Available online at www.sciencedirect.com

SciVerse ScienceDirect

Solar Energy 92 (2013) 47–61

SOLAR ENERGY

www.elsevier.com/locate/solener

A high-resolution, cloud-assimilating numerical weather prediction model for solar irradiance forecasting

Patrick Mathiesen [a], Craig Collier [b], Jan Kleissl [a,*]

[a] *Department of Mechanical and Aerospace Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0411, USA*

[b] *GL-Garrad Hassan, 9665 Chesapeake Drive #435, San Diego, CA 92123, USA*

Received 10 August 2012; received in revised form 23 January 2013; accepted 24 February 2013
Available online 9 April 2013

Communicated by: Associate Editor David Renne

Abstract

It is well established that most operational numerical weather prediction (NWP) models consistently over-predict irradiance. While more accurate than imagery-based or statistical techniques, their applicability for day-ahead solar forecasting is limited. Overall, error is related to the expected meteorological conditions. For regions with dynamic cloud systems, forecast accuracy is low. Specifically, the North American Model (NAM) predicts insufficient cloud cover along the California coast, especially during summer months. Since this region represents significant potential for distributed photovoltaic generation, accurate solar forecasts are critical.

To improve forecast accuracy, a high-resolution, direct-cloud-assimilating NWP based on the Weather and Research Forecasting model (WRF-CLDDA) was developed and implemented at the University of California, San Diego (UCSD). Using satellite imagery, clouds were directly assimilated in the initial conditions. Furthermore, model resolution and physics parameterizations were chosen specifically to facilitate the formation and persistence of the low-altitude clouds common to coastal California. Compared to the UCSD pyranometer network, intra-day WRF-CLDDA forecasts were 17.4% less biased than the NAM and relative mean absolute error (rMAE) was 4.1% lower. For day-ahead forecasts, WRF-CLDDA accuracy did not diminish; relative mean bias error was only 1.6% and rMAE 18.2% (5.6% smaller than the NAM). Spatially, the largest improvements occurred for the morning hours along coastal regions when cloud cover is expected. Additionally, the ability of WRF-CLDDA to resolve intra-hour variability was assessed. Though the horizontal (1.3 km) and temporal (5 min) resolutions were fine, ramp rates for time scales of less than 30 min were not accurately characterized. Thus, it was concluded that the cloud sizes resolved by WRF-CLDDA were approximately five times as large as its horizontal discretization.

Keywords: Solar forecasting; High-resolution numerical weather prediction (NWP); Direct cloud assimilation

1. Introduction

The accurate characterization of cloud fields, their evolution, and their optical properties is critical for solar irradiance forecasting. For short-term forecasting, imagery based cloud-advection techniques (Perez et al., 2010; Chow et al., 2011) provide excellent characterizations of cloud fields and cloud motion. However, clouds are highly dynamic and cloud properties can change drastically over just a few hours. As such, the accuracy of frozen-cloud advection techniques diminishes significantly over the first 6 h. For forecast horizons exceeding 5 h (on average), physics-based weather models (numerical weather prediction (NWP)) are generally regarded as the most accurate method for predicting solar irradiance (Fig. 2 of Perez et al., 2010).

Though more accurate than cloud-motion techniques for long forecast horizons, previous studies have conclusively demonstrated consistent and systematic errors in NWP

* Corresponding author. Tel.: +1 858 534 8087.
E-mail address: jkleissl@ucsd.edu (J. Kleissl).

0038-092X/$ - see front matter
http://dx.doi.org/10.1016/j.solener.2013.02.018

irradiance forecasts. Remund et al. (2008) compared several months of irradiance forecasts from three NWP sources: The National Digital Forecast Database (NDFD), the European Centre for Medium-range Weather Forecasts (ECMWF), and the Weather and Research Forecasting (WRF) model as initialized by the Global Forecasting System (GFS). Generally, mean bias errors (MBEs) for day-ahead hourly forecasts were positive indicating a consistent under-prediction of cloud cover and/or cloud optical depth. For the three models, hourly root-mean square errors (RMSEs) ranged from 87 W m^{-2} to 223 W m^{-2}. Perez et al. (2010) validated hourly irradiance forecasts derived from the NDFD against seven ground measurement stations across the continental US. Over 1 year, RMSE was at least 150 W m^{-2} and increased for forecast horizons of greater than 1 day. Similarly, Lorenz et al. (2009) validated intra-day ECWMF irradiance forecasts for more than 200 ground measurement locations in Germany over a year. Excluding night-time hours, relative RMSE (RMSE normalized by the average daily irradiance) was near 40%. Furthermore, irradiance was consistently over-predicted, particularly for moderately cloudy conditions near midday (MBE $\approx$ 100 W m^{-2}). Lorenz et al. (2009) attributed this to incorrect modeled cloud water content and deficient cloud optical thickness. Mathiesen and Kleissl (2011) found comparable systematic errors when comparing the North American Mesoscale (NAM), GFS, and ECMWF models' irradiance forecasts to ground measurements in the US over about a year. For all models, MBE exceeded 30 W m^{-2} and RMSE was larger than 110 W m^{-2}. Again, a general under-prediction of cloud cover was observed. Out of all measured cloudy conditions, 52.4% were forecast incorrectly as clear by the NAM. Additionally, Mathiesen et al. (2012) related NAM forecast accuracy to location and the likelihood of cloud cover for hourly data in California. Due to the high probability of cloud cover, summertime coastal forecasts were strongly biased (MBE > 125 W m^{-2}). Inland, where cloudy conditions were less likely, NAM forecasts were less biased. Pelland et al. (2011) observed similar trends in Environment Canada's Global Environmental Multiscale (GEM) model. Relative MBE (MBE normalized by the average observed irradiance) for hourly data ranged from 0% to 14% and relative RMSE exceeded 16.7%. Lastly, Lara-Fanego et al. (2012) compared hourly intra-day irradiance forecasts from a 3-km WRF model driven by the GFS to four ground measurement sites in southern Spain. Here, MBE ranged from 49 to 64 W m^{-2} and RMSE was 136–170 W m^{-2}. Regardless of model, irradiance NWP forecasts are generally positively biased. This consistent under-prediction of cloud cover demonstrates the limitations of the current operational NWP for solar irradiance forecasting.

Coarse model resolutions and inadequate physics parameterizations contribute to NWP cloud cover error. The operational NWP models generally have spatial resolutions on the order of 10 km or larger. In this configuration, it is impossible to resolve fine-scale cloud features or even large convective clouds. Tselioudis and Jakob (2002) compared ECMWF T42 ($\Delta x \approx 2.5°$), T106 ($\Delta x \approx 1°$), and GISS ($\Delta x \approx 2°–5°$) cloud forecasts to satellite observations and found that the higher-resolution ECMWF models generally predicted cloud coverage and cloud properties more accurately for all meteorological regimes. This was attributed to an increase in vertical resolution. Similarly, Lin et al. (2009) compared cloud forecasts of multiple nested WRF simulations that ranged in resolution from 20 to 0.8 km. While large scale features were qualitatively captured by all models, simulations with spatial resolutions coarser than 4 km tended to under-predict cloud cover. Additionally, the parameterization of physical processes, specifically the simulation of cloud microphysics and planetary boundary layer (PBL) mixing, has a large impact on cloud and irradiance forecast accuracy. Otkin and Greenwald (2008) thoroughly catalogued the effect that different physics parameterizations have on WRF simulated cloud fields.

Additionally, accurate model initialization is critical for NWP forecast accuracy. Generally, initial conditions derived from large-scale models will inherit the error of the parent model. To minimize this observation data can be assimilated into the initial conditions. Data assimilation is the specification of model initial conditions using the optimal combination of coarse-scale model output and observations. Typically, temperature, pressure, and velocity initializations are modified to match observation. However, since most operational data-assimilation techniques omit cloud observations, benefits of data assimilation for cloud-cover and irradiance forecasting are unknown. Notably, the Rapid Update Cycle (RUC, Benjamin et al., 2004a) uses a cloud-analysis system to assimilate cloud observations into the model initial conditions. In this system, satellite imagery, radar data, and local cloud cover reports are used to construct a three-dimensional observed cloud field matrix. Clouds are built into the initial conditions by directly modifying the model hydrometeors (cloud and water mixing ratios) and the state variables which support them (Benjamin et al., 2002, 2004b; Weygant et al., 2006; Hu et al., 2007). Similar systems (Albers et al., 1996) are in use in the Center for Analysis and Prediction of Storms' (CAPS) Advanced Regional Prediction System (ARPS, Xue et al., 2003).

In this study, a new, high-resolution, cloud-assimilating NWP model is developed and tested at the University of California, San Diego (UCSD) for solar irradiance forecasting (WRF-CLDDA). Using fine spatial resolution, physics parameterizations that promote cloud-cover formation, and a cloud-assimilation system, this model is specifically designed to minimize the errors typically associated with NWP irradiance forecasts (Sections 2 and 4). Using WRF-CLDDA, irradiance forecasts are produced for late spring (5/1/11–6/30/11) and validated against a dense UCSD pyranometer network. During this time, marine layer stratocumulus clouds (Section 5.1) are common. Optically thick, these clouds often reduce irradiance by as much as 75%. Additionally, since their evaporation is spatially correlated, large positive irradiance ramps