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# Solar radiation forecasting in the short- and medium-term under all sky conditions

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Meteorological conditions are decisive in solar plant management and electricity generation. Any increases or decreases in solar radiation mean a plant has to adapt its operation method to the climatological phenomena. An unexpected atmospheric change can provoke a range of problems related to various solar plant components affecting the electricity generation system and, in consequence, causing alterations in the electricity grid. Therefore, predicting atmospheric features is key to managing solar plants and is therefore necessary for correct electrical grid management. Accordingly, a solar radiation forecast model is presented, where the three solar components (beam, diffuse and global) are predicted over the short- and medium-term (up to three hours) for all sky conditions, demonstrating its potential as a useful application in decision-making processes at solar power plants.

## 1. Introduction

Electricity production from renewable energy sources is increasingly competing with conventional electricity generation methods [1] as a means of avoiding a variety of environmental and economic problems [2–4]. Over recent years, solar energy has become more relevant with an expansion in the number of solar plants in operation [5]. CSP (Concentrated solar power) plants and another system [PV (photovoltaic) plants] are sophisticated electricity generation methods which work best under favorable meteorological conditions. Knowing when clouds or attenuating atmospheric factors might appear over the solar field helps avoid various problems, such as thermal stress on concentrator mirrors or on CSP plants receivers [6]. Other problems are related to electricity integration into the grid, where electricity generation instability might appear. Therefore being able to predict meteorological phenomena is important to solar plant operators, as this can affect the plant's management and, consequently, the resultant electricity generation.

A range of technologies have been used to study different atmospheric features.

Over the years, satellite images have built up a spatial view of the Earth's surface. These images have been used by many scientists to develop a variety of atmospheric studies, such as those for cloud cover. Cloud cover was examined in Ref. [7], where the authors presented an estimation method using the thermal-infrared channel at night time. In addition to this, the sky was classified into three different sky conditions: cloudless, partially-cloudy and overcast [8]. Cloud identification also using satellite images, was carried out in Ref. [9], where the authors classified clouds into three different heights (high, medium and low) and studied cloud motion using the maximum cross-correlation method. Cloud cover was likewise studied using another emerging technology, the total sky imager where sky cameras are installed at ground level, giving a different sky vision to the satellite images. A sky classification was presented in Ref. [10]; the authors used a KNN (K nearest neighbors) classification algorithm to divide the sky into seven different groups according to cloud presence. Combining sky camera images with radiometric data, the clouds were classified into four groups, showing radiation attenuation based on cloud type [11]. in addition

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to this, a cloud identification system was developed where the sky camera images were processed according to a sky classification [12], thus solving the saturation problem in the solar area [13]. By combining both satellite and sky camera imagery, a cloudiness forecast was made for the short- and medium-term [14], where a user interface provided cloudiness forecasting in real-time [15].

Other studies have focused on solar radiation estimation. Traditionally, solar radiation was estimated using parametric and empirical models. Parametric models required detailed atmospheric information in order to calculate atmospheric transmittance [16–19]. Empirical models were obtained from different correlations [20–22]. Consequently, some authors began to use satellite images to quantify solar radiation. The model developed in Ref. [23], was tested using an independent dataset of 1-year hourly ground measurements in a location of USA [24]. Global and direct horizontal irradiance were estimated from the model, whereas that diffuse horizontal irradiance was estimated from the other irradiance components. The rRMSE (relative root mean square error) values were 21.5%, 40.9% and 54.2% for global, direct and diffuse irradiance, respectively, and the rMBE (relative mean bias error) values were −4.9%, 2% and 15.4% in the aforementioned order. Also, the model developed for estimating direct normal irradiance in Ref. [25] was tested over eight stations in Saudi Arabia for hourly satellite-derived DNI (Direct normal irradiance) values and obtained an rRMSE of 36.1% and an rMBE of 4.3% for all sky conditions [26]. Global solar radiation was also estimated using MSG (Meteosat Second Generation) satellite imagery [27]. Moreover, solar radiation was estimated above Turkey, where the authors used satellite images and artificial neural network [28]. One of the most consolidated models for estimating solar radiation under clear sky conditions was been used in the Heliosat-2 method to estimate the three solar radiation components, this was developed in the ESRA (European Solar Radiation Atlas) [29]. One study [30] combined the Heliosat-2 method with digital terrain models to obtain a solar radiation estimation, whereas [31] made a global radiation prediction combining two methods: one focused on satellite images with the Heliosat-2 method; and the other focused on ground-based lineal model.

As demonstrated above, the study of atmospheric features is constantly evolving and expanding. However, to improve solar systems and solar power plants management, predicting solar radiation has proven to be essential information [32], greatly contributing to stable electricity generation and its integration from solar plants into the public electricity grid.

In this work, we have looked at the need to provide future atmospheric information by developing a system capable of predicting the three solar radiation components (beam, diffuse and global) over the short- and medium-term (up to three hours) under all sky conditions, and then comparing the results with ground-level radiometric measurements.

## 2. Materials and methods

In a general way, the structure of the methodology can be defined as follow:

### 2.1. Data collection

Satellite data from the years 2010–2014 were used. For the forecasting estimation, five MSG satellite channels were collected (VIS 0.6, VIS 0.8, IR 3.9, IR 10.8 and IR 12.0) out of a total of 12 spectral channels received every 15 min. For each of the five chosen channels, a 121 × 161 pixel raster image, centered on the University of Almería, was saved and then used via an algorithm whenever the solar altitude was higher than 10° — this was done to avoid mistakes in cloud detection due to low image brightness. (see Fig. 1)

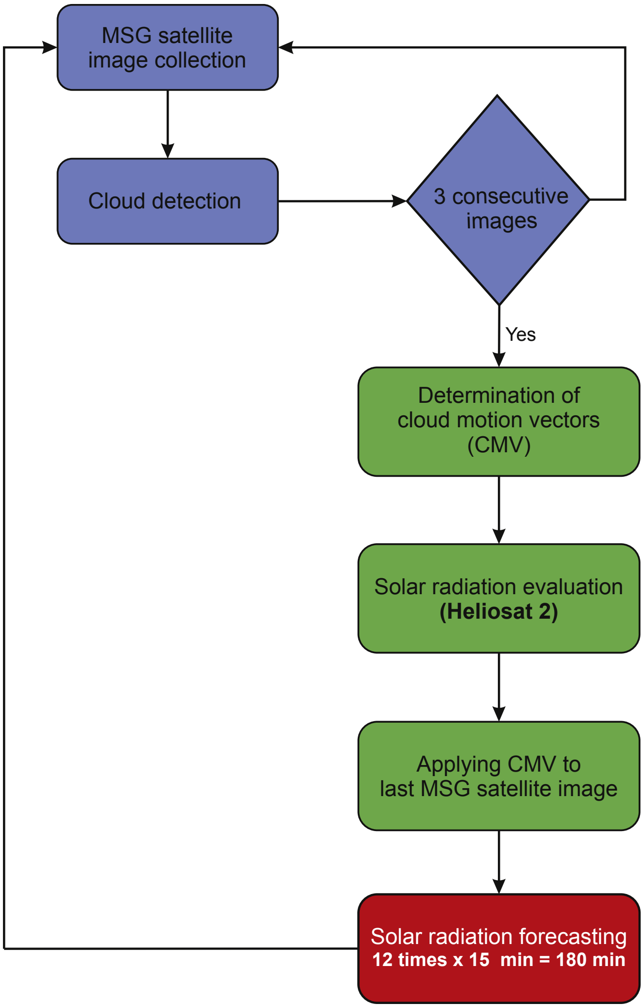

**Fig. 1.** Flowchart of the methodology developed for the solar radiation forecasting.

Furthermore, diffuse and global irradiance measurements were taken from two *CMP11 Kipp & Zonen* pyranometers, while beam irradiance was measured using a *CH1 Kipp & Zonen* pyrheliometer; these instruments were installed on a horizontal two-axes solar tracker.

The testing facility is located at the CIESOL (Solar Energy Research Center) at the University of Almería, Spain (36.8$^o$N, 2.4$^o$W, at sea level), which has a Mediterranean climate and a high maritime aerosol presence.

### 2.2. Image collection and cloud detection

The first step in carrying out solar radiation forecasting is correct satellite image collection. The images are received and converted into reflectance and temperature (from visible and infrared channels, respectively).

When the images are converted, the atmospheric conditions can be obtained for each satellite pixel, combining spectral channels with different remote sensing techniques. Clouds are the most attenuating factor in the solar radiation environment. Cloud identification in satellite images, is carried out using various spectral tests propose in a study by Ref. [9], in which the studied area is fully analyzed, looking for the presence of any clouds in the different atmospheric layers.