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Streamline-based method for intra-day solar forecasting through remote sensing

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Abstract

This work presents an enhanced deterministic solar irradiance forecasting approach that relies on satellite images and ground measurements as inputs. The proposed method is based on a ground-truth improved satellite-to-irradiance model for the prediction of global horizontal irradiance (*GHI*). This approach relies on cloud tracking and advection with an optical flow algorithm. The application of the optical flow algorithm between two consecutive satellite image frames allows for the calculation of a vector field covering each pixel in the satellite image. This cloud motion vector (*CMV*) field determines the streamline passing through the location of interest. The estimated cloud advection along the quasi-steady streamline to the location of interest is than computed, and this information is translated into an irradiance forecast for the location of interest. In order to reduce the error associated with a linear satellite-to-irradiance model, a novel approach employing ground measurements is proposed. Additionally, decision heuristics are identified and implemented to issue a forecast based on *CMV* or persistence, depending on the current sky conditions. The overall method is tested for over 110 days of operational 1-, 2- and 3-h ahead *GHI* forecasts, implemented and evaluated for San Diego, California. The continual forecasting skill of this method for the 110 days ranges between 8% and 19% over persistence, depending on the forecast horizon. While previously proposed methods achieve similar skills, the completely deterministic approach combined with comparably low computation and implementation costs makes the proposed method suitable for applications with limited availability of data.

Keywords: Solar forecasting; Remote sensing; Cloud tracking; Optical flow; Global horizontal irradiance

1. Introduction

Solar power is a virtually inexhaustible energy resource that is likely to play an increasing role in the future energy supply of most, if not all, societies. While technological improvements enable more efficient and cost effective solar power generation, the fluctuation of solar irradiance at the surface of the Earth still constitutes a major obstacle for power grid integration. Solar forecasting on multiple time horizons is an effective approach to mitigate the adverse effects of variable solar power generation on the operation and management of the electric grid. A detailed review of current solar forecasting methods can be found in Inman et al. (2013). While short term forecasts (intra-hour) became more sophisticated based on recent advances in ground based sky-imagery and modeling techniques (Chow et al., 2011; Ghonima et al., 2012; Marquez and Coimbra, 2013a; Dong et al., 2013; Handa et al., 2014), intra-day methods still lack accuracy. Several previous studies propose and evaluate methods for intra-day forecasts (Mathiesen and Kleissl, 2011; Marquez et al., 2013).

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Nomenclature

ANN	artificial neural network
CDF	cumulative distribution function
CMV	cloud motion vector
CS	clear sky
DCA	Difference Centroid Algorithm
DNI	direct normal irradiance
$Err.$	Error calculated as $Err. = \Delta GHI = GHI_{GT} - GHI_F$
$GHI_{CS,GT}$	global horizontal irradiance, indices: CS – clear sky, GT – ground truth
$GHI_{M1,M2}$	global horizontal irradiance, M1, M2 – irradiance Models 1 and 2
GHI_{kt}	global horizontal irradiance modeled with k_t-persistence
$\widehat{GHI}, GHI_F$	global horizontal irradiance forecasted with the proposed method
$GOES$	Geostationary Operational Environmental Satellite
$I(x,y,t)$	brightness of pixel at location x, y at time t
Im	downloaded satellite image
L	geometrical length
MAE	mean absolute error
MBE	mean bias error
MFR-7	multi filter radiometer
N	number of bins
$NOAA$	National Oceanic and Atmospheric Administration
NWP	numerical weather prediction

PIV	Particle Image Velocimetry
$RMSE$	root mean squared error
RTM	radiative transfer model
T	threshold
UTC	Coordinated Universal Time
$\vec{V}$	average velocity vector of streamline
X	probability bin
a	shift parameter
i,j	summation indices
k_t	clear-sky index
k,l	geometric averaging parameters
n	linear cloud index
p,q	number of pixels in the x- & y-direction
px	pixel
s	forecasting skill
u	velocity in x-direction (horizontal)
v	velocity in y-direction (vertical)
$xcor$	cross correlation
$\bar{\alpha}$	average albedo image
β	cloud fraction image
Δt	forecast horizon
δ, ϵ	penalty function parameters
$\vec{\zeta}$	streamline vector
η	cloud index image
λ	regularization parameter
ρ	pixel intensity, max & min occurring in data set
$\varrho_{S,D}$	spatial and data penalty functions

However, especially the direct use of satellite images is currently not very common due to difficulties concerning data availability, albedo correction, resolution, cloud segmentation and tracking and real time processing of images. Previous methodologies utilizing satellite images for solar forecasting have been proposed by Hammer et al. (1999, 2003) and Marquez et al. (2013). This contribution seeks to take advantage of the online near real-time availability of processed satellite images derived from the visible channel (0.55–0.75 μm) of the Geostationary Operational Environmental Satellites West and East ($GOES$-W and $GOES$-E) with a resolution of approximately 1 km, combined with a fast cloud segmentation algorithm. Two consecutive frames of cloud index images (ηs) are the foundation for the application of an advanced optical flow algorithm proposed by Sun et al. (2010), applied to derive cloud motion vectors (CMV) between two consecutive frames. This approach also enables the derivation of cloud velocity. Optical flow was found the most suitable approach for cloud tracking during this study, while other cloud tracking methods were the topic of several previous publications (Endlich and Wolf, 1981; Guillot et al., 2012; Escrig et al., 2013). The CMV field and velocities are utilized to calculate the streamline of the flow field reaching the location of interest. This streamline enables the identification of an area of pixels most likely to propel to the location of interest. All of these inputs are deterministic and therefore provide a method that can be applied without any training for every location covered by satellite images. This method is heavily based on the performance of a satellite-to-irradiance model that translates the identified region of cloud intensity values into forecast values of GHI at the region of interest. In this context, a ground measurement enhanced semi-empirical satellite-to-irradiance model has been developed.

This work is divided into two main parts, the satellite-to-irradiance model and the forecasting model. Section 2 gives an overview of previously proposed methods covering the same forecast horizons for GHI and highlights the purpose for this study. Section 3 focuses on the processing of the satellite images provided by National Oceanic and Atmospheric Administration ($NOAA$), the applied cloud segmentation and the satellite-to-irradiance model. Section 4 includes the selection of a cloud tracking method, cloud tracking with optical flow and the deterministic solar irradiance forecasting approach. Section 5 contains the