th | 5 | 20 | 0.904 | 3.21 | 0.002 |
| | June 21th | 6 | 14 | 0.952 | 6.91 | 0.000 |
| | December21th | 13 | 17 | 0.943 | 13.08 | 0.000 |
| **Molineaux** | March20th | 25 | 33 | 0.855 | 11.79 | 0.000 |
| | September23th | 16 | 25 | 0.902 | 10.82 | 0.000 |
| | June 21th | 4 | 13 | 0.954 | 4.28 | 0.000 |
| | December21th | 40 | 42 | 0.932 | 33.31 | 0.000 |
| **REST2** | March20th | 22 | 31 | 0.856 | 10.48 | 0.000 |
| | September23th | 13 | 23 | 0.902 | 8.77 | 0.000 |
| | June 21th | 1 | 12 | 0.954 | 1.22 | 0.225 |
| | December21th | 22 | 25 | 0.939 | 21.63 | 0.000 |
| **Guelmime** | Date | $|rMBE| \%$ | $|rRMSE| \%$ | $R^2$ | $t_{obs}$ | $p$-value |
| **Bird Model** | March20th | 21 | 31 | 0.858 | 12.39 | 0.000 |
| | September23th | 19 | 34 | 0.819 | 9.37 | 0.000 |
| | June 21th | 6 | 18 | 0.9212 | 5.32 | 0.000 |
| | December21th | 0 | 12 | 0.945 | 0.45 | 0.652 |
| **Atwater and Ball Model** | March20th | 29 | 37 | 0.856 | 16.53 | 0.000 |
| | September23th | 27 | 39 | 0.818 | 12.51 | 0.000 |
| | June 21th | 13 | 22 | 0.912 | 10.60 | 0.000 |
| | December21th | 7 | 13 | 0.944 | 7.72 | 0.000 |
| **Paltridge & Platt model** | March20th | 42 | 48 | 0.855 | 24.32 | 0.000 |
| | September23th | 44 | 52 | 0.814 | 21.26 | 0.000 |
| | June 21th | 27 | 32 | 0.908 | 22.14 | 0.000 |
| | December21th | 19 | 22 | 0.945 | 18.44 | 0.000 |
| **Linke-Kasten model** | March20th | 23 | 32 | 0.863 | 13.53 | 0.000 |
| | September23th | 20 | 34 | 0.823 | 9.54 | 0.000 |
| | June 21th | 10 | 20 | 0.914 | 8.18 | 0.000 |
| | December21th | 2 | 11 | 0.944 | 1.98 | 0.049 |
| **Hoyt** | March20th | 40 | 46 | 0.853 | 22.82 | 0.000 |
| | September23th | 39 | 49 | 0.815 | 18.65 | 0.000 |
| | June 21th | 24 | 29 | 0.909 | 19.42 | 0.000 |
| | December21th | 17 | 20 | 0.944 | 17.46 | 0.000 |
| **Ineichen & Perez** | March20th | 18 | 29 | 0.856 | 10.09 | 0.000 |
| | September23th | 14 | 32 | 0.819 | 6.91 | 0.000 |
| | June 21th | 4 | 18 | 0.912 | 3.44 | 0.001 |
| | December21th | 4 | 12 | 0.945 | 4.62 | 0.000 |
| | March20th | 11 | 25 | 0.864 | 6.78 | 0.000 |
| | September23th | 7 | 28 | 0.823 | 3.42 | 0.001 |
References


