



Assessment of surface solar irradiance retrieved by CERES

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ABSTRACT

This study compared and evaluated the monthly global solar radiation generated by Clouds and the Earth's Radiant Energy System (CERES) with the surface radiation registered in 232 meteorological stations located in whole Spain, for the period of July 2006–July 2015. Results showed strong correlations between CERES and registered data with R^2 values greater than 0.96, for all stations considered. When the temporal evolution of recorded and provided by CERES solar radiation was analysed, a systematic overestimation by CERES was detected from July 2011, although the shapes of both curves were respected in the whole period. This finding led us to propose a linear adjustment model since July 2011. After applying the developed model to rescale CERES data for the whole period, an improvement in solar radiation fit was observed. Our finding offers an insight into error patterns of CERES solar radiation, since July 2011, and proposes a model for improving accuracy allowing therefore a reliable use of this product. Moreover, our study on radiation data of Spain provides a case example for worldwide validation.

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1. Introduction

Solar radiation is the most important source of renewable energy on the planet. Global solar radiation is an important variable for a wide range of applications in meteorology, hydrology, crop simulation models, estimation of crop evapotranspiration and renewable energy. In Spain, the potential for solar energy is massive, determined by the level of solar irradiation; and also is a determinant element for climate change. The increase in solar energy applications is making it necessary to study solar radiation related to improving production and system efficiency (Alonso-Montesinos, Batlles, and Bosch 2015; Girard et al. 2016). Hence, accurate estimation of the global solar radiation is also an important input for many crop growth models, which are primarily based on the photosynthetic processes and use radiation and its conversion into chemical energy, determining irrigation water needs and potential yield of crops (Mariscal, Orgaz, and Villalobos 2000; Almorox, Bocco, and Willington 2013; Zhang et al. 2015).

The acquisition and recording of solar radiation series is not simple, although its importance is recognized. Its measurement requires the use of specific equipment, such

as pyranometers and pyrheliometers, which have expensive requirements of maintenance and calibration. As indicated by Will et al. (2013) solar radiation is one of the climatic variables whose lack of data is quite generalized in quantity and quality. Moreover, even in the cases where solar radiation is measured, an organization does not always exist to centralize this information, verify its consistency and calibrate the sensors regularly.

In the absence of solar radiation records, several methods have been developed to estimate the solar radiation based on available measured meteorological variables. In the literature a number of empirical models, statistical approaches coming from time-series analysis, and soft-computing techniques, have been applied to estimate the global solar radiation. Solar radiation can be easily estimated from sunshine duration (Prescott 1940); therefore, these models have been widely applied. However, sunshine and cloudiness data are not available in most of the meteorological stations. For this, daily solar radiation estimation models based on geographical location, air temperature, relative humidity, precipitation and wind speed and direction, which are available at the great majority of the stations, are viable options (Hargreaves and Samani 1982; Bristow and Campbell 1984). On the other hand, solar radiation can be estimated with soft-computing techniques. These set of techniques are within the framework of artificial intelligence that has received much attention as feasible methods for dealing with practical problems (Gopalakrishnan, Khaitan, and Kalogirou 2011; Sayago et al. 2011).

As Journée and Bertrand (2010) indicate, the availability solar radiation measurements are spatial and temporarily inadequate, therefore, the Earth's images taken by polar-orbiting and geostationary satellites for mapping of the global irradiation impinging on a horizontal surface at the ground improve the spatial-temporal resolution of the surface global solar radiation data. Mapping solar radiation over an area is fundamental for exploring the solar energy potential and analysing the spatial variability. Due to unavailability of a dense database, solar radiation maps may be designed using satellite data that are used for mapping global solar radiation at regional to global scales (Alonso-Montesinos, Batlles, and Bosch 2015).

The remote sensing products provide a form to obtain information of global radiation with temporal continuity and spatial homogeneity (Liang 2005; Liang et al. 2010; Zhang et al. 2014). The first operational meteorological Television Infrared Observation Satellite (TIROS-1), launched on 1960, provided four years of Earth radiation budget data (Kondratyev and Varotsos 1995). At the end of the past century, several authors (Tarpley 1979; Gautier, Diak, and Masse 1980) for regions of the USA verified that physical and statistical models estimated radiation data from satellite Geostationary Operational Environmental Satellite (GOES) with accuracy more than sufficient for most agricultural uses. Masuda (2004) compared the monthly mean downward surface solar radiation products from the Global Energy and Water Cycle Experiment Surface Radiation Budget (GEWEX-SRB), International Satellite Cloud Climatology Project (ISCCP-FD), and the University of Maryland Surface Radiation Budget for Asia and Oceania, and found that the three products showed similar agreement with *in situ* measurements except for the Tibetan Plateau. Jia et al. (2013) evaluated and compared the solar radiation data from the Fengyun-2 series (FY-2 C) and Fast Longwave and Shortwave Radiative Fluxes (FLASHFlux) of National Aeronautics and Space Administration (NASA) satellite products and datasets using surface *in situ* observations and they quantified and

investigated the spatial and seasonal variations over East Asia. Chen, Zhuang, and He (2014) developed a method to estimate the global-scale total, direct, and diffuse solar radiation using Moderate Resolution Imaging Spectroradiometer (MODIS), for the period 2003–2011, in 48 Baseline Surface Radiation Network sites.

For Spain, López and Batlles (2014) presented a parametric model to estimate the global solar radiation under cloudless conditions, considering as input only atmospheric precipitable water vapour content derived from the MODIS sensor. Polo (2015) described the methodology developed for deriving solar radiation incident components from geostationary satellites, and for mapping the global horizontal and direct normal irradiation components. In particular, he applied this methodology to Meteosat satellites images and generated solar radiation maps of Spain for the period of 2001 to 2011. Recently, Sancho et al. (2012) released an atlas for providing monthly, seasonal and annual average of global, direct and diffuse radiation on the horizontal plane using monthly data sets from 1983 to 2005, from Climate Satellite Application Facilities (CM-SAF). In the work of Alonso-Montesinos, Batlles, and Bosch (2015), the authors presented a solar radiation estimation using Meteosat second Generation MSG images; and in the Mediterranean area, solar models were also recalibrated using aerosols optical depth and ozone column from MODIS and Ozone Monitoring Instrument (OMI), (Bilbao et al. 2015).

Owing to the importance of the role of product data from Clouds and Earth's Radiant Energy System (CERES) to understand climate change, different studies were recently developed to evaluate the parameters of CERES on all types of surfaces matching ground-based observations (Zhang et al. 2014; Yan et al. 2011; Krishna, Manavalan, and Rao 2014; Pan, Liu, and Fan 2015).

The objective of this article was to compare and evaluate the global solar radiation generated by CERES with the surface radiation registers, for different meteorological stations located in Spain. The final aim was to validate the information of CERES derived products for use in regions where meteorological information is not available.

2. Materials and methods

2.1. Study area and meteorological data

In this article, we considered registers of daily global solar radiation from 232 meteorological stations in Spain, which belong to eleven autonomous communities (Table 1 and Figure 1). The radiation data were collected using two different pyranometers (Kipp @ Zonen and Campbell Scientific-Skye), and they were registered by the Spanish National Agro-climatic Information System for Irrigation SIAR (Ministry of Agriculture, Food and Environment of Spain). The regional governments maintain the stations, and all parameters were checked, and the sensors were periodically calibrated for quality control. The registers were obtained on the scale of the day, and they were monthly averaged, in the period from July 2006 to July 2015 (for Catalonia the period began on January 2007). In this study, quality control procedure was implemented, particularly an assessment based upon physical limits using the

Table 1. Spain communities and number of stations by province used in this study.

Autonomous community	Province	Number of stations
Andalusia	Almería	4
	Cádiz	5
	Córdoba	5
	Granada	5
	Huelva	5
	Jaén	6
	Málaga	5
	Sevilla	6
Aragon	Huesca	10
	Teruel	6
	Zaragoza	9
Castile-La Mancha	Albacete	7
	Ciudad Real	6
	Cuenca	7
	Guadalajara	4
Castile and León	Toledo	7
	Ávila	1
	Burgos	5
	León	9
	Palencia	6
	Salamanca	1
	Segovia	2
	Soria	4
	Valladolid	8
	Zamora	5
	Catalonia	Barcelona
Gerona		4
Lérida		12
Tarragona		7
Extremadura	Badajoz	7
	Cáceres	7
Galicia	A Coruña	2
	Lugo	2
Community of Madrid	Madrid	7
Region of Murcia	Murcia	9
Navarre	Navarra	7
Valencian community	Alicante	6
	Castellón	6
	Valencia	8

atmospheric daily clearness index (Khorasanizadeh and Mohammadi 2013; Linares-Rodriguez et al. 2013).

2.2. CERES data

The datasets used in this work were obtained from CERES (http://neo.sci.gsfc.nasa.gov/view.php?datasetId=CERES_INSOL_M), which were produced, archived, and made available to the scientific community by the Langley Research Center (LaRC), the Atmospheric Sciences Data Center (ASDC), and the National Aeronautics and Space Administration (NASA) by the FLASHFlux project (<http://flashflux.larc.nasa.gov/>). FLASHFlux data are produced using CERES observations convolved with MODIS measurements from both the Terra and Aqua satellite. This project uses the CERES instrument as principal information, which operates in various NASA satellites. CERES has three channels, one short wave measuring reflected sunshine in the region from 0.3 to

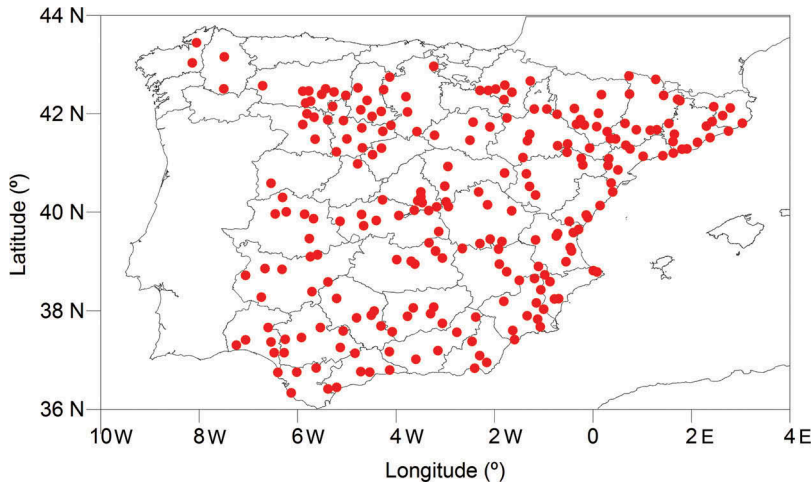


Figure 1. Site location within the Spain territory of global solar radiation measurements stations used in the study.

5.0 μm , another measurement of thermal radiation emitted by the Earth, between 8.0 and 12.0 μm , and a third, which accounts for the full spectrum of outgoing radiation from Earth. The spatial and temporal resolutions of the product used in this study were 0.25° latitude/longitude and monthly, respectively. Further details about the algorithms and data processing are described in the work of Pan, Liu, and Fan (2015).

2.3. Metrics for accuracy assessment

To evaluate the accuracy of solar radiation values provided by CERES with those recorded at meteorological stations, the coefficients of determination (R^2), root mean square error (RMSE), and the average difference between both values (Bias) were calculated. In addition, linear regression and scatter plot approach was designed. RMSE represents the sample standard deviation of the differences between pixel and observed values, and Bias quantifies the average of the difference between surface observations and pixel values. The indices used are defined as follows:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^N (R_{s,\text{reg},i} - R_{s,\text{sat},i})^2}{N}}, \quad (1)$$

$$\% \text{RMSE} = \frac{100}{\overline{R_{s,\text{reg},i}}} \sqrt{\frac{\sum_{i=1}^N (R_{s,\text{reg},i} - R_{s,\text{sat},i})^2}{N}}, \quad (2)$$

$$\text{Bias} = \frac{1}{N} \sum_{i=1}^N (R_{s,\text{reg},i} - R_{s,\text{sat},i}), \quad (3)$$

where $R_{s,reg}$ is the mean monthly registered global solar radiation ($W m^{-2}$); $\overline{R_{s,reg}}$ is the average mean monthly registered global solar radiation ($W m^{-2}$); $R_{s,sat}$ is the mean CERES solar radiation ($W m^{-2}$), and N is the observations number.

3. Results and discussions

The values of minimum and maximum horizontal global solar radiation recorded for each autonomous community, considering all analysed period (July 2006–July 2015), are presented in Table 2.

If the stations are grouped latitudinally, the most extreme recorded values belong to the stations located further north (Galicia), following the influence of the annual variation of solar declination (Kiehl and Trenberth 1997). The stations located further south (Andalusia) have the highest minimum values of radiation for the entire study period. This radiative gradient towards the South significantly accentuates in the mountainous regions with predominantly east-west orientation. It is the remarkable case of the Cantabrian Mountains and Pyrenees, registering in these mountains a sharp radiative contrast between the regions of the north with those of the south (Sancho et al. 2012).

The values minimum and maximum of R^2 , obtained for CERES and recorded global solar radiation, exceeded for all stations covering the entire Spanish territory the value of 0.88, with the exception of the region of Andalusia (Table 3).

Table 2. Values of minimum and maximum monthly solar radiation recorded by community for period July 2006–July 2015.

Autonomous community	Registered solar radiation ($W m^{-2}$)	
	Minimum	Maximum
Andalusia	67.54	373.32
Aragon	44.55	343.89
Castile-La Mancha	49.38	365.97
Castile and León	37.36	376.04
Catalonia	49.06	342.90
Extremadura	41.92	372.19
Galicia	32.41	287.68
Community of Madrid	53.69	359.67
Region of Murcia	51.56	353.72
Navarre	44.48	332.48
Valencian community	59.58	339.12

Table 3. Determination coefficients for different autonomous communities (Spain) for period July 2006–July 2015.

Autonomous community	Minimum R^2	Maximum R^2
Andalusia	0.83	0.96
Aragón	0.91	0.95
Castile-La Mancha	0.88	0.97
Castile and Leon	0.89	0.95
Catalonia	0.88	0.95
Extremadura	0.88	0.97
Galicia	0.94	0.95
Community of Madrid	0.92	0.95
Region of Murcia	0.87	0.94
Navarre	0.93	0.96
Valencian community	0.90	0.96

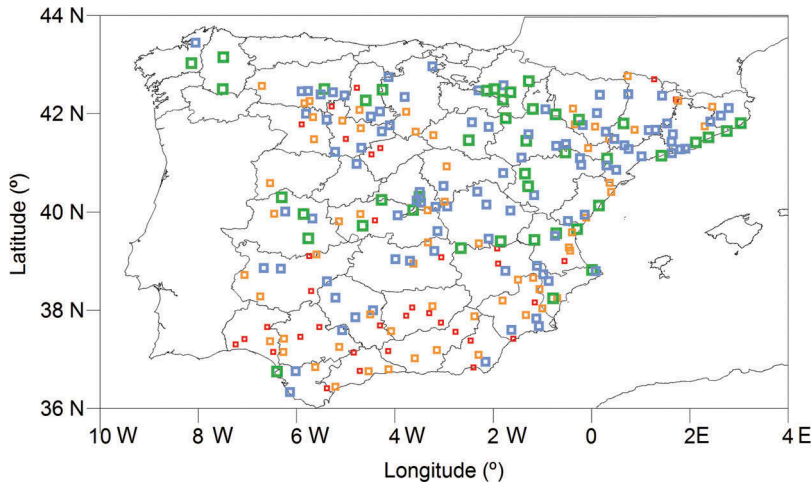


Figure 2. Determination coefficients between global solar radiation from CERES and recorded for Spain stations, for period July 2006–July 2015. (In red $R^2 < 0.90$; orange $0.90 \leq R^2 < 0.92$; blue $0.92 \leq R^2 < 0.94$ and green $R^2 \geq 0.94$).

Figure 2 shows the spatial distribution of the R^2 values, clustered in 4 intervals. The range of values obtained in this work for this coefficient of determination, is similar to that presented by Pan, Liu, and Fan (2015). These authors reported an average value of $R^2 = 0.77$ with values between 0.54 and 0.95, using solar radiation from CERES in the period March 2000 to December 2007, for 50 stations distributed in China.

The best R^2 values were observed in the central-north region of Spain, however when analysing RMSE statistic, different situations were found (Figure 3). Higher RMSE values were mostly presented in stations located at the coastal zone, which had also been

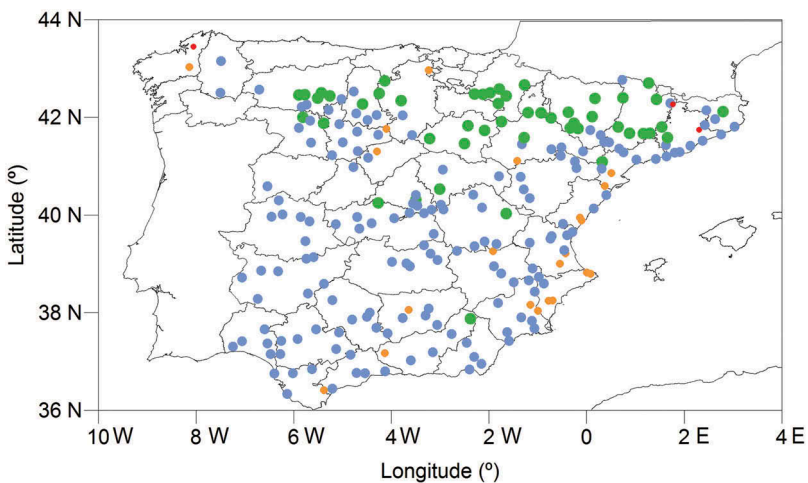


Figure 3. Root mean square error (RMSE) between solar radiation from CERES and recorded for Spain stations, for period July of 2006–July 2015. (In red $RMSE \geq 49.5 \text{ W m}^{-2}$; orange $39 \text{ W m}^{-2} \leq RMSE < 49.5 \text{ W m}^{-2}$; blue $28.5 \text{ W m}^{-2} \leq RMSE < 39 \text{ W m}^{-2}$ and green $RMSE < 28.5 \text{ W m}^{-2}$.)

observed by Pan, Liu, and Fan (2015) in China. A similar situation was reported by Sancho et al. (2012) who compared solar radiation data from National Radiometric Network of Spain and from Climate Satellite Application Facilities (CM-SAF) founding that the error increased for stations located at lower latitudes. This behaviour would be attributed to a possible underestimation of the amount of water vapour and/or aerosol with consequent overestimation in the value of observed solar radiation.

In Table 4, values of RMSE and Bias are presented; these statistics were obtained for CERES and recorded solar radiation relation, for all stations covering the entire Spanish territory. These values are similar to those pointed out by Pan, Liu, and Fan (2015), who showed RMSE values of monthly global solar radiation greater than 20 and 40 $W m^{-2}$, for mountain and coastal sites, respectively.

When the temporal evolution of recorded and provided by CERES solar radiation was analysed, for all stations considered in this work, regardless the coefficient of determination and geographic location, a systematic overestimation by CERES was detected from July 2011. As an example, Figure 4 shows the temporal evolution of global solar radiation, corresponding to twelve stations located at the north (Tordesillas, Fraga, Banyoles, Boimorto), center (La Rinconada, Herencia, Chinchón, Villa del Prado), and south (Jimena de la Frontera, Málaga, Corvera, Crevillente) of Spain, considering the same partition of intervals for R^2 described in Figure 2.

It is important to note that, although a difference between recorded radiation and the derived from CERES was observed, the shapes of both curves (radiation in different months of the year) were respected in the whole period.

Overestimation of the values of solar radiation by CERES regarding the observed was confirmed when RMSE values were evaluated for two periods: July 2006–June 2011 and July 2011–July 2015 (Table 5). This statistic presented, for the first period, values significantly lower than those obtained for the last five years (Figures 5 and 6).

Table 5 shows, for each autonomous community, the average values of RMSE and Bias for the two periods considered in Figures 5 and 6. An important difference between the two periods was observed for both statistics. The values corresponding to July 2006–June 2011 are comparable with those reported by Zhang et al. (2015). These authors informed, for 1053 stations covering the entire planet, $RMSE = 18.8 W m^{-2}$ and $Bias = 5.01 W m^{-2}$.

Galicia was the only community that presented higher values than the others, although those were in the order of other works, such as Jia et al. (2013) who, for

Table 4. Root mean square error (RMSE) and Bias for different autonomous communities, for period July 2006–July 2015.

Autonomous community	RMSE ($W m^{-2}$)	Bias ($W m^{-2}$)
Andalusia	34.69	17.21
Aragón	28.74	13.03
Castile-La Mancha	32.56	16.55
Castile and León	30.73	12.20
Catalonia	31.68	17.96
Extremadura	34.00	19.13
Galicia	41.90	34.54
Community of Madrid	29.59	16.60
Region of Murcia	36.10	20.49
Navarre	21.34	4.34
Valencian community	37.58	27.76

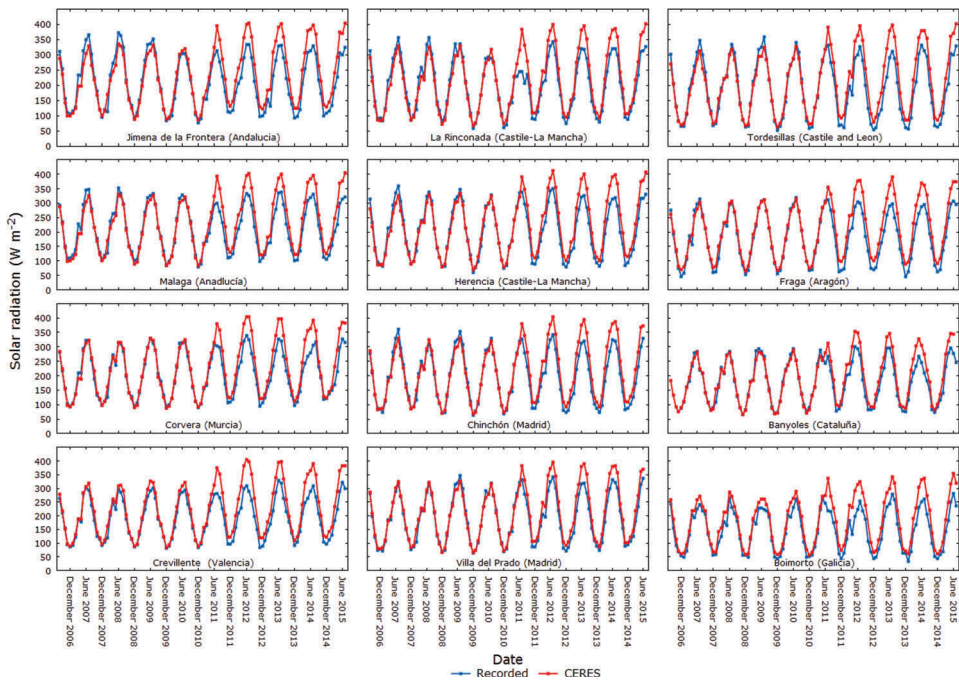


Figure 4. Temporal evolution of CERES and recorded global solar radiation, for different locations and R^2 values. Selected stations of Spain, for period July 2006–July 2015 (from top to bottom are stations with coefficients $R^2 < 0.90$; $0.90 \leq R^2 < 0.92$; $0.92 \leq R^2 < 0.94$ and $R^2 \geq 0.94$, respectively).

Table 5. Average RMSE and Bias for different autonomous communities, for two periods from July 2006 to July 2015.

Autonomous community	July 2006–June 2011		July 2011–July 2015	
	RMSE ($W m^{-2}$)	Bias ($W m^{-2}$)	RMSE ($W m^{-2}$)	Bias ($W m^{-2}$)
Andalusia	18.20	−4.20	47.92	44.53
Aragón	15.34	−4.15	39.08	34.97
Castile-La Mancha	15.32	−3.50	45.82	42.16
Castile and León	18.75	−7.08	40.66	36.82
Catalonia	16.28	0.95	43.10	38.36
Extremadura	15.87	−0.72	47.89	44.43
Galicia	27.31	21.90	55.08	50.67
Community of Madrid	13.30	−0.52	42.14	38.70
Region of Murcia	20.58	2.43	48.68	43.55
Navarre	16.45	−9.69	25.56	22.06
Valencian community	17.86	9.01	53.04	47.38

solar radiation registered and produced by CERES in China, reported RMSE = $30.5 W m^{-2}$ and Bias = $19.5 W m^{-2}$.

For the period July 2011–July 2015, the high values of RMSE and Bias (Table 5), show the important difference between recorded and CERES solar radiation. For this, we propose an adjustment model since July 2011. The fitting linear equation obtained between the radiation values provided by CERES and the recorded (Figure 7) is

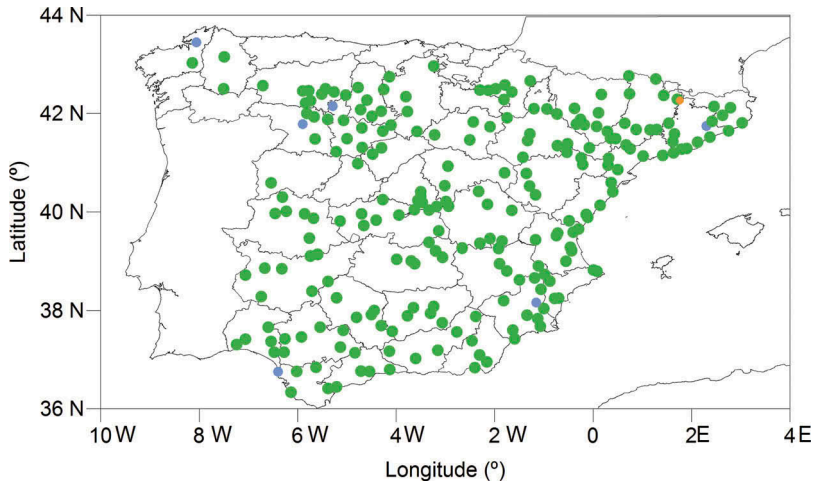


Figure 5. RMSE between solar radiation from CERES and recorded for Spain stations from July 2006 to June 2011. (In red $\text{RMSE} \geq 49.5 \text{ W m}^{-2}$; orange $39 \text{ W m}^{-2} \leq \text{RMSE} < 49.5 \text{ W m}^{-2}$; blue $28.5 \text{ W m}^{-2} \leq \text{RMSE} < 39 \text{ W m}^{-2}$ and green $\text{RMSE} < 28.5 \text{ W m}^{-2}$.)

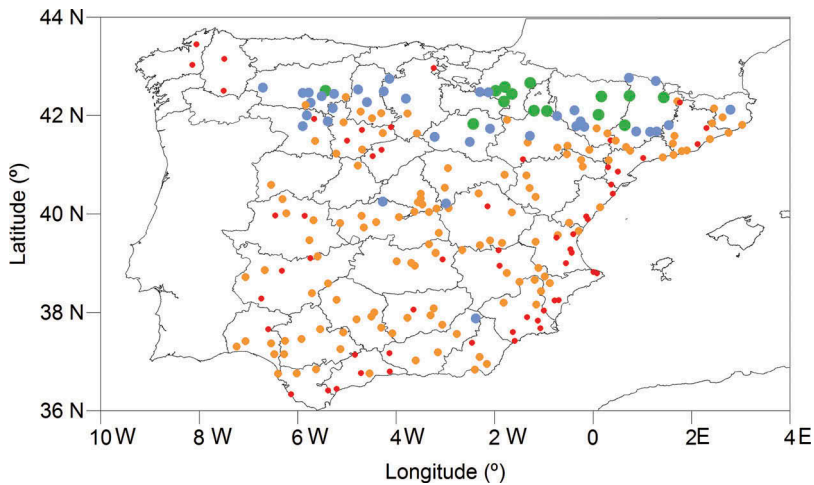


Figure 6. RMSE between solar radiation from CERES and recorded for Spain stations from July 2011 to July 2015. (In red $\text{RMSE} \geq 49.5 \text{ W m}^{-2}$; orange $39 \text{ W m}^{-2} \leq \text{RMSE} < 49.5 \text{ W m}^{-2}$; blue $28.5 \text{ W m}^{-2} \leq \text{RMSE} < 39 \text{ W m}^{-2}$ and green $\text{RMSE} < 28.5 \text{ W m}^{-2}$.)

$$R_{s,\text{sat}} = 1.164 R_{s,\text{reg}} + 7.985. \quad (4)$$

With this linear equation, a coefficient of determination R^2 equal to 0.978 was obtained. This systematic overestimation of CERES, since 2011, was not informed yet by other authors. In future work we will further investigate this behaviour in other locations.

Using the proposed model, new solar radiation from CERES values were scaled, for the period from July 2011 to July 2015 and the new RMSE values were calculated and presented in [Figure 8](#).

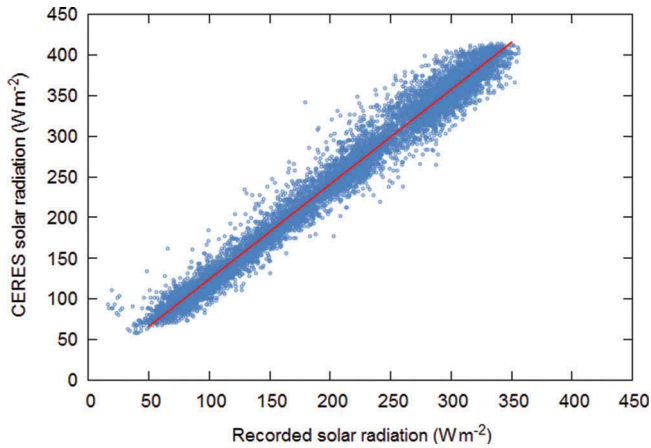


Figure 7. Scatter plot between recorded and CERES global solar radiation, for all stations in Spain, from July 2011 to July 2015.

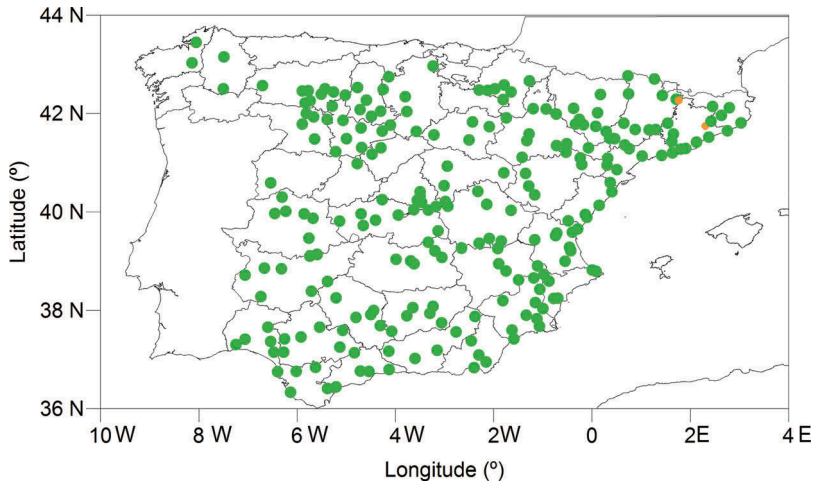


Figure 8. RMSE, between recorded and rescaled CERES solar radiation, from July 2011 to July 2015. (In red $\text{RMSE} \geq 49.5 \text{ W m}^{-2}$; orange $39 \text{ W m}^{-2} \leq \text{RMSE} < 49.5 \text{ W m}^{-2}$; blue $28.5 \text{ W m}^{-2} \leq \text{RMSE} < 39 \text{ W m}^{-2}$ and green $\text{RMSE} < 28.5 \text{ W m}^{-2}$.)

Using values reported by CERES, for the period July 2006–June 2011 and the rescaled values, from July 2011 to July 2015, the curves that show radiation temporal evolution were plotted again, for the same stations of Figure 4. An excellent fit between the measured and estimated solar radiation, can be observed (Figure 9).

The improvement in solar radiation fit observed in the 12 stations (Figure 9) also occurred in the remaining stations. This behaviour was validated by RMSE and Bias statistics, which were obtained for the whole period for each autonomous community, after CERES correction from July 2011 to July 2015 (Table 6).

After applying the model developed to rescale CERES data for the whole period, R^2 values increased ($R^2 > 0.95$ for all stations). These values are similar to those presented by

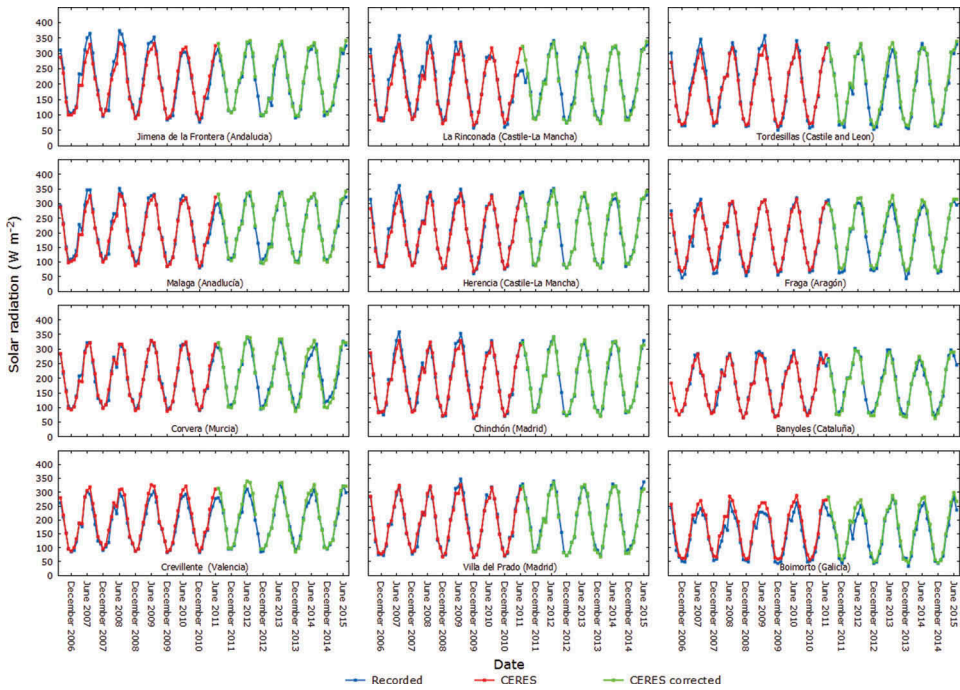


Figure 9. Temporal evolution of recorded solar radiation (whole period), and CERES values from July 2006 to June 2011 and rescaled CERES values, from July 2011 to July 2015.

Table 6. Average determination coefficient, RMSE, %RMSE, and Bias for different autonomous communities for period July 2006–July 2015.

Autonomous community	R^2	RMSE ($W\ m^{-2}$)	RMSE (%)	Bias ($W\ m^{-2}$)
Andalusia	0.97	15.18	7.23	-1.67
Aragón	0.98	14.13	7.41	-4.14
Castile-La Mancha	0.98	13.22	6.59	-1.62
Castile and León	0.98	16.42	8.78	-4.67
Catalonia	0.98	15.64	8.85	0.50
Extremadura	0.98	13.33	6.68	0.91
Galicia	0.97	24.09	16.35	19.13
Community of Madrid	0.98	11.48	5.83	-1.00
Region of Murcia	0.96	17.11	8.33	1.69
Navarre	0.99	16.70	9.24	-11.34
Valencian community	0.97	16.62	8.74	7.72

Chen, Zhuang, and He (2014) who obtained using CERES values of $R^2 = 0.92$, on average, for worldwide distributed stations. The RMSE statistic decreased about 50%, on average, with values ranging from 21.8% (Navarre) to 61% (Madrid) and the new values of Bias also showed an improvement in the estimation of solar radiation. Consequently, solar radiation obtained from satellite data can be used reliably in different applications after being rescaled.

Finally, an average of 8.85% of RMSE resulted for the monthly means solar radiation; this value was lower than $\%RMSE = 11\%$ informed by Polo (2015) for Spain using Meteosat for the period 2001–2007. Galicia (placed in the north-west of Spain, with

only four stations) was the community with highest errors in the computation of the monthly means.

4. Conclusions

This study verified that the monthly global solar radiation provided by CERES fits, with very good accuracy, to the registered solar radiation in different meteorological stations located in whole Spain, for the period July 2006–July 2015.

A systematic overestimation of solar radiation provided by CERES was detected from July 2011, when its temporal evolution was compared with the recorded data. A linear adjustment model since this month was proposed and evaluated to correct this behaviour.

As a result of applying the rescaling to CERES data from July 2011, for the whole period, a better match between registered and estimated by satellite solar radiation data was observed, as indicated by the validation statistics (R^2 , RMSE, and Bias).

Our finding offers an insight into error patterns of CERES solar radiation, since July 2011, and proposes a model for improving accuracy allowing therefore a reliable use of this product. For this the monthly global solar radiation derived from CERES takes advantage of the high spatial-temporal resolution and is adequate for use in Spain and other regions where meteorological information is not available, as long as being rescaled. This work contributes to the field of global solar radiation estimation using CERES product.

Disclosure statement

No potential conflict of interest was reported by the authors.

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