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Preprint

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Presented at the 37th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2020)
September 7–11, 2020

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Conference Paper
NREL/CP-5D00-77693
September 2020

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Contract No. DE-AC36-08GO28308

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Suggested Citation
Kim, Ju-Hye, Pedro A. Jimenez, Jimy Dudhia, Jaemo Yang, Manajit Sengupta, and Yu Xie. 2020. *Probabilistic Forecast of All-Sky Solar Radiation Using Enhanced WRF-Solar: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-77693. https://www.nrel.gov/docs/fy20osti/77693.pdf.

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This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

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PROBABILISTIC FORECAST OF ALL-SKY SOLAR RADIATION USING ENHANCED WRF-SOLAR

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ABSTRACT: This study presents enhancements of the Weather Research and Forecasting model with solar extensions (WRF-Solar) to provide probabilistic forecasts of solar radiation. Our approach builds ensemble WRF-Solar runs by introducing stochastic perturbations of variables that produce the largest uncertainties in predicting surface irradiance and clouds. The key variables are identified using tangent linear sensitivity analysis of six physics packages responsible for all-sky irradiance variability. An optimal strategy to stochastically perturb the selected variables is developed and applied to WRF-Solar to generate ensemble members for day-ahead solar prediction. The National Solar Radiation Database (NSRDB) is used to validate the ensemble forecast at arbitrary locations on the model grid. Preliminary results indicate that the proposed technique can potentially produce WRF-Solar ensembles providing reliable information of solar prediction uncertainty. This study describes the implemented methodology and initial results as well as future research to improve ensemble-based probabilistic forecasts with WRF-Solar.

1 INTRODUCTION

Integrating solar generation in recent years has highlighted the need for improved skills in predicting solar power. Uncertainty and variability of solar energy resources, which introduce major challenges in power system management, have necessitated high-quality probabilistic solar forecasts [1]–[3]. It is difficult to quantify the prediction uncertainty from a single numerical weather prediction (NWP) model [4]. Deterministic solar prediction has considerable limitations under cloudy-sky conditions because an underprediction of clouds leads to model biases [5]. The accuracy of deterministic solar prediction is restricted by uncertainties in advanced physics schemes describing extensive feedback processes for cloud formation and dissipation. The limitations of the deterministic solar forecast of NWP can be compensated by designing optimized ensembles that can provide reliable information of solar forecast uncertainty for decision making.

The main objective of this study is to develop an optimized ensemble-based solar forecasting system under all-sky conditions. The Weather Research and Forecasting model with solar extensions (WRF-Solar) [6], an NWP model specifically designed to provide specialized products for solar power application, is used to produce probabilistic solar forecasts based on ensemble members. To generate optimized WRF-Solar ensemble members, we propose a method to stochastically perturb model state variables of WRF-Solar modules by controlling the formation and dissipation of clouds and solar radiation. The key variables responsible for the largest uncertainties in surface irradiance and clouds are identified using tangent linear sensitivity analysis of six physics packages of WRF-Solar [7]–[9]. An additional goal of this work is to assess the ensemble forecast using the National Solar Radiation Database (NSRDB) [10] for a more in-depth quantification of the model performance.

2 METHODOLOGY

2.1 Selection of Perturbing Variables by Tangent Linear Sensitivity Analysis

Prior to developing the methodology for adding stochastic perturbations to model state variables of selected WRF-Solar modules, we implemented a sensitivity analysis to identify the model state variables that significantly influence solar radiation as well as cloud formation and dissipation. The sensitivity of solar radiation and clouds with respect to various model state variables is analyzed using the tangent linear approach, which is computationally efficient because this method does not require individual WRF-Solar runs to perturb each model state variable individually.

The tangent linear approach for the application to sensitivity analysis has four phases: 1) A stand-alone version of WRF-Solar modules is developed for efficient testing of variables under a variety of input conditions. 2) A tangent linear model is developed for each of the selected modules by using Transformation of Algorithm in Fortran (TAF) [11–[12]. 3) The tangent linear codes are verified by linearity test. 4) A sensitivity analysis is implemented for outputs with respect to inputs of each WRF-Solar module under various scenarios, and model state variables to perturb are selected based on the sensitivity results.

2.2 Stochastic Perturbations for Ensemble Solar Forecasts

The stochastic perturbation, which will be added to or subtracted from selected model state variables in the WRF-Solar modules, is employed to generate ensemble members. Stochastic perturbation for each variable is controlled by six parameters. Table 1 shows 14 selected variables and their optimal configurations by considering their physical properties. Six parameters (Table 1) are used to perturb the variables: σ for the size of perturbation as a relative percentage of the value of each variable; λ and τ for the wavlength (length scale in meters) and the frequency (time scale in seconds) of each perturbation, respectively; z for a truncated Gaussian distribution (3% trimmed); r for the random seed to produce different sequences of random numbers; and I for identifiing 2D/3D variables (e.g., 0 for 2D and 1 for 3D) in the selected WRF-Solar modules.

Table 1. Settings for adding stochastic perturbations to WRF-Solar for ALBEDO (surface albedo), AOD5502D (aerosol optical depth), Angexp2d (Ångström wavelength exponent), Aerasy2d (asymmetry factor of aerosol), QVAPOR (water vapor mixing ratio), QCLOUD (cloud water mixing ratio), QICE (ice mixing ratio), QSNOW (snow mixing ratio), NI (ice number concentration), Theta (potential temperature), QKE (turbulent kinetic energy), SMOIS (soil moisture), TSLB (soil temperature), and W (vertical velocity).

Variable Number	Variable	σ	λ	τ	z	r	I
1	ALBEDO	0.1	100000	86400	3	17	0
2	AOD5502D	0.25	100000	3600	3	18	0
3	Angexp2d	0.1	100000	3600	3	19	0
4	Aerasy2d	0.05	100000	3600	3	20	0
5	QVAPOR	0.05	100000	3600	3	21	1
6	QCLOUD	0.1	100000	3600	3	22	1
7	QICE	0.1	100000	3600	3	23	1
8	QSNOW	0.1	100000	3600	3	24	1
9	NI	0.05	100000	3600	3	25	1
10	Theta	0.001	100000	3600	3	26	1
11	QKE	0.05	80000	600	3	27	1
12	SMOIS	0.1	80000	21600	3	28	1
13	TSLB	0.001	80000	21600	3	29	1
14	W	0.1	80000	21600	3	30	1

2.3 WRF-Solar Configuration for Ensemble Simulation

The WRF-Solar ensemble system is designed for a day-ahead solar irradiance forecast with perturbations of 14 variables. We plan to deliver the forecast using an optimized small set of ensembles, and currently a run with 10 members is tested. The WRF-Solar domain covers the contiguous United States (CONUS) with 9-km horizontal grid spacing (Fig. 1). The National Centers for Environmental Prediction Global Forecast System (0.25°×0.25°; 3-hour intervals) forecast data are used for the initial and boundary conditions.

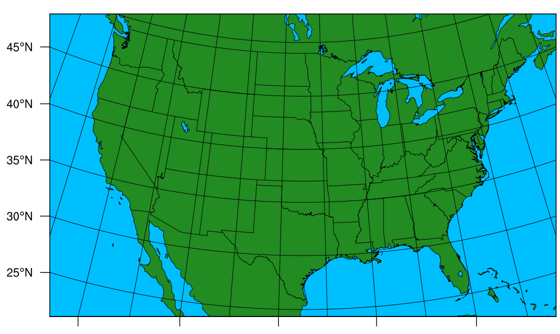

Figure 1. The computational domain of WRF-Solar.

3 RESULTS

We used the NSRDB observations to evaluate the WRF-Solar ensemble forecasts on the model grid. This data set provides satellite-based solar irradiances at a 4-km horizontal resolution. Figure 2 shows the comparison of observed GHI from the NSRDB and forecasts from WRF-Solar Version 1 and the WRF-Solar ensemble system (ensemble mean of 10 members). Two experiments capture general distributions of clouds and surface irradiance well, though model forecasts tend to produce thicker clouds near the Great Lakes compared to observations. When we run the WRF-Solar ensemble forecasting system, cloud distributions move closer to observations by reducing spurious clouds and overpredicted clouds.

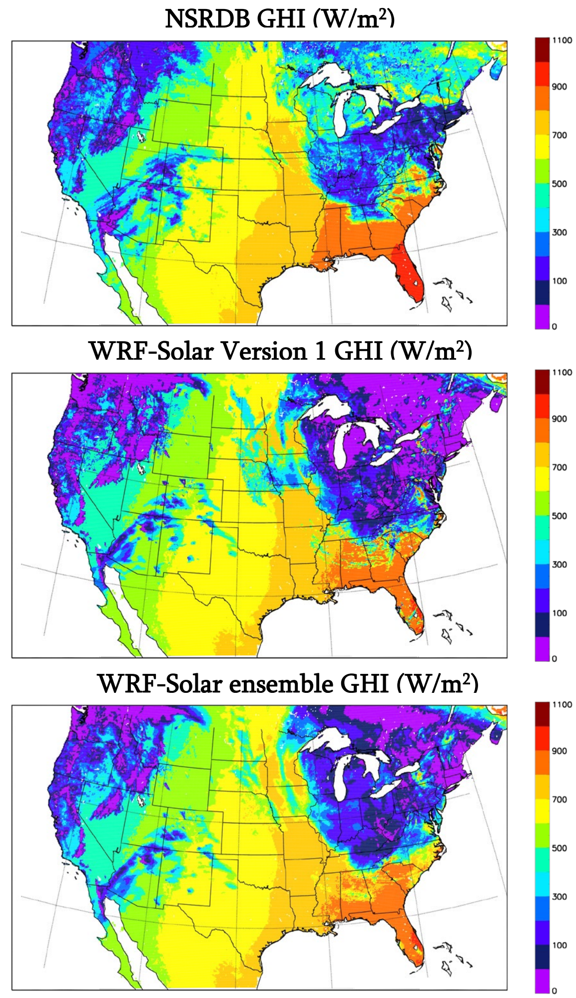

Figure 2. Geographic maps of GHI (W/m^2) over CONUS for (top) the NSRDB, (middle) WRF-Solar Version 1, and (bottom) the WRF-Solar ensemble proposed in this study (ensemble mean of 10 WRF-Solar members). 33.5-hour forecast results initialized at 0600 UTC 15 April 2018 and valid at 1530 UTC 16 April 2018.

Given the focus on the ensemble forecast of global horizontal irradiance (GHI), there is interest in looking closely at the time series for individual ensemble members to evaluate their performances for a day-ahead prediction. Figure 3 displays the time series of GHI from 48-hour forecasts for individual WRF-Solar ensemble members and their differences compared with Surface Radiation Budget (SURFRAD) network observations at their TBL site (40.13°N, 105.24°W). All ensemble members exhibit similar GHI forecasts during the first 24 hours, excluding 1200 UTC 15 April 2018–1500 UTC 15 April 2018 (Fig. 3). In contrast, 10 ensemble members perform differently for the second day, with some members displaying effects of clouds present in observations. This result also shows that the impact of perturbations is pronounced in cloudy regions and provides the potential to provide a well-dispersed ensemble prediction.

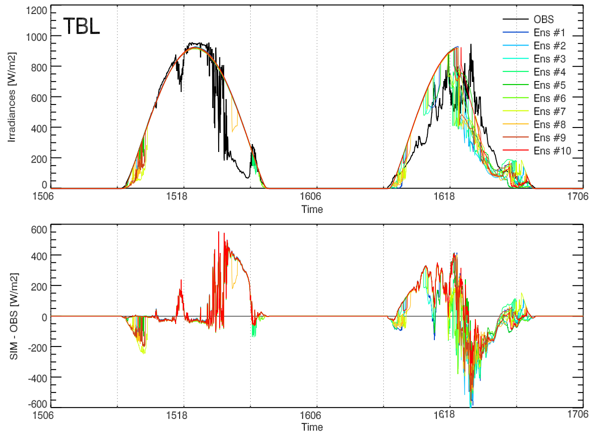

Figure 3. The time series of (top) simulated GHI and (bottom) error from individual WRF-Solar ensemble members of WRF-Solar at the TBL SURFRAD site in Boulder, Colorado, (40.13°N, 105.24°W) from 0600 UTC 15 April 2018 to 0600 UTC 17 April 2018.

4 SUMMARY

In this research, we present a new approach for stochastically perturbing forecasting variables to develop a WRF-Solar ensemble prediction system. A tangent linear sensitivity analysis is implemented to identify relevant forecasting variables by controlling surface irradiance and clouds in six WRF-Solar modules. Unique stochastic perturbations are derived for each ensemble member by specifying characteristics of the stochastic perturbations and adding them to the selected variables based on the sensitivity analysis. Preliminary results indicate that the proposed technique has the potential to produce high-quality probabilistic solar forecasts and discriminating ability across cloudy-sky conditions. Future extensions of this work will include optimized configuration of the ensemble members and calibration of the ensemble. Further, our development will be publicly available.

ACKNOWLEDGMENTS

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

This material is also based upon work supported by the National Center for Atmospheric Research, which is a major facility supported by the National Science Foundation under Cooperative Agreement No. 1852977.

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