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Review

Short-term solar irradiance forecasting via satellite/model coupling

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A R T I C L E I N F O

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A B S T R A C T

The short-term (0–3 h) prediction of solar insolation for renewable energy production is a problem well-suited to satellite-based techniques. The spatial, spectral, temporal and radiometric resolution of instrumentation hosted on the geostationary platform allows these satellites to describe the current cloud spatial distribution and optical properties. These properties relate directly to the transient properties of the downwelling solar irradiance at the surface, which come in the form of 'ramps' that pose a central challenge to energy load balancing in a spatially distributed network of solar farms. The short-term evolution of the cloud field may be approximated to first order simply as translational, but care must be taken in how the advection is handled and where the impacts are assigned. In this research, we describe how geostationary satellite observations are used with operational cloud masking and retrieval algorithms, wind field data from Numerical Weather Prediction (NWP), and radiative transfer calculations to produce short-term forecasts of solar insolation for applications in solar power generation. The scheme utilizes retrieved cloud properties to group pixels into contiguous cloud objects whose future positions are predicted using four-dimensional (space + time) model wind fields, selecting steering levels corresponding to the cloud height properties of each cloud group. The shadows associated with these clouds are adjusted for sensor viewing parallax displacement and combined with solar geometry and terrain height to determine the actual location of cloud shadows. For mid/high-level clouds at mid-latitudes and high solar zenith angles, the combined displacements from these geometric considerations are non-negligible. The cloud information is used to initialize a radiative transfer model that computes the direct and diffuse-sky solar insolation at both shadow locations and intervening clear-sky regions. Here, we describe the formulation of the algorithm and validate its performance against Surface Radiation (SURFRAD; Augustine et al., 2000, 2005) network observations. Typical errors range from 8.5% to 17.2% depending on the complexity of cloud regimes, and an operational demonstration outperformed persistence-based forecasting of Global Horizontal Irradiance (GHI) under all conditions by ~10 W/m^2.

1. Introduction

Ephemeral cloud cover (e.g., fair-weather cumulus fields) presents a key challenge to the generation of power using photovoltaic (PV) and concentrated solar power (CSP) systems distributed worldwide. Cloud shadows reduce the direct beam solar irradiance significantly and modulate the diffuse-sky radiation distribution as well, impacting the overall global horizontal irradiance (GHI) available for renewable energy production. The rapid, high-amplitude fluctuations to the available solar energy at the surface that result from shadow passage are referred to in the power and energy industry as 'ramps.' These ramps have a marked impact on power generation efficiency at multiple space and time scales (Perez et al., 2016a).

The high variability of the solar resource, caused principally by ramps of various strength and intervals, are tied to the macro- and microphysical properties of the intervening cloud cover. A surface/satellite perspective on broken cumulus clouds, most often associated with complex ramping behavior, is shown for an example over the Colorado Front Range in Fig. 1. In this case, an approximately 700 W/m^2 increase (upward ramp) of solar irradiance corresponds to a break in the optically thick, broken cloud cover formed by sporadic afternoon thunderstorms. The solar radiation subsequently drops by a similar amount as a downward ramp upon the arrival of shadows from clouds to the southwest.

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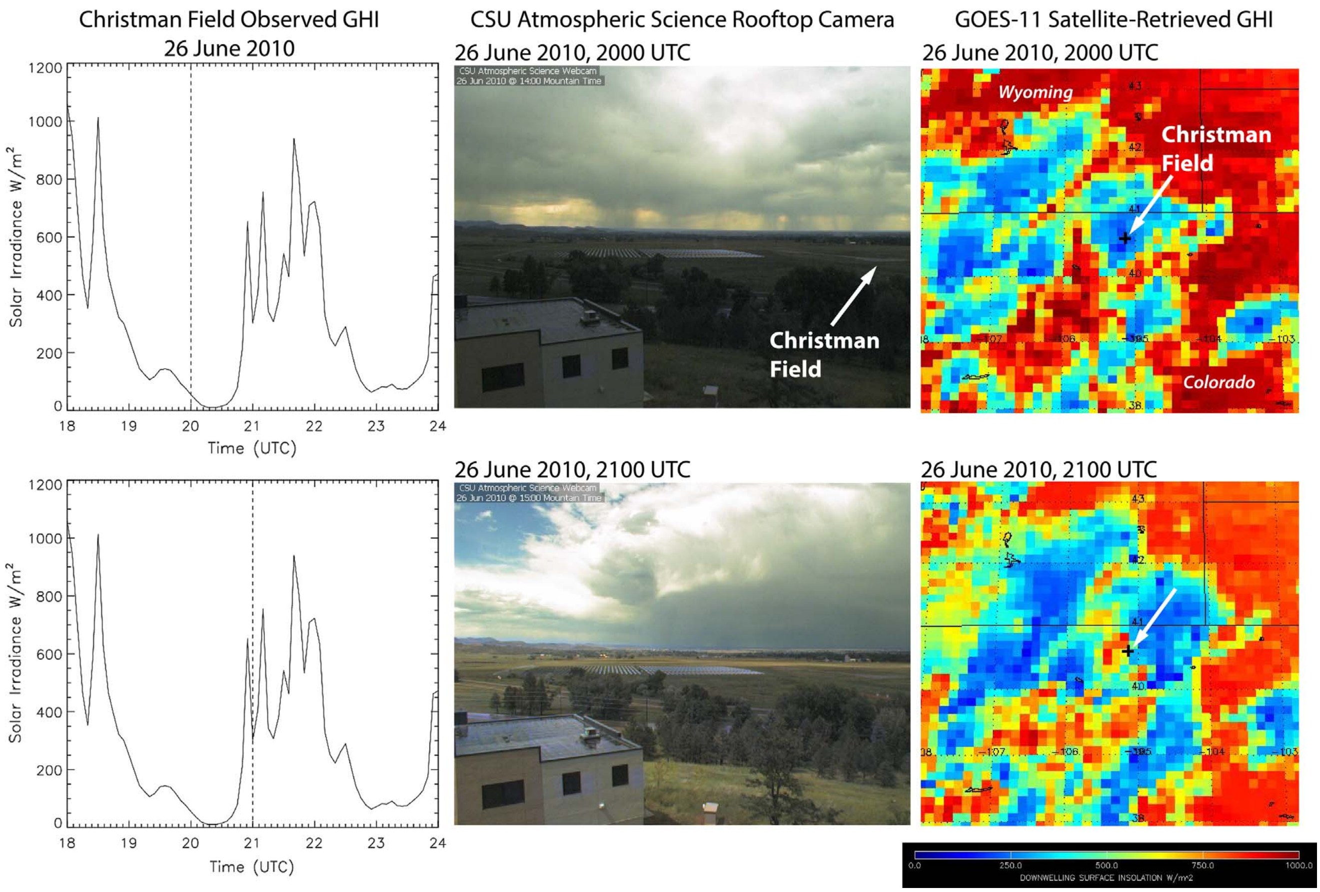

Fig. 1. Example of a solar irradiance ramping event as measured from the surface and satellite for a case at Christman Field, Ft. Collins, CO on 26 June 2017 at 2000 UTC (top row) and 2100 UTC (bottom row). The left, center, and right columns show (respectively) (i) time-matched GHI from a pyranometer located at Christman Field, Ft. Collins, CO (vertical dashed lines denote the 2000 and 2100 UTC times corresponding to the photos and satellite data), (ii) observations from a north/northwest (335° azimuth, 64° field of view) viewing rooftop camera, and (iii) GOES-11 satellite-retrieved estimates of GHI (blue regions correspond to thick clouds, orange/red regions correspond to clear-sky, and the location of Christman Field denoted by white arrow).

Optimal integration of PV and CSP systems into a power grid requires advanced knowledge of both the general likelihood and specific timing of ramps. Accurate ramp prediction requires in turn an accuracy in identifying and predicting the motion of clouds, and specifically the locations and magnitude of their shadows. Addressing this need both probabilistically and deterministically in the short-term forecast time horizon (e.g., 0–7 h) provides solar energy suppliers with information critical in supporting decisions on load balancing and transmission switching in a spatially distributed network, dispatching energy at optimal times, and facilitating the overall penetration of solar power on the electric grid.

There exist several methods for forecasting cloud impacts to solar energy (referred to here as radiation falling between the wavelength range of 290 nm–3 μm, which accounts for ~97% of the total energy; Sengupta et al., 2015), each optimized to a specific spatial and temporal scale (Diagne et al., 2013). Observational techniques at short time windows are better suited to describing the current distribution of clouds and cloud properties deterministically, leading to better short-term forecasts of ramps predicated on the continuity and simple advection of this field. At temporal scales of 0–0.5 h, information from persistence (Lee et al., 2017), giving way to surface-based all-sky camera networks (Kleissl et al., 2010; Chow et al., 2011), provide the most accurate predictive capability. At intra-day forecast timeframes of ~0.5 to 3 h, airborne or satellite-based platforms provide a useful description of clouds that reside beyond the local horizon view of surface-based networks. The skill associated with forecasting simple (non-evolving) cloud field advection via observed or model-supplied motion vectors depends on the cloud type and meteorological regime. At multi-hour to day-ahead timeframes, observation-based methods give way in skill to Numerical Weather Prediction (NWP) based systems (Inman et al., 2013). At these longer time horizons, the cloud field is best described by atmospheric dynamics and thermodynamics which drive cloud formation, dissipation, and cloud microphysical evolution rather than advection of the initially observed cloud field.

Environmental satellites have measured solar energy reflected from the earth/atmosphere system for many decades (Vonder Haar et al., 1973), and satellite-based methods for solar energy forecasting and resource assessment are now very well established (Miller et al., 2013). Empirical methods (e.g., Tarpley, 1979; Cano et al., 1986; Schmetz, 1989; Perez et al., 2002) relate satellite observations of cloud reflectance to atmospheric transmittance. Specifically, ground-based measurements of the minimum and maximum observed GHI are related linearly to a normalized cloud index derived from the satellite reflectance data. Physical methods (e.g., Gautier et al., 1980; Diak and Gautier, 1983; Dedieu et al., 1987; Darnell et al., 1988) enlist radiative transfer modeling to retrieve the surface radiation field directly from the satellite observations. Typical RMSE for satellite-based global hourly radiation assessment is 17–25% (Polo et al., 2008). The main sources of error reside in microscale variability of the radiation field, caused by cloud shadows (Zelenka et al., 1999).

The focus of this paper is on improving satellite-based solar forecasting techniques of cloud-induced solar energy ramps over time scales that help to bridge the gap in capabilities between the near-casting (persistence and all-sky camera systems) and forecasting (i.e., NWP) regimes. As mentioned above, determination of the mesoscale cloud distribution and tracking its motion via advection techniques is tailored