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Cloud enhancement of global horizontal irradiance in California and Hawaii

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Abstract

Clouds significantly attenuate ground-level solar irradiance causing substantial reduction in photovoltaic power output capacity. However, partly cloudy skies may lead to temporary enhancement of local Global Horizontal Irradiance (GHI) above the clear-sky ceiling and, at times, the extraterrestrial irradiance. Such enhancements are referred to here as Cloud Enhancement Events (CEEs). In this work we study these CEEs and assess quantitatively the occurrence of resulting coherent Ramp Rates (RRs). We analyze a full year of ground irradiance data recorded at the University of California, Merced, as well as nearly five months of irradiance data recorded at the University of California, San Diego, and Ewa Beach, Hawaii. Our analysis shows that approximately 4% of all the data points qualify as potential CEEs, which corresponds to nearly 3.5 full-days of such events per year if considered sequentially. The surplus irradiance enhancements range from 18 $\mathrm{W\,m^{-2}\,day^{-1}}$ to 73 $\mathrm{W\,m^{-2}\,day^{-1}}$. The maximum recorded GHI of $\sim$1400 $\mathrm{W\,m^{-2}}$ occurred in San Diego on May 25, 2012, which was nearly 43% higher than the modeled clear-sky ceiling. Wavelet decomposition coupled with fluctuation power index analysis shed light on the time-scales on which cloud induced variability and CEEs operate. Results suggest that while cloud-fields tend to induce variability most strongly at the 30 min time-scale, they have the potential to cause CEEs that induce variability on time-scales of several minutes. This analysis clearly demonstrates that CEEs are an indicator for periods of high variability and therefore provide useful information for solar forecasting and integration.

Keywords: Global horizontal irradiance; Cloud enhancement; Ramp rate; Wavelet

1. Introduction

The total extraterrestrial beam irradiance incident on the earth's atmosphere I_0 fluctuates about an average value of approximately 1360 $\mathrm{W\,m^{-2}}$ (Kopp and Lean, 2011). This incident radiation is attenuated as it negotiates its way to ground level through a complex series of multiple reflections, absorptions and re-emissions due to interactions with atmospheric constituents (Goody and Yung, 1995). This results in the division of the incident extraterrestrial beam radiation into two distinct components; Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI), the geometric sum of which is the Global Horizontal Irradiance (GHI), defined by the closure equation,

$$\mathrm{GHI} = \mathrm{DNI}\cos\theta_z + \mathrm{DHI} \tag{1}$$

where θ_z is the solar zenith angle, see Fig. 1.

In addition to the partitioning of the radiation, atmospheric cloud-formation is typically associated with

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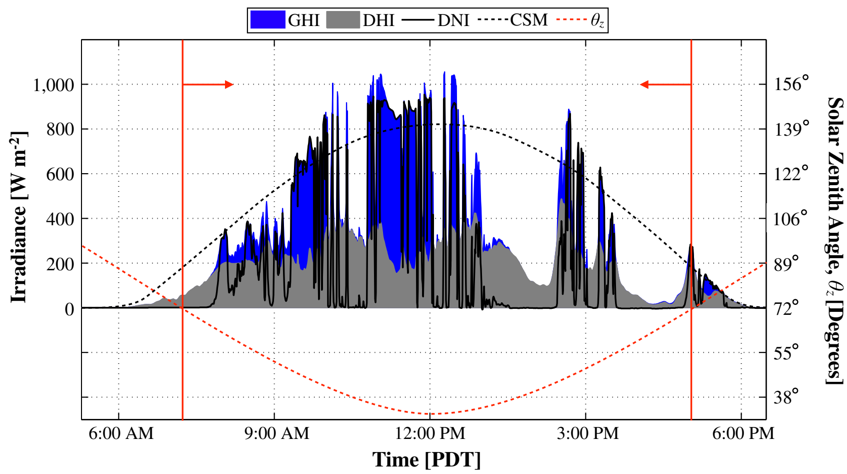

Fig. 1. Components of solar irradiance sampled every 30 s at the University of California, Merced, on March 21, 2011. Global Horizontal Irradiance (GHI) was measured with a Precision Spectral Pyranometer (PSP), manufactured by the Eppley Laboratory, Inc. Direct Normal Irradiance (DNI) was measured using a Normal Incidence Pyrheliometer (NIP) and 2-axis automatic solar tracker (SMT-3), both of which are also available from the Eppley Laboratory, Inc. Diffuse Horizontal Irradiance (DHI) was measured using an additional PSP and SMT-3 with accompanying Shade Disk Kit (SDK). Solar zenith angle is also plotted and observations with $\cos\theta_z \leqslant 0.3$ ($\theta_z \geqslant 72.5°$), shown outside solid red-lines, being excluded from the study. The Clear-Sky Model (CSM) used in this figure is explained in detail in Section 3.2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

a pronounced decrease in the intensity of solar irradiance components. In fact, the attenuation of incoming solar radiation by clouds is routinely larger than any other atmospheric component (Inman et al., 2013). Furthermore, the driving effects of clouds on radiative energy budgets include short wave cooling, as a result of absorption of incoming solar radiation, and long wave heating, due to reduced emission of thermal radiation by relatively cool cloud tops (Schade et al., 2007). However, partly cloudy skies may lead to the reverse; i.e., multiple scatterings and reflections of short wave radiation by cloud fields may lead to increased irradiance from a portion of the sky above the corresponding cloud-free value (Franceschini, 1968; Wen et al., 2001; Wyser et al., 2002; Pfister et al., 2003; Emck and Richter, 2008; Berg et al., 2011). In rare occasions, these enhancements can cause the local GHI to instantaneously exceed the extraterrestrial solar constant I_0 (McCormick and Suehrcke, 1990; Tapakis and Charalambides, 2014). Such enhancement of GHI above the corresponding clear-sky value are referred to here as Cloud Enhancement Events (CEEs).

With the exception of two studies, one by Luoma et al. (2012) and a second by Tapakis and Charalambides (2014), little work has been done in the realm of CEEs with respect to PhotoVoltaic (PV) power generation. In this work we do not intend to suggest a new mechanism by which CEEs occur, but rather investigate the coherent Ramp Rates (RRs) associated with CEEs and their potential impact on the quality of PV power generation. To clarify, a coherent CEE RR is defined as a series of monotonically increasing or decreasing GHI observations whose maximum value exceeds the expected clear-sky value by a given threshold. These CEEs and their associated RRs are of interest for several reasons: current models typically do not consider the ability of clouds to increase the local available irradiance, these events commonly precede or follow periods of lower than normal irradiance associated with the presence of passing opaque clouds leading to relatively large RRs, large RRs can cause voltage flicker that in turn trigger tap chargers on distribution feeders increasing operations cost for utilities, and therefore the successful forecasting of these events could lead to an effective control scheme to reduce the cost associated with high levels of variability in photovoltaic power generation.

Analysis of the amplitude, persistence, and frequency occurrence of ground-level irradiance fluctuation requires a decomposition of the input time-series into a set of orthogonal sub-signals each representing a specified time-scale of fluctuation. Due to the stochastic and non-periodic nature of the atmospheric processes that drive ground-level fluctuations in clearness, Fourier analysis is typically not suitable. Alternatively, spectral analysis of high frequency (e.g., 1 s to 1 min) irradiance time-series on a wavelet basis rather than a periodic basis can be found in the literature. Kawasaki et al. (2006) decomposed 2-years of 1-min irradiance data from 9 sites in a 4 × 4 km grid using the Daubechies 4 wavelet (Hazewinkel, 2001). Woyte et al. (2007) applied the Haar (1911) wavelet to clearness index time-series and defined a fluctuation power index (fpi) that quantified the amplitude and frequency occurrence of variability on specified time-scales. Perpiñán and Lorenzo (2011) analyzed several days of 1 s irradiance time-series using the MOD-WT wavelet and later used wavelet transform correlations to study fluctuations of the electrical power generated by an ensemble of 70 DC/AC inverters from a 45.6 MW PV plant (Perpiñán et al., 2013). Lave et al. (2012) applied a wavelet transform to clear-sky index time-series from a single site to the average of six sites and showed a strong reduction in variability at short time-scales (i.e., shorter than 5-min) with lesser