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Use of satellite data to determine the cloud optical depths present during overirradiance conditions

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Abstract. Overirradiance conditions can negatively impact the operation of photovoltaic systems if no protective measures have been implemented, leading to potential damages and economic losses in photovoltaic generation plants. Current simulation models attempt to understand the mechanism of overirradiance conditions. However, their observations still differ significantly from experimental ones, emphasizing the need to better understand the two main hypotheses that account for overirradiance events: reflection at the edges of thick clouds and Mie scattering in thin clouds. This paper studies the qualitative correlation between the global tilted irradiance measured by a spectroradiometer on the surface and the optical depth of the clouds measured by the GOES-16 satellite to shed more light on this phenomenon. Our results show a good qualitative correlation between the global tilted irradiance and the optical depth of the clouds present during overirradiance events. We also show that all overirradiance conditions occurred when thick clouds were present. These results indicate that the overirradiance events analyzed have been produced predominantly by reflections at the edges of thick clouds, supporting the hypothesis that the increase in global irradiance is mainly due to a substantial increase in direct irradiance.

1. Introduction

The potential for overirradiance (OI) conditions to compromise photovoltaic systems has gained increasing attention within the photovoltaic community, as evidenced by a growing body of literature [1–6]. Conditions of high irradiation and prolonged exposure have been documented across the globe [7–11], yet investigations into their origins remain insufficient.

In 1968, Norris first posited that irradiance levels at the Earth's surface could surpass expected values under clear sky (CS) conditions, attributed to solar irradiance reflections from the sides and edges of fragmented clouds [12]. Over four decades later, Yordanov et al. suggested that OI conditions could also result from intense direct Mie scattering within thin clouds, characterized by cloud optical depths (COD) less than 3 [13–15]. A notable OI event, peaking at 1.6 kW/m² in Grimstad, southern Norway, was documented by Yordanov et al. in 2015, linked to disintegrating thin altocumulus clouds around the solar disk [16].

Despite these observations, the physical mechanisms underpinning OI phenomena remain largely unexplored. It is established that such events invariably occur in the presence of clouds, regardless of



whether they are thick ($COD \geq 3$) or thin. Consequently, researchers have devised simulation models, including the renowned Monte Carlo radiative transfer model, to probe the causes and mechanisms behind OI [17,18]. Nevertheless, these models have struggled to align with empirical observations.

Recent studies have also delved into the effects of CS, OI, and cloudy sky (Clo) conditions on spectral distribution, revealing a blueshift under Clo conditions and a redshift during OI events compared to CS conditions [19–21]. The average photon energy (APE) has been analyzed to gauge its impact on spectral distribution, given its significance as a spectral irradiance distribution index [22–26]. Zamalloa-Jara et al. [21] reported a modest redshift in the APE of about 8 meV under OI conditions in three cities: Lima, Madrid, and Berlin, suggesting that OI-inducing processes are consistent and independent of geographic location. The findings indicate that OI predominantly stems from an increase in direct rather than diffuse irradiance, as inferred from the observed slight redshift.

Nonetheless, the availability of irradiance sensor data, especially spectral data, is relatively limited on a global scale, in stark contrast to satellite meteorological data. This scarcity hampers efforts to accurately assess the global impact and frequency of OI conditions. Alternatively, the COD obtained from satellite data can potentially help understand the origin of OI conditions and predict their occurrences.

Therefore, this study examines the qualitative relationship between COD and global tilted irradiance (GTI) on days with observed OI conditions in Lima, Peru. COD, a dimensionless measure, quantifies the diminution of light or energy transmitted through clouds due to cloud particle interactions. The COD for this study is obtained from the GOES-16 geostationary satellite, while the GTI has been calculated from the spectral irradiance measured by a calibrated spectroradiometer in Lima, Peru.

2. Methodology

A class A spectroradiometer EKO MS-711 was used to measure the solar spectral irradiance at 300 nm - 1100 nm. This instrument is located in Lima (-12.07° , -77.08°), has a tilted angle of 20° due north, and is part of the Photovoltaic Research Laboratory of the Pontifical Catholic University of Peru. Days with CS, Clo, and OI conditions were analyzed. From May 2019 to May 2021, 17 days were identified for this analysis. To estimate the global tilted irradiance (GTI) spanning from 280 nm to 4000 nm in watts per square meter (W/m^2), two extrapolation methods were applied for the ultraviolet (UV) and infrared (IR) spectra, enabling the classification of the observed conditions into CS, Clo, and OI, following the methodology described by Zamalloa-Jara et al. [21].

The COD data were acquired from the GOES-16 satellite, a geostationary meteorological satellite managed by the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA). The satellite is equipped with the Advanced Baseline Imager (ABI), capable of capturing Earth's full-disk images every 10 minutes at a maximum spatial resolution of 2 km. The ABI features 16 spectral bands, encompassing two in the visible spectrum, four in the near-infrared, and ten in the infrared, facilitating detailed observation of Earth and its atmosphere.

The reduction of the light or energy transmitted through the cloud due to the interaction of the cloud particles yields the COD using the equation [27]:

$$Transmission = e^{-COD} \quad (1)$$

In this context, clouds are categorized as thin with a COD of less than 3 and thick with a COD greater than or equal to 3. COD information can be accessed via the Archive Information Request System (AIRS), which delivers data to researchers' e-mails. Each data file comprises an image capturing 10 minutes of Earth observation, enabling the extraction of COD at specified latitudes and longitudes. Images are provided in netCDF4 format, which can be processed using Python, and are timestamped in Universal Time Coordinated (UTC), necessitating conversion to local time for alignment with Lima's time zone (GMT-5). This conversion allows for the overlay of GTI and COD data on a time scale based on Lima's local time. For instance, Figure 1 displays a COD image of Earth observed by GOES-16 on

March 23rd, 2020, from 17:50 to 18:00 UTC. Each pixel in the image corresponds to a specific COD value. To analyze COD, one must utilize the GOES package and the netCDF4 library in Python, inputting the necessary longitude and latitude - in this case, the precise coordinates where the spectroradiometer is located in Lima. The file size for each image is approximately 7 MB, and around 67 files may be required to cover a single day's data.

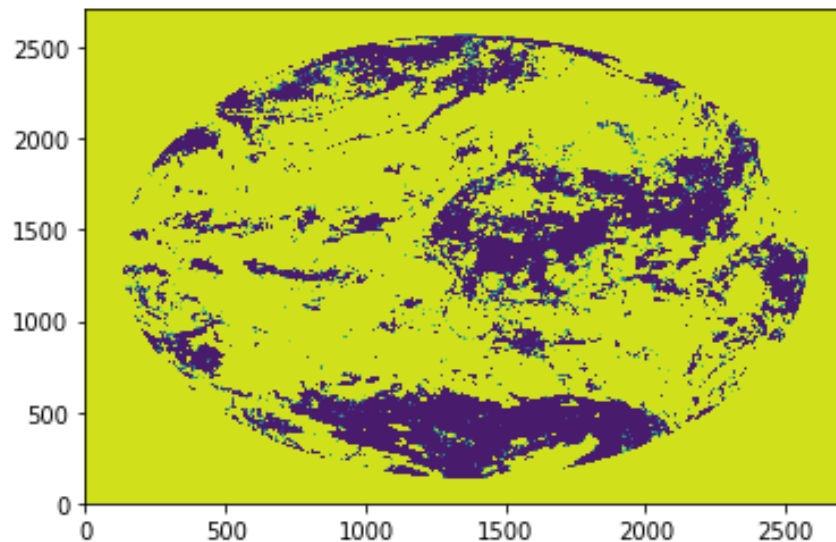


Figure 1. COD from GOES-16 for March 23rd, 2020, between 17:50 and 18:00 UTC.

3. Results and discussion

Our investigation explored the qualitative correlation between COD and GTI during overirradiance events across a two-year monitoring period. Figure 2 presents GTI and COD data over time for selected days, showcasing CS, OI, and Clo conditions. Each instance depicted in Figure 2 is annotated with its date, including the year and the day of the year in parentheses, aligning with the GOES-16 satellite's recording system where day 001 represents January 1st and day 365 December 31st.

By overlaying COD and GTI data, we observed a notable qualitative correlation between these variables. This relationship is pivotal for understanding the type of clouds present during OI conditions and determining their thickness. Identifying whether the clouds during OI events are thick ($COD \geq 3$) or thin ($COD < 3$) aids in attributing the OI to either cloud edge reflections (associated with thick clouds) or forward Mie scattering (associated with thin clouds).

From the data illustrated in Figure 2, OI conditions invariably occurred in the presence of thick clouds ($COD \geq 3$), suggesting that these incidents are most likely due to reflections off the edges and sides of fragmented clouds surrounding the sun. Consequently, we can deduce that the increase in global irradiance primarily stems from its direct component, leading to a slight redshift of approximately ~ 8 meV, a phenomenon consistent across various latitudes as evidenced by Zamalloa Jara et al. [21].

Interestingly, CS conditions were typically associated with a near-zero COD. For instance, in Figure 2(c), we note that even with thin clouds averaging a COD of 1.5, the irradiance levels corresponded to CS conditions without indicating OI events during those intervals. The reason for this discrepancy may be the spatial resolution of the COD data of 2 km, indicating that during the observed periods of CS, thin clouds may have been present in the satellite's observed pixel but without covering the spectroradiometer.

Nevertheless, within the scope of this study, the OI events were all detected in the presence of thick clouds, giving no clear indication for Mie scattering for the conditions and dataset analyzed. Furthermore, across all instances of OI conditions depicted in Figure 2, irradiance variations were noted to be several hundred W/m^2 , suggesting the presence of thick, fragmented clouds between the solar disk and the spectroradiometer.

Consequently, our analyses suggest that reflections at the edges of thick clouds predominantly caused the observed OI conditions, implying that the observed increase in irradiance can be attributed to an amplification of the direct irradiance component.

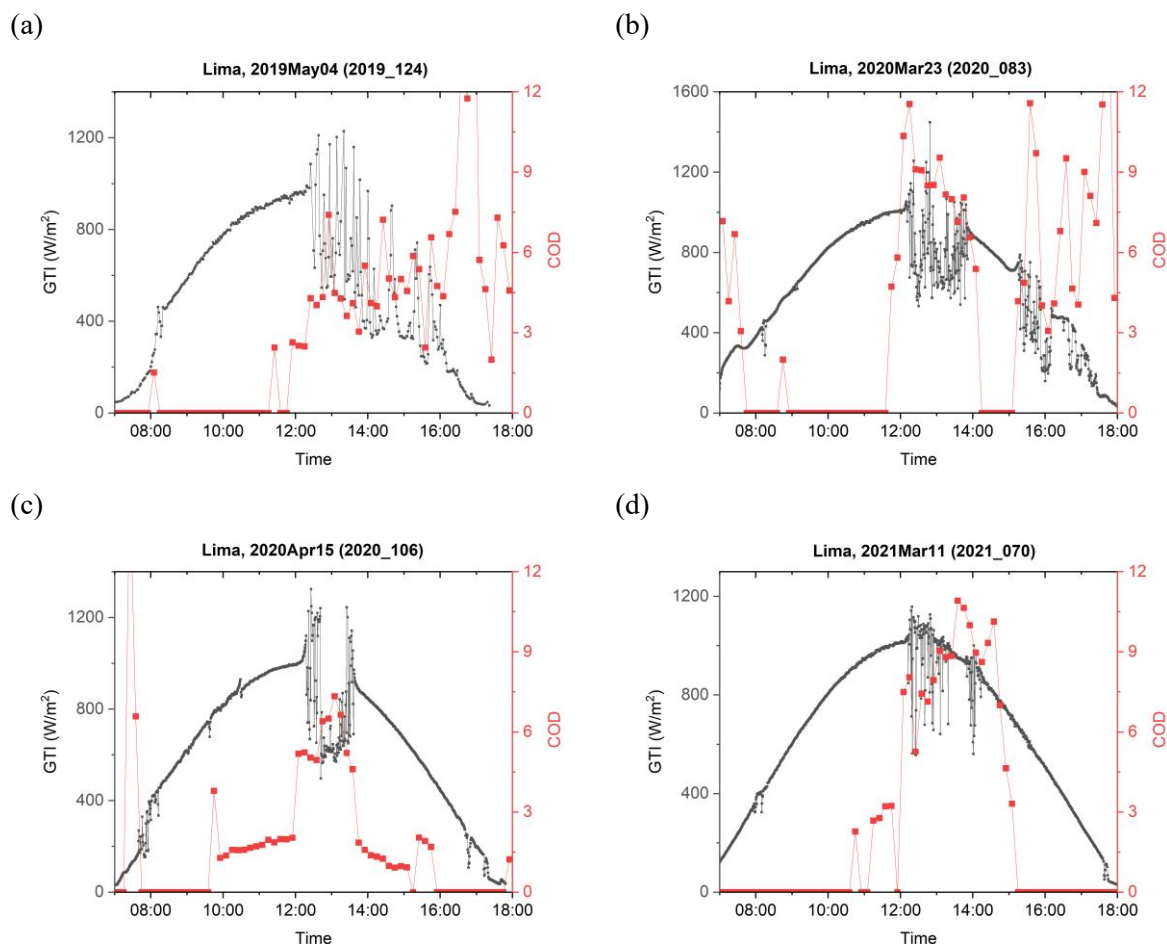


Figure 2. GTI and COD as a function of local Time for some days in Lima between May 2019 and May 2021.

4. Conclusions

This study explored the qualitative correlation between GTI and COD in Lima, Peru, focusing on days with reported overirradiance conditions as documented by Zamalloa Jara et al. [21]. Our findings indicate a qualitative correlation between GTI and the COD of clouds present during overirradiance events. The COD data provided by the GOES-16 satellite, despite its 2 km resolution, successfully correlates with ground-based experimental observations.

Analysis of COD on days experiencing overirradiance revealed the predominant presence of thick clouds. These observations lead us to conclude that the overirradiance events we analyzed are primarily

caused by reflections off the edges of these thick clouds, resulting in a significant increase in direct irradiance.

To further validate this conclusion, we recommend that future research endeavors include simultaneous measurements of direct, diffuse, and global irradiance combined with sky images and COD data for multiple locations. Such comprehensive data collection would enable a more detailed analysis, potentially confirming the hypothesis that overirradiance events are significantly influenced by the interplay between direct irradiance and the reflective properties of thick cloud edges. Finally, a more widespread correlation analysis between COD and OI conditions with more data from multiple locations would potentially allow for predicting worldwide OI occurrences solely based on satellite data.

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