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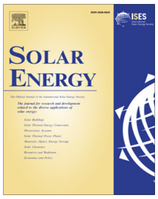

Cloud and albedo enhancement impacts on solar irradiance using high-frequency measurements from thermopile and photodiode radiometers. Part 1: Impacts on global horizontal irradiance

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ABSTRACT

Using many years of high-quality measurements from a variety of radiometers at both 1-min and 1-s resolution, this study provides a detailed analysis of cloud enhancement (CE) and albedo enhancement (AE) effects on solar irradiance. This first part focuses on global horizontal irradiance. Various possible definitions of the CE phenomenon are extracted from the literature and discussed, in the context of PV applications most importantly. Based on 10 years of 1-min measurements of all shortwave irradiance components at a high-elevation site (1829 m) on the foothills of the Rocky Mountains in Colorado, a frequency analysis of extreme events triggered by enhancement effects is carried out, using three different criteria to delineate enhancement effects: global horizontal irradiance (GHI) above 1 sun, and clearness index (K_T) above either 0.8 or 1.0. This analysis shows that the annual frequency of these extreme events is extremely variable, and also largely dependent on the type of instrumentation (thermopile vs. photodiode). Although the scattering of light off cumulus-type cloud edges is directly associated with CE effects, three different types of CE phenomenon are proposed, which depend on the relative mix of diffuse and direct irradiance prior and during an episode, and on the magnitude of the regional albedo. The maximum observed global irradiance varies between 1546 and 1891 W m^{-2} at this site, depending on type of instrument and temporal resolution. The latter value (≈1.9 suns), obtained with a photodiode sensor at 1-s resolution, corresponds to $K_T = 1.62$ and appears to constitute a new GHI world record. It results from the combination of CE and AE effects, the latter being caused by strong backscattering, itself triggered by a fresh snow cover over the region. If the magnitude and frequency of enhancement events are critical to detect rapid transients that can be harmful to PV installations, it is suggested to rely on photodiode sensors at 1-s resolution or better.

1. Introduction

During the last two decades, a sharp transition occurred in the field of solar energy applications, whereby the dominant technology switched from fluid-heating thermal collectors to direct electricity conversion via photovoltaic (PV) modules. This profound evolution in technological paradigm was accompanied by a less visible change: Whereas thermal collectors have substantial inertia, with a response time constant of the order of minutes, that of PV modules is many orders of magnitude less. Short-lived transient effects (lasting only seconds or less) are thus likely to affect PV more than thermal applications.

In parallel, another significant transition also occurred in the field of solar radiation measurement: Before the dawn of the PV era, most radiometric stations used the conventional 60-min (hourly) time step to report solar radiation observations with thermopile pyranometers and pyrheliometers. Current measurements are now typically done at 1-min resolution, and may rely on either thermopile or photodiode sensors. Some research stations even monitor irradiance at 1-s or better temporal resolution. This means that the current 1-min resolution standard may continue to evolve toward faster speeds in the future. Higher temporal resolutions allow better detection of transient phenomena, such as those caused by the passage of clouds.

Transient effects in PV systems have started to become worthy of study because of their potential impact on the safety and stability of these systems and of their power production (Lave et al., 2012, 2015; Ranaweera et al., 2014). As a result, pressure has mounted on various research institutions to evaluate the output and upward or downward ramps of PV systems' output at time

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steps of 1 min or less. Although the resulting huge amounts of data may be efficiently handled by current computer systems, other issues do exist. Indeed, important questions remain to be addressed in detail, most particularly: How frequent are these rapid fluctuations in incident irradiance at any specific location, and how can they be best defined and explained? Moreover, what impact has the measurement frequency on the detection of rapid irradiance variations?

This study intends to provide valuable answers to these questions, and to bring both a new perspective and a quantitative assessment on phenomena that have previously received attention in other fields. For instance, the intense transient effects of clouds, particularly under tropical conditions, had already been qualitatively noted long ago by experimenters (e.g., (Norris, 1968)). Their impact on surface ultraviolet (UV) irradiance (e.g., (Antón et al., 2011, 2012; Cede et al., 2002; Estupiñan et al., 1996; Feister et al., 2015; Häder et al., 2015; Nack and Green, 1974; Piacentini et al., 2003)) or surface solar irradiance (de Andrade and Tiba, 2016; Gu et al., 2001; Inman et al., 2016; Lappalainen and Valkealahti, 2015; Pecenak et al., 2016; Piedehierro et al., 2014; Schade et al., 2007; Suehrcke and McCormick, 1988; Tapakis and Charalambides, 2014; Thuillier et al., 2013; Tomson, 2013, 2014; Vamvakas and Kazantzidis, 2017; Yordanov et al., 2015), have become important topics of research of their own. The interaction between these effects and the performance of PV systems is now perceived as an important issue, because of their potentially negative impact on inverters (Burger and Rüther, 2006; Chen et al., 2010, 2013; Luoma et al., 2012), or on the local stability of the electric grid (Lave et al., 2015; Quiroz and Cameron, 2012). The rapid passage of obscuring clouds in front or around the sun results in large power ramp rates (Inman et al., 2016; Lave et al., 2012), often accompanied by transient *cloud enhancement* (CE) effects just before and after the sun's masking (Almeida et al., 2014; Ranaweera et al., 2014; Roy, 2015; Zehner et al., 2011). These effects also negatively impact the accuracy of PV power forecasts (Chicco et al., 2016). It is clear that more research on CE effects can help the rapid penetration of variable PV power generation into electric grids, and can support the developing interest for safety, durability, and optimal design of PV power plants.

In parallel to CE effects, spatial or temporal variations in surface albedo can also affect the incident diffuse horizontal irradiance (DIF) component of global horizontal irradiance (GHI). The underlying backscattering process has been studied primarily for UV radiation (Parisi et al., 2003). In the past, this process has been investigated mostly because it triggers higher-than-usual surface UV levels, a phenomenon sometimes referred to as "UV enhancement" (Simic et al., 2011; Weihs et al., 1999). Complex interactions exist between clouds and surface albedo, particularly when the latter is spatially inhomogeneous (Degünther and Meerkötter, 2000a, b; Huber et al., 2004; Schmucki et al., 2001). Situations of high surface albedo, usually caused by snow cover, have also been shown to impact the diffuse fraction (Gueymard and Ruiz-Arias, 2016; Hay, 1976; Kierkus and Colbrone, 1989). Such situations, where the diffuse component is significantly increased compared to low-albedo conditions, are referred to as *albedo enhancement* (AE) in what follows.

Part 1 of this contribution is aimed at a better understanding of the general features of the CE and AE effects, and how they relate to transient effects during which GHI can be unusually large. In Part 2, further investigation is conducted into the effects of rapid fluctuations in GHI on the modeled global tilted irradiance (GTI) due to CE and/or AE. Even though most of the literature so far has focused on the CE effects on just GHI, the ramping effects on inverters and PV power output are actually dependent on GTI rather than GHI, since the vast majority of solar panels are not installed horizontally. This justifies the additional analyses conducted in Part 2. In both parts, a mostly experimental approach is followed, like in most contributions so far—with a few notable exceptions such as (Pecenak et al., 2016), (Thuillier et al., 2013), or (Yordanov, 2015) in recent years—with, however, an original long-term perspective through the use of a decadal time series of irradiance and cloud data.

2. Terminology, definitions, and physical explanation of enhancement processes

2.1. Literature survey

The literature shows that there is still no precise terminology or definition for the CE concept. Synonymous terms are frequently employed in the current literature, such as "cloud lensing" or "overirradiance". Historically, other terms have also been employed, such as "silver lining" (Norris, 1968), as well as "super irradiance", "cumulus solar-irradiance reflection", "cloud gap effect" (Gu et al., 2001), or more recently "cloud edge" (Wirth et al., 2015), "irradiance spikes caused by broken clouds" (Chicco et al., 2016), and "irradiance enhancement" (Pecenak et al., 2016).

In addition to this confusing terminology, there is no well-accepted definition of the phenomenon. For instance, Quiroz and Cameron (2012) provide this very succinct definition:

> "Cloud enhancement: Reflections off cloud edges."

Similarly, the online Perkin-Elmer Glossary of Terms [http://www.perkinelmer.com/Content/RelatedMaterials/Solar-Energy-Glossary-of-Terms.pdf] suggests:

> "Cloud enhancement: The increase in solar intensity caused by reflected irradiance from nearby clouds."

A more detailed definition (albeit not necessarily better) is offered by Balfour and Shaw (2011):

> "Cloud lensing results when atmospheric moisture acts like a magnifying lens. This commonly occurs at the leading edge of a cloud. Cloud lensing focuses the solar input irradiance for a few seconds, boosting power by as much as 30 percent."

Almost 50 years ago, Norris (1968) commented that:

> "Evidence has been obtained that with broken cumulus clouds reflections from them may increase the amount of radiation reaching the Earth's surface to more than that which would be received on a clear day."

A similar statement was made more recently (Zehner et al., 2010):

> "Increased irradiation values are mainly caused by reflection on cumulus clouds".

Later on, (Zehner et al., 2011) refined this definition, while still focusing on the role of cumulus clouds:

> "The enhanced values for global irradiance mainly originate from the reflections of light waves from cumulus clouds. These clouds appear as isolated, consistently thick clouds forming cotton-wool shapes in the vertical plane."

The above definitions attempt to explain the causing factors, but might not be general enough. For instance, for the case of UV radiation, David Schoonmaker [http://www.americanscientist.org/issues/pub/sunshine-on-a-cloudy-day] comments that

> "Several studies suggest that reflection off the sides of cumulus clouds is one mechanism by which UV radiation can become focused. Sabburg and Joe Wong (...) have also postulated that refraction and scattering of direct and diffuse radiation could result in markedly increased enhancement. Thus cloud condi-

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