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Analysis of intra-day solar irradiance variability in different Brazilian climate zones

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ABSTRACT

One of the main barriers to increasing the solar energy share is its intermittency. Solar energy's large variability in different timescales is driven by natural solar astronomical cycles and weather. Ground-based measurements are important for evaluating variability at high temporal resolutions, but they are only representative of small areas close to the measurement sites. Satellite observations come as an alternative to analysis over large areas. However, they have coarse temporal and spatial resolutions. In our study, we first evaluated the variability in different time steps, using one-year of 1-min resolution ground-based irradiance measured at three sites located in different Brazilian climate regimes. The results showed that more humid months have the largest variability. By contrast, the driest locations presented more variability on short timescales, probably due to the presence of a large number of clouds, even in very dry conditions. This characteristic can be of concern to Brazilian energy planning since the site is located in the most prominent region for solar energy generation. We also compared ground observations with satellite cloud variability, with 30-min resolution. For the same timescale, the results were promising, with a Pearson correlation of up to 0.93, depending on the site. However, when the frequency of the solar irradiance measurements increased, the correlation decreased. A solution may be to analyze a larger pixel area around the sites. Another option would be the use of downscaling methods. This topic, however, will be the subject of the future study. The most important result achieved in this study was the development of a simple methodology for evaluating the surface solar irradiance variability using cloud cover obtained from visible satellite imagery.

1. Introduction

One of the main barriers to increasing the solar energy share is its intermittency. Solar energy has a large variability over different timescales and is driven mostly by the natural solar cycles (diurnal and annual - four seasons) and weather. The solar cycle is precisely estimated by calculating the apparent motion of the sun in the sky. On the other hand, the variability caused by weather and atmospheric conditions is mostly governed by cloud motion and weather systems and is much less predictable (Perez et al., 2016; Watanabe et al., 2016).

Clouds passing in front of the sun can cause drastic fluctuations in the surface solar irradiance and this variability has a huge impact on the power output of PV, or concentrated solar power plants (Ari and Baghzouz, 2011; Lave et al., 2015; Perez et al., 2016). Also, the solar radiation variability ends up producing transients that are incompatible with the required standards for electricity distribution systems, including voltage variability and frequency disturbances caused by an imbalance between power generation and electricity demand (Kleissl, 2013). In addition, the solar energy intermittency can cause rapid changes in the receiver temperature and it may lead to thermal stress on the devices, increasing the maintenance costs (Ari and Baghzouz, 2011; Kazantzidis et al., 2012).

Thus, in order to understand the output variability of a solar power plant, it is important to find out the best method for quantifying it. Different physical variables are relevant for different technologies, similarly, different timescales are important for different technologies and areas of interest (Perez et al., 2016). Assuming that cloud cover is the major driver of surface solar irradiance, it is useful to examine the cloud variability in an appropriate spatial and temporal perspective to get a better understanding of the intermittency of the solar power generation. In any specific location on a partly cloudy day, the one-

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Nomenclature

CPA	Cachoeira Paulista measurement site
Ceff	effective cloud cover coefficient
Kt	clearness index
Kt′	adjusted clearness index
L_r	radiance
L_{clr}	clear sky radiance
L_{cld}	overcast radiance
PTR	Petrolina measurement site
RMSD	Root Mean Square Deviation
$RR_{\Delta t}^{Kt'}$	Kt′ ramp rates with timescale Δt
$RR_{\Delta t}^{Ceff}$	Ceff ramp rates with timescale Δt
SMS	São Martinho da Serra measurement site
VS	Variability Score

minute incoming solar irradiance will experience a very large variability because of the clouds shadowing the sun. However, the daily total of incoming solar radiation will experience much less inter-day variability. Furthermore, for the same time step, the larger the area of interest (footprint), the lower the variability of the incoming solar radiation (Perez et al., 2016).

The solar generation footprint and timescale are of major concern for PV grid operators and lead to different load management challenges with different solutions. Increasing the footprint from a single location to a resource dispersed over an entire region will reduce intermittency considerably. One-minute fluctuations are relevant for both single distribution systems and large centralized plants due to voltage control issues. On the other hand, for the grid balancing of distribution systems, variability below 30 min is not relevant, while hourly and above variability remains a higher concern (Perez et al., 2016). Furthermore, for concentrating technologies, one-hour data gives simplistic results on the prediction of plant performance. Smaller timescales are more likely to provide a realistic representation of control system operations (Meybodi et al., 2017).

Prior to the analysis of the solar irradiance variability, it is necessary to define which is the most appropriate physical variable. Grid operators use the power output, which reflects the underlying variability of solar irradiance. For this, two fundamental parameters can be used: global horizontal irradiance (relevant for PV technologies) and direct normal irradiance (relevant for concentrating technologies). However, these two parameters embed both Sun-Earth relative movement and cloud weather effects. To focus on the second, it is helpful to use a parameter that normalizes the incoming solar irradiance so as to minimize the variability linked to the Sun-Earth relative position (Perez et al., 2016). For PV technologies, the clearness index, Kt (ratio between surface and the extraterrestrial global irradiances) and the clear sky index, Kt^* (ratio of the measured solar data and the global irradiance in clear sky condition) are good parameters for meeting this criterion (Lave et al., 2017; Perez et al., 2016; Watanabe et al., 2016).

Watanabe et al. (2016) used the mean, standard deviation and sample entropy to evaluate the variability of the surface solar irradiance over Japan. Perez et al. (2016) proposed the nominal variability of Kt^* ramp rates (RR) as a metric to study the solar power variability. The RR, defined as the change in magnitude over a specific timeframe, was also used by Lave et al. (2015) to quantify the local high-frequency variability based on their cumulative distribution functions.

Although ground-based measurements are important in explaining the high-frequency variability, they only represent small areas within a limited field of view. This limitation makes it difficult to understand the impact of cloud variability in power plants located far away from the measurement sites. Satellite observations come as a solution to the analysis over large areas. They have, however, coarse temporal and spatial resolutions (Lave et al., 2017; Watanabe et al., 2016).

Combining ground-based and satellite measurements is a good way to overcome this difficulty. Nonetheless, the satellite poor temporal and spatial resolutions make using temporal downscaling and/or spatial interpolation necessary (Perez et al., 2016). Many authors have used different spatial interpolations to estimate the solar irradiance variability at some distance from the measurement sites (Arias-Castro et al., 2014; Elsinga and van Sark, 2015; Perez et al., 2012; Yang et al., 2014). Ngoko et al. (2014) and Wegener et al. (2012) used different downscaling methods to synthetize data with higher frequency than the available, while Stein et al. (2011) synthetized high-frequency solar data from satellite data. Hummon et al. (2012) and Lave et al. (2017) found associations between 1-h satellite data and high-frequency ground data acquired in several locations in the USA and Watanabe et al. (2016) characterized the variability in Japan using cloud properties provided by satellite images.

In this study, we propose a methodology for evaluating the variability of the incoming surface global solar irradiance using ramp rates of the effective cloud cover coefficient estimated from the visible GOES-EAST satellite imagery data, using one year of data (July/2016 until June/2017). The study investigates the variability of ground-based Kt ramp rates at different timescales (1-, 5- and 30-min) and compared them to ramp rates of the cloud cover coefficient obtained from 30-min time resolution satellite data. The novelty of this research lies in the use of a simple method for analyzing solar variability using only visible satellite imagery instead of estimating irradiance on the surface. The large extension of the territory that Brazil covers makes it possible to evaluate the applicability and the performance of the method for different climate characteristics. The key characteristics of the three ground sites and the methodology are described in Section 2. Section 3.1 encompasses the evaluation of the ground-based irradiance variability at the three ground sites and Section 3.2 describes the relationship between the satellite cloud ramp rates and the Kt ground-based ramp rates. The major conclusions are presented in Section 4.

2. Methodology

2.1. Study area

Brazil has several distinct climate regimes, mostly because of its large territorial extension and its atmospheric circulation. As a consequence, the rainfall and nebulosity regimes are quite different throughout the Brazilian territory. Fig. 1 shows the location of measurement sites superimposed on a map presenting the major Brazilian climate regimes. The climate in the central area of the Northeastern region (in orange[1] color) is the semi-arid and it is characterized by very dry weather all year long (Pereira et al., 2017). The Petrolina (PTR) measurement site designed to acquire meteorological and solarimetric data is located in this area. The other two measurement sites, Cachoeira Paulista (CPA) and São Martinho da Serra (SMS), are located in the humid subtropical climate zone.

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.