VALIDATION OF DNI ESTIMATIONS IN BRAZIL USING BRAZIL-SR MODEL

Fernando Ignacio Matties
Eneu Basuto Pereira
Brazilian Institute for Space Research
P. O. Box 315, São José dos Campos, Brazil. 12245-970
ean@ibge.gov.br

ABSTRACT
This work describes the methodology to estimate the direct normal component (DNI) of surface solar irradiation using the radiative transfer model BRADL-SR. The model validation was performed by using two reference sites in Brazil: at Cuiabá (05°28'10"S - 05°19'50"W; 175.8 m), and Florianópolis (27°14'41"S - 40°13'42"W; 10 m). Satellite data were collected by INPE/CPTEC for GOES-8. The validation results showed a mean square factor among measured and estimated values around of 0.9 and relative root mean square error (RMSE) around 0.20.

1. INTRODUCTION
The international concerns on the increasing demands for energy in developing countries and the necessity to conciliate development and environment protection, lead to the creation of the Solar and Wind Energy Resource Assessment (SWERA) project. SWERA - Solar and Wind Energy Resource Assessment in Project (INPE) and the United Nations Environment Programme (UNEP), with co-ordinating by CPTEC in the area of renewable energies, more specifically, solar and wind energy. The project is assembling high quality information on solar and wind energy resources and ancillary data into consistent GIS (Geographic Information System) analysis tools. The project is aimed at the public and private sectors involved in the development of the energy market and it shall enable policy makers to assess the technical, economic, and environmental potential for large-scale investments in renewable and sustainable technologies.

The Brazilian Institute for Space Research (INPE) is coordinating the SWERA activities in Brazil which is now in its final stage. The Solar Energy Laboratory of University of Santa Catarina (INPE/Unicam), the Brazilian Center of Wind Energy (CERNE) and Brazilian Center for Research in Blowing Wind (CENPE) are partners involved with SWERA activities in Brazil and they are working together to develop several products and tools.

The INPE and LANSOLAR/UFS are working together to produce solar energy resources maps for Brazil and for South America using the radiative transfer model BRADL-SR (Martins, 2001; Cote and Pereira, 1998). The solar irradiation maps are being calculated from satellite images of the GOES-8 and GOES-12. In addition, global solar irradiation maps, maps of solar direct and diffuse components were also generated as well as irradiation values for tilted surfaces.

This work describes how direct normal solar irradiation (DNI) modeling was implemented in model BRADL-SR. In this work we also report the validation step where DNI estimations were compared with ground truth data measured in Cuiabá (Northeast region of Brazil) and in Florianópolis (a BSRN site located in South of Brazil).
2. BASIC DESCRIPTION OF SOLAR RADIATION

The DNI estimates were compared to ground truth data acquired in two reference sites:
- Cairu (60°28'0'"S - 37°57'0'"W /176m)
- Tóminuspolis (27°34'18''S - 048°30'42''W /15m)

The two sites were chosen because they provide high quality radiation data and represent climatic/environmental regions and different ground cover. The measure data is qualified according to RSN network and are available at each minute interval.

The ground site at Cairu is in this small city located in the semi-arid region of the Brazilian northeast (annual precipitation under 950 mm), over a relatively flat area with a sparse, hardtype vegetation known as "catinga" (average albedo 13.9%). It is characterized by a large variation of about 1200 millimeters, and high annual mean temperature (22°C to 33°C), which allows it to be a good place for model adjustments for two errors under climatic ideals. The site become operational in November 2000 collecting data for global and direct solar radiation. The site is operated in partnership with University of Sao Paulo (USP/USP).

The site at Tóminuspolis is located in a medium size city (under 90,000 inhabitants) situated on an island in the Brazilian south region. Rainfall is fairly distributed along the year. The summer is hot and the winter is mild with some few cold days. The radiosolic station was installed in 1991 as part of the Brazilian Solar Radiation Network (RSN) and provides data to global, direct, and diffuse radiation. The RSN site is operated by the Solar Energy Laboratory of the University of Sao Carlos (LABSOR/USP).

3. SATLLITE DATA

Effective cloud cover index (ECCI), an input data for model BRASIL-SR, was obtained from GOES-8 images collected by INPE-CPTEC, which also provide for the quality assessment, rectifying, and routing. The GOES-8 satellite was launched in April 1994 and was located at longitude 75°W, latitude 0° and altitude of 36,000 km. The main purposes of GOES-8 are weather monitoring and forecasting and it has a scanner camera that supplies images from a small sector to the full extent of the Earth's disk in five different channels. Visible images (channel 1, 0.52-0.72μm) and infrared images (channel 4, 10.0-11.5μm) from the measurement area are also available in the SWLUSA Latin America website:
http://www.cpe.eng.br/latam/

4. RADIATIVE TRANSFER MODEL BRASIL-SR

The INPE (Brazilian Institute for Space Research) and LABSOR/USP (Solar Energy Laboratory) are working together to develop a radiative transfer model BRASIL-SR in order to map the surface solar irradiation in Brazil and South America. The model BRASIL-SR is a physical model that combines satellite and climatological data with the "two-stream" approach to solve the radiative transfer equation for atmosphere (Marina, 2001).

The model assumes that the global solar irradiation at ground and at top of the atmosphere is linearly correlated (Marina, 2001; Tempea et al., 2000; Stohlmann et al., 1990). Global horizontal solar irradiance incident on the surface is provided by equation (1):

\[
GHI = G_0 (\tau_{tot} - \tau_{sun}) (0 - C_d) + \tau_{sun}
\]

(1)

where GHI is the global horizontal irradiance at surface, \(G_0\) is the solar irradiation at the top of the atmosphere. The "two-stream" approach is used to obtain two independent components that are used as boundary conditions for the model: the clear-sky transmittance, \(T_{clear}\), and the overcast sky transmittance, \(T_{cloud}\). The first component is a function of the surface albedo, the solar zenith angle and the optical thickness of the aerosol scattering components. The component \(T_{cloud}\) is a function of the solar zenith angle, the cloud optical thickness, and height of cloud top. Both components may be estimated from climatic data (temperature, relative humidity, surface albedo and cloud properties) and parameters of well-known physical processes that occur in the atmosphere.

The dimensionless effective cloud cover index, \(C_d\), describes both effects: the cloud cover and the spatial variation of cloud optical depth. It is determined from satellite images by using the following equation:

\[
C_d = \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}}
\]

(2)

where \(\rho\) is the visible reflectance measured by satellites, \(\rho_{max}\) and \(\rho_{min}\) stand for overcast and clear sky reflectance measured by the satellites, respectively. The \(\rho_{max}\) and \(\rho_{min}\) are obtained monthly from statistical analysis of visible (channel 1 - 0.52-0.72μm) and thermal infrared (channel 4 - 10.0-11.5μm) images of GOES-8 satellite. By using this scheme, the degradation of the satellite sensors with time has no influence on the model estimations.

4.1 First estimates
The methodology developed to estimate direct normal irradiance (DNI) assumes that cloud cover contribution to the direct transmittance can be added to the clear sky direct transmittance ($\tau_{\text{dir}}$) due to all other atmospheric constituents (aerosols and gases). Therefore, the direct solar estimate is calculated from the following equation:

$$DNI = G_0 \tau_{\text{dir}} \tau_{\text{cloud}}$$

where $\tau_{\text{dir}}$ represents the cloud transmittance for direct component of solar irradiation. The $\tau_{\text{dir}}$ is obtained using the "Two-Stream" technique for clear sky calculation and $\tau_{\text{cloud}}$ is estimated from cloud cover index. $G_0$ is the approach presented by Stoltenbeck et al. (1996):

$$\tau_{\text{cloud}} = \frac{(1 - \tau_c)}{(\beta - \tau_c)}$$

where

$$\tau_c = \left(\tau_{\text{cloud}} + 0.05\right)$$

if $\tau_{\text{cloud}} < 0.95$

$$\tau_c = 1.0$$

if $\tau_{\text{cloud}} \geq 0.95$

4. MODEL RESULTS AND VALIDATION

This work presents the validation results for summer season — from November/2002 until February/2003. The ground sites were chosen due to high quality radiation data and geographical location. The geographical location is an important factor to be considered in order to evaluate the model's performance for different climate and environments. Table 1 shows the main information for the two ground sites. These ground sites represent different climatic environments in the tropics: the coastal semi-arid region and a sub-tropical humid area. The climatological and geographical data presented in Table 1 was used to feed model BRASIL-SR.

Table 2 presents the deviations values for daily DNI estimations. The following criteria were adopted to calculate the MBE and RMSE for daily estimations: a) discard hourly estimates with solar zenith angle larger than 80°; b) discard days with less than 3 estimates fulfilling the first criteria.

The Figure 3 shows the "estimated values" versus "measured values" for daily DNI in Florianópolis and Caxias. It can be noted a good correlation between estimated and measured values. The correlation factors calculated using all data were 0.92 and 0.88 for Florianópolis and Caxias, respectively. The lowest correlation factor and larger RMSE deviation value were obtained for February in Caxias (0.70). The calculation procedure to obtain cloud cover index from satellite images is the most feasible reason for this lower correlation. Caxias has a great number of clear sky days per year and cloud types are mainly fair weather Cumulus, which are hard to detect in satellite images with the spatial resolution adopted in this task. Besides that, shadows of the broken clouds can mask clear sky radiation. $\beta_{\text{max}}$, used to get effective cloud cover index from satellite images. However, the reason of these low correlation factor obtained in February for Caxias must be better investigated in the future.

The validation procedure is being prepared for one year period to allow a more comprehensive analysis in order to find out the sources of errors and weak points of the parameterization adopted. Simultaneously, a cross-comparison task is being prepared in order to evaluate the BRASIL-SR performance with other three radiative models: NREL model, SUNY-Albany model and HELIOSAT model.

---

**Table 1: Geographical and Climatological Information for the Validation Sites**

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude Longitude</th>
<th>Altitude (m)</th>
<th>Month</th>
<th>Temp. (°C)</th>
<th>RH (%)</th>
<th>Surface Albedo</th>
<th>Other Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caxias</td>
<td>49°28′01″S 37°05′03″W</td>
<td>175.85</td>
<td>Nov</td>
<td>27.98</td>
<td>60.5</td>
<td>0.134</td>
<td>Installed to provide ground site and SWERA Project</td>
</tr>
<tr>
<td>Florianópolis</td>
<td>27°34′18″S 48°31′42″W</td>
<td>12</td>
<td>Nov</td>
<td>21.53</td>
<td>80.2</td>
<td>0.164</td>
<td>BSKN site</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dec</td>
<td>28.26</td>
<td>64.6</td>
<td>0.136</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Jan</td>
<td>28.06</td>
<td>74.6</td>
<td>0.130</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Feb</td>
<td>22.82</td>
<td>82.9</td>
<td>0.145</td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 2. DEVIATIONS OF DNI ESTIMATES PROVIDED BY MODEL BRASIL-SR FOR THE TWO VALIDATION SITES

<table>
<thead>
<tr>
<th>Month</th>
<th>Ground Site</th>
<th>Floranopolis</th>
<th>CatO</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 2002</td>
<td></td>
<td>0.12</td>
<td>0.11</td>
</tr>
<tr>
<td>December 2002</td>
<td></td>
<td>0.15</td>
<td>0.25</td>
</tr>
<tr>
<td>January 2003</td>
<td></td>
<td>0.08</td>
<td>0.30</td>
</tr>
<tr>
<td>February 2003</td>
<td></td>
<td>0.12</td>
<td>0.17</td>
</tr>
</tbody>
</table>

![Fig. 1: Schematic diagram of radiative transfer model BRASIL-SR.](image-url)
Fig. 2. Estimated versus Measured values for daily DNI in (A) Florianópolis and (B) Caicó.
4. CONCLUSIONS

The works presented a 2D parametrization, implemented in model BRESIL-SR and its first validation results. The comparison among simulated DNI values and ground truth data was done for two sites located in very different climate and environment in Brazil: Caracau in the Northeast semi-arid region and Fortaleza in the South industrialized region. The estimators provided by the model have presented a good agreement with measured values for both sites and correlation factor around 0.9 were obtained. The large RRMSE was obtained in February, 2003 for Caracau. Probably, this large deviation is related to errors in determination of effective cloud cover index, from satellite images and consequence of climatic features observed in Caracau: long periods of clear sky condition, and presence of broken clouds (fair weather cumulus) hard to detect in spatial resolution of satellite images available for this work. A more detailed analysis of weak points of the DNI parameterization and sources of errors will be possible after finish the validation task for one-year period and the comparison with other bounded radiative transfer models.

5. ACKNOWLEDGMENTS

The SWERA project was possible thanks to the UNED/GEF project no. GRL-22972/1436 - SWERA. The SONDRA project was possible thanks to the FINITE project no. 22O1.0569.00. Thanks are due to the following colleagues: Silvia V. Pereira, Marins P. S., Richter, Cristino Yazzobitha, Sheila A. L. Silva, Hugo Corrêa, Rafael Chagas, Chao Sin Chau. The following institutional acknowledgment is due to Center for Weather Forecast and Climatic Studies (CPTEC/INPE). The author was supported by a grant from CNPq (No. 381702/2002-9).

6. REFERENCES

(3) INMET, Normais Climatológicas - 1931-1990. [online]