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Characterization of surface solar-irradiance variability using cloud properties based on satellite observations

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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 variation in surface solar irradiance (SSI) on short timescales has been investigated previously in relation to ground-based observations. Such results are limited to the locality of the observation stations, leading to insufficient knowledge about the spatial distribution of variation features. We propose a method for characterizing variations in SSI using cloud properties obtained from satellite observations. Datasets of cloud properties from satellite observation and SSI from ground-based observation are combined at simultaneous observation points to investigate their relations. The SSI variations are classified statistically into six categories. The cloud properties related to the categorized variation features are then analyzed. From such relations, a statistical discriminant method is used to design a classifier to assign a category to the SSI variation over an area from the cloud properties obtained by satellite observation. The accuracy of classification and feature selection is discussed.

1. Introduction

Solar energy is expected to be part of the solution to the problem of global warming. Variation in solar irradiance at ground level causes fluctuation in the power output from solar power systems, which is a disadvantage of generating power that way. This work focuses on variation over timescales of no more than a few hours, which is caused mainly by clouds. The effects of aerosol and water vapor are also important, but these contribute primarily to slower variation over more than a few hours. Variation in surface solar irradiance (SSI) occurs in two ways: interception by clouds between observation stations and the sun, and reflection and scattering by cloud particles.

Observation using ground-based equipment is the main method for obtaining temporal resolutions shorter than a few minutes. An advantage of ground observations is that they can allow continuous high-temporal-resolution data at a single position. However, they are disadvantaged by their narrow (and thus limited) field of view. In contrast, satellite observations provide a large field of view, but the frequency of observations over a single location is lower than that with ground-based observation, and spatial resolutions are also coarser. However, satellite observations also provide information about cloud properties. Combining ground and satellite observations should therefore be a good way to investigate the relation between clouds and SSI.

Some metrics relevant to SSI are used to analyze its short-term variation. Lave and Kleissl (2010) and Lave et al. (2012) analyzed the ramp rate (RR) to investigate geographic smoothing effects. The RR is defined as the change in magnitude of solar irradiance over a given period. Tomson and Tamm (2006) investigated the stability of SSI by using absolute values of its increments for given periods. Woyte et al. (2007) applied wavelet spectrum analysis to classify fluctuations in solar irradiance. Watanabe et al. (2016) used three metrics—the mean, standard deviation, and sample entropy—to evaluate regional features of variation in SSI over Japan.

The relation between SSI and clouds has also been investigated using metrics related to SSI. These studies are based fundamentally on measurements of solar irradiance at ground level integrated with cloud effects. Duchon and O'Malley (1999) used a 21-min window mean of solar-irradiance data with 1-min resolution and the corresponding standard deviation to develop a method for classifying cloud type according to these two metrics. Ornisi et al. (2002) also proposed cloud classification using metrics similar to those used by Duchon and O'Malley (1999) and improved the classification accuracy. Martínez-Chico et al. (2011) performed cloud classification by considering an index for direct solar irradiance at the ground. Their index is defined as the ratio of direct solar irradiance to extraterrestrial irradiance. Pages et al. (2003) classified cloud type using temperature, wind speed, and air relative humidity data in addition to solar-irradiance data.

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Previous work has thus deepened our understanding of SSI variation. However, the results of these studies are based mainly on analyses using ground-based observation data of the area around observation stations, leading to insufficient knowledge about the spatial distribution of variation features. This work aims at filling such gaps. We first investigate the relation between SSI variation and cloud properties from satellite observations. We then characterize the SSI variability by cloud properties. By applying such relations, we propose a method for estimating the variability of SSI using cloud properties as retrieved from satellite observation. The spatial distribution of the variability will contribute to new understanding of the surface solar variation and aid the development of applications to solar energy engineering. For example, the operators of a grid system could anticipate likely regions of strong variability and consider alternative operational measures. Seasonal and regional features of SSI variation would also be useful support information when planning to construct solar power plants.

We used the Moderate Resolution Imaging Spectroradiometer (MODIS) cloud products for the analysis in this study. Cloud properties from MODIS data are available for long periods. However, only one or two images can be obtained in a day for any particular location. This is a disadvantage in solar energy engineering. Recently a new-generation geostationary meteorological satellite, HIMAWARI-8 of the Japan Meteorological Agency (JMA), was launched and is now in service (Bessho et al., 2016). Other such satellites (e.g., GOES-R of NOAA/NASA, Meteosat Third Generation (MTG) of EUMETSAT) are scheduled for launch in the next few years (Mohr, 2014). These will have more observation bands and higher observation frequencies than previously launched geostationary satellites. Abundant information about cloud, aerosol, and solar irradiance will be obtained from geostationary meteorological satellite observation. At present, practical applications based on using MODIS data in solar energy engineering may be limited, but we expect that in the future the proposed approach can be applied to cloud products based on geostationary satellite observation.

The remainder of this paper is structured as follows. Sections 2 and 3 describe our data and methods, respectively. Section 4 describes the processing of data from ground- and satellite-based observations for analysis. Section 5 discusses cloud properties in relation to variations in SSI. Section 6 develops a method for classifying SSI variability that is designed using statistical discriminant methods. Section 7 discusses and summarizes this work.

2. Data

2.1. Surface solar irradiance

We use existing SSI data from Japan. The JMA maintains ground-based observation stations and performs quality control and routine maintenance of their equipment. Solar irradiance is defined as the total radiation measured over 1 min of data sampled at 10 s intervals, and its temporal interval is 1 min. Pyranometers were replaced at most stations in the middle of 2011 (Ohtake et al., 2015). Forty-seven observation sites are selected based on availability of solar irradiance data for the five years from 2010 to 2014. Data mainly from six observation stations in the Kanto region, which is on the Pacific side of eastern Japan (Fig. 1) are ana-

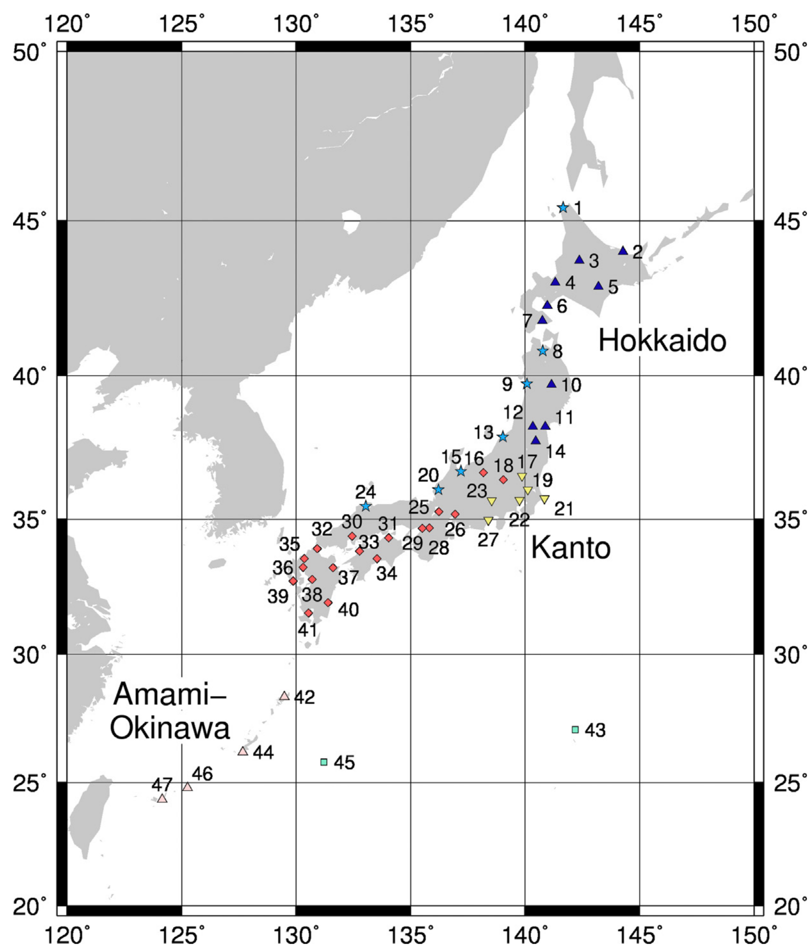

Fig. 1. Observation stations throughout Japan. Stations 17, 19, 21, 22, 27, and 27 are located in the Kanto region. Colors and marks indicate classes with similar variation features, as determined by Watanabe et al. (2016).