CROSS VALIDATION OF SATELLITE RADIATION TRANSFER MODELS DURING SWERA PROJECT IN BRAZIL

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Abstract – This work describes the cross validation between two different core radiation transfer models that will be applied during the SWERA (Solar and Wind Energy Assessment): the BRAZIL-SR, and the SUNY-Albany. The model cross validation was performed by using two reference sites in Brazil: at Caicó (06°28'01"S – 037°05'05"W,175.8 m), and Florianópolis (27°34'18"S – 048°31'42"W, 10 m), Satellite data were collected by INPE-CPTEC for GOES-8, that also provides for its quality assessment, sectoring, storing and distribution to the participating teams. In this work we show the first results of this cross-validation along with some discussions on model deviations and uncertainties.

1. INTRODUCTION

The international concerns on the increasing demands for energy in developing countries and the necessity to conciliate development and environment protection, led to the creation of the Solar and Wind Energy Resource Assessment (SWERA) project. SWERA is a multinational project financed by UNEP-GEF aimed at performing a detailed survey of solar and wind energy resources of various developing countries employing the most modern techniques presently available. This work describes an important task within SWERA: the cross validation among the project's core radiation transfer models. In this work we report the first results for two of the models:

(1) BRAZIL-SR model: a spectral physical model that combines the utilization of the "two-stream" method to solve the radiative transfer equation using satellite data and climatological information;
(2) SUNY-Albany model: a statistical satellite method based on the Kasten's formulation using cloud information derived from satellite data; and

Results for the HELIOSAT model was also used as a reference using METEOSAT data: HELIOSAT is a statistical method that uses Linke turbidity to model atmospheric contribution to radiative transmittance and cloud index derived from satellite images to model cloud extinction.

Results for the two other SWERA's core radiative transfer models , one developed by NREL1 and other by DLR[2] are were not yet available..

The model cross validation was performed in two reference sites:

- Caicó (06°28'01"S – 037°05'05"W / 176m)
- Florianópolis (27°34'18"S – 048°31'42"W / 10m)

2. BASIC DESCRIPTION OF SOLAR RADIATION SITES

The two sites were chosen because they provide high quality radiation data and represent different climatic/environmental regions and different ground cover. The BSRN site of Florianópolis is operated by the LABSOLAR[3]. Caicó site is operated in partnership with UFRN[4];. The measure data is qualified according to BSRN[5] criteria and are available at each minute interval.

The ground site at Caicó is this small city located in the semi-arid region of the Brazilian northeast (annual precipitation under 700 mm), over a relatively flatland area with a sparse brushwood type vegetation known as "caatinga" (average albedo 13.3%). It is characterized by a large insolation of about 120 days/year, and high annual mean temperature (22°C to 33°C), which allows it to be a good place for model adjustments for bias errors under cloudless skies. The site became operational in November 2002 collecting data for global and direct solar radiation.

The site at Florianópolis is located in a medium size city (under 400,000 inhabitants) located on an island in the Brazilian South region. Rains is fairly well distributed along the year characterize its weather, the summer is hot and the winter is mild with some few cold days. This

[1] NREL – National Renewable Energy Laboratory (USA).
[2] DLR - Deutsches Zentrum für Luft- und Raumfahrt/ Inst. für Physik der Atmosphäre (Germany)

[3] LABSOLAR – Solar Energy Laboratory, Department of Mechanical Engineering, Federal University of Santa Catarina (Brazil).
[4] UFRN – Federal University of Rio Grande do Norte (Brazil).
[5] BSRN – WMO Baseline Surface Radiation Network.

radiometric station was installed in 1991 as part of the BSRN and provides data of global, direct, and diffuse radiation.

3. SATELLITE DATA

Satellite data used by BRAZIL-SR and SUNY-Albany models are provided by GOES-8 images collected by CPTEC-INPE[6], which also provides for its quality assessment, sectoring, storing and distribution to the participating modelers. The GOES-8 satellite was launched in April 1994 and were 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 – 0.72 μm) and infrared images (channel 4, 10.2 – 11.2 mm) from the measurement sites are as well as ground data are available in the SWERA Latin America web page: http://www.dge.inpe.br/swera/EN/en_swera_home.html.

Half hourly images from METEOSAT 7 are used to run the HELIOSAT model for the three measurement sites. The imager of the METEOSAT satellite is a high-resolution radiometer with three spectral bands in the visible, the infrared and the water vapor range of the light spectrum. Radiation measurements of Earth's complete disk are obtained during a scanning period of 25 minutes. The scanning is followed by a five-minute period for stabilization and adjustment, so that a full set of images of Earth's full disk is available every 30 minutes.

4. DESCRIPTION OF THE RADIATION MODELS

4.1 BRASIL-SR model

BRASIL-SR is a physical model to obtain solar radiation estimates incident on the ground that combines the "two-stream" approach to solve the radiative transfer equation. Information on cloud optical thickness is obtained from the satellite images. The model assumes that the global solar irradiation at ground and at top of the atmosphere is linearly correlated. (Martins, 2001; Pereira *et al.*, 2000; Stuhlmann *et al.*, 1990). Incident global horizontal irradiance in the ground is obtained by equation (1).

$$GHI = G_0\{(\tau_{clear} - \tau_{cloud})(1 - C_{eff}) + \tau_{cloud}\} \qquad (1)$$

where *GHI* is the global horizontal irradiance at surface, G_0 is the irradiation at the top of the atmosphere. The "two-stream" approach is used to obtain two independent components that are used as boundary condition for the model: the clear sky transmittance, τ_{clear}, and the overcast sky transmittance, τ_{cloud}. The first component is a function of the surface albedo, the solar zenith angle and the optical thickness of the atmospheric constituents. The component τ_{cloud} is a function of the solar zenith angle, the cloud optical thickness, and height of cloud top. Both components may be estimated from climactic data and parameterizations of well-known physical processes that occur in the atmosphere.

The dimensionless cloud cover index, C_{eff}, describes both the cloud coverage and the spatial variation of cloud optical depth. It is determined using the following equation:

$$C_{eff} = \frac{\rho - \rho_{clear}}{\rho_{cloud} - \rho_{clear}} \qquad (2)$$

where ρ is the visible reflectance measured by satellite, ρ_{cloud} and ρ_{clear} stand for overcast and cloudless reflectance measured by the satellite, respectively. The ρ_{cloud} and ρ_{clear} are obtained monthly from statistical analysis of satellite images by using both the visible and the infrared channels of GOES-8. By using this scheme, the degradation of the satellite sensors with time has no influence on the model estimations..

4.2 SUNY-Albany model

The State University of New York at Albany developed a model to calculate global irradiance using a statistical method based on a modified Kasten model for clear sky irradiance. The global horizontal irradiance, *GHI*, is obtained from the following expression:

$$GHI = \{0.02 + 0.98 \cdot (1 - CI)\} \cdot G_{clear} \qquad (4)$$

where *CI* is the cloud index, G_{clear} is the clear sky global irradiance estimated with the modified Kasten model:

$$G_{clear} = 0.84 G_0 \cos(\theta_0) \exp\left[\begin{array}{l} -0.027 m \exp(-z/8000) + \\ \exp(-z/1250)(TL - 1) \end{array}\right] \qquad (5)$$

where G_0 represents the extraterrestrial solar irradiance, θ_0 is the solar zenith angle, *m* is the air mass, *z* represents the ground elevation in meters and *TL* is the Linke turbidity obtained from the direct irradiance of clear sky (Kasten, 1984). The direct irradiance of clear sky is obtained as a function of the Rayleigh scattering; the extinction by aerosols; and the absorption by atmospheric gases, water vapor and ozone, using an independent zenith angle of Kasten's formula.

4.3 HELIOSAT model

The HELIOSAT method was used as reference in this study. This model is used to derive the global horizontal irradiance from images of satellites of the METEOSAT family and was developed originally by Cano *et al.* (1986). It was improved in various aspects, as described by Beyer *et al.* (1996) and Hammer (2000). The current version used in this study is presented in Hammer *et al.* (2001).

The basic idea of the HELIOSAT is the separate modeling of the atmospheric and cloud extinction. First, the time and site-specific clear sky irradiance is calculated using the models of Page (1996) for the direct

[6] CPTEC-INPE – Centre for Weather Forecast and Climatic Research/Brazilian Institute for Space Research.

irradiance, and Dumortier (1995) for the diffuse irradiance. The Linke turbidity is input for this step. In a second step a cloud index is derived from the relative reflectance given by METEOSAT images. For this purpose the images are normalized, taking into account an instrument offset and the atmospheric backscatter as a function of the zenith angle and the angle between the Sun and the satellite (Hammer, 2000). From these normalized reflectance values, ρ, the cloud index is given by:

$$n = \frac{\rho - \rho_{\min}}{\rho_{\max} - \rho_{\min}} \qquad (6)$$

ρ_{min} is the minimal reflectance for the pixel of interest derived from a series of images and ρ_{max} a unique value for maximum normalized reflectance of a maximum overcast cloud cover that is specific for the radiometer *i.e.* the satellite in use (Hammer et al., 2001).

The clear sky index, giving the ratio of the actual irradiance to the clear sky irradiance is derived from the cloud index using the relations as described in Fontoynont *et al*. (1997). In a subsequent step the diffuse and the direct irradiances are calculated using the model for the diffuse radiation given by Skartveit *et al*. (1998).

5. RESULTS

The radiative transfer models described above were used to obtain the incident global horizontal solar irradiation for the three validation sites. The cross validation period begun in November/2002 and is still being carried out. In this report, preliminary results for the cross-validation will be reported. Solar estimates from other project's core radiation transfer models: NREL and DLR models are not yet available, but they will be included in the comparison analysis in a latter phase of the project.

The methodology used in this cross validation compares hourly and daily estimates for all the three models. Three statistical parameters were used to evaluate the quality of global solar estimates obtained from the radiative transfer models:

i) relative mean bias error (rMBE): defined as the ratio between the mean bias error (MBE) and monthly average ground data;
ii) relative root mean square error (rRMSE): defined as the ratio between the root mean square error (RMSE) and the monthly average of ground data; and;
iii) relative root mean square for "percentile match curves" (rRMSEpm): defined as the root mean square of the differences of satellite and ground data with same rank (i.e. a measure for the match of the distribution of the daily sums).

The percentile match curve is defined as follows: first, both ground and satellite data are ranked in a descending array and then, pairs of ground and satellite data with the same rank are plotted in a scatter graph (i.e. the uppermost satellite value against the uppermost ground value, the second highest satellite value against the second highest from ground data, and so on).

The benchmarks values for hourly and daily estimates for Caicó are shown in Table 1 and Table 2. The HELIOSAT model, that uses METEOSAT data, presented the best results for Caicó. The BRASIL-SR and SUNY-Albany models presented similar performances. The C_{eff} determination from GOES-8 images was the main difficulty for BRASIL-SR model. The regional climate at Caicó is characterized by and large of cloudless skies even during the wet season (from October to May). Owing to this characteristic, the determination of ρ_{cloud} from statistical analysis of satellite images presented large errors. An alternative technique was developed to get ρ_{cloud} for Caicó using an empirical fit for maximum reflectance measured by satellite in function of solar zenith angle. The empirical fit was obtained using all images for a latitude interval from 5°S to 10°S in a month's period.

All models have presented good results for Florianópolis. In contrast with the difficulties found to derive ρ_{cloud} in Caicó, we found no problem in obtaining this parameter for Florianópolis because fully overcast condition are frequent during the summer season in south of Brazil. In Florianópolis the main difficulty was large dissimilarities in the ground albedo. The radiation site at Florianópolis is located on coastal region. This could masks the values of ρ_{clear} because ocean reflectance is significantly lower than the ground reflectance. Table 3 and Table 4 show the benchmarks values for hourly and daily global horizontal solar irradiation estimates.

Figure 1 shows the plots for estimated versus measured values of hourly global horizontal solar irradiation for Caicó validation site. Only models that use the standard tri-hourly GOES-8 images are presented. The correlation factor between global horizontal solar irradiation estimates and measured values is lower for BRAZIL-SR model. It can be noted that BRAZIL-SR model overestimates the hourly global solar irradiation due to the inaccuracy in the determination of C_{eff}. The technique employed to get ρ_{cloud} still needs improvements to better represent the real cloud reflectance. The empirical fit used must be corrected to take in account parameters like satellite zenith angle and Sun-satellite angle. The data scattering is very similar for both models.

Table 1. Comparison between statistical benchmarks for hourly estimates obtained with each radiative transfer model for Caicó radiometric station.

	rMBE		
	BRASIL-SR	SUNY	HELIOSAT
Nov/02	0.016	n.a.	-0.021
Dec/02	0.088	-0.046	0.027

Jan/03	0.052	-0.009	0.001
Feb/03	0.091	0.029	0.012

	rRMSE		
	BRASIL-SR	SUNY	HELIOSAT
Nov/02	0.205	n.a.	0.116
Dec/02	0.217	0.150	0.182
Jan/03	0.207	0.224	0.179
Feb/03	0.317	0.472	0.204

	rRMSEpm		
	BRASIL-SR	SUNY	HELIOSAT
Nov/02	0.100	n.a.	0.031
Dec/02	0.126	0.084	0.046
Jan/03	0.088	0.059	0.026
Feb/03	0.112	0.093	0.026

Table 2. Comparison between statistical benchmarks for daily estimates obtained with each radiative transfer model for Caicó radiometric station.

	rMBE		
	BRASIL-SR	SUNY	HELIOSAT
Nov/02	0.025	n.a.	-0.021
Dec/02	0.096	-0.046	0.027
Jan/03	0.033	-0.009	0.001
Feb/03	0.101	0.029	0.015

	rRMSE		
	BRASIL-SR	SUNY	HELIOSAT
Nov/02	0.109	n.a.	0.048
Dec/02	0.131	0.079	0.055
Jan/03	0.072	0.119	0.067
Feb/03	0.229	0.282	0.063

	rRMSEpm		
	BRASIL-SR	SUNY	HELIOSAT
Nov/02	0.058	n.a.	0.030
Dec/02	0.112	0.074	0.046
Jan/03	0.050	0.048	0.029
Feb/03	0.109	0.075	0.037

Table 3. Comparison between statistical benchmarks for hourly estimates obtained with each radiative transfer model for Florianópolis radiometric station.

	rMBE		
	BRASIL-SR	SUNY	HELIOSAT
Nov/02	0.037	n.a.	-0.010
Dec/02	0.105	0.020	n.a.
Jan/03	0.030	0.055	0.054

	rRMSE		
	BRASIL-SR	SUNY	HELIOSAT
Nov/02	0.250	n.a.	0.227
Dec/02	0.325	0.274	n.a.
Jan/03	0.277	0.431	0.293

	rRMSEpm		
	BRASIL-SR	SUNY	HELIOSAT
Nov/02	0.084	n.a.	0.086
Dec/02	0.125	0.082	n.a.
Jan/03	0.087	0.109	0.084

Table 4. Comparison between statistical benchmarks for daily estimates obtained with each radiative transfer model for Florianópolis radiometric station.

	rMBE		
	BRASIL-SR	SUNY	HELIOSAT
Nov/02	0.035	n.a.	-0.010
Dec/02	0.111	0.020	n.a.
Jan/03	0.054	0.055	0.054

	rRMSE		
	BRASIL-SR	SUNY	HELIOSAT
Nov/02	0.109	n.a.	0.081
Dec/02	0.160	0.146	n.a.
Jan/03	0.178	0.259	0.121

	rRMSEpm		
	BRASIL-SR	SUNY	HELIOSAT
Nov/02	0.047	n.a.	0.050
Dec/02	0.130	0.079	n.a.
Jan/03	0.131	0.118	0.085

Figure 2 shows the same behavior for daily global horizontal solar irradiation. The correlation factor between daily estimated values, provided by BRAZIL-SR and SUNY-Albany models and measured values in Caicó are comparable. Again, it can be noted that BRAZIL-SR model overestimates global solar irradiation as a consequence of inaccuracy in C_{eff} determination. The data presented in Figure 1 and Figure 2 are for January/2003, but similar performances are observed in others months.

The BRAZIL-SR model presents better results for Florianópolis than for Caicó as can be seen in Figure 3 and Figure 4. The best estimates provided by SUNY-Albany model were obtained using only one pixel of GOES-8 images over site coordinates (latitude/longitude). The estimates provided by BRAZIL-SR show good agreement using either one pixel or the entire standard nine pixels around geographical coordinates of the radiometric station. In Figure 3 and Figure 4 are presented the data obtained by adoption one pixel of satellite image.

Similar results were obtained for November and December of 2002. The scattering of data observed for Florianópolis is larger then for Caicó, and it can be related with dynamic of clouds and microclimatic factors associated with the already mentioned large differences between ground and ocean albedoes at this site..

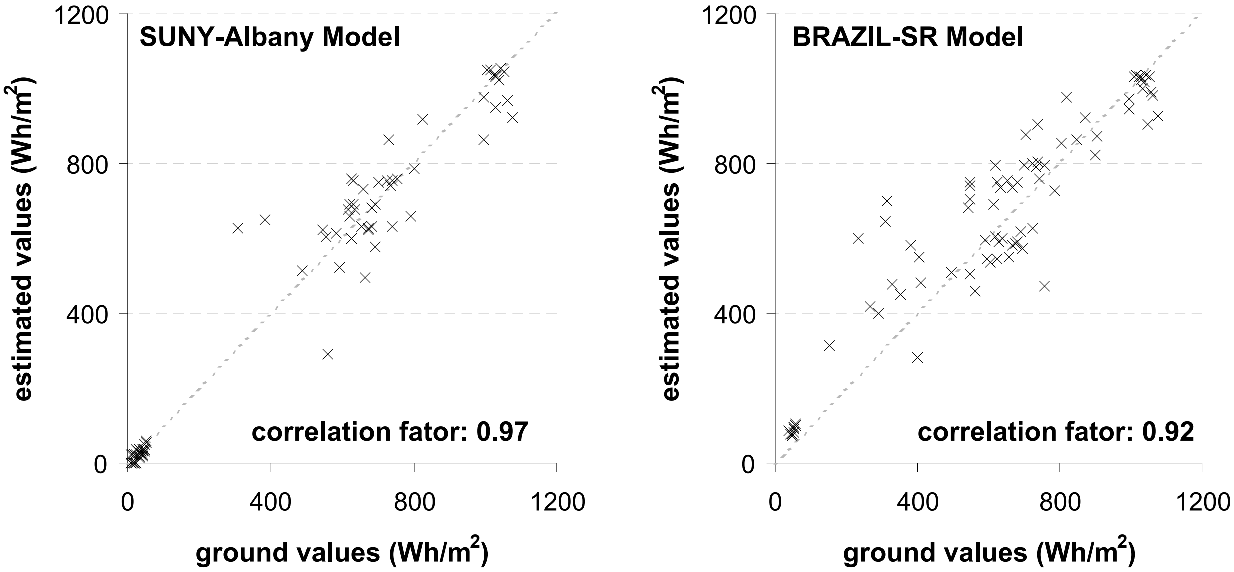

Figure 1. Scatter plot between hourly global solar irradiation estimates versus ground values measured in Caicó for January/2003. Only SUNY-Albany and BRAZIL-SR models are presented. Both models use the tri-hourly GOES-8 images to estimate solar irradiation.

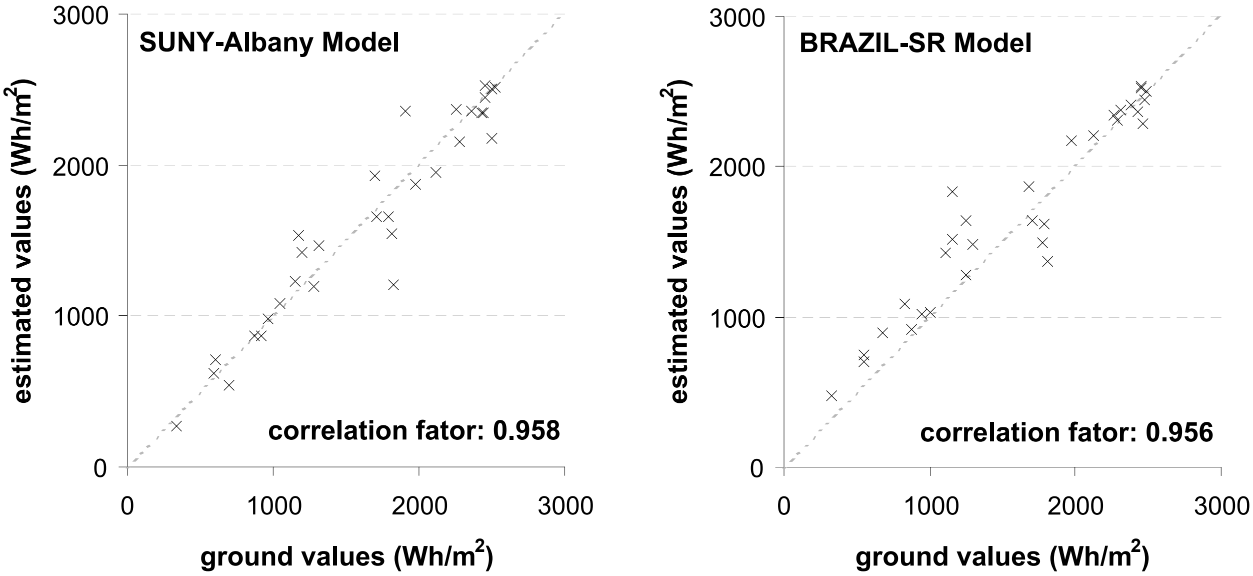

Figure 2. Scatter plot between daily global solar irradiation estimates versus ground values measured in Caicó for January/2003. Only SUNY-Albany and BRAZIL-SR models that use the standard tri-hourly GOES-8 images are presented.

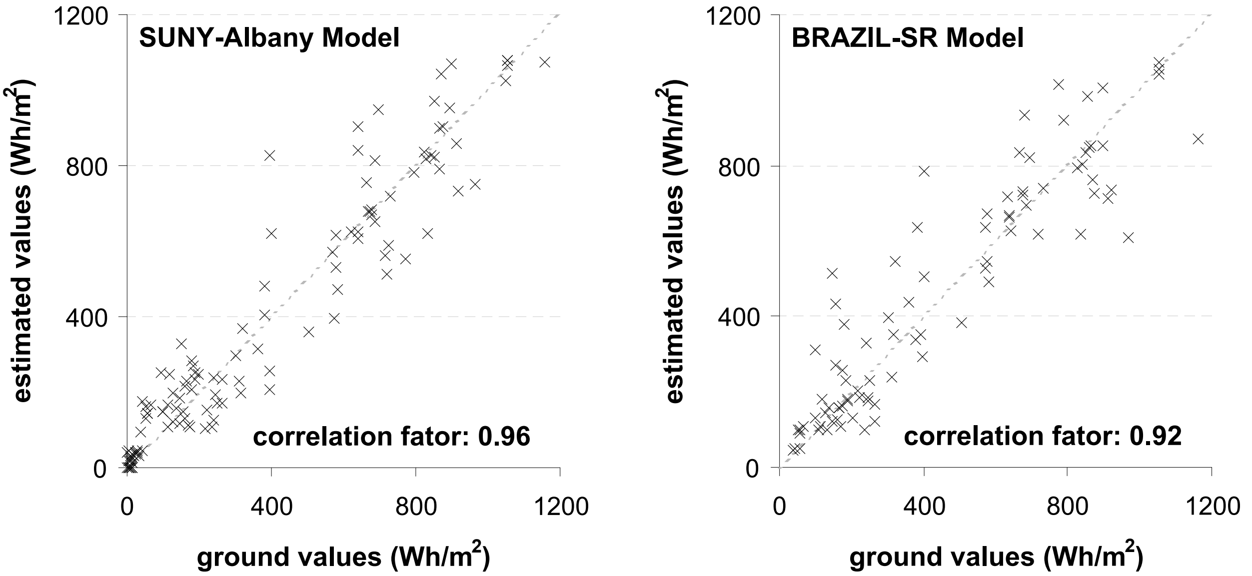

Figure 3. Scatter plot between hourly global solar irradiation estimates versus ground values measured in Florianópolis for January/2003. Only SUNY-Albany and BRAZIL-SR models are presented as in Figure 2.

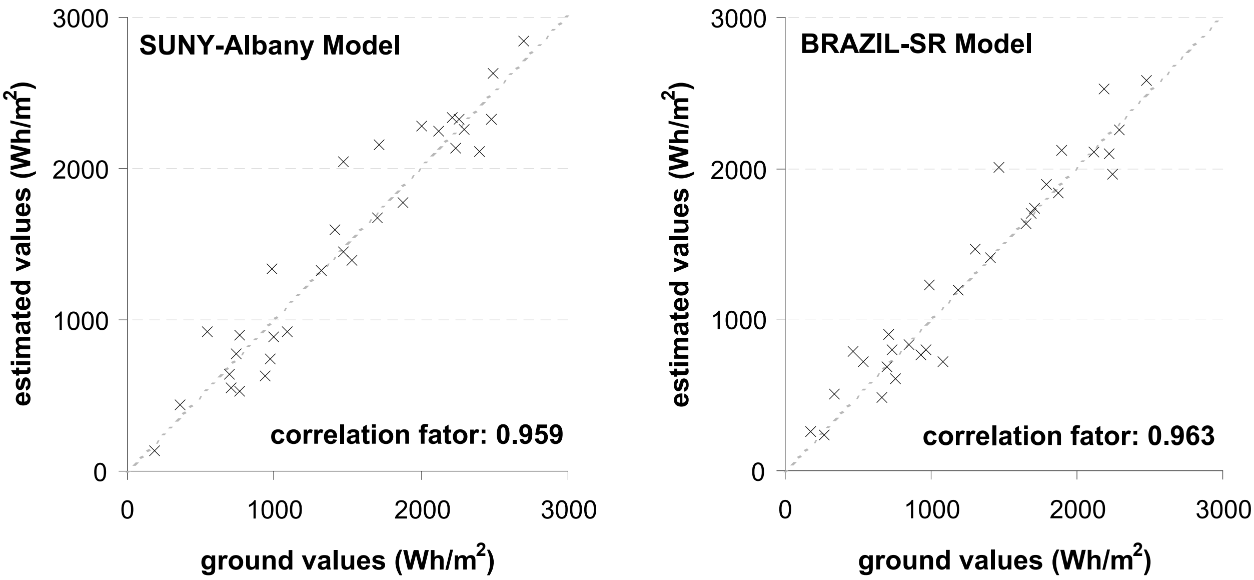

Figure 4. Scatter plot between daily global solar irradiation estimates versus ground values measured in Florianópolis for January/2003. Also here, only SUNY-Albany and BRAZIL-SR results are presented.

6. CONCLUSIONS

From the preliminary cross-validation we concluded that:

1) Both BRAZIL-SR and the SUNY-Albany produced estimates that are statistically comparable for the studied sites;
2) Correlation factors are good in both core models for hourly and daily estimates;
3) There is a need to improve the method to estimate $\square_{cloud}$ that is capable to take into account situations of mostly cloudless sky such as in Caicó;

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