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# The influence of cloud cover index on the accuracy of solar irradiance model estimates

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With 8 Figures

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**Summary**

Cloud cover index (*CCI*) obtained from satellite images contains information on cloud amount and their optical thickness. It is the chief climate data for the assessment of solar energy resources in most radiative transfer models, particularly for the model BRASIL-SR that is currently operational at CPTEC. The wide range of climate environments in Brazil turns *CCI* determination into a challenging activity and great effort has been directed to develop new methods and procedures to improve the accuracy of these estimations from satellite images (Martins 2001; Martins et al. 2003a; Ceballos et al. 2004). This work demonstrates the influence of *CCI* determination methods on estimates of surface solar irradiances obtained by the model BRASIL-SR comparing deviations among ground data and model results. Three techniques using visible and/or thermal infrared images of GOES-8 were employed to generate the *CCI* for input into the model BRASIL-SR. The ground-truth data was provided by the solar radiation station located at Caicó/PE, in Brazilian Northeast region, which is part of the UNEP/GEF project SWERA (Solar and Wind Energy Resources Assessment). Results have shown that the application of the bi-spectral techniques have reduced mean bias error up to 66% and root mean square error up to 50% when compared to the usual technique for *CCI* determination based on the straightforward determination of month-by-month extremes for maximum and minimum cloud states.

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## 1. Introduction

The increase in energy demand in developing countries and the apprehension with environmental problems linked to fossil fuel consumption are stimulating new researches in order to develop new energy technologies, mainly in the renewable energy area (Pereira et al. 2000; IPCC 2001; Sims 2004; Martins et al. 2005a, b, c). The solar radiation is a renewable source of energy with reduced environmental impact and it is becoming economically and technically viable (Palmer and Burtraw 2004; Sims 2004; Lako and Keits 2005). Nowadays, the solar energy assessment is a vital task for energy planning in developing countries like Brazil. The use of radiative transfer models is the best way to evaluate the solar energy resources in large continental areas such as Brazilian territory (Perez et al. 1997). The reliability and confidence levels of the assessment are linked to the method of cloud cover index (*CCI*) determination from satellite images since clouds are the foremost atmospheric factor that controls the solar irradiance incident at the surface.

The Brazilian Centre for Weather Forecast and Climate Studies of the Brazilian Institute for Space Research (CPTEC/INPE) and Solar Energy Laboratory of the University of Santa Catarina (LABSOLAR/UFSC) are working together to develop model BRASIL-SR (Gambi 1998; Martins 2001; Martins et al. 2005a). The model BRASIL-SR calculates *CCI* for each image pixel using the following equation:

$$CCI = \frac{L_r - L_{clr}}{L_{cld} - L_{clr}}, \quad (1)$$

where $L_r$ is the pixel radiance measured by satellite and $L_{clr}$ and $L_{cld}$ are the radiance measured for the same pixel in clear sky and overcast conditions, respectively.

Numerous computational techniques to obtain $L_{clr}$ and $L_{cld}$ from spatial and temporal analysis of satellite images can be found in scientific literature (Saunders 1986; Gutman et al. 1987; Minnis et al. 1987; Seze and Desbois 1987; Moussu et al. 1989; Rossow 1989; Rossow et al. 1989a, b; WMO 1991; Simpson and Gobat 1995). The dependence on surface properties, the presence of partially cloudy covered pixels, clouds with different emissivity properties, persistent cloud cover (or persistent clear sky condition) and discrimination among clouds and snow are the primary sources of errors for all of them (England and Hunt 1985; Seze and Desbois 1987).

The persistent cloudy sky is very common in the Amazon Forest region where the Inter-Tropical Convergence Zone (ITCZ) has a great impact on the precipitation and weather conditions. By the other side, persistent clear sky condition is very common in Brazilian Northeast region regulated by the semi-arid climate. All other sources of errors are of minor importance for Brazilian conditions.

Another issue is the validation of *CCI* values obtained from satellite data. The International Satellite Cloud Climatology Project (ISCCP project) has evaluated many of published techniques and it was noted that the performance evaluation is limited by two factors: lack of reliable ground data to validate the satellite algorithms, and spatial and spectral resolution of satellite images (Simpson and Gobat 1995).

The main goal of this work is to compare and evaluate three methods to obtain *CCI* from satellite images by comparing the measured and estimated solar irradiation for Caicó in the semi-arid area of northeast region of Brazil. The ground truth data was measured as part of the project SWERA (Solar and Wind Energy Resources Assessment). The estimated values were provided by the radiative transfer model BRASIL-SR using three methods to obtain *CCI* data. The first method is the threshold technique where the maximum and minimum visible radiance values measured by satellite are attributed to $L_{clr}$ and $L_{cld}$. The second technique uses again the visible radiances of satellite data but it takes in account the geometry of Sun/Earth/Satellite system to get $L_{cld}$ values. The third technique uses a bi-spectral analysis of satellite data (visible plus infrared radiances) to get clear sky radiances and the same geometry analysis to obtain cloudy radiances applied in the second technique. First of all, the paper will describe the ground and satellite data acquisition, model BRASIL-SR. After that, the three methods employed to get *CCI* will be discussed, and finally, the comparison results will be discussed.

## 2. Methodology

### *2.1. Caicó SWERA cross-validation site*

The ground-truth data of global solar irradiation were acquired by a solar radiometer Eppley CM311, located in the northeastern Brazilian city of Caicó (06°28′01″S–037°05′05″W/176 m). Besides the global solar irradiation, temperature and relative humidity data were also acquired with one-minute time resolution. This ground-truth site is in service since 2002 and Fig. 1 depicts the measurement site.

The site was deployed as part of the project SWERA to perform cross-validations between the several core solar radiation models (Martins et al. 2003b) that were employed to map the solar energy resource in many developing countries. The project SWERA financed by United Nations Environment Program (UNEP), with co-financing by GEF aims at compiling high quality information on solar and wind energy resources in several pilot countries into consistent with GIS (Geographic Information System) analysis tools (Martins et al. 2005a; Renné et al. 2005).

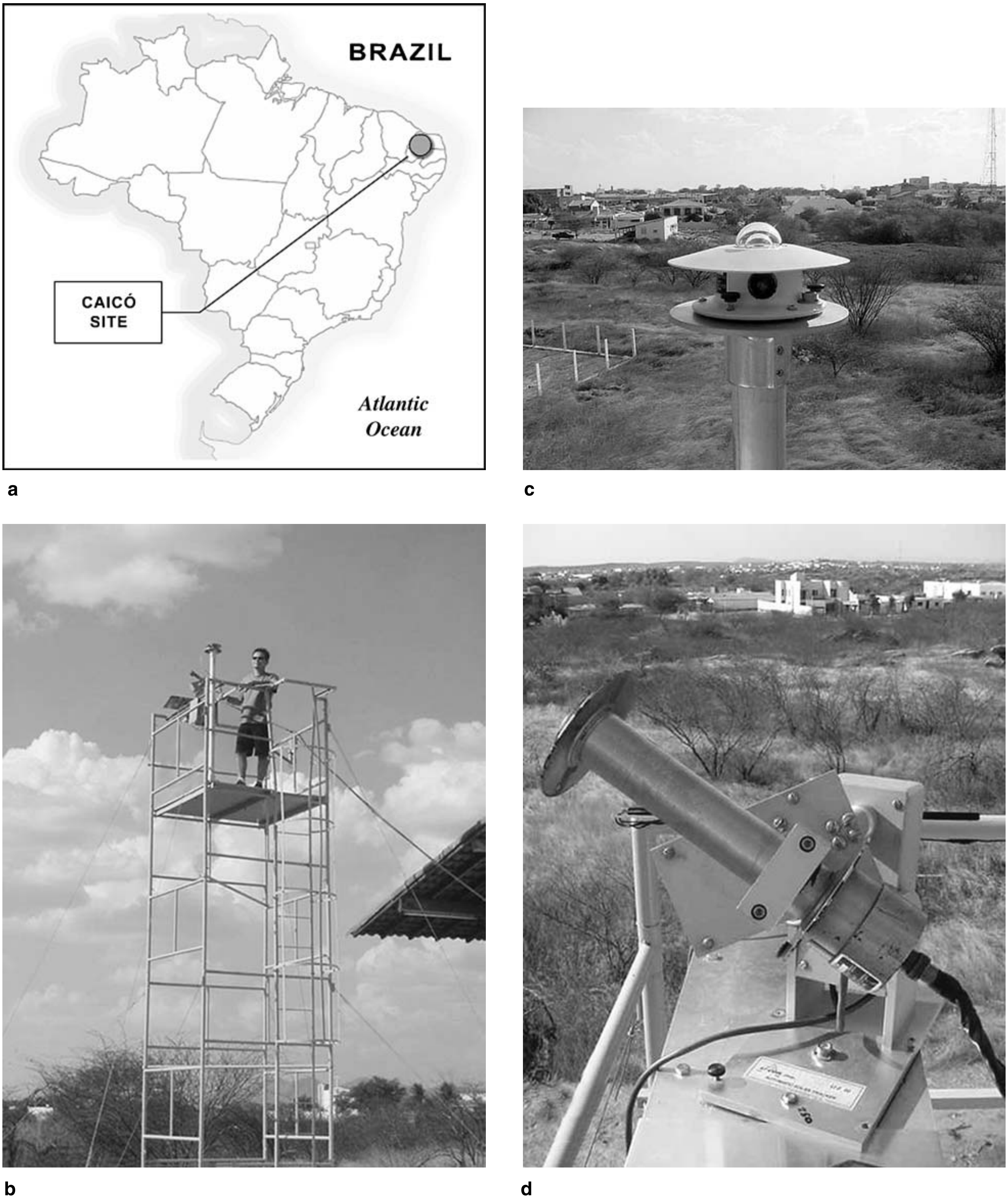


**Fig. 1a–d.** Localization map and pictures of the ground data acquisition site located in Caicó operating since November/2002

More details on project SWERA and ground data from Caicó site can be downloaded from *www.cptec.inpe.br/swera/* or *http://swera.unep.net/*.

This ground-truth radiation site is located in the semiarid area in the Brazilian northeast region which is characterized by low precipitation levels (<700 mm/year) and very large number of clear-skies days (>120 days/year). This region is suitable to evaluate the performance of radiative transfer models for clear sky condition and that was one of the main reasons for its choice as far as the cross-validation task of SWERAs project is concerned. However, the persistence of clear sky condition turns out to be major challenge as it became difficult to identify the conditions of overcast skies ($L_{cld}$), which is the value that along with the clear sky situation ($L_{clr}$), composes the boundary condition of the sky-state in that area or the metric that is used to determine the *CCI* by Eq. (1).

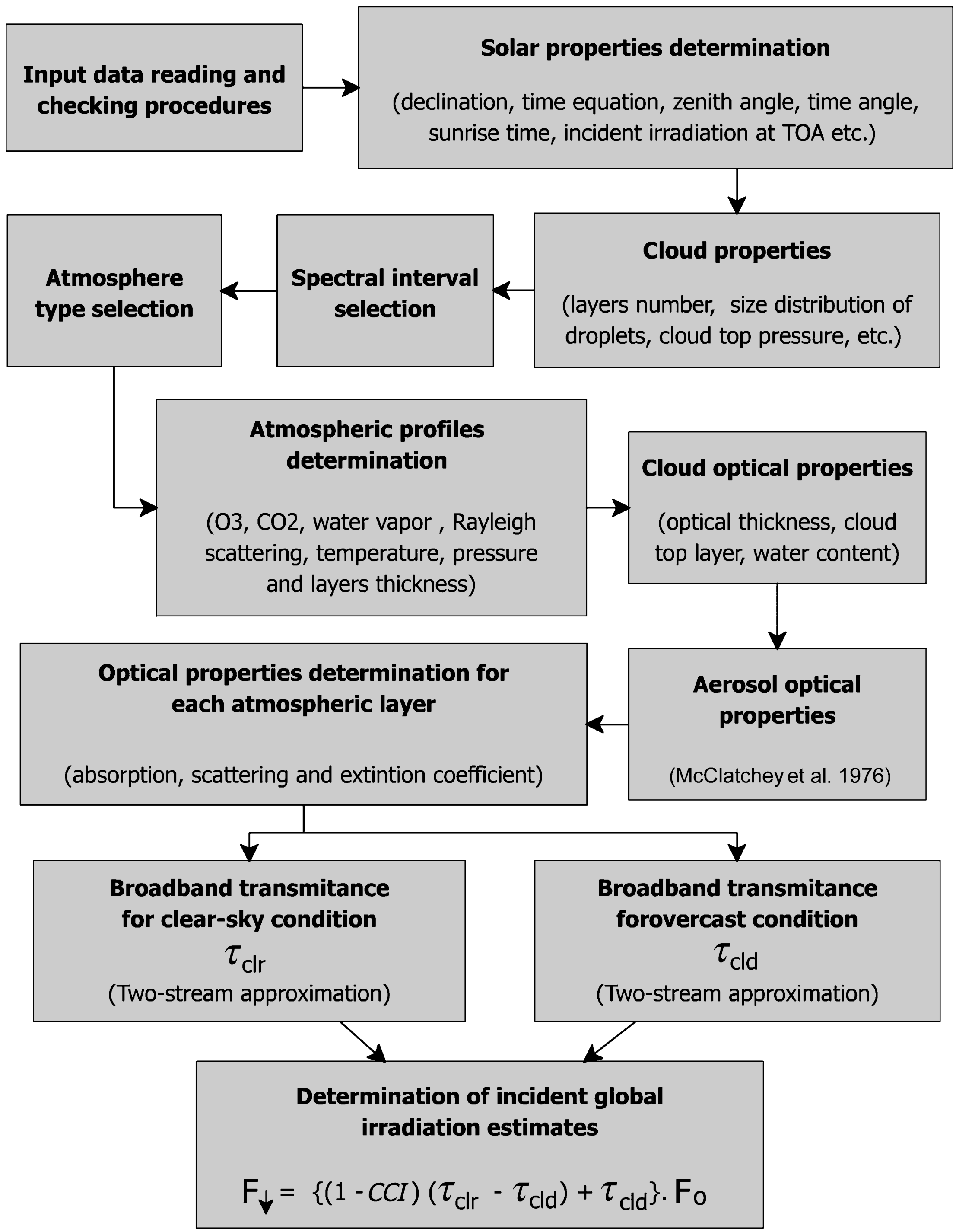


**Fig. 2.** Schematic diagram of radiative transfer model BRASIL-SR

### 2.2. Model BRASIL-SR

The Centre for Weather Forecast and Climate Studies/Brazilian Institute of Space Research (CPTEC/INPE) and Solar Energy Laboratory/ University of Santa Catarina (LABSOLAR/ UFSC) are working together to developed the radiative transfer model, BRASIL-SR, in collaboration with the 0GKSS Institute (Germany), based on the same basic principles of the IGMK model (Stuhlmann et al. 1990). The model combines satellite and climate data with a "two-stream" radiative transfer scheme to solve the radiative transfer equation for atmosphere (Martins 2001).

Figure 2 presents a schematic diagram of model. The estimates for surface solar irradiation, $F_{\downarrow}$, are obtained from Eq. (2) where $F_0$ is extraterrestrial solar irradiation. The first term is associated with clear sky condition, and the second one is related with overcast condition. The clear ($\tau_{\mathrm{clr}}$) and cloudy ($\tau_{\mathrm{cld}}$) transmittances can be obtained by solving radiative transfer equation using atmospheric parameterization and climate data (temperature, relative humidity, surface albedo, visibility and cloud properties) and geographical position (latitude, longitude and altitude). The cloud cover effective coefficient is a weighting function for the linear relation between clear and overcast sky conditions. In spite of being a quite simple relationship, Eq. (2) presents very good results as demonstrated by Colle and Pereira (1998).

$$F_{\downarrow} = F_0\{\tau_{\mathrm{clear}}(1 - CCI) + \tau_{\mathrm{cloud}}CCI\}. \qquad (2)$$

### 2.3. GOES-8 images

The Channel 1 (visible – 0.52 μm to 0.72 μm) and Channel 4 (thermal infrared – 10.2 μm to 11.2 μm) images were used to generate the necessary input data for the model. Only three-hourly images were available for the Southern Hemisphere and all were used in this study: 08 h 45 UTC, 11 h 45 UTC, 14 h 45 UTC, 17 h 45 UTC, and 20 h 45 UTC. The image resolution was 0.125° (latitude) × 0.155° (longitude). A 0.5° × 0.5° area around the SWERA cross-validation site in Caicó/Brazil were used to get *CCI* using the three techniques described in the following topic. The *CCI* values obtained were used to feed radiative transfer model that provided solar irradiation estimates.

### 2.4. CCI Techniques

#### 2.4.1. Threshold technique

The threshold method has been used in many researches (Gautier et al. 1980; Saunders 1986; Dedieu et al. 1987; Diekmann et al. 1988). This method uses the minimum and the maximum visible radiance measured by satellite as $L_{\mathrm{clr}}$ and $L_{\mathrm{cld}}$, respectively, for each pixel. The accuracy of this method is very sensitive on this time interval (Rossow 1989). Once surface albedo and atmospheric properties change along the year, the $L_{\mathrm{clr}}$ and $L_{\mathrm{cld}}$ values must be corrected (Moussu et al. 1989) or its application should be limited to a particular time period (Rossow 1989). The time period must be short enough to guarantee that effect of variation in the surface albedo and in the Sun/Earth distance will have the less practical influence on the variability of the measured radiance. No significative degradation in the efficiency of the satellite radiometers should occur during this period. Besides that, the time interval should be large enough to guarantee at least one clear sky condition for each pixel. The major difficulty is that as the time interval gets bigger, the probability to occur events that can mask the clear sky radiance measured by satellite also increases. Shadows of broken clouds, navigation errors on satellite images, and changes in vegetation due to humidity variation are examples. Another issue is the persistent condition of clear skies in regions like Caicó area that may persist for periods larger than the time period adopted to get $L_{\mathrm{clr}}$ and $L_{\mathrm{cld}}$ from satellite images. In this case, $L_{\mathrm{cld}}$ would not represent the overcast irradiance condition for that region.

It was implemented a one month time interval to find out $L_{\mathrm{clr}}$ and $L_{\mathrm{cld}}$ values in the operational version of the model BRASIL-SR running at CPTEC/INPE.

#### 2.4.2. Modified threshold technique

This technique uses minimum visible radiance measured by the satellite in a month's period as $L_{\mathrm{clr}}$ value. But, in general, the maximum radiance measured by satellite for Caicó location does not correspond to an overcast sky condition. The persistence of clear sky or partially cloudy sky condition can last for more then 30 days uninterruptedly as a consequence of semi-arid cli-

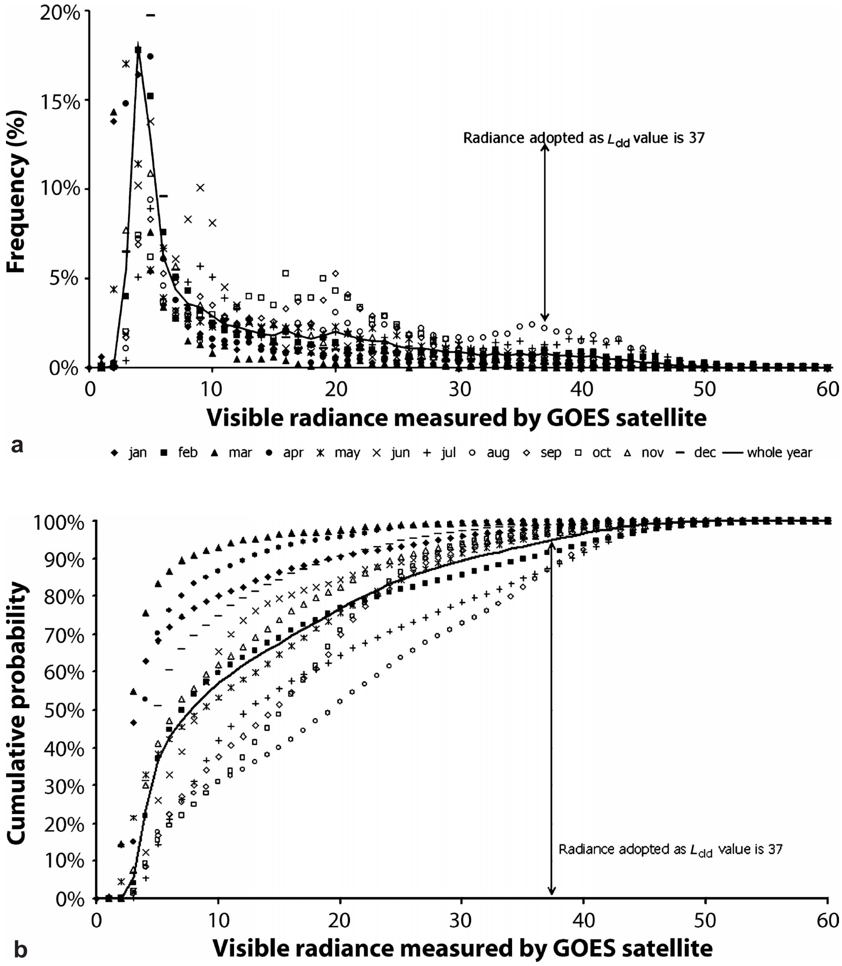


**Fig. 3a.** Frequency histogram of visible radiance measured by satellite for pixels under the following geometry: satellite zenith angle equals to 16° and solar zenith angle equals to 50°; (**b**) Cumulative probability for visible radiance for the same geometry condition

mate and it reflects on the determination of *CCI* causing an overestimation of *CCI* (more cloudiness) if $L_{cld}$ values are lower than expected for true overcast conditions.

Considering that $L_{cld}$ values should be associated to overcast condition with high optical thickness, it can be assumed that the geometry of Sun/Pixel/Satellite system will be the first order factor affecting the solar radiance measured by satellite under this condition. Therefore, the $L_{cld}$ values can be obtained for a specific Sun/Pixel/Satellite geometry and not for a specific pixel in the image.

The satellite zenith angle for Caicó is 16°. The solar zenith angle will vary according to the time of the day and seasons. Statistical analysis of maximum radiances measured by GOES-8 throughout one year period for pixels where satellite zenith angle equals to 16° was used to obtain $L_{cld}$ values for each solar zenith angle. Figure 3 shows the frequency distribution of radiance values measured by satellite for solar zenith angle equals to 50°. Similar plots were obtained for others solar zenith angles.

The radiance value obtained when the cumulative probability reaches 95% was attributed to $L_{cld}$. The maximum radiance obtained for each geometry was not used to avoid errors associated to rare events like reflections on cloud borders or others high reflective surfaces, not to mention data transmission flaws between satellite and ground station. Figure 4 shows the $L_{cld}$ values as a function of solar zenith angle for Caicó taking into account one year of satellite images. It also presents the number of cases when each solar angle happens along 1 year. More investigation is necessary to understand the variability of $L_{cld}$ values mainly close to solar zenith angles equals 40°.

### 2.4.3. Bi-spectral technique

The $L_{clr}$ values can also be a source of error in *CCI* determination even at Caicó where a lot of

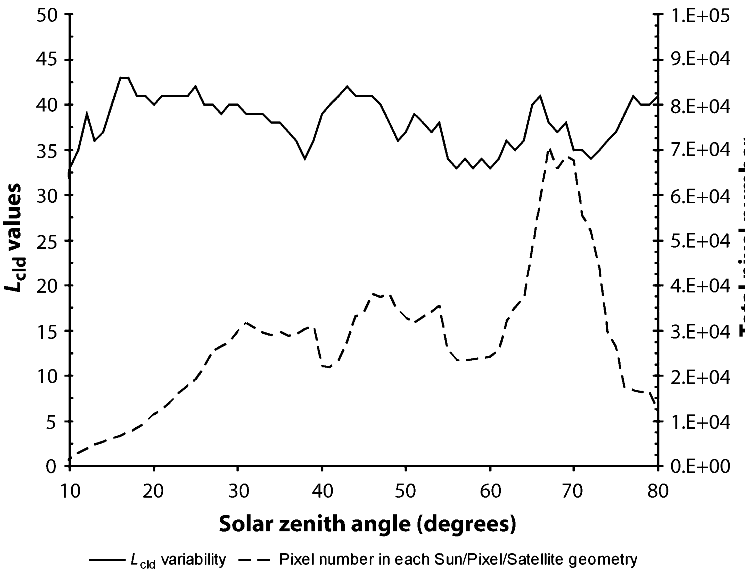


**Fig. 4.** Variability of $L_{cld}$ values in function of solar zenith angle (solid line) and number of pixels observed for the each solar zenith angle and satellite zenith angle equals to 16°

clear sky days occur. The radiance measured by satellite can be reduced to lower than expected values as a consequence of shadows by broken clouds or by flaws in the satellite data transmissions. Other source of error it is the presence of clouds with low optical thickness such as cirrus clouds. The visible data provided by satellite does not allow distinguishing among ground and low optical thickness clouds as shown in Fig. 5 (Bunting and Hardy 1984). Bi-spectral analysis using visible and thermal infrared satellite images should be used to better identify cirrus contamination and to reduce errors associated with cloud shadows and flaw in the satellite data transmission.

This technique assigns $L_{clr}$ value as the average of the five visible radiances associated with the five largest infrared radiance measured by satellite for a pixel if standard deviation is lower than a given threshold. If standard deviation is larger than the threshold, the pixel is assumed as contaminated with clouds (broken clouds or

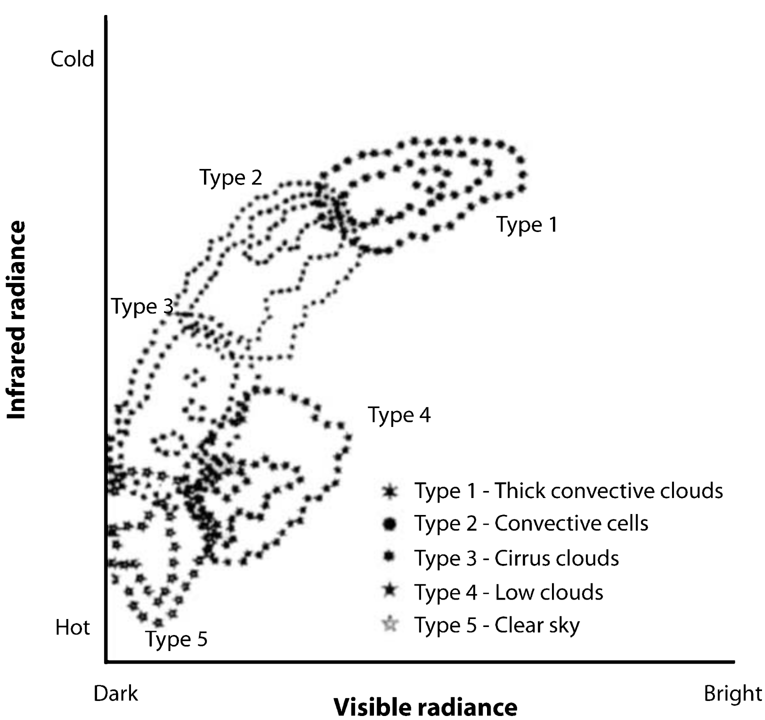


**Fig. 5.** Cloud classification according to infrared and visible radiances measured by satellite. Type 1 represents thick convective clouds; Type 2 is the convective masses; Type 3 is the cirrus clouds; Type 4 represents low clouds; and Type 5 is the surface. Source: Bunting and Hardy (1984)

low optical thickness clouds) (Rossow et al. 1989a, b). A second try is made discarding the visible radiance associated with the lowest of the five infrared radiance data selected in the earlier step. If standard deviation remains high, the pixel is flagged undefined. The errors due to shadows are reduced by this technique once mean value of the events associated with clear sky are taken in place of the minimum visible radiance.

The $L_{\text{cld}}$ values were obtained by using the methodology described for the Modified Threshold technique where statistical analysis is applied for the geometry of Sun/Pixel/Satellite system.

## 3. Results and discussion

Figures 6 and 7 presents a comparison of deviations obtained for solar irradiation estimates provided by model BRASIL-SR when each of the techniques to get *CCI* were used. The solar irradiation estimates were obtained for the period from November/2002 till February/2003. The HELIOSAT deviations presented in both figures were provided by Beyer (2003). The following expressions were used to calculate mean bias error (MBE) and root mean square error (RMSE):

$$\mathrm{MBE} = \sum_{i}^{n} \frac{(R_{\text{estimado},i} - R_{\text{medido},i})}{R_{\text{medido},i}},$$

$$\mathrm{RMSE} = \frac{\sqrt{\sum_i^n (R_{\text{estimado},i} - R_{\text{medido},i})^2}}{\sum_i^n R_{\text{medido},i}} \qquad (3)$$

where *n* is the amount of data used in the validation task and $R_{\text{estimado}}$ and $R_{\text{medido}}$ stands for BRASIL-SR estimates and ground data of solar irradiation, respectively.

It can be noted a significant reduction on MBE and RMSE deviations for hourly and daily solar irradiation estimates provided by the model

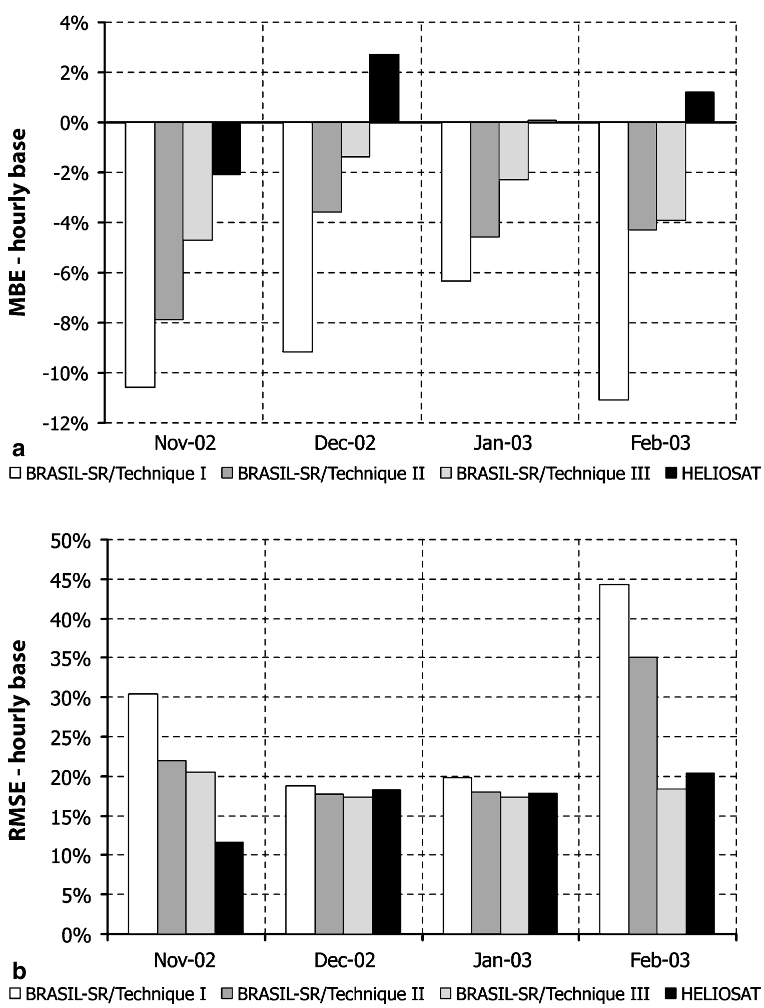


**Fig. 6a, b.** Deviations for hourly estimates of solar irradiation provided by model BRASIL-SR

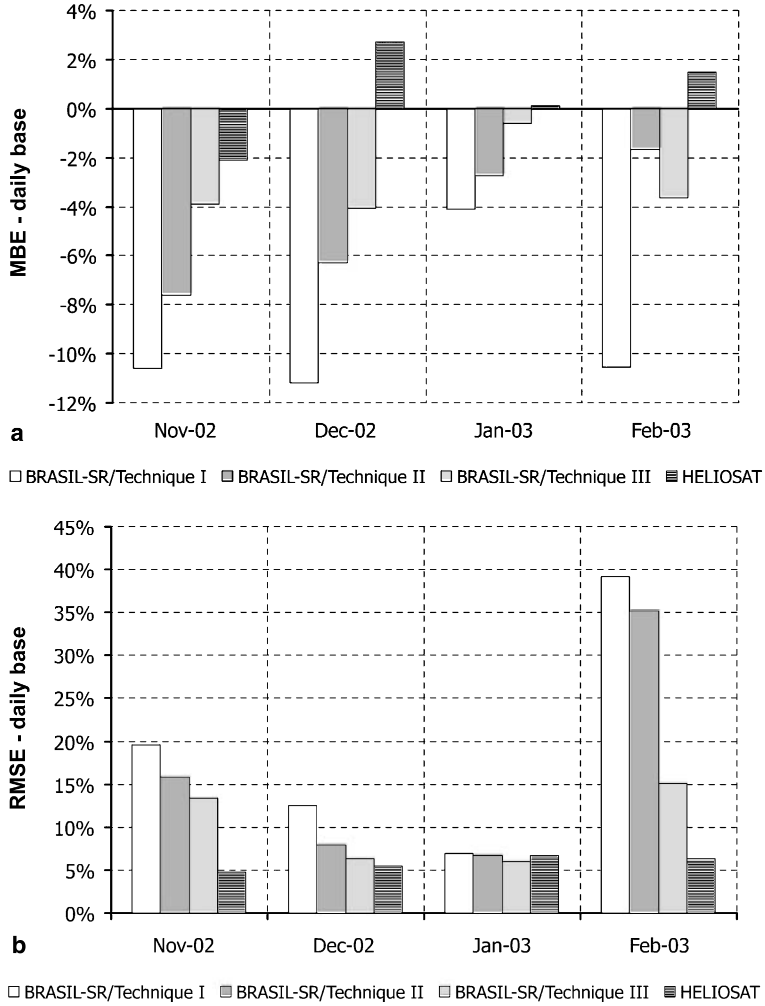


**Fig. 7.** Deviations for daily estimates of solar irradiation provided by model BRASIL-SR

BRASIL-SR when the Modified Threshold Technique and Bi-spectral Analysis were used to obtain *CCI* data from satellite images.

The third technique has presented up to half of the MBE and RMSE when compared with Threshold Technique in the hourly base. The decrease in deviations is larger when a daily base is considered. This difference can be explained by the wrong values attributed to $L_{\mathrm{cld}}$ in the first technique due to persistent clear sky condition in Caicó.

Figure 8 presents a comparison among measured and estimated solar irradiation values when each of the three techniques was used to provide *CCI* data. Although the third technique has improved the correlation factor among measured and estimated values, the model BRASIL-SR still underestimates the global solar irradiation in Caicó. The $L_{\mathrm{cld}}$ values lower than expected is the most probably reason for this underestimation once the model BRASIL-SR shows lower deviations for clear sky conditions in other regions were persistent clear sky do not occur (Martins et al. 2003b). In summary, the *CCI* values provided by Bi-spectral technique still indicate more cloud cover than the real observation at the Caicó measurement site. More evaluation is necessary to improve the Bi-spectral technique to get more confident solar radiation estimates from model BRASIL-SR, but similar deviations were obtained for hourly basis when compared with model HELIOSAT largely applied in solar assessment in Europe.

At daily basis, model HELIOSAT presents quite better results, even when Bi-spectral technique is applied to feed model BRASIL-SR. It is important to mention that the model HELIOSAT provided daily solar irradiation estimates by using hourly METEOSAT images. The better time resolution is supposed to contribute for the lower deviations, however it is out of discussion that BRASIL-SR underestimates solar irradiation

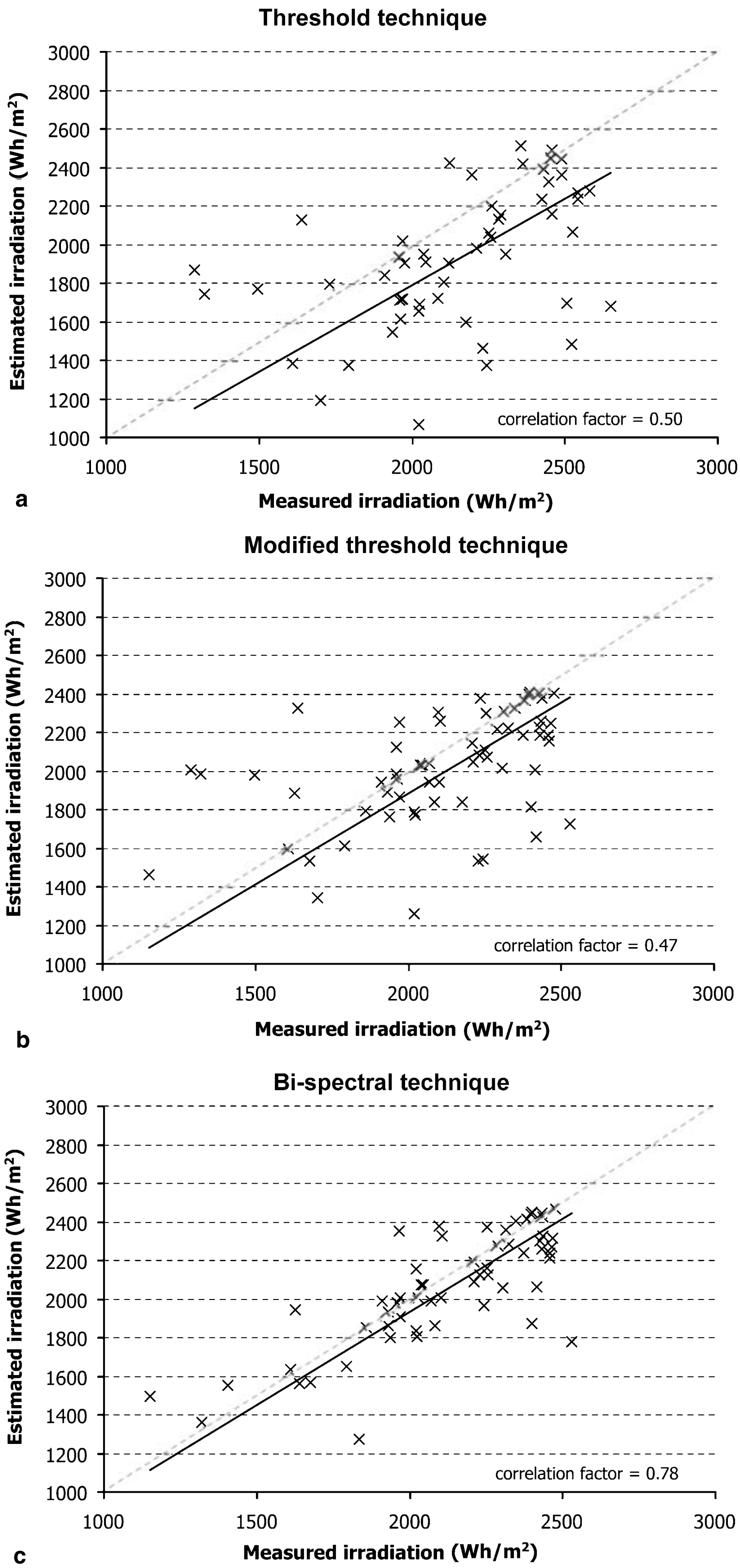


**Fig. 8.** Comparison among measured and estimated solar irradiation in Caicó using the three techniques to get *CCI*: (**a**) Threshold technique; (**b**) modified Threshold technique and (**c**) bi-spectral technique

meanwhile HELIOSAT do not. The methodology applied by model HELIOSAT to assess cloud cover index is less sensitive to persistence of clear sky conditions presented in Brazilian northeast region. More complete comparison among BRASIL-SR, HELIOSAT and other radiative transfer models was presented by Beyer et al. (2004).

## 4. Conclusions

This work demonstrates the influence of *CCI* values on the assessment and reliability of surface solar irradiation estimations provided by the radiative transfer model BRASIL-SR. Three techniques were presented and applied to obtain *CCI* values from GOES images. Those *CCI* values were used to feed the radiative transfer model BRASIL-SR in order to provide solar irradiation estimates for Caicó, located at Brazilian northeastern region, were high quality ground data is acquired. An alternative technique was developed to obtain the overcast radiance values, $L_{cld}$, from satellite images. It is based on that the reflected radiation at the top of atmosphere in overcast pixels is only related with the geometry of the Sun/Pixel/Satellite system, independent of the pixel location. Although the application of this method associated with Bi-spectral technique to get $L_{clr}$ values has improved the reliability of global solar estimates for Caicó site, the radiation model still underestimates the solar irradiation as compared to ground truth observations. The most probable reason was linked to errors in the determination of $L_{cld}$ due to the persistent clear sky conditions.

For the time period considered in this paper, the application of Bi-spectral technique reduced the MBE in the order of 50%, and the RMSE of 40% when compared to the Threshold technique. The best correlation factor among measured and estimated values of surface solar irradiation was obtained for Bi-spectral technique (0.78) while the worst correlation was observed for modified Threshold technique (0.47).

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