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Temporal scaling analysis of irradiance estimated from daily satellite data and numerical modelling

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ABSTRACT

The temporal variability of global irradiance estimated from daily satellite data and numerical models has been compared for different spans of time. According to the time scale considered, a different behaviour can be expected for each climate. Indeed, for all climates and at small scale, the persistence decreases as this scale increases, but the mediterranean climate, and its continental variety, shows higher persistence than oceanic climate. The probabilities of maintaining the values of irradiance after a certain period of time have been used as a first approximation to analyse the quality of each source, according to the climate. In addition, probability distributions corresponding to variations of clearness indices measured at several stations located in different climate zones have been compared with those obtained from satellite and modelling estimations.

For this work, daily radiation data from the reanalysis carried out by the European Centre for Medium-Range Weather Forecasts and from the Satellite Application Facilities on climate monitoring have been used for mainland Spain. According to the results, the temporal series estimation of irradiance is more accurate when using satellite data, independent of the climate considered. In fact, the coefficients of determination corresponding to the locations studied are always above 0.92 in the case of satellite data, while this coefficient decreases to 0.69 for some cases of the numerical model. This conclusion is more evident in oceanic climates, where the most important errors can be observed. Indeed, in this case, the RRMSE derived from the CM-SAF estimations is 20.93%, while in the numerical model, it is 48.33%.

Analysis of the probabilities corresponding to variations in the clearness indices also shows a better behaviour of the satellite-derived estimates for oceanic climate. For the standard mediterranean climate, the satellite also provides better results, though the numerical model improves significantly. In fact, for continental climate, both sources offer similar outcomes.

1. Introduction

The regional solar resource can be assessed by using both satellite-derived and numerical weather prediction model (NWP) estimations (Linares-Rodríguez et al., 2011; Ruiz-Arias et al., 2011). In some works (Allan, 2011; Liu et al., 2015), both sources have been combined in order to achieve an improved model.

Numerical models present some advantages relative to satellites as they provide forecasting for a wider span of time (Lara-Fanego et al., 2012; Perez et al., 2013) and can therefore be evaluated during longer time periods. In addition, the atmospheric system may be simulated with high precision by NWP models (Ruiz-Arias et al., 2015). However, a higher accuracy is obtained when using satellite estimations to calculate the surface solar radiation. Indeed, Lohmann et al. (2006) showed that yearly Global Horizontal Irradiance (GHI) values obtained from the ERA-40 global atmospheric reanalysis are underestimated on average by 6%. Their analysis was carried out during the period 1984–2000 in three areas: South Africa, Australia and the Near East. They ultimately concluded that better long-term assessments of solar resource quality should be based on satellite-derived irradiance data. In the work of Kennedy et al. (2011), better estimations from satellite data were obtained by using the North American Regional Reanalysis (NARR) and the Modern-Era Retrospective analysis for Research and Applications (MERRA) at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site over the period 1999–2001. Jia et al., 2013 evaluated the surface solar radiation from two satellite products, the Fengyun-2C (FY-2C) and the Fast Longwave and Shortwave Radiative Fluxes project (FLASHFlux), and from two reanalysis datasets, the ERA-Interim and the National Centers for Environmental Prediction from the Department of Energy (NCEP–DOE) reanalysis, by

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comparing against ground-based observations from 94 stations in mainland China over the period July 2006–June 2009. According to this study, the surface solar radiation from both satellite products presented lesser biases than the two reanalyses. ERA-Interim showed a root mean square error (RMSE) of 53.1 W/m^2, for daily values, and 37.1 W/m^2, for monthly values, while NCEP-DOE had a RMSE of 71.4 W/m^2 daily, and 56.5 W/m^2 monthly. Finally, Bojanowsky et al., 2014 performed a comparison between two sources (Meteosat and ERA-Interim) by using a wide station network distributed all over Europe, during the period 1983–2011. Different statistical measures, such as the coefficient of determination (R^2), the Mean Bias Error (MBE), the Mean Absolute Error (MAE) and the Root Mean Square Error (RMSE), confirmed the better behaviour of the satellite-derived estimations. Indeed, the Relative Root Mean Square Error (RRMSE), the MBE and the R^2 obtained from the CM-SAF for all of the stations considered are 18.88%, 0.85 and 0.94, respectively, while for the ERA-Interim dataset these errors increase up to 29.6%, 1.11 and 0.83.

While both satellite data and numerical model have been compared previously, these comparisons were limited to validating both estimations relative to ground measurements. A comparative analysis of the scaling of irradiance, or more specifically, of the persistence of irradiance estimations relative to the temporal scale chosen, has not yet been considered. Therefore, the main novelty of this work is on understanding this aspect of the solar variability.

In general, a variability analysis is of great interest when designing or operating solar energy systems (Hall et al., 1978; Argiriou et al., 1999; de Miguel and Bilbao, 2005). Variability can be statistically described by the standard deviation (Lave and Kleissl, 2010; Wilcox and Gueymard, 2010; Perez and Fthenakis, 2012), the variability index (Stein et al., 2012; Huang et al., 2014) or, as in the case of this work, by using the corresponding probability density functions at different timescales (Lave and Kleissl, 2010; Shedd et al., 2012; Vindel and Polo, 2014; Anvari et al., 2015).

The main aim of this work is to compare the temporal variability of daily global solar irradiance estimates derived from satellite data and numerical modelling. A scaling analysis is performed to assess the persistence of these estimates with regard to the time scale considered. For this, data have been taken over mainland Spain from the Satellite Application Facilities on climate monitoring (CM-SAF) and the ERA-Interim reanalysis corresponding to the European Centre for Medium-Range Weather Forecasts (ECMWF).

2. Theoretical background

Different scales can be considered with regard to atmospheric motions (Stull, 1988; Pielke, 2002; Lin, 2007). The microscale refers to local motions which do not affect more than few kilometres and have scarce duration (seconds to minutes). Microscale motions are mainly the result of atmosphere-surface interactions. Convective phenomena, such as breezes or thunderstorms, occur on the mesoscale. The lifetime of mesoscale motions can be several hours, and their spatial coverage spreads to a few hundred kilometres. Finally, the synoptic scale covers the motions typical of great air masses that move for days over an area of thousands of kilometres across.

Different climates are associated with different scales of atmospheric motions. Spain, due to its geography and orography, has very different climates and so with this in mind, it was chosen as the study area (Linés, 1970; Capel, 2000; Bladé et al., 2010; Agencia Estatal de Meteorología and Instituto de Meteorología de Portugal, 2011). In the north, the climate is oceanic, like much of the Atlantic coast of Western Europe. This climate is characterized by continuous cloud cover all year. As we move further inland, the climate becomes continental with more variable cloud cover according to the season. Finally, in the eastern and southern regions, by the sea, the climate is a standard mediterranean climate, in which the variability is not so pronounced and clouds are scarce for a good part of the year.

In zones with an oceanic climate, there is continuous frontal activity and so the synoptic scale plays a very important role. In these climates, shifts in irradiance between one day and the next, or over the span of a few days, can be expected. This lack of memory can stretch onto longer periods, on the order of one or several months, and thus, a very low persistence is expected on these scales. In the mediterranean climate the role of the synoptic scale is not as pronounced as in the oceanic case. Indeed, in this climate convective phenomena, on an hourly scale, gain relevance and shifts between days are less significant than in the oceanic climate. In other words, the persistence is more marked for one day or a few days than in the oceanic case, although this persistence decreases as the scale increases because on a monthly scale, the climate shows more variability. This feature of the mediterranean climate becomes more notable over the continent that occupies a great part of the central and southern peninsula. In this climate, referred to as the continental mediterranean climate, the mesoscale is less important than in the mediterranean case, and the daily variability is even less so. In spite of the fact that small changes from one day to another are expected, the variability increases as longer periods are considered.

3. Data

As previously mentioned, Spain was chosen as the study site (only the peninsular part) due to its wide climate variability. To cover the Peninsular geography, an area from 44°N to 35.25°N latitude and from −9.5°E to 3.25°E longitude was taken. This area was divided into 36 rows and 52 columns, by using a spatial resolution of 0.25°, providing a total of 1872 grid points for the study.

Daily data for the year 2005, corresponding to the grid indicated, were computed from Eumetsat's Satellite Application Facilities on climate monitoring (CM-SAF) (https://wui.cmsaf.eu/safira/action/viewProduktDetails?id=21093) (Müller et al., 2015). More details about the satellite data generated can be seen in CM-SAF (2014). These data, available following registration, show an error less than that allowed for CM-SAF catalogue: the daily mean of the data for global solar irradiance has a mean absolute difference of 12.1 W/m^2, while the threshold value for inclusion in the catalogue is 25 W/m^2 (page 5 of CM-SAF, 2015). The physical feasibility of all data used for this study has been checked, so that all values fall between 9.5 and 377 W/m^2.

In addition, daily data for the year 2005 and the grid of study, from ERA-Interim reanalysis (Uppala et al., 2005) carried out by the European Centre for Medium-Range Weather Forecasts (ECMWF) (http://apps.ecmwf.int/datasets/data/interim-full-daily/) was used for this study. These data are also available following registration. A suitable quality control in data selection is carried out for all observations used in ERA-Interim, including physical feasibility among other checks. Data selection rules are very strict in order to remove detrimental observations for the reanalysis (Dee et al., 2011). Daily accumulated values have been obtained by the sum of two requests: one for step 12 made from a forecast beginning at 0000 and another for step 12 from a forecast beginning at 1200 UTC. After that, from these accumulated data, the hourly mean value for each day was obtained. Thanks to the strict quality control in selection data, all values taken from ERA-Interim for this study are positive and below 367 W/m^2.

Finally, daily data of 2005 corresponding to three stations with pyranometers have also been used in order to carry out a more complete analysis. Of these stations, one (Burriana) belongs to the Ministerio de Agricultura, Alimentación y Medio Ambiente of Spain (MAGRAMA) (http://eportal.magrama.gob.es/websiar/Inicio.aspx) and two (Madrid and Oviedo) to the Agencia Estatal de Meteorología of Spain (AEMET - www.aemet.es). The AEMET measurements were taken with Kipp & Zonen CM-11 or CM-21 pyranometers that are secondary-standard instruments (ISO-9060) which meet the specifications established by World Meteorological Organization (WMO) (2008) for high-quality class sensors. The daily data obtained from MAGRAMA are subject to several different processes of validation: