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On the properties of aggregate clear-sky index distributions and an improved model for spatially correlated instantaneous solar irradiance

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ABSTRACT

An important factor in grid integration of solar power is the so-called dispersion-smoothing effect, i.e., that differences in cloudiness over dispersed systems make the aggregate output less variable. This effect has been studied for irradiance step-changes on different time horizons, but not so much for instantaneous irradiance. In this paper, an improved probabilistic model is proposed for how instantaneous solar irradiance is correlated and aggregated over a network with arbitrary number of sites and dispersion. The model is fitted to irradiance data with a 1-s resolution from a network with 17 pyranometers in Hawai'i. A previously proposed three-state model of the instantaneous clear-sky index is partly confirmed by showing that clear and cloudy states can be separated and modeled by independent distribution models. It is also shown that the station-pair correlations for the instantaneous clear-sky index, as well as the shape of the distribution for the cloudy states, depend characteristically on the average degree of cloudiness, represented by the daily clear-sky index. For dispersed sites within the studied network, separated by distances up to 1 km, and for daily clear-sky indices above approximately 0.5, the model performs better in reproducing the aggregate clear-sky index than non-spatial data. The proposed model could assist distribution system operators (DSOs) in grid planning and operation, as shown in a case study.

1. Introduction

Several applications of solar energy require knowledge of high-resolution spatio-temporal properties of solar irradiance. Large-scale integration of photovoltaic (PV) systems into power grids depends on how geographically dispersed solar power contributes to net demand variability on different time scales (Olauson et al., 2016) and how both power fluctuations and instantaneous power are smoothed out when systems are spatially dispersed, the so-called dispersion-smoothing effect (Widén et al., 2015). Also, there are solar forecasting methods that directly depend on accurate spatio-temporal models of solar irradiance, for example methods using high-resolution irradiance data in spatial networks to forecast the irradiance at unobserved locations (Yang et al., 2014; Aryaputera et al., 2015).

Many spatio-temporal characteristics of solar irradiance have been described and modeled in previous studies, in particular, correlations between dispersed sites and how they depend on factors such as station separation (Perez et al., 2012) time resolution (Hoff and Perez, 2012), cloud speed (Lave and Kleissl, 2013), cloud movement, cloud radius and cloud cover fraction Arias-Castro et al., 2014, wind direction (Hinkelman, 2013), and overall daily variability (Widén, 2015). Modeling approaches to reproduce spatio-temporal characteristics of solar irradiance include, e.g., wavelet modeling to smooth out irradiance time series depending on spatial dispersion (Lave et al., 2013) and models based on cloud field generation using simplified geometric shapes (Bright et al., 2017) or fractal cloud models (Lohmann et al., 2017).

Most of these studies concern irradiance fluctuations between time steps. However, the *instantaneous* irradiance and how it can likewise be smoothed out by geographical dispersion is equally important. Instantaneous irradiance, defined as the average irradiance over a time period Δt as $\Delta t \to 0$, is an idealized concept, as measurement devices always measure over some finite time period. However, measured data can come very close to approximating instantaneous values; for example, Hollands and Suehrcke (2013) used a measurement period of 0.02 s. Most importantly, the measurement period should be sufficiently short to capture the important characteristics of instantaneous irradiance. Usually, these characteristics are averaged away for time periods above one minute (Suehrcke and McCormick, 1988). Characterizing instantaneous solar irradiance has been motivated in previous literature, e.g., Hollands and Suehrcke, 2013, the most important reason being that if the instantaneous irradiance is known, irradiance

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Nomenclature

Abbreviations

CDF	cumulative distribution function
CSI	clear-sky index
DCSI	daily clear-sky index
DSO	distribution system operator
KSI	Kolmogorov-Smirnov integral
PDF	probability density function
PLF	probabilistic load flow
PV	photovoltaic
rKSI	relative Kolmogorov-Smirnov integral
RSR	rotating shadowband radiometer

Variables

α,β	PV array azimuth and tilt, Ångström parameters
$\overline{\kappa}$	daily (time-averaged) clear-sky index
η	PV module efficiency
κ_a	instantaneous clear-sky index averaged over all stations
	instantaneous clear-sky index at station *i*
$\kappa_{c,i}$	instantaneous clear-sky index in the cloudy states at station *i*
$\kappa_{s,i}$	instantaneous clear-sky index in the clear state at station *i*
μ_1,μ_2	cloudy-state distribution component mean values
μ_s,μ_c	clear and cloudy state distribution mean values
ρ_g	ground-reflectance
ρ_s^{ij},ρ_c^{ij}	clear and cloudy state correlation between stations *i* and *j*
ρ_{cop}^{ij}	Copula correlation between stations *i* and *j*
σ_1, σ_2	cloudy-state distribution component standard deviations
σ_s,σ_c	clear and cloudy state distribution standard deviation
A	PV array area
A_i	anisotropy index
d_{ij}	distance between stations *i* and *j*
F_0	empirical CDF of clear-sky index at one site
F_a,F_a^*	empirical and modeled CDFs of aggregate clear-sky index
G	global horizontal irradiance
G_b	beam horizontal irradiance
G_c	clear-sky horizontal irradiance
G_d	diffuse horizontal irradiance
G_T	global irradiance on tilted plane
K	number of samples
k_d	diffuse fraction of global irradiance
N	number of stations
P_{dc0}, P_{ac0}	inverter rated DC and AC power
P_{dc}, P_{ac}	array DC and inverter AC output
P_{s0}	inverter threshold power
q_a	PV array losses
R_b	geometric factor
S	clear/cloudy state variable
s	fraction of time of bright sunshine
w_1, w_2	cloudy-state distribution component weights

Note: Additional parameters for parameterizing some of the variables above are listed in Table 2.

on any resolution can be deducted from that. A time-continuous model of solar irradiance also requires the instantaneous irradiance at continuous time, rather than time-averaged at discrete time steps.

One example of applications of instantaneous irradiance models is probabilistic load flow (PLF) simulations, in which load and generation data for buses in a power grid are drawn from probability distributions and the power flow is solved numerically with Monte Carlo methods (Bollen and Hassan, 2011). As discussed by Munkhammar et al. (2017), spatially resolved modeling of probability distributions for instantaneous solar irradiance, from which it is possible to draw correlated samples, could greatly improve PLF simulations and assist distribution system operators (DSOs) in grid planning and operation.

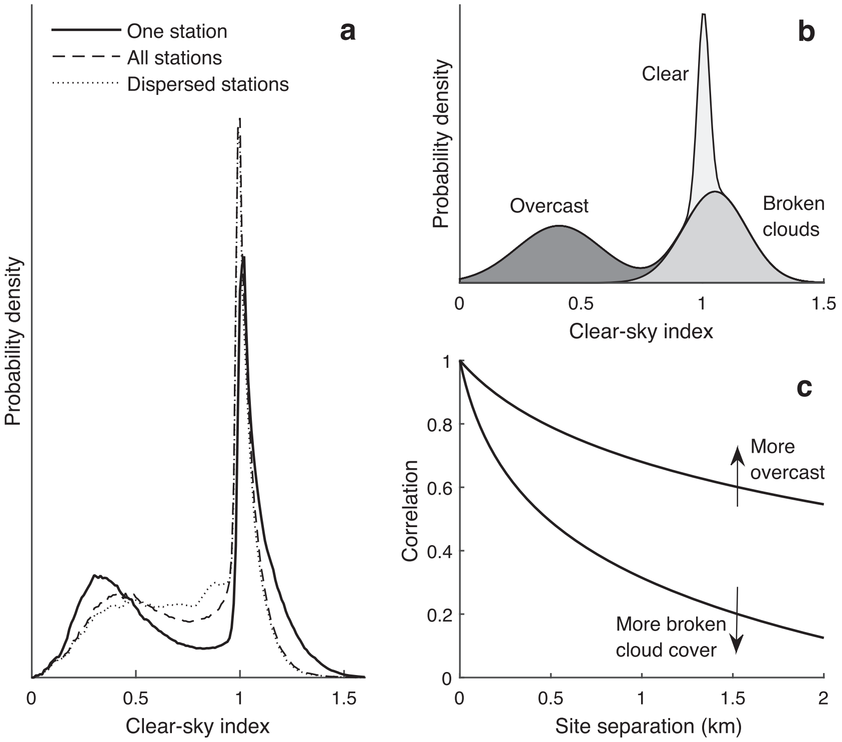

Fig. 1. (a) Observed probability densities for 1-s clear-sky index data at one station and averaged over all stations and the four most dispersed stations in the Hawai'i pyranometer network (NREL, 2017) as determined by Munkhammar et al. (2017). (b) Outline of the assumed three-state distribution model of the instantaneous clear-sky index at an individual station. (c) Outline of the assumed correlation model, with hypothesized dependence on cloud cover.