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Satellite-derived solar irradiation map for Uruguay

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Abstract

A brightness-dependent version of Tarpley's model adjusted to ground data is used with a thirteen-year GOES satellite image data bank to obtain satellite-derived monthly averages of daily global solar irradiation on a horizontal surface with 20 km spatial resolution. The estimates cover all the territory of Uruguay and neighboring areas. These results are validated against other satellite derived irradiation data and against independent long-term ground data. The comparison with the previous solar map shows that the solar irradiation is 5 - 7 % higher than previous estimates derived from long term sunshine hours observations. The first map of direct irradiation at normal incidence (DNI) for the area is also calculated, using a pre-existing global to diffuse model to separate the direct and diffuse components of hourly global irradiation.

Keywords: Tarpley model; satellite derived solar irradiation; solar map; DNI map

1. Introduction.

The first Solar Irradiation Map for Uruguay [1, 2] was developed in 2009 using three long-term series of global horizontal irradiation, several series of long-term observations of sunshine hours and the Angstrom-Prescott correlation. This methodology was dictated by the data available at the time, but it provides limited temporal and spatial resolution (about 100 km). An important measurement effort was developed since then and this new ground data allows the use of other methodologies, such as the use of satellite images together with statistical [3] or physical [4] models, to estimate the solar resource at the surface. There are several examples of satellite-based solar irradiance models [5-7] which can be used to derive meaningful information about the solar resource distribution and variability.

In this work, an improved version of Tarpley's statistical model [8-10], that we call BD-JPT, is used together with a set of 13-year GOES satellite visible channel images, to generate hourly global solar irradiation estimates at the surface. Based on these estimates a new solar map is constructed, with

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improved spatial and temporal resolutions and reduced uncertainty. The results are compared to the previous map, and validated against well established satellite-based models and independent ground data. The new solar map also includes estimates of monthly-averaged daily direct irradiation on normal incidence (DNI), which is of great interest to assess the CSP potential in the country.

This work is organized as follows: in Section 2, the details about the databases (ground data and satellite data) used in this work are discussed. In Section 3, a brief introduction to the enhanced version of Tarpley's model is given, and the resulting spatial distribution of solar irradiation is given in graphical form. Validation with independent ground data and comparisons with other models are discussed in Section 4. Finally, in Section 5 we summarize our conclusions.

2. Data base

Three types of data sets are used in this work. Firstly, a GOES satellite visible channel image database which spans the thirteen year period from 2000 to 2012 is used as input for the modified version of Tarpley's solar hourly irradiation model. This is the satellite set (SAT). Secondly, a short term (three years or less) of good quality ground data for several sites is used to adjust the coefficients in the BD-JPT model. This is the training set (TRN). Finally, a long term data set of ground data (daily global irradiation on a horizontal plane) of proven quality is used for validation purposes and we refer to it as the validation set (VAL).

2.1 Satellite data

GOES-East visible channel satellite images have been manually downloaded from the CLASS/NOAA website[1] in packages of 100 images. The images, which have a nominal resolution of 1 km, are trimmed before download to a window which include all of Uruguay and surrounding areas. An image is available every 30 minutes approximately. The data set used for this work holds information for the thirteen year period between 01/01/2000 and 31/12/2012. The images are in NetCDF format and come geo-referenced, but uncalibrated (composed of raw counts with brightness information). Other (IR) channels are present but not used in this work. The GOES satellites are controlled by NOAA and higher priority is given to observations over North America, especially during the hurricane season. For this and other operational reasons many images of Latin America's southern latitudes are missing from the sequence. It is one the objectives of this investigation to determine if meaningful long-term trends in solar irradiation can be derived from the available images.

During this 13 year period, three different physical satellites have operated at the GOES-East location (GOES 8 from January 2000 to April 2003, GOES 12 from may 2003 to April 2010 and GOES 13 since April 2010). Thus, it is necessary to calibrate the images before they can be used as a single data set. We have used the information given in NOAA/STAR website and in Ref. [11] to convert brightness counts into radiance (W/m^2 sr), and then into reflectance factor using the information given in NOAA/OSO website. The calibrated images are averaged for each daytime hour to provide average cloudiness information in cells of about 20 x 20 km (10 x 10 minutes latitude-longitude interval).

2.2 Ground data

1 http://www.class.ncdc.noaa.gov/saa/products/welcome

A ground data set composed of controlled quality data of global horizontal irradiance for three sites is used to adjust the coefficients of the statistical model used to estimate irradiation from satellite image information. This data has been collected (and recorded at a rate of one record per minute) by our group using three new Kipp & Zonen CMP6 pyranometers connected to autonomous data acquisition systems, which automatically send the data to a web server with daily frequency. These pyranometers are intercompared to one of our secondary standards (Kipp & Zonen, CMP22) every 24 months. The secondary standards are kept mostly indoors and are sent for factory calibration every 24 months. The collected data was checked for consistency with a well adjusted clear-day model and integrated to provide estimates of hourly global irradiation on a horizontal plane. The details for this data set (TRN) are listed in Table 1 below, together with information from a second long-term ground data set of daily global irradiation on horizontal surface (VAL) which was used for validation purposes in this work. Two of the series from this set (coded LV and ZU) have been used as a basis for the first solar map for Uruguay [1, 2] and are of good quality. The LV series corresponds to the city of Livramento at the border between Brazil and Uruguay and was originally provided to us by the Brazilian Meteorological Service (INMET). The ZU series is based on a Black and White Eppley pyranometer and it was recorded on paper and integrated with great care at an agronomical research facility (INIA) located in a rural area near Colonia, several decades ago. The third series used for validation has been recorded (at 15 minute intervals) at the Salto Airport station using a Kipp & Zonen CM11 pyranometer and a Campbell Scientific data logger by the National Meteorological Service and was provided to us very recently. We have made no quality checks on this data set.

Table 1. Details of the ground stations whose data was used for this work. Latitude and longitude is in decimal degrees, and negative values correspond to south of the equator and west of Greenwich respectively.

Site	**Code**	**LAT** (deg)	**LON** (deg)	**ALT** (m)	**Start**	**End**	**Owner**	**Type**
Las Brujas	**LB**	-34.67	-56.34	37	29/12/2009	31/12/2012	**GMARS**	**TRN**
Salto Grande	**SG**	-31.27	-57.89	50	02/06/2010	31/12/2012	**GMARS**	**TRN**
Treinta y Tres	**TT**	-33.28	-54.17	32	28/05/2010	31/12/2012	**GMARS**	**TRN**
Livramento	**LV**	-30.83	-55.60	328	01/01/2002	31/12/2010	**INMET**	**VAL**
La Estanzuela	**ZU**	-34.33	-57.73	82	01/10/1969	18/11/1977	**INIA**	**VAL**
Salto Airport	**SA**	-31.44	-57.98	41	01/01/1998	31/12/2004	**DNM**	**VAL**

Table 2. Coefficients used in Eq. (1), obtained by adjusting the model to the ground data in the TRN set described in Table 1.

Case	**a**	**b**	**c**	**d (kJ/m²)**
$F_r > F_{r\,m}$	-0.0894	1.3998	-0.6339	-0.5512
$F_r \leq F_{r\,m}$	0.3631	0.9234	-0.5393	-3.0052

3. Irradiation estimates

3.1 Improved Tarpley's model

Tarpley's model estimates hourly global solar irradiation at a horizontal plane using information from a visible channel satellite image. The original version of this model [8, 9] is known to produce biased estimates. An improved version of this model uses different sets of coefficients for mostly cloudy and mostly clear conditions and the bias is remarkably reduced [10]. When tested against independent ground data it shows a relative RMS deviation of 14% for hourly estimates and of 7% for daily estimates [10]. We refer as BD-JPT to the improved version of Tarpley's model which introduces a brightness dependence.

In this work, in order to use the 13 years statistic of GOES satellite images, we have trained the model using the reflectance factor instead of the raw brightness counts. We use the model at hourly scale, to obtain estimates of hourly global irradiation of a horizontal surface using the following multiple regression model,

$$I_h = I_o \cos\theta_z \left(a + b\cos\theta_z + c\cos^2\theta_z\right) + d\left(F_r^2 - F_{ro}^2\right) \tag{1}$$

where I_o is the extraterrestrial irradiation on normal incidence (the hourly solar constant times the orbital correction factor), θ_z is the solar zenith angle and F_r and F_{ro} are the observed and background reflectance factor for the location, respectively. Two different sets of parameters (a, b, c, d) are adjusted: one for mostly cloudy hours *($F_r > F_{r\,m}$)* and another for mostly clear hours *($F_r \leq F_{r\,m}$)*. The average reflectance factor $F_{r\,\mathrm{m}}$ for the location is used as threshold between both regimes. The coefficients used are indicated in Table 2. For more details see Ref. [10].

For each desired site, the available images are processed to obtain the reflectance factor, and thus global irradiation on horizontal surface from Eq. (1), for each hour. These hours are accumulated in the day to obtain daily irradiation and thus its monthly average. We have also calculated estimates for average DNI (direct irradiation at normal incidence) from hourly estimates. The hourly global irradiation is composed of direct and diffuse components,

$$I_h = I_b \cos\theta_z + I_{dh} \tag{2}$$

where I_b is the hourly beam irradiation at normal incidence, I_{dh} is the hourly diffuse irradiation on a horizontal surface and the solar zenith angle is taken at the mid-point in the hour. The hourly diffuse component is estimated from the clearness index, $kt = I_h / I_{0h}$ using Ruiz-Arias' model [12] which uses a Gompertz function correlation between kt and the diffuse fraction $fd = I_{dh} / I_h$. In Ref. [13] several global to diffuse models were tested with data from three sites of global and diffuse solar irradiance measurements. Of the tested models, Ruiz-Arias' model was the one which reported better agreement with local data and thus it was selected for this work. Then, the hourly beam irradiation at normal incidence (I_b) is obtained from Eq. (2) and accumulated daily from which the monthly averages are derived.

3.2 Maps of monthly average irradiation

The procedure described in the previous section is used to obtain monthly average estimates of daily irradiation on a horizontal surface and corresponding DNI at the nodes of a regular grid of about 20 x 20 km. This information is displayed in the form of a colored map for each month, with this spatial resolution. Fig. 1 shows the radiation maps for October, as an example.

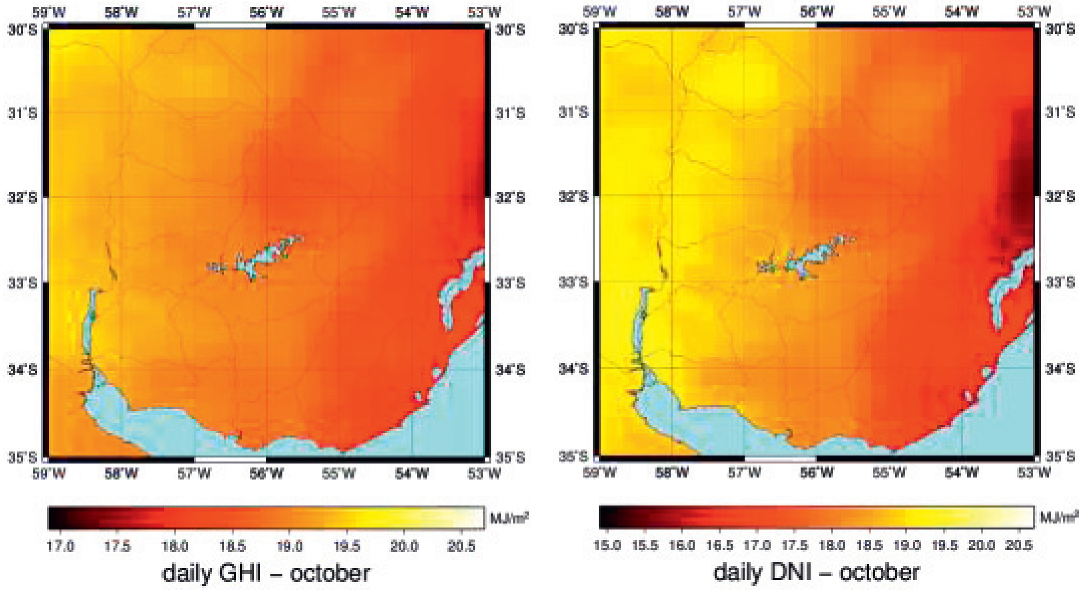


Fig. 1. (a) Spatial distribution of monthly average global daily irradiation on a horizontal plane for October. The spatial resolution is 20 x 20 km. (b) Corresponding spatial distribution for DNI (Direct daily irradiation at normal incidence).

The monthly maps can be used to obtain a yearly average, which characterizes the spatial variability of the solar resource. Figure 2 shows these maps, for horizontal (GHI) and DNI respectively. The yearly average for GHI varies from 15.9 MJ/m^2 at the southeastern coastal area to 17.7 MJ/m^2 at the northwestern part of the country, increasing with increasing distance to the Atlantic Ocean. The geographical variability is low, about ± 5 % of the mean value of 16.9 MJ/m^2. The yearly average for DNI varies in a similar way, from 15.3 MJ/m^2 in the southeast to 18.6 MJ/m^2 in the northwest. Its variability is higher, about ± 10 % of the mean 17.3 MJ/m^2. These new results, suggest that ground radiation levels are higher than the previous estimation (MSU1 map based on sunshine hour records) indicated. The annual average GHI over the territory is 16.9 MJ/m^2, as compared to 15.8 MJ/m^2 from the MSU1 [1, 2], which represents a 7 % overall increase in the solar resource estimates. Inspection of Fig. 2 shows that the same variability trends found in MSU1 are found in this work: a yearly variability radiation levels increase from southeast to northwest, as the distance to the coast increases.

4. Validation

This first validation of our results is done by comparing monthly means of global horizontal daily irradiation (GHI) to modeled values from other models (NASA/SSE) and to the most reliable long-term ground measurements available in the region of interest. We use the usual measures of discrepancy between a set of N estimated values (X_e) and measured or reference (X_m) values. The Root Mean-square deviation, RMSD, is defined as,

$$RMSD = \sqrt{\frac{1}{N}\sum\left(X_e(i) - X_m(i)\right)^2} \tag{3}$$

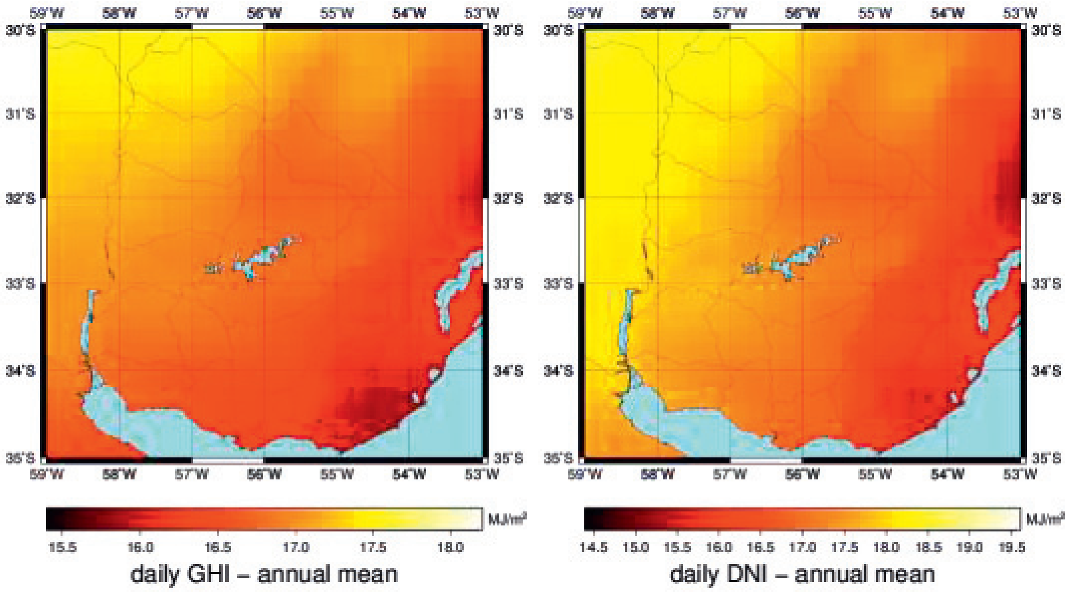


Fig. 2. (a) Spatial distribution of yearly average of global daily irradiation on a horizontal plane. The spatial resolution is 20 x 20 km. (b) Spatial distribution of yearly averaged daily DNI (Direct daily irradiation at normal incidence).Notice the different scales used to accommodate the greater variability of DNI.

and it is regarded as a good measure of how close on the average are the modeled and measured values. The Mean Bias Deviation, MBD, is defined as the simple average of the differences,

$$MBD = \sum \left(X_e(i) - X_m(i) \right) \quad (4)$$

and it is regarded as an expression of any systematic bias between the estimated and the reference values. A positive value of this indicator implies that the model tends to overestimate the measurements. We shall also report relative RMSD and MBD, as a percentage of the simple average X_m of the reference values. Thus we shall use the indicators $rRMSD = 100\ RMSD/\ X_m$ and $rMBD = 100\ MBD/\ X_m$ for relative root mean square deviation and relative mean bias deviation, respectively.

4.1 Comparison with SSE/NASA estimates.

The NASA/SSE service provides estimates (at their site http://eosweb.larc.nasa.gov/sse/) of monthly averaged daily global irradiation over a 1° x 1° grid in latitude and longitude. This amounts to 22 points regularly spread over the (dry) territory of interest in this work. The NASA estimates result from a 23-year set of satellite images (from June 1983 to June 2006) and a model based in Pinker and Lazlo's model [5] combined with ground data from different sources [14]. The NASA/SSE model is used and trusted worldwide, thus we chose it for our first comparison. The results of this comparison are indicated in Table 3 below.

Table 3. Indicators for the comparison between SSE/NASA estimates (taken as reference values) and the present model. The columns refer to the months of the year and the monthly means refer to the NASA/SSE estimates, which are taken as reference values for this comparison.

	Annual	1	2	3	4	5	6	7	8	9	10	11	12
days	**3047**	343	264	299	230	202	173	205	184	218	294	319	316
Mean (MJ/m²)	**16.6**	24.4	20.9	17.7	13.2	10.4	8.5	9.5	12.2	15.9	19.1	23.0	24.9
RMSD (MJ/m²)	**0.2**	1.2	0.9	0.6	0.9	0.4	0.5	0.3	0.7	1.2	0.4	0.9	0.9
rRMSD (%)	**1.3**	4.8	4.5	3.2	7.1	3.9	5.5	2.9	5.9	7.4	2.0	4.0	3.7
MBD (MJ/m²)	**0.2**	1.1	0.8	0.5	0.9	-0.4	-0.4	-0.2	-0.7	-1.2	-0.3	0.9	0.9
rMBD (%)	**1.0**	4.6	3.8	2.6	6.9	-3.7	-5.3	-1.9	-5.4	-7.3	-1.5	3.8	3.6

The agreement between both models is remarkable, considering that they are based on different data sets and methodologies. The overall mean bias deviation is 0.2 MJ/m2 which is a very small bias, representing less than 1 % of the NASA/SSE yearly average of 16.6 MJ/m^2. The RMSD calculated from Eq. (3) for each month, ranges from 0.3 to 1.2 MJ/m2 in absolute terms. These overall average relative RMSD is 1.3 %, which is representative of the observed deviations between both models.

The monthly average daily irradiation on horizontal surface (GHI) estimated from both models is shown as bar-plots in Fig. 3 (left). The right frame in this figure shows the difference between both models, defined as GHI(MSU) – GHI(SSE). A seasonal trend can be seen: the present model (MSU2) gives higher values of irradiation than the SSE model in the summer months and lower values in the winter months.

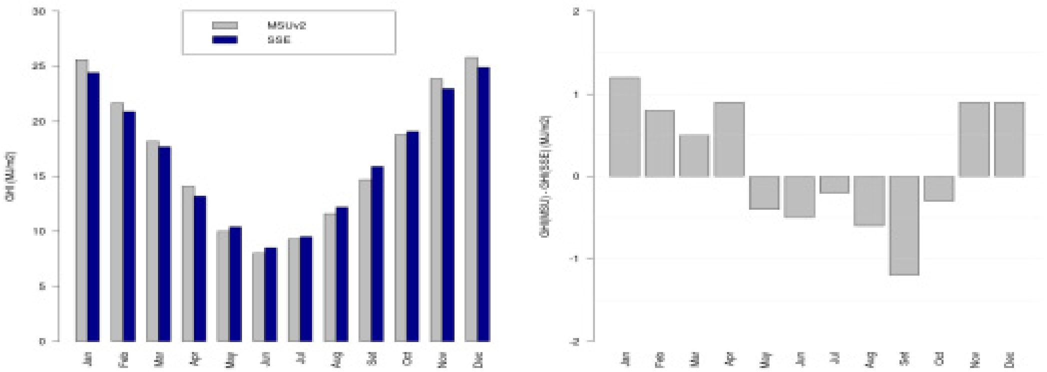


Fig. 3: Comparison between estimates from this work (MSU2) and from the NASA/SSE model for the territory of interest. Left: monthly mean daily global irradiation (GHI) on a horizontal surface from Right: Differences in GHI between both estimates, expressed in MJ/m^2.

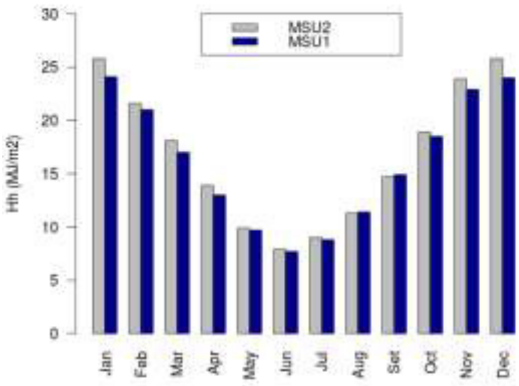
4.2 Comparison with previous Solar Map derived from ground data.

The first solar map [1, 2] (MSU1) is characterized the monthly average daily global solar irradiation at twelve sites distributed over the territory. These sites constitute the support of irradiation estimates used to generate the maps with interpolation techniques. We have used the model discussed in this work (MSU2) to generate monthly averages for the twelve sites that support the MSU1. Here we provide a graphical monthly comparison and the overall indicators for the monthly averages over these sites.

Table 3. Indicators for the comparison between the MSU1 estimates (taken as reference values) and the present model. The average values for the reference set (MSU1, average of twelve locations) are indicated..

	1	2	3	4	5	6	7	8	9	10	11	12	Y
H_h MSU1 (MJ/m^2)	24.1	21.0	17.0	13.0	9.7	7.7	8.8	11.4	14.9	18.5	22.9	24.0	16.1
H_h MSU2 (MJ/m^2)	25.8	21.6	18.1	13.9	9.9	7.9	9.0	11.3	14.7	18.9	23.9	25.8	16.7
RMSD (MJ/m^2)	2.0	0.9	1.3	1.1	0.5	0.4	0.3	0.6	0.8	0.9	1.4	2.0	1.0
rRMSD (%)	8.3	4.4	7.8	8.3	5.3	4.7	3.6	4.9	5.4	4.8	6.1	8.4	6.0
MBD (MJ/m^2)	1.7	0.6	1.1	0.9	0.2	0.2	0.2	0.0	-0.2	0.4	1.0	1.8	0.7
rMBD (%)	7.0	2.8	6.6	7.3	1.9	2.8	2.2	-0.4	-1.0	2.1	4.4	7.3	3.6

Fig. 4 compares the MSU1 estimates and MSU2 estimates for GHI (averaged over the twelve sites which support the MSU1 model) in absolute terms. The right panel of this figure shows the monthly average deviations, defined as Hh (MSU2) – Hh (MSU1), so that positive values indicate that the estimates from the model discussed in this work are higher. It is clear that the MSU2 model gives higher estimates of GHI for most of the year, except in August-September.



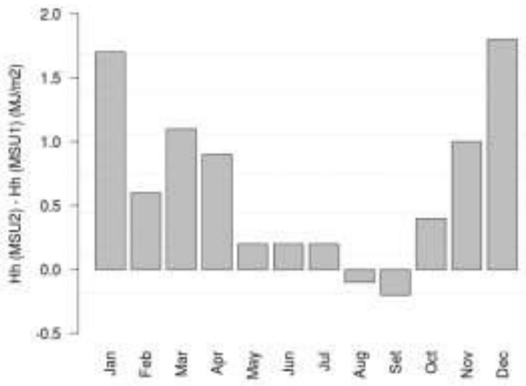


Fig. 4: Left panel: monthly average daily GHI (average of twelve sites) for MSU1 model compared to this work. Right panel: monthly mean deviates for GHI (MSU2 – MSU1) averaged over twelve sites.

4.3 Comparison with independent long-term ground data.

We compare the modeled monthly means for global irradiation on a horizontal surface generated for the three sites indicated as VAL in Table 1, for which we have medium and long term data of good quality. The indicators are shown in Table 4. The overall relative Mean Bias Deviation less that 1 % and the overall relative RMSD is 3.2 %. The monthly deviations are shown in Fig. 5.

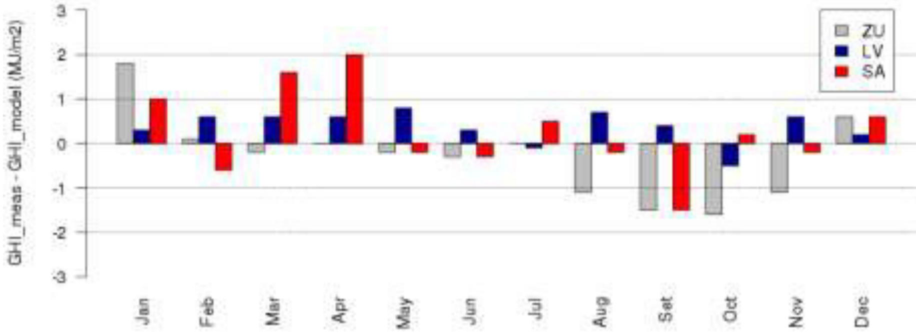


Fig. 5: Absolute deviations in MJ/m^2 between ground measurements and modeled values for daily global irradiation on a horizontal plane defined as GHI (measured) – GHI (modeled).

Table 4. Indicators for the comparison between ground data from the VAL sites indicated in Table 1 and estimates (taken as reference values) and the present model..

Ground Site	Mean (MJ/m^2)	RMSD (MJ/m^2)	rRMSD (%)	MBD (MJ/m^2)	rMBD (%)
ZU	**16.9**	1.0	5.7	-0.3	-1.7
LV	**16.5**	0.5	3.0	0.4	2.2
SA	**16.9**	0.9	0.9	0.3	1.5
Mean	**--**	**0.8**	**3.2**	**0.1**	**0.7**

5. Conclusions and Discussion

A recently developed (improved) version of Tarpley's statistical model has been used, together with a 13-year set of GOES satellite visible channel reflectance factor images, to generate hourly estimates of global horizontal irradiation on a 10'x10' minute grid. The model was adjusted to good quality data from three ground stations operated by our group. The hourly estimates where used to produce monthly averages of daily means over the territory of Uruguay and neighboring areas with a spatial resolution of about 20 x 20 km.

A comparison with the monthly average irradiation from the NASA/SSE model on a uniformly spaced grid of 1^o x 1^o shows a relative RMSD of 1.3 % and a relative Mean Bias deviation of 1 % relative the reference average of 16.6 MJ/m^2. These indicators suggest that the methodology is applicable and meaningful long-term information can be retrieved from satellite images even at southern latitudes in Latin America, where many images are missing due to operational issues with the satellite. A second comparison against independent (not used to train the model) long and medium-term ground data shows a relative RMSD of 3.2 % and a relative Mean Bias deviation of less that 1 %, provides further evidence of the model's performance.

When compared to the first Solar Map (MSU1) available for Uruguay, this preliminary results indicate that the solar resource is up to 7 % higher than the previous estimates based on sunshine hour records, depending on the month of the year. The overall relative RMSD between MSU2 and MSU1 estimates is 6 %. This satellite-based methodology provides a substantial improvement of an order of magnitude in spatial resolution over the MSU1, which was 100 km in the previous map and is 20 km in the MSU2. The temporal resolution is also increased substantially, since the MSU1 methodology was based on the Angström-Prescott correlation, and this can only provide monthly means. The current model (MSU2) generates irradiation estimates on an hourly basis, so that temporal resolution is increased from monthly to hourly. This is a preliminary report on the results of this satellite-based statistical model and further analysis is required in order to identify at which sites both models differ most. Work is now under progress in order to use the same information base (ground data + satellite images) with a suitable physical model to generate hourly irradiance at ground level.

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