Solar Energy 163 (2018) 610–622

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Conditional summertime day-ahead solar irradiance forecast

John F. Mejia[a,*], Marco Giordano[b], Eric Wilcox[a]

[a] Department of Atmospheric Sciences, Desert Research Institute (DRI), USA
[b] Atmospheric Sciences Graduate Program, University of Nevada-Reno, Department of Atmospheric Sciences, DRI, USA

ARTICLE INFO

Keywords:
Model Output Statistics
Global horizontal irradiance
Moisture surges
North American Monsoon
Numerical Weather Prediction

ABSTRACT

We investigated the accuracy of numerical weather prediction (NWP)-based global horizontal irradiance (GHI) and clear-sky index forecasting over southern Nevada. Accurate forecasts of solar irradiance are required for electric utilities to economically integrate substantial amounts of solar power into their power generation portfolios. Solar irradiance forecasting can enhance the value of renewable energy by anticipating fluctuations in these variable resources. Summertime cloud variability depends largely on the combination of tropical and extratropical synoptic-scale forcing, most of which is observable, predictable, and highly related to the North American Monsoon moisture surge events. We used high-resolution realtime NWP output based on the weather and research forecasting (WRF) model to study the ability of the model to deliver day-ahead GHI and clear-sky index forecasts for a the National Renewable Energy Laboratory (NREL)-University of Nevada site, located in Las Vegas, Nevada. High-resolution forecast products were obtained from the Desert Research Institute (DRI) archived real-time numerical weather forecasting products. Results showed the importance of developing a site-specific seasonal and weather-dependent model output statistics (MOS) approach to improving forecast accuracy, which removes the bias and reduces the overall relative root-mean – square error (rRMSE) of GHI by as much as 6%, when compared to the uncorrected model output; improving forecast accuracy is obtained by adding information that relates regional-scale circulation patterns driving cloudiness, hence irradiance variability to the target area. We show the seasonal dependence of the NWP forecast accuracy and demonstrate that intelligent weather functions provide a pathway to improve accuracy of solar forecasts further.

1. Introduction

Current solar forecasting technologies use a mixture of tools to improve the forecast, ranging from statistical data approaches to physically-based deterministic and probabilistic models. Optimizing the implementation of these tools to increase forecast accuracy can reduce costs and increase the reliability of integrating solar power into the electricity grid (Lorenz et al., 2009).

Numerical weather prediction (NWP) models are physically based and generally the most accurate tool for solar global horizontal irradiance (GHI) forecasting for forecast windows lasting hours to several days (Perez et al., 2013; Mathiesen and Kleissl, 2011; Jimenez et al., 2016). Improved forecasting requires high quality and reliable real-time data from widespread networks of upper-air and ground-based instruments. These data define the model's initial conditions using data assimilation tools. Today, state-of-the-art, high-resolution NWP models are capable of resolving clouds (stratiform and convective), fog-filling valleys, orographic precipitation, and even local processes related to the urban heat island effect. NWP systems such as NOAA's High-Resolution Rapid Refresh (NOAA-HRRR; Benjamin et al., 2004), the Advanced Research-Weather and Research Forecasting model (WRF; Skamarock et al., 2008), among other models, are becoming essensial tools to provide critical information for various weather-related sectors, including the energy industry. Nevertheless, stubborn sources of uncertainty – because of imperfections in parameterization of the model's physics, chaotic behavior of the weather, complex topography, imperfect initial conditions, among other challenges – persist in NWP systems, leading to model imperfections. Quantifying the model's errors, systematic and random, is then a necessary task to assess whether its output is suitable to guide resource-management decisions.

Forecast post-processing approaches called model output statistics (MOS) can improve NWP model forecasts (Perez et al., 2013) and have proved to be more useful in correcting systematic biases (Perez et al., 2013; Zhang et al., 2013a,b; Sengupta et al., 2015). MOS approaches implement statistical regressions ranging from linear regression methods to sophisticated machine-learning tools designed to perform deeper error structure and pattern recognition for more intelligent NWP output correction (Sharma et al., 2011; Lauret et al., 2014; Alessandrini

* Corresponding author.
E-mail address: john.mejia@dri.edu (J.F. Mejia).

https://doi.org/10.1016/j.solener.2018.01.094
Received 17 August 2017; Received in revised form 25 January 2018; Accepted 31 January 2018

et al., 2015). In general, all MOS approaches seek to optimize NWP model output by relating locally or regionally observed parameters to site-specific conditions (Badosa et al., 2015). Bias correction approaches are often implemented without careful consideration of the source of the bias (a challenging task), however, and without considering regional or local physical processes responsible for cloudiness variations in the region. Differentiating between error sources can be important to selectively correct forecasts and create more accurate MOS tools (Lauret et al., 2014).

Mejia et al. (2016) showed that cloudiness over the U.S. Southwest – including New Mexico, Arizona, and southern Nevada – is related to North American Monsoon (NAM; Adams and Comrie, 1997) synoptic-scale wet spells called "moisture surges." Moisture surges are observable and predictable weather patterns in the NAM region and are modulated by different tropical and extratropical synoptic-scale features – including inverted troughs, tropical easterly waves, eastern Pacific tropical storms, tropical cyclones, and extratropical waves (Higgins and Shi, 2001; Seastrand et al., 2014; Mejia et al., 2016). These features predominantly occur during July-September and then tend to increase monsoonal moisture transport through the Gulf of California – reaching northwestern Mexico and the southwestern U.S. and increasing moisure instability – leading to increased storminess and organized convection in the region. We argue that this cloudiness drives variability of solar resources in the southwestern US during the NAM.

Kim and Clarkson (2016) developed a study to improve GHI and direct normal irradiance using an NWP model based on the WRF (with aerosol interaction) over Arizona and showed that the model performed poorly during the 2011 NAM season, likely related to the frequent but variable nature of clouds during the 2011 NAM season. Here we argue that forecast improvement for hours to day-ahead time windows can be improved by conditioning the forecast products by developing a process-based MOS that considers NAM moisture-surge episodes.

We focused on performing a detailed forecast accuracy assessment of day-ahead GHI and clear-sky index (Kt∗) using real-time forecast output from the NWP model based on the WRF. Specifically, we present forecast comparisons against GHI observations from a site in Las Vegas, Nevada. The accuracy assessment implements multiple forecast error metrics that enable us to quantify the benefit and sensitivity of implementing different MOS approaches and training techniques. Specifically, the training technique determines parameter and site (or region) specific bias correction quantities associated with composite events characterized by canonical relative humidity state and regional-scale flow regimes referred to as weather functions in this study.

2. Data and methodology

2.1. Evaluation observations

We used GHI surface observations from a National Renewable Energy Laboratory (NREL)-University of Nevada, Las Vegas site (NREL-UNLV; Andreas and Stoffel, 2006; 36.06° N, 115.08° W, 615 m ASL). The station provides observations at 1-min. time increments, aggregated and synchronized using 1-h time increments to match the model output. Of note is that observations were not categorized by changes in GHI because of haze, smoke, or dust – which can be an important source of GHI variations (~10%; Zack, 2010) in the Las Vegas region (Chow et al., 1999) and can impact model evaluation procedures.

2.2. Clear sky index

A common parameter derived from GHI is the clear sky index (Kt∗). The Kt∗ is defined as the ratio of irradiance to irradiance during clear sky conditions at any given time (GHI_{clear}). Kt∗ normalizes GHI between 0 and 1 (for clear sky conditions), reducing the potential of introducing non-stationarities into the statistical approaches from the irradiance diurnal cycle and seasonality (Voyant et al., 2015). In this study and for simplicity, we estimated the GHI_{clear} using the Ineichen and Perez clear sky model with climatology parameters for the state of the atmosphere (Ineichen and Perez, 2002; Reno et al., 2012) and using Holmgren and Groenendyk (2016) procedures.

2.3. High-resolution NWP model

We implemented archived weather forecast data from the Desert Research Institute (DRI) operational weather forecast system starting August 1, 2015 and continuing to December 31, 2016. DRI performs real-time, fine-resolution NWP simulations based on the Weather and Research Forecasting model (WRF; Skamarock and Klemp, 2008; Skamarock et al., 2008). The model domains are 18 km over the western U.S., 6 km-nested domains covering California and Nevada, and two nested domains at 2 km independently covering the Reno-Tahoe and Las Vegas urban and suburban areas (Fig. 1).

The WRF configuration follows physics and integration strategies shown in Dorman et al. (2013), with some modifications and different domain-grid configuration outlined below. We designed the selection of model setup through basic and common knowledge of the prevailing physical processes that dominate regional climate variations over the western U.S. (Leung et al., 2003; Rasmussen et al., 2011; Liou et al., 2013; Silverman et al., 2013; Zhang et al., 2013a,b; Dorman et al., 2013). A summary of the WRF model main configuration and parameters is presented in Table 1. It is well known, however, that the selection of optimal parameters and physics configuration for WRF is a challenging task depending on many factors, including the following: initial/boundary conditions, regional climate and its variability, and simulation grid size (Liang et al., 2012; Diagne et al., 2014; Fernández-González et al., 2015). Controlling all these factors and all the parameters involved in the WRF as a real-time forecasting tool is outside the scope of this report, requiring time and resources not available for this study. The WRF is driven by initial and lateral boundary conditions provided by Global Forecast Systems (GFS; http://www.emc.ncep.noaa.gov/GFS/doc.php), while integrating the dynamic equations and physics parameterizations at the interior grids at finer spatial and temporal scales. GFS is produced and periodically updated by the National Centers for Environmental Prediction (NCEP). The horizontal grid spacing for GFS data is 0.25 arc degree with 32 vertical layers, including lateral boundary conditions of surface, atmosphere, and soil variables every three hours. The GFS data assimilation system was updated in May 2016 to include a dual-resolution hybrid four-dimensional ensemble-variational assimilation system intended to improve the model's initialization and forecast accuracy. At the time of this study, we were not aware of any studies and showing evidence of any improvements in the GFS system. Note that these GFS changes could have introduced some systematic differences and trends in the forecast error structure of this study. Our relatively short period of simulated records prevents us from examining and accounting for such potential differences. In this study, we assumed that such differences were small and to the best of our knowledge, there are no published results indicating that this assumption precludes our methodological approach and assessment.

Zempila et al. (2016) and Ruiz-Arias et al. (2013) found that the Dudhia scheme performs adequately under clear-sky conditions. If aerosols are considered, however, Ruiz-Arias et al. (2013) suggested that the RRTMg (a different shortwave parameterization approach implemented within the WRF) tends to perform better than the Dudhia scheme. The NWP systems described above does not consider aerosol interactions with clouds and radiative processes, which could be important drivers of solar irradiance variability (on the order of 10%) in the southwestern U.S. (Kim and Clarkson, 2016).

Real-time forecast products were produced twice per day (00 and 12 UTC). For this study, the model GHI and other ancillary forecast parameters were retrieved using the nearest grid point to the NREL-UNLV site. Day-ahead hourly GHI forecasts were archived consistently