Assessing satellite derived irradiance information for South America within the UNEP resource assessment project SWERA

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Introduction
The UNEP-GEF financed project 'Solar and Wind Energy Resource Assessment' (SWERA) overall goal is to promote the integration of wind and solar alternatives in national and regional energy planning and sector restructuring as well as related policy making. The project will enable informed decision making and enhance the ability of participating governments to attract increased investor interest in renewable energy. This will be achieved by providing high quality information of solar and wind energy resources in various developing countries, promoting alternate business scenarios, and developing tools for analysis and use of renewable energy resource information. Within this framework, a detailed solar radiation Atlas for South America should be established. The Atlas should be based on the application of validated technologies for deriving continuous solar radiation maps from images taken by geostationary satellites.
In order to identify the best data sources and methodologies for this task, a comprehensive cross validation task is performed. In following we report on the intercomparison methodology and give some preliminary results on the achievable data quality.

Radiation maps for South America within the project SWERA

In order to establish maps of the global irradiance two procedures are applied. These are the satellite-image-to-global-irradiance-models Brazil-SR and SUNY-Albany, which also perform a subsequent estimation of the diffuse component. These two models apply images from the satellite GOES-EAST, form which series of 3-hourly images are available. For cross-comparison the Heliosat model as reference model, using half-hourly Meteosat-7 images is applied for the same task. Due to the position of this satellite above 0°N, 0°W an analysis of the respective images is possible only for longitudes up to about 55°W.

For the evaluation of the direct irradiance from satellite images the DLR model is applied, which perform a direct calculation of this radiation component. For comparison the direct irradiance is also modeled by SUNY from the global irradiance using a global-to-direct-irradiance conversion procedure.

Satellite data

Satellite data used by BRAZIL-SR and SUNY-Albany models are provided by GOES-EAST images collected by INPE-CPTEC, which also provides for its quality assessment, sectoring, storing and distribution to the participating modelers. The GOES-EAST satellite is located at a geostationary position at longitude 75°W, latitude 0°. The main purposes of GOES-EAST 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. Three-hourly visible (channel 1, 0.52 – 0.72mm) (see example in figure 1) and infrared images (channel 4, 10.2 – 11.2 mm) from the measurement sites as well as ground data are available in the SWERA Latin America web page: http://www.cptec.inpe.br/swera/.

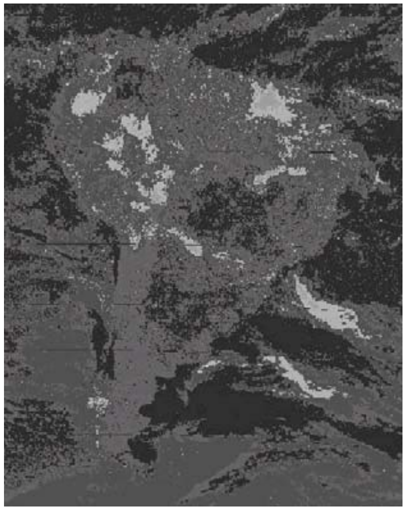

Figure 1: Image from the visible channel of the GOES-EAST satellite

Half hourly images from METEOSAT 7 are used to run the Heliosat and the DLR model for the measurement sites. The imager of the METEOSAT 7 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 (see example given in figure 2). 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. Due to the position of METEOSAT 7 above 0°S, 0°W the images may be used to retrieve irradiance data up to a longitude of approx. 55°W.

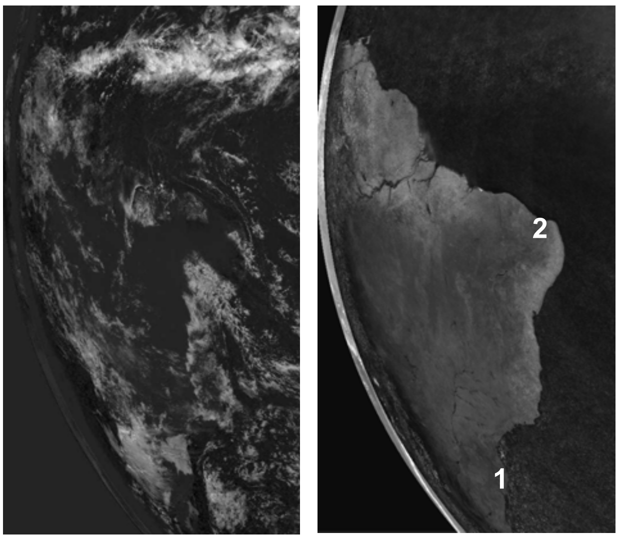

Figure 2: Two presentations of the section of the Image in the visible channel of Meteosat 7 covering South America. The plot on the right gives an original view. The plot on the left shows a synthetic image representing a cloud free view. The numbers indicate the locations of the 2 meteorological stations used for comparisons presented in this paper.

Description of the radiation models

BRASIL-SR model

BRASIL-SR is a physical model to obtain solar radiation estimates incident on the ground that employs 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),.

$$GHI = G_0\{(t_{clear} - t_{cloud})(1 - c_{eff}) + t_{cloud}\} \quad (1)$$

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, 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 atmospheric constituents. 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 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:

$$c_{eff} = \frac{\rho - \rho_{clear}}{\rho_{cloud} - \rho_{clear}} \quad (2)$$

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} *clear* are obtained monthly from statistical analysis of satellite images by using both the visible and the infrared channels of GOES-EAST. By using this scheme, the degradation of the satellite sensors with time has no influence on the model estimations.

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:

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$$GHI = \{0.02 + 0.98(1 - CI)\} \cdot G_{clear} \quad (3)$$

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

$$G_{clear} = 0.84 \cdot G_0 \cos(\theta_0) \cdot \exp(-0.027m \cdot \exp(-z/8000) + \exp(-z/1250) \cdot (TL - 1)) \quad (4)$$

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. The direct normal irradiance DNI is gained from the clear sky direct irradiance by a modulating factor based on a global-to-DNI model as described by Perez et al. (2002).

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 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:

$$c_{eff} = \frac{\rho^* - \rho^*_{clear}}{\rho^*_{cloud} - \rho^*_{clear}} \quad (5)$$

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 may be calculated using the model for the diffuse radiation given by Skartveit *et al*. (1998).

The DLR Model

For the DNI calculation the DLR method as described in SCHILLINGS *et al*. (2004a,b) is applied. This method uses atmospheric data of aerosol, water vapor and ozone as input for the parameterization model of BIRD and HULSTROM (1981) as described in IQBAL (1983). Monthly ozone data are taken from the TOMS-Total Ozone Mapping Spectrometer, monthly climatological data of the aerosol optical depth from the GACP-Global Aerosol Climatology Project and daily water vapor data from the reanalysis of the NCEP/NCAR National Centers for Environmental Prediction. Cloud information is extracted from IR and VIS-data of the geostationary satellite Meteosat using a cloud detection algorithm developed at DLR.

Model intercomparison

For the model intercomparison data from 3 ground reference sites are available. In present paper data from the 2 sites with the best data availability are applied. The two sites are: Caicó

(06°28’01”S – 037°05’05”W / 176m) and Florianópolis (27°34’18”S – 048°31’42”W / 10m) representing different climatic/environmental regions and different ground cover. The site at Caicó (see number 2 in figure 2) is in 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) situated on an island in the Brazilian South region. Rains is fairly well distributed along the year. The summer is hot and the winter is mild with some few cold days. This radiometric station was installed in 1991 as part of the BSRN and provides data of global, direct, and diffuse radiation. The data of both sites are qualified according to the criteria of the WMO Baseline Surface Radiation Network.

For the purpose of the intercomparison with the satellite derived data the ground data, which are recorded as one-minute averages are aggregated to hourly means and daily totals. In the following results for the intercomparison of hourly averages are presented.

As parameters for the quality of the models, the generic measures ‘mean bias error’ MBE and ‘root mean square error’ RMSE are evaluated for the different irradiance components are calculated for monthly periods. In addition, a measure for the ability of the methods to give a realistic representation of the probability distribution of the data, the root mean square error of the percentile match curves RMSEpm, is applied. To derive this value, both, ground and satellite derived data are sorted according amplitude. From the sorted sets the root mean square of the difference of the values with the same rank in each set is calculated.

These evaluations are presented here for hourly data of the global irradiance G and the direct normal irradiance DNI stemming from the period November 2002 to June 2003.

Global Irradiance

The tables 1 and 2 give the error measures for the satellite derived estimates for the global irradiance at the two sites as derived by SUNY and BRASIL-SR from GOES-8 images and by Heliosat from METEOSAT images. The gabs in the tables are mostly due to the partially detailed availability of the satellite data sets. The errors are normalized with the respective means of the analyzed sets. It can be remarked, that the bias error for all methods is in the range of about 5%. The RMSE is typically in the range of 20 - 30 %. These results are similar to those gained with the Heliosat/METEOSAT Method for sites in Europe.

Table 1

The error measures for the satellite derived global irradiance data at the site Caicó.

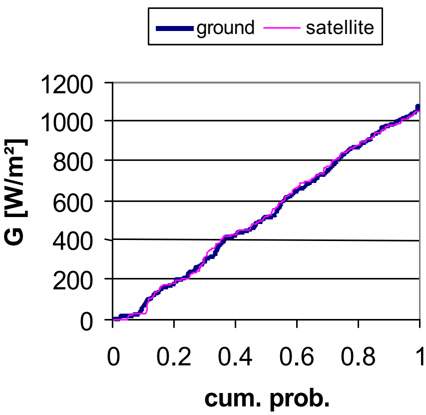
Caicó	BRASIL-SR			Suny			Heliosat		
	MBE	RMSE	RMSEpm	MBE	RMSE	RMSEpm	MBE	RMSE	RMSEpm
11.02	0.016	0.205	0.100	-0.010	0.246	0.063			
12.02	0.088	0.217	0.126	-0.014	0.298	0.102			
1.03	0.052	0.207	0.088	0.036	0.281	0.113	0.001	0.179	0.026
2.03	0.091	0.317	0.112	0.031	0.495	0.118	0.011	0.203	0.025
3.03				0.013	0.318	0.085	0.005	0.281	0.047
4.03							0.023	0.207	0.048
5.03							0.016	0.236	0.043
6.03							0.016	0.164	0.035

Table 2
The error measures for the satellite derived global irradiance data at the site Florianópolis.

Florianó-	BRASIL-SR			Suny			Heliosat		
polis	MBE	RMSE	RMSEpm	MBE	RMSE	RMSEpm	MBE	RMSE	RMSEpm
11.02	0.037	0.250	0.084				-0.010	0.081	0.050
12.02	0.105	0.325	0.125	0.020	0.274	0.082			
1.03	0.030	0.277	0.087	0.070	0.290	0.120	0.054	0.288	0.085
2.03				0.031	0.260	0.075	0.095	0.259	0.123
3.03				-0.004	0.320	0.086	0.045	0.280	0.065
4.03							0.021	0.212	0.048
5.03							-0.016	0.225	0.044
6.03							0.006	0.135	0.091

As example for the quality of the satellite derived irradiance data, figure 3 gives the comparison of the probability distribution for the ground measured and the satellite derived values for one month. In general the RMSEpm values are remarkably reduced as compared to the basic RMSE values. This indicates, that despite the fact that for individual hours the satellite derived data may be associated with remarkable errors, these sets offer a reliable presentation of the radiation climate.

Figure 3
Comparison of the cumulative distributions of the ground (thick line) and satellite derived data of the hourly global irradiance data. This example refers to the site Caicó, month of January. The satellite derived data are gained with Heliosat from METEOSAT images.



Direct Normal Irradiance

11 For the case of the direct normal irradiance DNI results from the DLR model based on at METEOSAT and the SUNY model based on GOES are compared. Table 3 and 4 give the respective error measures. As the DNI data tend to a bimodal distribution, the relative root mean square errors are more pronounced here.

Figure 4 gives an example for the comparison of the measured and modeled cumulative distribution of the hourly DNI values. Looking at the similarity of the curves for the cumulative distributions, it is again obvious, that the elevated RMSE errors may to a large extend be traced back to 'phase errors', caused by the incommensurabilitity of the spatially averaged satellite information and the point measured ground data. However, a detailed inspection shows some tendency to exaggerate the bimodality of the data, which calls for closer inspection.

Table 4
The error measures for the satellite derived direct normal irradiance data at the site Caicó.

Caicó	SUNY			DLR		
	MBE	RMSE	RMSEpm	MBE	RMSE	RMSEpm
1.03	-0.019	0.547	0.129	-0.046	0.511	0.199
2.03	0.190	1.235	0.251	-0.169	0.652	0.326
3.03	-0.069	0.733	0.128	-0.189	0.992	0.359
4.03				-0.060	0.513	0.174
5.03				0.110	0.527	0.240
6.03				-0.071	0.324	0.134

Table 5
The error measures for the satellite derived direct normal irradiance data at the site Florianopolis.

Florianó-polis	SUNY			DLR		
	MBE	RMSE	RMSEpm	MBE	RMSE	RMSEpm
1.03	0.151	0.697	0.297	0.003	0.721	0.185
2.03	0.028	0.421	0.202	0.029	0.491	0.116
3.03	0.196	0.984	0.482	0.155	1.455	0.209
4.03				0.019	0.676	0.167
5.03				0.129	1.098	0.259
6.03				-0.137	0.485	0.248

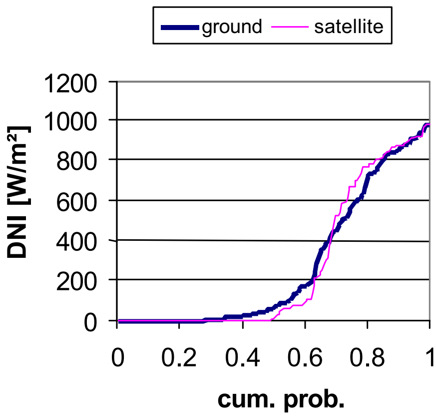


Figure 4
Comparison of the cumulative distributions of the ground (thick line) and satellite derived data of the hourly direct normal irradiance. This example refers to the site Caicó, month of January. The satellite derived data are gained with the SUNY model from GOES images.

Conclusions and outlook

Within the SWERA project, the activities for the intercomparison are ongoing. Currently none of the models has revealed major advantaged or disadvantages as compared to its competitors. After the completion of the intercomparison taking into account a complete annual cycle, the finally selected model or models will be used for mapping the solar resource with different spatial resolutions, depending on the region. These maps will be complemented by procedures for the generation of the specific input data necessary for the analysis of various types of solar energy systems.

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