Proceeding Paper

Statistical Correction of the Distribution of Solar Radiation, Estimated by the Heliosat Method for Cuba †

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Abstract: In this work, a statistical correction of the distribution of solar radiation in Cuba estimated by the Heliosat method is obtained, using the images collected from the GOES-13 satellite, for the period 2012–2017. The need arises for an improvement in the update of the distribution of solar radiation in the country, because when the average annual maps of solar radiation estimated by the Heliosat method are compared with data from stations where solar radiation is measured and also, when compared with the Annual Average Map of solar radiation, published by the firm Solargis, a certain overestimation of the solar radiation values is noted, as if the effect of cloud cover attenuation, as calculated by Heliosat, were less than the effect of real cloud attenuation. Therefore, it is necessary to improve the updating of the behavior of solar radiation in Cuba due to the marked relevance of this information as a renewable source of energy and also due to its use in the evaluation of the country's helioenergetic potential.

Keywords: Heliosat; solar radiation; statistical correction; satellite

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1. Introduction

In Cuba, a project was carried out in 2018, in which the characterization of solar radiation in Cuba is presented from the visible images of GOES-13, using the method known by Heliosat-2, adapted to visible images of this satellite during the period 2012–2017. The most conveniently located geostationary satellite, for the selected study period and for our geographical location, is the one mentioned above, this has been the source of images used in the development of the research, taking advantage of an existing file in the INSMET (Institute of Meteorology of Cuba), of GOES images, with a temporal frequency of approximately 15 minutes, which covers from the year 2012 to the end of the year 2017. From each daytime image, the corresponding radiation map is calculated, estimated by the Heliosat method. In a very general way, it is a method that allows calculating the distribution of solar radiation in a region (W/m^2), using information from a visible satellite image. In the research carried out by Borrajero; Peláez and Hinojosa [1], the monthly average maps and the annual average map of solar radiation were prepared and the results obtained were validated with data from automatic stations. At the same time, when the values of the maps made, are compared with data from stations where solar radiation is measured and also compared with the Annual Average Map of solar radiation, published by the firm Solargis, a certain overestimation of the values of solar radiation is noted, as if the cloudiness attenuation effect, as calculated by Heliosat, were less than the actual cloudiness attenuation effect, therefore it is necessary to improve the updating of the behavior of solar radiation in Cuba, due to the marked relevance of this information as a renewable source of energy and also for its use in the evaluation of the helioenergetic potential of Cuba [2].

This type of systematic error is very common in different estimation or forecasting methods, and the practical solution is the elaboration of statistical correction methods, as is the main objective of this research, said correction is implemented to the solar radiation maps, elaborated with the Heliosat method, using the saved satellite images of the GOES-13. To make the correction, at first, it is necessary to calculate the daily radiation sums, adding the values every fifteen minutes, for each day and for each selected station, through the use of scripts, written in the Python programming language, then the values estimated by the method are compared with real data measured at the selected stations, which have quality measurements and good calibration. Being able to establish a functional relationship between what the stations measure and what the Heliosat method estimates, this dependency is applied to the estimates and, rectified values of the estimated values are obtained. In the work presented by Borrajero; Peláez and Hinojosa **[1]** the calculation of the solar radiation was made for each image of the daytime period for the entire interval, and from these, the hourly means, the daily sums and the monthly and annual mean values were calculated, this research is the basis of this work. The maps obtained by Borrajero; Peláez and Hinojosa [1] reflect the main characteristics of the behavior of the variable in question, an increase in solar radiation is observed towards coastal regions and areas of keys and also a decrease in mountainous regions (Figure 1). The behavior throughout the year shows a double maximum in the months of May and July, with a slight decrease in June [1].

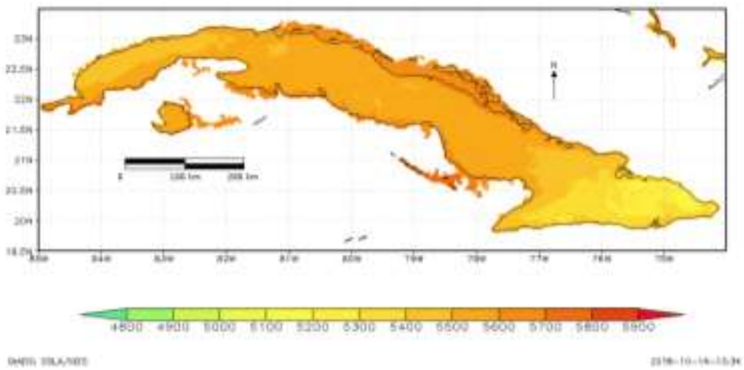


Figure 1. Annual mean map of global solar radiation **(**Wh/m^2**).**

2. Methods

2.1. Description of the Heliosat Method

The method used to estimate the solar irradiance on earth is the Heliosat-2, this method was originally developed for the visible images of the Meteosat geostationary satellite, which makes it unusable in our region, therefore, the satellite used in question is: GOES-13. From the files obtained for the daily sum by the Heliosat method, which are maps with a resolution of 1 km^2, the values corresponding to the positions of the stations are extracted. The tuning of the Heliosat-2 method for GOES-13 was carried out using the public information available on the technical specifications of this satellite and the work carried out by Borrajero; Peláez and Hinojosa [1], its evaluation was carried out against reports of hourly and daily sums of a group of automatic meteorological stations of the INSMET network for the years 2014 and 2015. In the implementation of the Heliosat-2 method for the GOES-13 satellite, the conversion relationship between pixel values and reflectance and the time variation of the radiometer calibration constant (ageing) typical of this satellite were taken into account. The modifications made include a change in the calibration formula and in the calculation of cloud albedo [3,4]. After pairing the daily sum data at the stations with the values calculated at those positions by Heliosat, the regression equation is calculated.

2.2. Obtaining the Regression Equation

The adjustment function proposed in the research is a second degree equation, Figure 2. This figure corresponds to the behavior of the error depending on the values estimated by Heliosat, an error that each estimated value must have with respect to the reported data. The predominance of cases of overestimation of global solar radiation can be seen, which reflects a marked insufficiency in the implementation of the method for the selected study area, where the cloudiness index calculated by said method does not modulate with sufficient precision, the global radiation calculated by the clear sky model. For the highest estimated daily sum values, corresponding to days that were mostly clear, the calculated error tends to decrease in that environment, as is clearly reflected in the adjustment obtained. This situation, that the calculated errors are maximum when the values of the daily sum of estimated solar radiation are around 7000 $\mathrm{Wh/m^2}$ and that they decrease both for the highest values of estimated global radiation, and for the lowest values of radiation, justifies in this research the use of a quadratic fit as more suitable for the correction than the use of a linear fit.

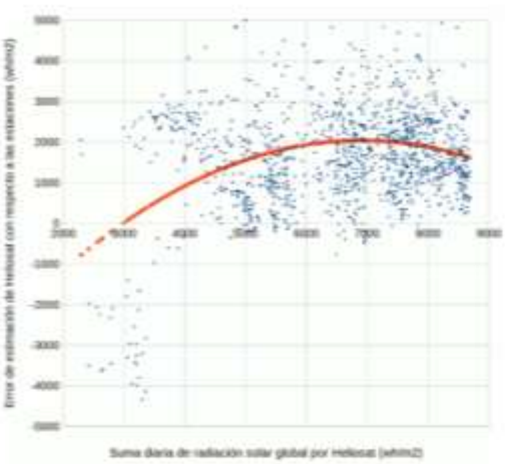


Figure 2. Error distribution (Heliosat–Stations) based on the value estimated by Heliosat and the adjusted second degree equation.

The equation has the form:

$$\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x}^2 + \boldsymbol{B}\boldsymbol{x} + \boldsymbol{C} \tag{1}$$

where, $\boldsymbol{y}$: Estimation of the error of the Heliosat method with respect to the values reported in the stations; $\boldsymbol{x}$: Daily sum value of solar radiation estimated by the Heliosat method; A: Quadratic coefficient = $-1.32914995491533 * 10^{-4}$; B: Linear coefficient = 1.83384712813072 and C: Independent term = $-4.28220731194757 * 10^{3}$.

2.3. Description of the Adopted Programming Language and Employed Statisticians

Obtaining the new Heliosat maps, applying the correction to them, is done with a set of scripts developed in the Python programming language. In the calculations, the Python language was used, with a set of general modules that are normally included, such as "numpy", "math", "datetime", "PIL", Python Image Library, for the reading of the images of the GOES in format tiff and "matplotlib". Specialized modules were also used, such as "ESRA", which implements the calculation of solar radiation fluxes under clear skies according to the methodology of the European Solar Radiation Atlas (ESRA), "daily_LINKE", which allows obtaining the index of Linke, of turbidity of the air according to the geographical position and the time of the year and "SatCoords", for the georeferencing of the images of the GOES satellite.

Employed statisticians:

• Bias: • Correlation: • Dispersion: [5]

$$\boldsymbol{BIAS} = \frac{\boldsymbol{\Sigma_i (y_i - x_i)}}{\boldsymbol{n}} \tag{2}$$

$$\boldsymbol{r} = \frac{\boldsymbol{\Sigma (x_i - \overline{x})(y_i - \overline{y})}}{\sqrt{\boldsymbol{\Sigma (x_i - \overline{x})^2 \Sigma (y_i - \overline{y})^2}}} \tag{3}$$

$$\boldsymbol{\sigma} = \sqrt{\frac{\boldsymbol{\Sigma_i^N \left(X_i - \overline{X}\right)^2}}{\boldsymbol{N}}} \tag{4}$$

3. Results and Discussion

3.1. Selection of Stations and Comparison of Estimated and Reported Global Radiation Values

Of the set of automatic stations that were installed in the 2014–2015 period, a selection was made based on a comparison between the reported data and the output data of the WRF model, under clear skies. The WRF model simultaneously returns the value of solar radiation before a clear sky and the value of "real" radiation, which in addition to depending on the previous elements, includes the effect of cloudiness, as the model develops it. When there is a very high correlation for one day between the hourly summation data of solar radiation reported at a station and the model′s clear-sky solar radiation data; this high correlation means that it is a really clear day and in that case the daily sums of solar radiation of the station and the model must coincide very closely. This proposed analysis does not occur on days with cloudy intervals, because the cloudiness predicted by the model does not exactly coincide with the actual cloudiness and this introduces an additional error to the analysis. In the cases of clear days, the presence of a significant difference between the values of the daily sums of the model and the values reported in the station, can be interpreted as a problem of the station considered in question. In this way, the appropriate stations for the study are selected.

The daily sum value used is obtained by integrating the values estimated by the method throughout the daytime period. On the other hand, automatic actinometric stations report instantaneous values, with an original frequency of 1 minute, at the position of the station in question. The daily sum in this case is obtained in the same way by integrating the reported values over time. To know the values of the maps generated by Heliosat, in the position of the stations, an interpolation of the values in their positions is performed, using the nearest neighbor interpolation criterion. The following Table 1 shows a fragment of the list of values of daily sums of global solar radiation by days and by seasons, values reported at the station against values estimated for that point by Heliosat.

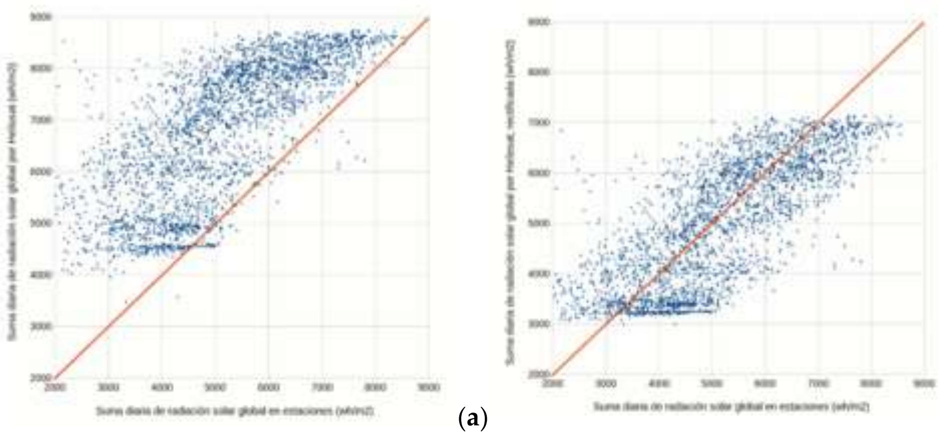
Station Name	Date	Station Value	Heliosat Value	Variance
Bahia Honda	2015-12-26	3506	4526	1020
Bahia Honda	2015-12-27	3808.3	4505	696.7
Bahia Honda	2015-12-28	4362	4567	205
Bahia Honda	2015-12-29	3971	4563	592
Bahia Honda	2015-12-30	4016.7	4577	560.3
Bahia Honda	2015-12-31	4081.2	4562	480.8

Table 1. List of daily sum values of global solar radiation reported at the stations and estimated by Heliosat (Wh/m^2).

Once the list of simultaneous values is obtained (a list for each station), it is separated into two samples, the days between the first and the tenth of each month constitute the sample with which the calculation of the adjustment function is made, between the difference or error (Heliosat–stations) and the values estimated by the Heliosat method. This error is important to know it, to know to what extent the estimate is different from the real value reported. The other sample (it is made up of the days between the 11th and the end of each month) will not be included in the adjustment obtained and will only be used as an independent sample, to evaluate it. The fit obtained had a coefficient of determination of 0.64407 and a standard error of 1335.4.

3.2. Analysis of the Rectified Values

By subtracting the error estimated by the adjustment Equation (1) from the value produced by Heliosat, a better approximation of the results to the values reported at the stations is obtained, as can be seen in Figure 2. This evaluation of the adjustment obtained is carried out using the data of the selected independent sample, corresponding to days eleven until the end of each month.



(**a**) (**b**)

Figure 2. (**a**) Dispersion diagram for the independent sample of the daily sum values of global solar radiation estimated by Heliosat and reported at the stations, the values are shown without rectification. (**b**) Dispersion diagram for the independent sample of the daily sum values of global solar radiation estimated by Heliosat and reported at the stations, the rectified values are shown.

From this comparison it is observed to what extent the error (deviation) of the sample decreases, it can also be seen how the rectified estimated values approximate with greater precision the slope $y = x$. The values of the statisticians calculated for the original estimate with Heliosat and for the rectified estimate (independent sample) are: for Heliosat method the correlation is = 0.681; standard error = 1225.3 and bias = 1795.0; but for Heliosat method rectified the correlation is = 0.685; standard error = 1196.6 and bias = 6.170. The improvements in the correlation and the standard error are marginal, as can be seen, which is explained by the way of conceiving the adjustment obtained, grouping all the stations and dates. The values of these statisticians are influenced by the fact that there are a number of cases where the values of the stations are incorrect. The main benefit of this research lies in the considerable reduction in the bias value obtained, which is very useful in rectifying the maps.

3.3. Comparison of Annual Maps

When comparing the average annual global solar radiation maps estimated by the Heliosat method, Figure 1 and Figure 3, the latter (Figure 3), shows the global solar radiation map, once rectified with the adjustment obtained in the investigation. It can be seen that the main characteristics of the distribution of solar radiation in Cuba are maintained, that is, an increase for coastal areas and keys and a decrease in mountainous regions. The greatest difference in the maps lies in the appreciable decrease in the distribution of the values estimated by the method in the rectified annual average map, where the negative variation of the values of solar radiation is observed, compared to the distribution of the values of the annual average map of global solar radiation, without rectification.

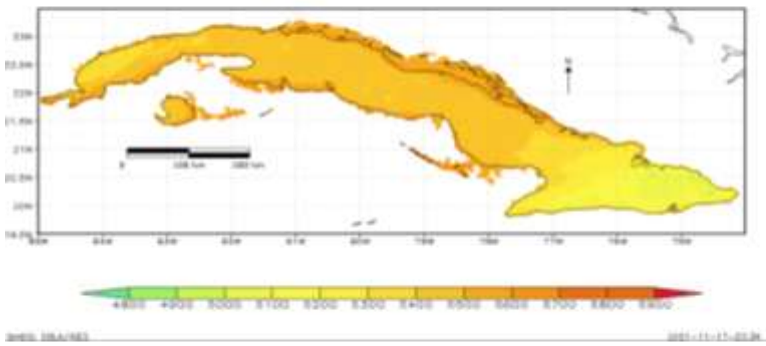


Figure 3. Annual mean map of global solar radiation rectified.

4. Conclusions

Taking into account the behavior of the error depending on the Heliosat values, the appropriate regression equation was obtained, thus achieving a better fit of the function. With the application of said adjustment, it was possible to appreciate the predominance of cases of overestimation, which reflects an insufficiency in the implementation of the method, where the calculated cloudiness index does not modulate with sufficient weight the radiation calculated by the clear sky model. By subtracting the error estimated by the regression equation from the value produced by Heliosat, a better approximation to the values reported at the stations is obtained.

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