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Research Paper

# Development and Analysis of a New Solar Radiation Atlas for Argentina from Ground-Based Measurements and CERES_SYN1deg data

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ABSTRACT

Currently, quantifying global solar radiation at surface in Argentina is crucial for the development of projects related to solar energy, calculation of evapotranspiration and eco-sustainability architecture, among other environmental issues. In recent years, several models have been developed to estimate the solar energy resources by means of various techniques, e.g. satellite imaging, kriging, or Artificial Neural Networks. The use of satellite data allows for a better spatial representation, being of great relevance in areas with lack of terrain measurements. In this paper, we use the CERES_SYN1deg to develop a new Global Solar Radiation Atlas for Argentina. In this study, we developed maps of annual and monthly mean daily global solar radiation using CERES_SYN1deg data between 2000 and 2016. In order to validate the global solar radiation data provided by CERES_SYN1deg, they were compared with ground-based measurements in the time overlap of both instruments, in four monitoring sites of the SAVER-Net project and an additional site in Tandil, which belongs to the Remote Sensing Group of IHLLA. The maps show the spatial and temporal variation of global solar radiation in Argentina. Comparisons with ground-based pyranometers reveal relative differences of around 3% at a monthly scale for all sites, while the biases can be neglected. Therefore, it is possible to conclude that the maps could be very useful for different technical and scientific purposes, and the comparison with ground-based data demonstrates CERES_SYN1deg's reliability.


## 1. Introduction

Currently, quantifying global solar radiation at surface in Argentina is crucial for the development of projects related to solar energy, calculation of evapotranspiration, and eco-sustainability architecture, among other environmental issues. The development of any solar energy facility requires a range of solar resource data, where the most critical aspect is the temporal and spatial distribution of solar radiation along with the estimation of data uncertainties (AlYahya and Irfan, 2016). The abovementioned data can be gathered by: 1) obtaining solar radiation data by means of a wide pyranometer network and interpolating their specific values, or 2) using satellite data to develop solar radiation maps and validating the products generated through a few measurement sites on terrain to ensure data quality.

In the first case, some research has been carried out in Argentina to generate maps of global average daily solar radiation using daily interpolation techniques based on ground-based measurement data (Grossi, 1998; Grossi and Righini, 2007). For several decades, various maps have shown the distribution of global solar radiation received on the surface using different time bases and information quality (Righini et al., 2005). In this sense, Grossi (1998) presented the average monthly distribution calculated from daily global radiation data, using all the information available up to that moment in Argentina, obtained from the Argentinean Solarimetric Network, pyranometers and measured sunshine hours by the Servicio Meteorológico Nacional (SMN) [Argentinian Meteorological Service]. However, the quality of solar radiation products using interpolation techniques depends strongly on the quantity and distribution of pyranometers, which are not fully available in Argentina due to high installation and maintenance costs.

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On the other hand, estimations of solar radiation have been carried out by some researchers and companies using different remote sensing data sets (Huld et al., 2012). In recent years, several models have been developed to estimate the solar energy resources combining different techniques, e.g. satellite imaging, kriging, or Artificial Neural Networks. The use of satellite data allows for a better spatial representation, being of great relevance in areas with lack of terrain measurements.

In this paper, the need for a wide pyranometer network is avoided using remote sensing data. Particularly, in this study we used the CERES_SYN1deg surface data product to develop a new Global Solar Radiation Atlas for Argentina. The CERES_SYN1deg surface data product was previously validated by means of 84 surface measurement sites (Rutan et al., 2001). However, these sites correspond to the CERES/ARM Validation Experiment (CAVE), which includes 59 land sites and 24 ocean buoy sites. Among the land measurement sites, only 6 sites are located below 3° S latitude (4 in the Antarctic area), and there are not any validation sites in Argentina. Thus, we think that it would be of great interest to validate this satellite data product with in situ measurements in Argentina, and to develop maps showing the global solar radiation received at surface.

Therefore, the objectives of this work are (a) to validate the CERES_SYN1deg product from global solar radiation data recorded at five sites in Argentina and (b) to obtain the maps of annual and monthly global solar radiation for the entire territory of Argentina. The paper is organized as follows: Section 2 presents validation sites, ground-based measurements and satellite data, along with methods and statistical errors used. Section 3 presents the results and discussion. Finally, Section 4 summarizes the main conclusions.

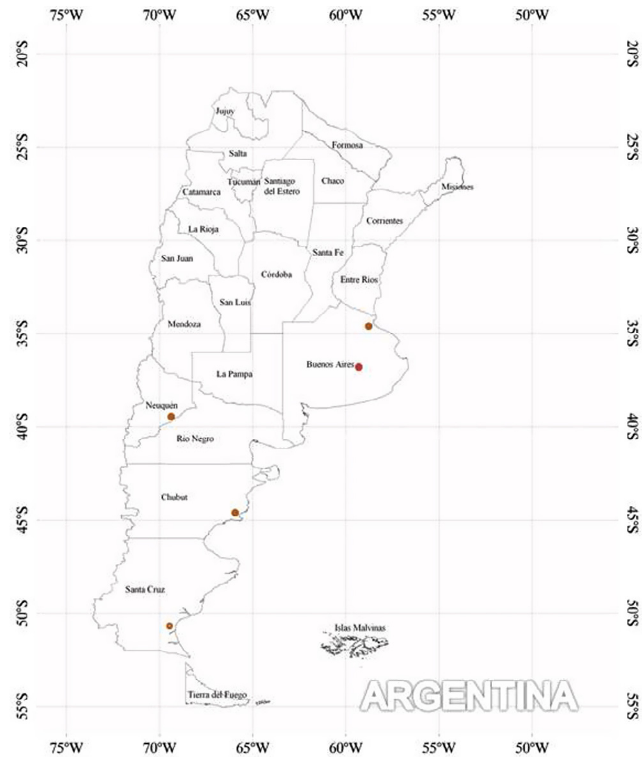


**Fig. 1.** Map of the Argentine Republic with measurement sites employed.

## 2. Materials and methods

### *2.1. Study area and ground-based measurements*

This study was carried out in Argentina, which is a federal republic located in southeastern South America. With a mainland area of 2,780,400 km$^2$, Argentina is the eighth largest country in the world and the second largest in Latin America. It lies in the solar belt between the latitudes 22° and 55° S and longitudes 74° and 54° O approximately (Fig. 1). The country is subdivided into twenty-three provinces and one autonomous city, Buenos Aires, which is the capital city of the nation (Argentina also claims sovereignty over part of Antarctica, the Falkland Islands, South Georgia and the South Sandwich Islands).

Measures of global solar radiation at five ground sites were used to validate the satellite product considered. Four sites correspond to the South American Environmental Risk Management Network (SAVER-Net, http://www.savernet-satreps.org/en/), which are located in Villa Martelli (34.5° S, 58.5° W, 2015–2016), Neuquén (39.0° S, 68.1° W, 2014–2016), Comodoro Rivadavia (45.9 ° S, 67.5 ° W, 2014–2016) and Río Gallegos (51.3° S, 69.3° W, 2014–2016). The fifth dataset used corresponds to measurements collected in Tandil (37.3° S, 59.1° W, 2006–2015), during different experimental campaigns carried out by the Remote Sensing Group of IHLLA (Carmona et al., 2011; Carmona and Rivas, 2016).

Measurements of incoming solar radiation were registered using CMP21 pyranometers (0.285–2.800 μm, Kipp & Zonen) for the four sites of the SAVER-Net project, and a CM3 pyranometer (0.305–2.800 μm) in Tandil, which is part of a CNR1 net radiometer (Kipp & Zonen).

### *2.2. CERES data*

In this study, we used the CERES_SYN1deg product, version Ed3A, which provides radiation data with a spatial resolution of 1 degree lat/lon (Smith et al., 2011). CERES (Clouds and the Earth's Radiant Energy System) is a satellite scientific instrument that is part of NASA's Earth Observation System (EOS). On board the Terra and Aqua platforms, CERES provides sampling at several hours of the day and geostationary meteorological satellite (GEO) data are used to account for changes in weather conditions from CERES observations. The Ed3A version of the CERES_SYN1deg product also offers other information, such as cloud properties that are determined using simultaneous measurements by other EOS instruments (Jia et al., 2016). Details of the CERES experiment are described by Wielicki et al. (1996).

### *2.3. Data processing and analyses*

#### *2.3.1. Validation*

Specific average daily and monthly values of global solar radiation were calculated from the five datasets of the ground-based measurement sites to validate the satellite product. On the other hand, the downward shortwave radiation (DSW) data of the CERES_SYN1deg_Ed3A product, corresponding to all-sky and clear-sky conditions, were downloaded for each site (http://ceres.larc.nasa.gov/).

At a local scale, the average daily and monthly values extracted from satellite data-based versus ground-based measurements were compared in each site. The following statistics were analyzed: the mean bias error (MBE), the root mean square error (RMSE), and the determination coefficient ($R^2$) of the linear regression.

#### *2.3.2. Elaboration of maps*

The monthly data of DSW from 1 March 2000 to 30 April 2016 (192 values) were selected to elaborate maps of annual and monthly mean daily global solar radiation for the whole Argentine territory. In addition, effective cloud cover (ECC) maps were elaborated to analyze the role of clouds in the radiative balance due to their spatial and temporal variations. The ECC was calculated according to Carmona et al. (2014):

$$ECC\ (\%) = \left(1 - \frac{Rs_{\downarrow}}{Rs_{\downarrow 0}}\right) * 100 \quad (1)$$

where $Rs_{\downarrow}$ is the global solar radiation at surface in all-sky conditions and $Rs_{\downarrow 0}$ is the global solar radiation at surface in clear sky conditions, both obtained from the CERES_SYN1deg_Ed3A product. Other monthly maps corresponding to basic statistics were also elaborated to analyze the results obtained. For processing remote sensing data, the Panoply (http://www.giss.nasa.gov/tools/panoply/) and ENVI 5.3 software were used. Fig. 2 shows the scheme of the methodology employed for the validation and the elaboration of global solar radiation maps.

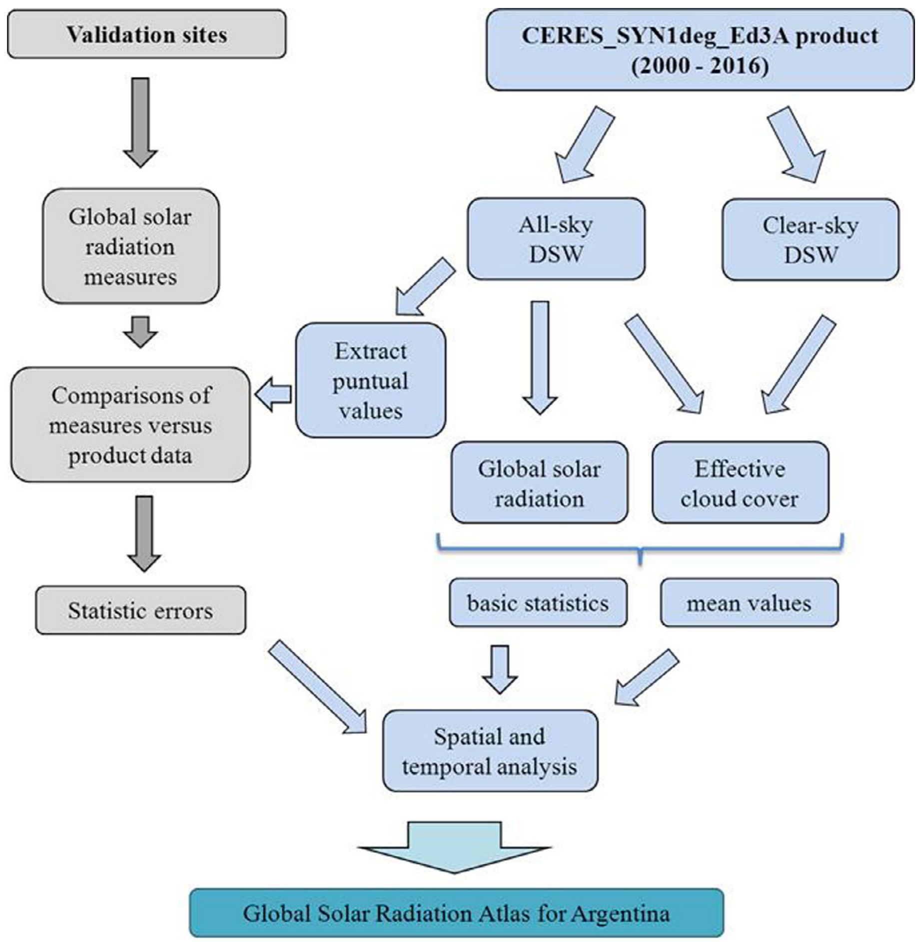


**Fig. 2.** Scheme of the methodology employed.

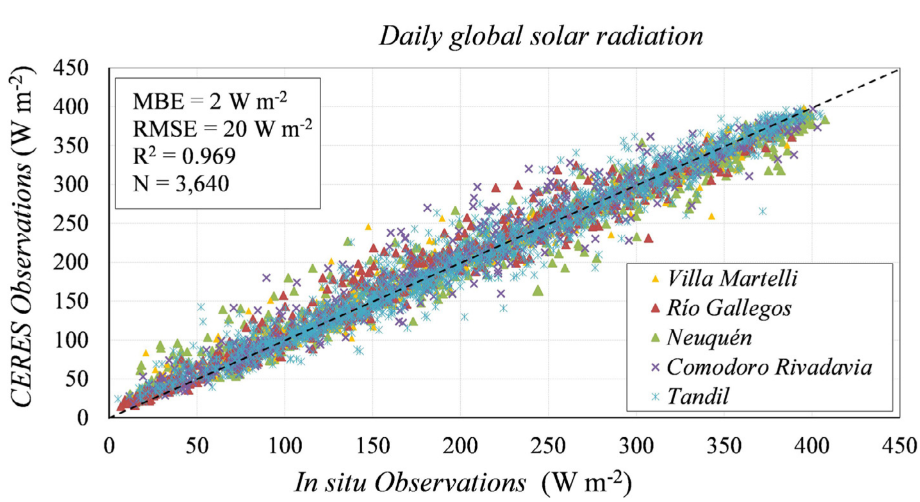


**Fig. 3.** Comparison of the CERES_SYN1 and ground-based observations of the daily global solar radiation for the five measurement sites. The 1:1 line is shown in the plot.

## 3. Results and discussion

### 3.1. Validation

Firstly, mean daily global solar radiation values were calculated from ground-based observations. Then, daily DSW data from CERES_SYN1 were downloaded for each validation site. A total of 3640 pairs of data were available for analysis: 521 for Tandil, 403 for Villa Martelli, 519 for Río Gallegos, 608 for Neuquén, and 589 for the Comodoro Rivadavia region. Fig. 3 shows the comparisons between the CERES_SYN1 and ground-based observations of the daily global solar radiation. The statistical results and number of pairs of data used, N, are also presented in the plot below.

Fig. 3 shows a very good general agreement between the CERES_SYN1 data and the ground-based observations of the daily global solar radiation. Analyzing the statistical results at each site,

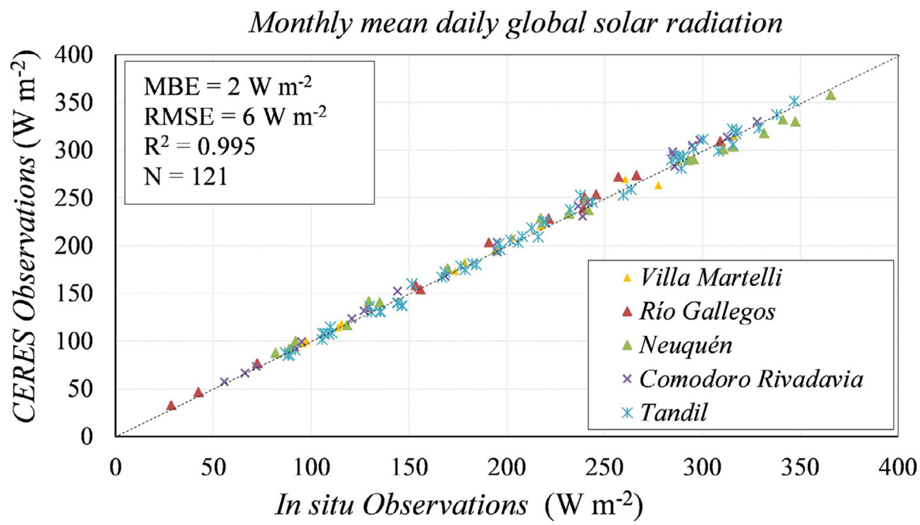


**Fig. 4.** Comparison of the CERES_SYN1 and ground-based observations of the monthly mean daily global solar radiation for the five measurement sites. The 1:1 line is shown in the plot.

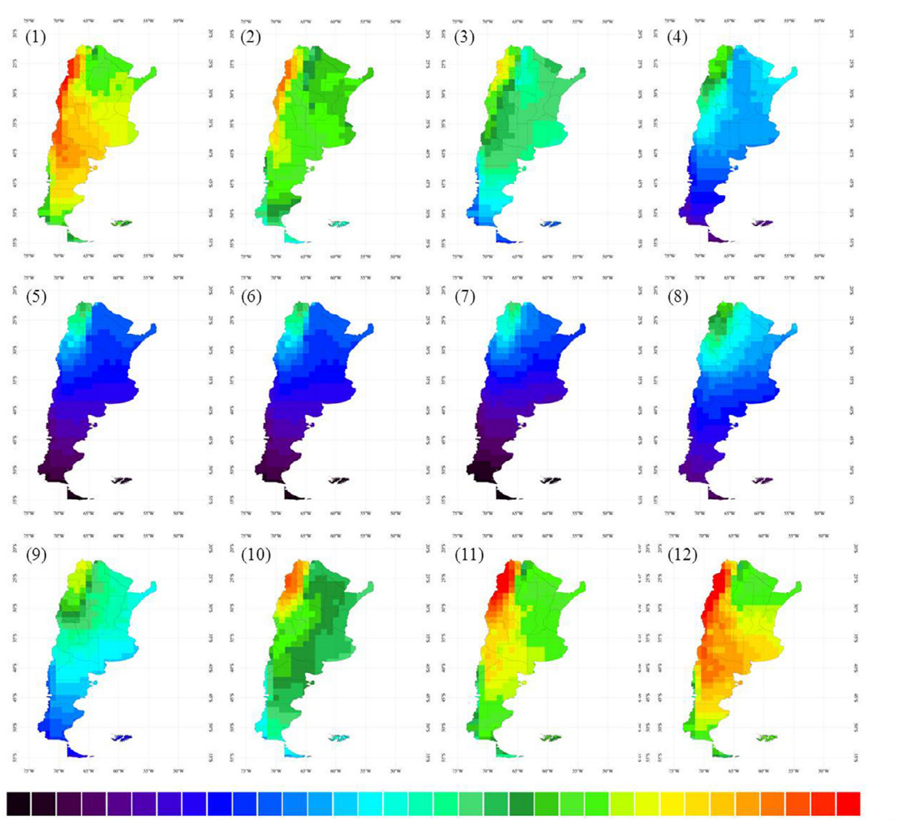


**Fig. 5.** Maps of monthly mean daily global solar radiation obtained from CERES-SYN1 product for the entire Argentinian territory; (1) January, (2) February, (3) March, (4) April, (5) May, (6) June, (7) July, (8) August, (9) September, (10) October, (11) November, and (12) December.

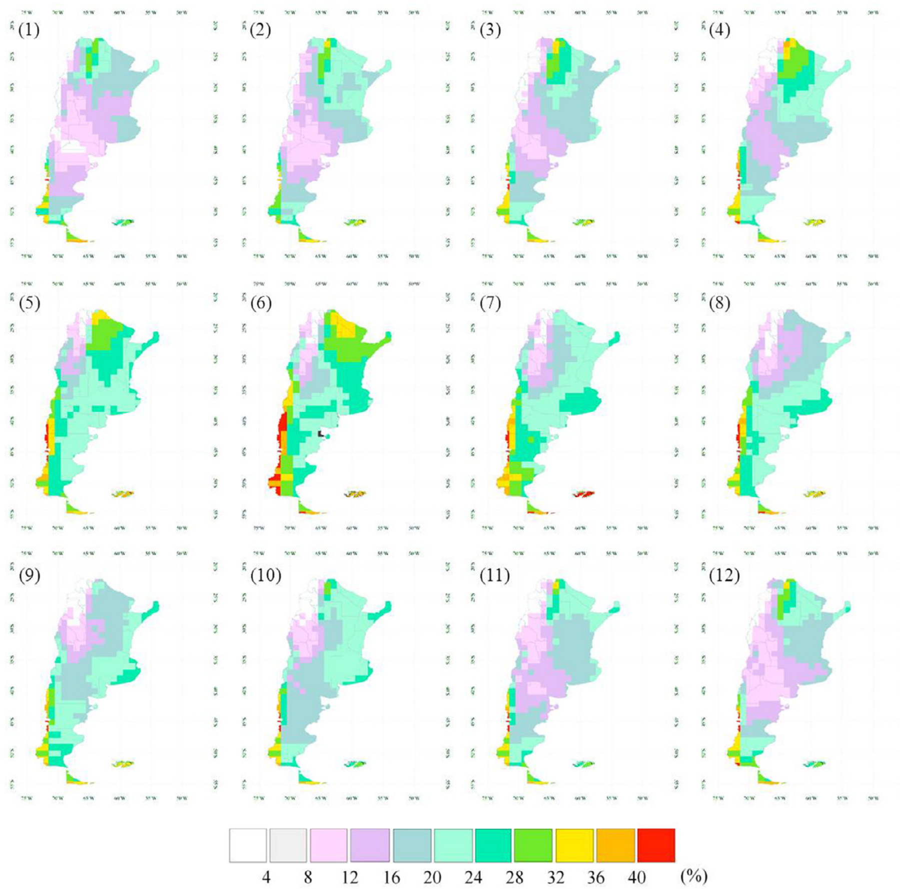


**Fig. 6.** Maps of monthly mean effective cloud cover obtained from the CERES-SYN1 product for the whole Argentine Republic; (1) January, (2) February, (3) March, (4) April, (5) May, (6) June, (7) July, (8) August, (9) September, (10) October, (11) November, and (12) December.

very good agreements are also observed in each of them, with statistical errors of MBE between 0 and 4 W $m^{-2}$, RMSE between ±15 and ±21 W $m^{-2}$, and $R^2$ between 0.959 and 0.969.

It is important to note that statistical errors are not mainly related to product quality rather with its spatial resolution, due that the comparison was performed between punctual ground-based observations and the data of CERES product for each location, which has one degree of spatial resolution (approximately 10,000 $km^2$ or higher in higher latitudes).

In addition, a comparison between monthly mean values of CERES_SYN1 and ground-based observations was carried out, which is the most important analysis for the main objective of this study. Due to the fact that ground-based datasets showed data gaps, the monthly mean values of CERES_SYN1 and ground-based observations were obtained from daily mean values, considering those months with at least 20 days of data registered. In this case, a dataset of N = 121 was available for analysis, consisting of 51 pairs of data of Tandil, 13 of Villa Martelli, 17 of Río Gallegos, 20 of Neuquén, and 20 of Comodoro Rivadavia. Fig. 4 shows the comparisons between CERES_SYN1 data and ground-based observations of the monthly mean daily global solar radiation.

This comparison presents a close-to-perfect agreement between CERES_SYN1 data and ground-based observations for monthly mean daily global solar radiation ($R^2$ = 0.995), with a MBE factor close to zero, and with statistical errors of RMSE of ±6 $Wm^{-2}$. This value is equivalent to ±0.14 kWh $m^{-2}$, these units being commonly used in solar energy studies.

*3.2. Global solar radiation products*

Considering the monthly DSW data of the CERES_SYN1 product, maps of monthly mean daily global solar radiation in Argentina were elaborated (Fig.5) together with map of the annual mean.

As expected, higher values of global solar radiation at surface are observed during the summer months, with values above 5 kWh $m^{-2}$ generally, and lower values during winter months, with values between 1 and 3 kWh $m^{-2}$ over most of the analyzed territory.

Further, latitude and topography of terrain are the main factors involved in the spatial variation of the global solar radiation at surface. The effect of latitude is easily observed, considering that the country covers latitudes between ∼22° and ∼55° S and approximately twice as much global solar radiation at surface is observed in the north compared to the south regions of Argentina. Regarding topography, higher values of global solar radiation are observed in northwest of Argentina due to the higher altitude terrain of the Andes Mountains.

Another important factor over the spatial variation of solar radiation is the attenuation produced by cloud cover. Fig. 6 shows the monthly maps corresponding to the effective cloud cover (Eq. (1)). For example, higher values of solar radiation in the central region with respect to the northeast region of Argentina for December are observed, which is explained by the higher ECC values observed in the northeast (see Fig. 6-(12)).

The monthly mean values of daily global solar radiation and the ECC for each province of Argentina are shown in Fig. 7. The highest

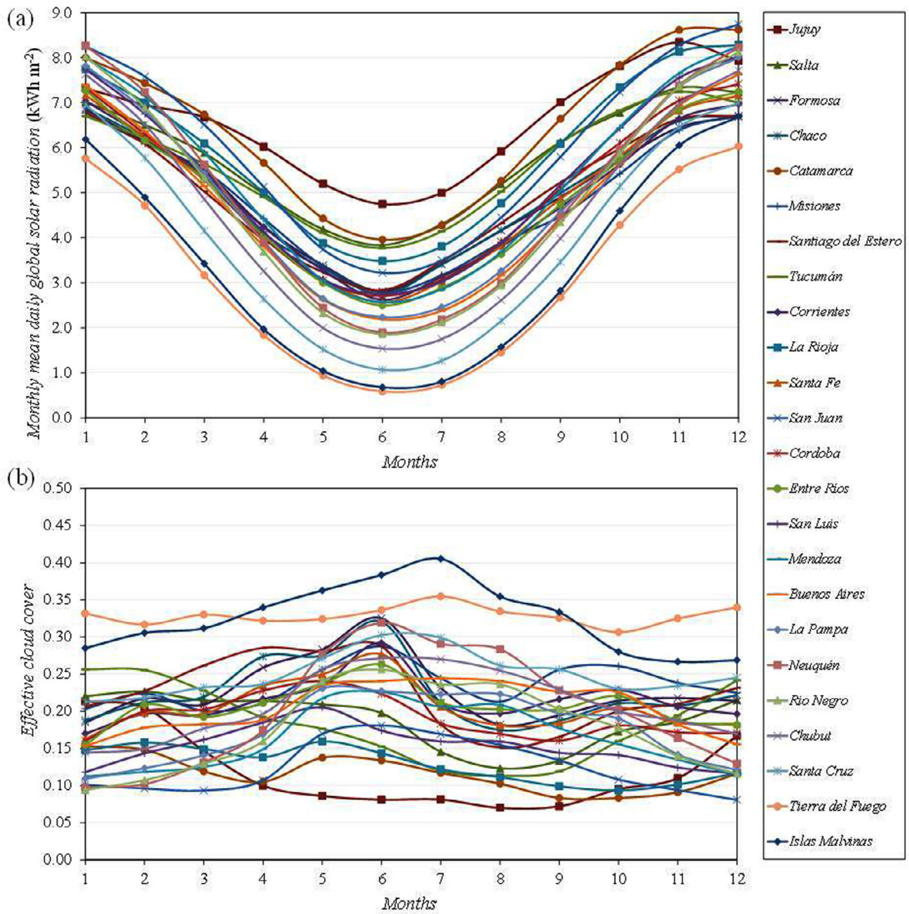


**Fig. 7.** Monthly mean daily global solar radiation (a) and ECC (b) for the provinces of Argentina.

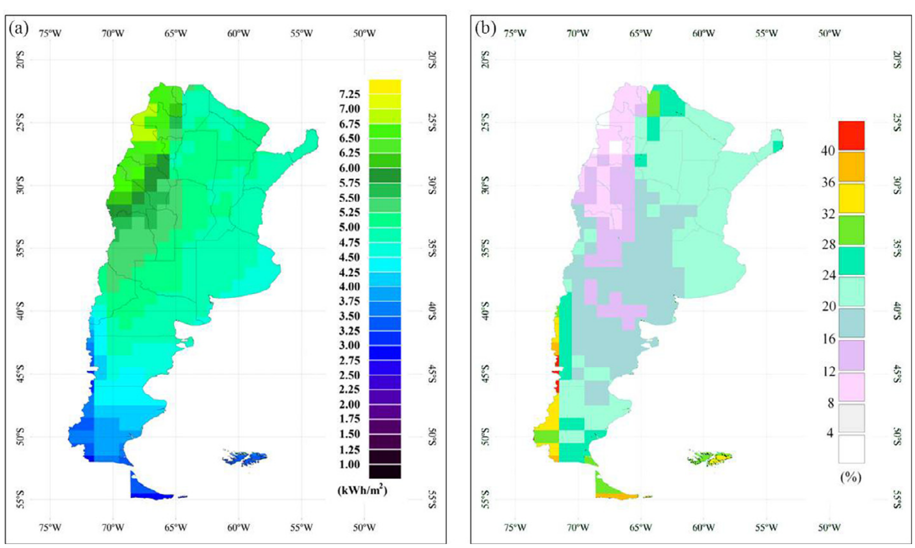


**Fig. 8.** Maps of annual mean daily global solar radiation (a) and annual mean ECC (b) obtained from the CERES-SYN1 product for the whole Argentine Republic (period 2000–2016).

solar radiation values are observed in the provinces of Jujuy, Catamarca and San Juan, located in northwestern Argentina, while minimum values are observed in Tierra del Fuego, south of the country. On the other hand, ECC values are generally higher in winter, particularly in June, except for some provinces located in northwestern Argentina, which recorded higher values in summer months. Such is the case of Jujuy, which shows a significant decrease of solar radiation between November and March, due to higher cloud cover values. Consequently, this is the time of the year when most rain events are observed.

Finally, Fig. 8 shows the map of annual mean daily global solar radiation and annual mean ECC for Argentina.

Fig. 8 shows (a) the annual mean daily global solar radiation, a variation between 2 and 7 kW $m^{-2}$ in the whole country with a higher spatial variation in the west and a lower variation in the east. A similar behavior is observed for the ECC (b) with values between 20 and 24% in the east and a large spatial variation in the west.

## 4. Conclusions

In this paper, we used the CERES_SYN1deg surface data product to develop a new Global Solar Radiation Atlas for Argentina. Previously, CERES_SYN1deg data of global solar radiation were compared with ground-based measurements in five monitoring sites. Comparisons with ground-based pyranometers showed relative differences of around 10% at a daily scale and only 3% at a monthly scale for all sites, without biases and $R^2$ close to 1. Then, we developed the maps of annual and monthly mean daily global solar radiation using the CERES_SYN1deg product data between 2000 and 2016. In addition, maps of effective cloud cover were elaborated to analyze its effect on the global solar radiation at surface. The developed maps showed the spatial and temporal variation of global solar radiation in Argentina. It is important to note that when using data from the CERES product, which has one degree of spatial resolution, similarly results are to those obtained with almost 300 terrestrial stations distributed throughout Argentina. Therefore, it is possible to conclude that the developed maps could be very useful for different technical and scientific purposes, and the comparison with ground-based data demonstrates the reliability of the CERES_SYN1deg product used.

## Conflict of interests

None.

## Acknowledgments

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