# RELATING SOLAR RESOURCE VARIABILITY TO CLOUD TYPE

Laura M. Hinkelman
University of Washington
P.O. Box 355672
Seattle, WA 98195-5672
e-mail: laurahin@uw.edu

Andrew Heidinger
NOAA/NESDIS Center for Satellite Applications and Research
Madison, WI 53706
e-mail: heindinger@ssec.wisc.edu

Manajit Sengupta
Aron Habte
National Renewable Energy Laboratory
1617 Cole Blvd., MS-5202
Golden, CO 80401
e-mail: Manajit.Sengupta@nrel.gov
e-mail: Aron.Habte@nrel.gov

ABSTRACT

In this paper we examine the characteristics of irradiance ramps produced by clouds of different types. Clouds are identified over several irradiance measurement sites using satellite images. These sites have been chosen to represent a number of climatological regions in the continental United States. 60-s ramps computed from the measurement time series are matched to the cloud types and the aggregated pools of data are characterized. The frequency of occurrence of each cloud type is found to differ among stations. However, the characteristics of the ramp distributions for the cloud classes are distinct and relatively stable.

## 1. INTRODUCTION

In recent years there has been an increase of power production from renewable energy (RE) resources. These RE sources generally have variable generation as solar and wind resources, which form the inputs, are themselves inherently variable. This explosion in variable generation has resulted in a need to understand the impact of renewable generation on the transmission grid. Especially important are studies that try to understand the impact of a high level of renewables on the grid. Satellites are the best source of long-term solar data in most locations. As satellite-based solar resource datasets are generally available at lower temporal and spatial resolution than required, there is, in turn, a need to downscale these resource data for use in transmission studies.

Downscaling in both space and time requires information about variability in the solar resource that is primarily a function of cloud type and properties. In this project, we analyze the relationship between solar resource variability and satellite-based cloud properties. High-resolution surface solar irradiance data at one-minute resolution were obtained from the National Oceanic and Atmospheric Administration (NOAA) Surface Radiation (SURFRAD) network. Cloud information has been derived from NOAA's Geostationary Operational Environmental Satellite (GOES) series of satellites. These cloud property data are available at a nominal 4 km resolution every half hour. Using this data, we study the variability of the ground data sets under various cloud conditions and derive relationships between variability in measured solar irradiance and cloud types and properties.

## 2. DATA SETS

### 2.1 Ground Measurements

Solar irradiance data for several diverse locations was obtained from the NOAA SURFRAD network (1). The locations of these sites are shown in Figure 1. These locations include sites near mountains, in a desert, on the northern Great Plains, and in midlatitude agricultural areas in the northeastern and central United States. Each of these areas is affected by different weather patterns, allowing us to study irradiance variability under a range of cloud conditions.

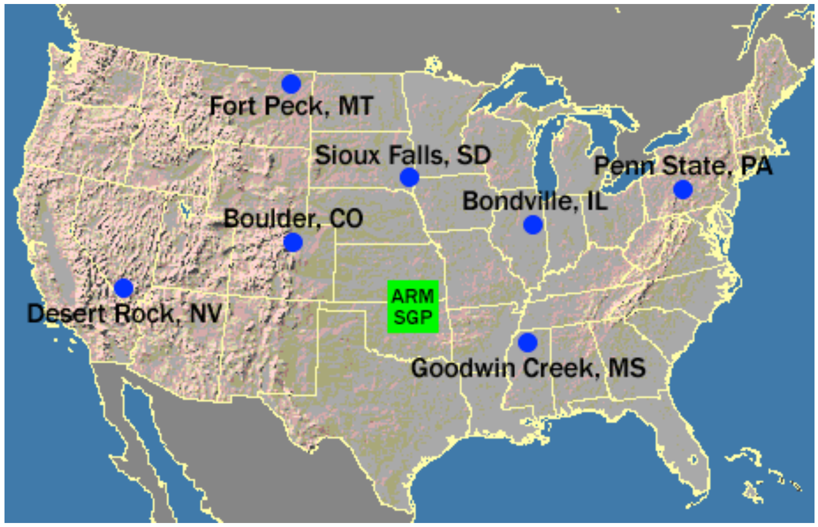


Fig. 1: Map of the continental United States showing the locations of NOAA's SURFRAD measurement sites.

Global horizontal irradiance (GHI, or total hemispheric irradiance) values were provided as 1-minute averages. The pyranometers used for these measurements are of the highest quality. SURFRAD measurements were made with Eppley Precision Spectral Pyranometers (PSPs, ISO first class radiometers) that are calibrated annually.

### 2.2 Satellite Data

Radiances from NOAA's GOES-East and GOES-West satellites were processed to provide a variety of cloud-related parameters including probability of cloud, qualitative cloud type, cloud amount, optical depth, and cloud phase, among others. Of these, the cloud types are most central to this study. These categories are listed in Table 1. Together, GOES-East and GOES-West cover the entire continental United States, thus including all of the SURFRAD measurement sites. The data was processed at a 4 km resolution for the year 2009. The temporal resolution is half-hourly.

## 3. FREQUENCY OF OCCURRENCE OF CLOUD TYPES AT SURFRAD LOCATIONS

Before addressing the characteristics of solar irradiances under different cloud conditions, we first investigated how often the different cloud types are observed in the vicinity of each measurement station. We compiled the frequency of occurrence of each cloud type over an area of approximately 160 km$^2$ (10-16 km on a side) centered on each station. The resulting distributions are shown in Figure 2.

Most of the distributions are similar, with clear skies being the most common, followed by supercooled liquid water and cirrus (thin ice clouds). Desert Rock stands out as having by far the most clear samples, and the least occurrences of cirrus and supercooled liquid clouds. Obviously this is due to its location in an arid region. The cloud distribution at Table Mountain also stands out. This site is outside of Boulder, Colorado, and is bounded by mountains to the upwind (west) side and dry plains to the east. The proportion of times with clear skies is surprisingly low, but is compensated for by unusually high amounts of mixed phase and opaque ice clouds. The frequency of occurrence of supercooled liquid clouds is lower than most. These clouds have likely been bumped up into the mixed phase and opaque ice categories because they rose to colder elevations when passing over the mountains. Most of the other distributions are similar. The range of occurrences is greatest for supercooled liquid clouds and the cloudiest location is Penn State (State College), Pennsylvania.

Table 1. Cloud type categories from GOES data.

| Category | Description |
|---|---|
| 0 | Clear |
| 1 | Probably clear |
| 2 | Fog |
| 3 | Water |
| 4 | Supercooled water |
| 5 | Mixed ice and water |
| 6 | Opaque ice |
| 7 | Cirrus |
| 8 | Overlapping |
| 9 | Overshooting |
| 10 | Unknown |
| 11 | Dust |
| 12 | Smoke |

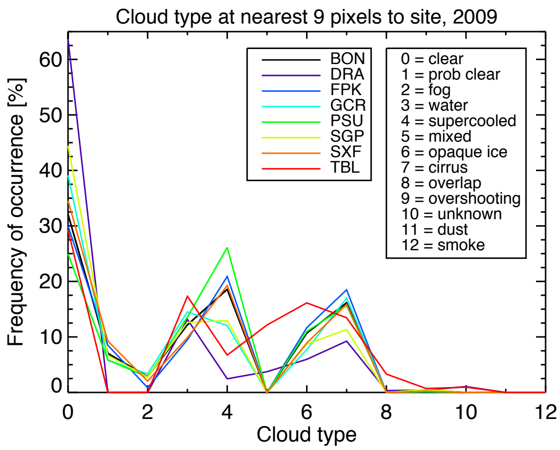


Figure 2. Distribution of cloud types occurring near each site during the course of 2009.

## 4. RAMP STATISTICS AS A FUNCTION OF CLOUD TYPE

Ramps were computed as the difference between consecutive 1-minute mean irradiances over the entire year of 2009 at all of the measurement sites. Nighttime samples and those with a solar elevation angle less than 5° were not included in these computations. These values were then matched to the times of the satellite observations. Since the satellite observations occurred every 30 minutes, 30 ramps were assigned to each observation, 15 before and 15 after this time. The ramp values were then aggregated over each cloud type at each location.

Example distributions of the ramps computed for the cloud types common to all locations are shown in Figure 3. We first note that, indeed, the characteristic irradiance variability does depend on the cloud conditions. Usually the ramps are smallest in the presence of opaque ice clouds and largest under fog. The cirrus (thin ice), supercooled, and liquid clouds fall in between. The results for the supercooled and cirrus clouds are often quite similar. At Fort Peck, the ramp distributions for fog or liquid clouds are also similar. Taken together, these results show that different cloud types do affect the incoming solar irradiance differently and that, while there are some differences from site to site, the relative variability of the ramps produced by the different cloud types is stable.

We characterize the ramp distributions by looking at the largest absolute ramp values, which are of greatest significance in power plant operations. For each distribution, we identify the absolute value within which 95% of the ramps fall, or, alternatively, beyond which 5%

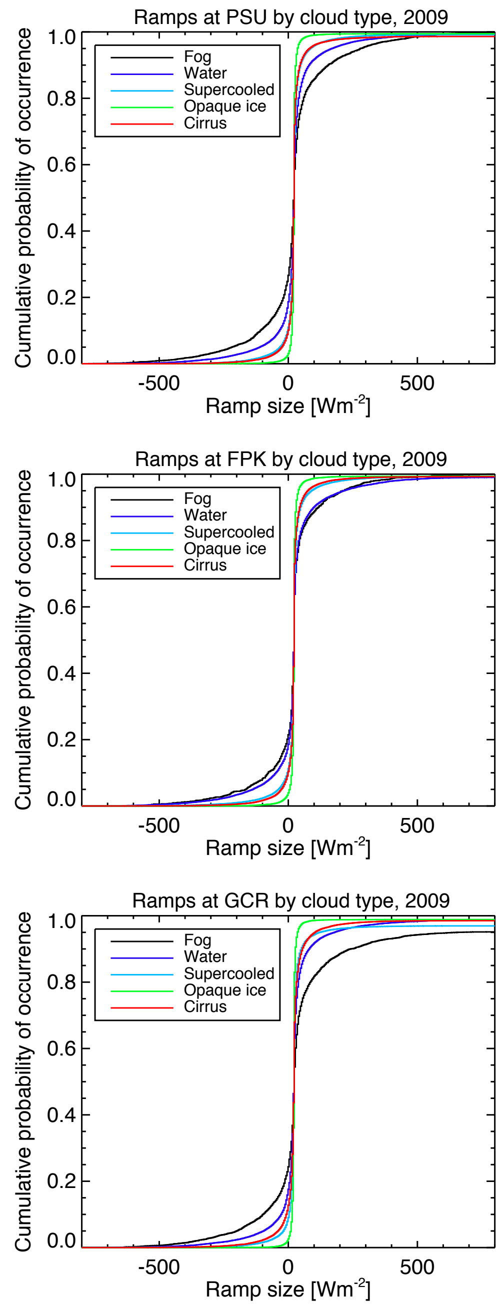


Figure 3. Cumulative distribution functions of 60-s ramps computed for five cloud types at three locations. Top: Penn State University, PA. Middle: Fort Peck, MT. Bottom: Goodwin Creek, MS.

of the ramps lie. These values are given in Table 2 for the sites and cloud types in Figure 3.

As we expect, the values differ from site to site although the ordering of the values is constant. The 95% points for the opaque cirrus clouds are extremely small, at about 25-30 $Wm^{-2}$. This is because these clouds are so dense that any variations within them affect the incident solar beam insignificantly. Fog and water clouds, on the other hand, contain significant variability. Both can be rather thin or patchy. 95% points for these categories typically range from 250 to 450 $Wm^{-2}$, with an extremely large value of 676 $Wm^{-2}$ observed at Goodwin Creek, Mississippi. The supercooled liquid and thin ice / cirrus clouds yield ramp extremes between these values.

Table 2. Boundaries enclosing 95% of the 60-s ramps (absolute value) for each location and cloud type, $Wm^{-2}$.

| | PSU | FPK | GCR |
|---|---|---|---|
| Fog | 370 | 296 | 676 |
| Water | 249 | 301 | 256 |
| Supercooled | 119 | 131 | 164 |
| Opaque ice | 26 | 33 | 25 |
| Cirrus | 108 | 101 | 142 |

Further work is necessary to establish the robustness of the ramp statistics for each cloud type, including the degree to which these statistics hold over a range of geographical areas. Further work is also being performed to determine the features of each cloud type that lead to the observed results.

4. Conclusions

Cloud information from GOES satellite images has been combined with solar irradiance (GHI) measurements at surface sites to characterize the irradiance variability as a function of meteorological conditions. Clear differences are seen among the cloud types, with relationships that hold across locations. Further study is needed to understand the specific conditions that lead to the observed results. This information can then be used for statistical downscaling of satellite observations or as a supplement to solar forecasts from weather models.

5. ACKNOWLEDGMENTS

This research was supported by subcontract AGG-2-22256-01 from the National Renewable Energy Laboratory.

6. REFERENCES

(1) Augustine, J. A., Hodges, G. B., Cornwall, C. R., Michalsky, J. J., Medina, C. I., An update on SURFRAD—The GCOS surface radiation budget network for the continental United States. J. Atmos. Oceanic Technol., 22, 1460–1472, 2005.