A Physics-Based DNI Model for Advancing Solar Resource Assessment and Forecasting

Preprint

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A PHYSICS-BASED DNI MODEL FOR ADVANCING SOLAR RESOURCE ASSESSMENT AND FORECASTING

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ABSTRACT: Direct Normal Irradiance (DNI) is one of the most used quantities to quantify the magnitude of solar energy resource. The concept of DNI is often interpreted differently for ground measurements and solar forecasting by numerical weather prediction (NWP) models, leading to apparently substantial bias during evaluation of DNI forecasts especially under cloudy-sky conditions. To eliminate the bias, we use the Fast All-sky Radiation Model for Solar applications with DNI (FARMS-DNI) to provide a physics-based solution of solar radiation in the circumsolar region. FARMS-DNI is coupled with the Weather Research and Forecasting model with solar extensions (WRF-Solar) to predict day-ahead DNI in 9-km pixels over an extended domain covering the contiguous United States. By comparing with conventional predictions from WRF-Solar and satellite observations from the National Solar Radiation Data Base (NSRDB), we found significant improvemens in our prediction of DNI.

Keywords: solar radiation, DNI, solar forecasting

1 INTRODUCTION

Following the definition of direct normal irradiance (DNI) in the ISO 9488 standard (https://www.iso.org), DNI represents “the quotient of the the radiant flux on a given plane receiver surface received from a small solid angle centerred on the sun’s disk to the area of that surface”. However, most radiative transfer models used in the NWP models compute direct solar radiation on the basis of the Lambert law assuming an infinitely narrow beam along the solar incident angle [1, 2]. This assumption ignores the scattered solar radiation in the circumsolar region, and thus often leads to a significant underestimation of DNI in the cloudy atmosphere. On the other hand, models empirically estimate DNI based on long-term observation of all-sky global horizontal irradiance (GHI) and DNI and often overestimate DNI in the cloudy atmosphere [3]. To precisely compute all-sky circumsolar radiation, Xie et al. [4] developed FARMS-DNI that is a physical solution of scattered solar radiation that falls in the circumsolar region. This model uses a precomputed lookup table of cloud transmittance and reflectance to compute solar radiation for differential solid angles. It further uses a finite-surface integration algorithm to efficiently infer the radiation received by a surface perpendicular to the direction of the sun.

To increase the computational efficiency, we parameterized the cloud transmittance and reflectance using functions of solar zenith angle, cloud type, cloud optical thickness, and cloud effective particle size. FARMS-DNI with the parameterization has been implemented in the Weather Research and Forecasting model with solar extensions (WRF-Solar) [5, 6] to improve the prediction of DNI. The performance of the DNI forecast is evaluated using satellite observations in North America.

2 METHODOLOGY

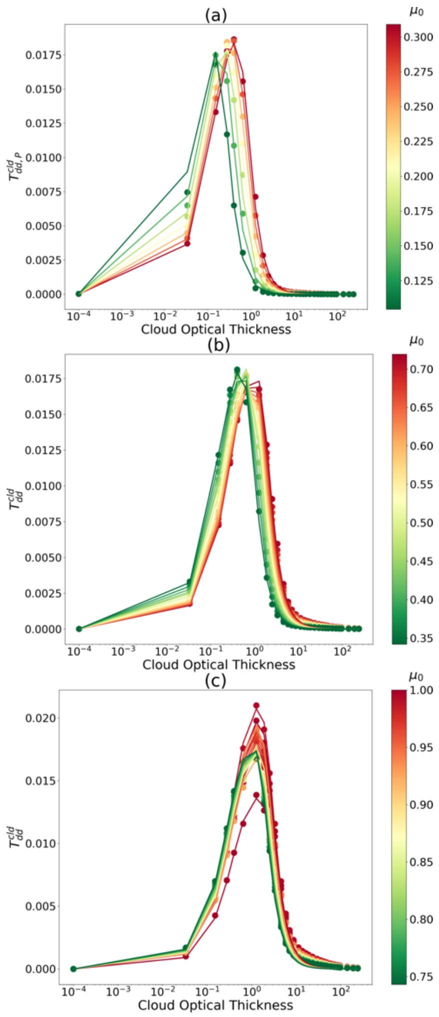

Fig. 1 A comparison between the lookup table and the parameterization of the cloud transmittance.

The cloud transmittance (T_{dd}^{cld}) for water and ice clouds was parameterized based on the hyperbolic tangent function. We tested a number of functions to approximate T_{dd}^{cld} including the exponential function used by [7]. We found that the hyperbolic tangent function has the best match to T_{dd}^{cld} for thin and thick clouds. The basic equation of cloud transmittance is represented by:

$$T_{dd}^{cld} = T_{dd,P}^{cld}(D_e, \mu_0)\, tanh[g(\alpha, \tau, \tau_P)] \qquad (1)$$

where D_e and μ_0 are the cloud effective particle size and the cosine value of the zenith angle, respectively and $T_{dd,P}^{cld}(D_e, \mu_0)$ is the maximum value T_{dd}^{cld} can have. $g(\alpha, \tau, \tau_P)$ is a function that controls two sections of T_{dd}^{cld} distribution around the peak. α is a function of μ_0, τ is the cloud optical thickness, τ_P is the cloud optical thickness when T_{dd}^{cld} reaches its maximum. Thus, the parameterization of cloud transmittance is divided into individual steps to parameterize τ_P, $T_{dd,P}^{cld}$, and $g(\alpha, \tau, \tau_P)$. The main steps for the parametrization of T_{dd}^{cld} include: 1) parameterization of τ_P 2) parameterization of $T_{dd,P}^{cld}$ and 3) parameterization of $g(\alpha, \tau, \tau_P)$. A comparison between the lookup table and the parameterization of the cloud transmittance can be found in Fig. 1.

3 FORECAST EVALUATION

To investigate the impact of the new DNI approach on solar forecasting, WRF-Solar with FARMS-DNI is configured to provide day-ahead prediction over the Contiguous U.S. using 9 km grid spacing. The day-ahead forecast spanning April 2014 is produced for every 15 minutes by WRF-Solar. Each simulation is initialized at 6 UTC with a forecast length of 48 hours. The National Centers for Environmental Prediction Global Forecast System (0.5°×0.5°; 3-hour intervals) forecast data are used for the initial and boundary conditions provide to the WRF-Solar model. Following the NCEP operational forecasting of the atmosphere using the High-Resolution Rapid Refresh (HRRR) model, we consider an extended domain covering the contiguous United States (the purple shadow in Fig. 2). The spatial resolution of the solar forecasting is 9 km, with a domain consisting of 211,447 grid boxes.

The forecast of DNI is evaluated using satellite data from the National Solar Radiation Data Base (NSRDB) [7-12]. The native NSRDB data (4km) are aggregated to the WRF-Solar grids (9km). In addition, the NSRDB data are produced over the ocean to evaluate the WRF-Solar forecast for its full extent in the North America. In this study, the 30-minute resolution satellite-based data are compared with the DNI forecasts in the matching time steps.

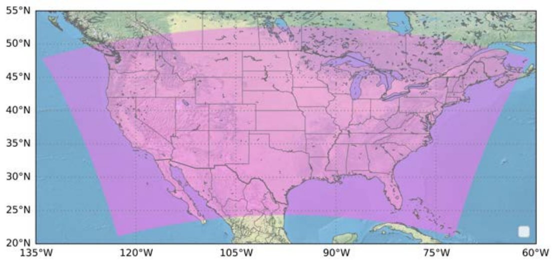

Fig. 2 The geographic domain of the solar forecasting by WRF-Solar.

The comparison of the new model against the Lambert law using global statistical metrics (computed with all pairs of observations and predictions for April 2014) shows that FARMS-DNI decreases root mean square error (RMSE), bias and mean absolute error (MAE) (Fig. 3). There is an improvement from using FARMS-DNI with a reduction of 10% in RMSE, a reduction of 69% in bias, and a reduction of 9% in MAE compared to the Lambert law. Considering bias, the models behave differently with positive (FARMS-DNI) and negative (Lambert law) values. This is attributed to FARMS-DNI that produces larger direct irradiances under cloudy-sky conditions. The performance of the two models has lower differences under clear-sky conditions.

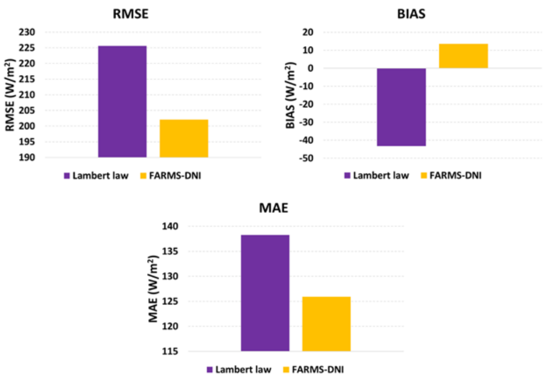

Fig. 3 RMSE, bias, and MAE of direct irradiance computed using the Lambert law and FARMS-DNI.

Figure 4 illustrates the RMSE, bias, and MAE of direct irradiance in the North America. WRF-Solar with the Lambert law substantially underestimates the DNI in virtually the entire domain, whereas FARMS-DNI primarily matches the spatial allocation of DNI obtained by the satellite data. The results demonstrate negative correlations between the magnitude of DNI and the relative bias in the forecast using both the Lambert law and FARMS-DNI. For example, the DNI forecasts in the western United States show moderate biases compared to the oceanic area and the eastern area, particularly around New England and the Great Lakes region. This is attributed likely to the fewer clouds on average in the western United States and consequently the reduced uncertainty in cloud forecasting with smaller fluctuations in solar radiation. The negative correlations become less apparent in the forecasts by FARMS-DNI owing to the improvements in the cloudy-sky DNI simulations.

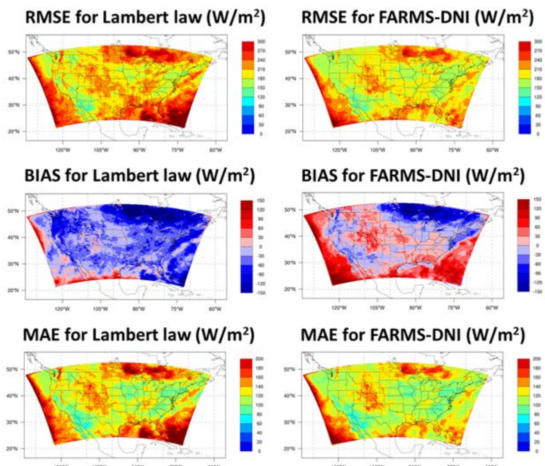

Fig. 4 RMSE, bias, and MAE of direct irradiance in the North America.

4 CONCLUSIONS

This study employs FARMS-DNI in the state-of-the-art solar forecasting model, WRF-Solar, to make physics-based predictions of all-sky radiation in the circumsolar region. The performance of FARMS-DNI is evaluated against satellite-based data in an extended domain covering the contiguous United States. The forecasts based on FARMS-DNI are compared with the Lambert law which is used by the latest version of WRF-Solar, as well as a variety of other NWP models to predict direct solar radiation. It is revealed from the satellite-based data that the DNI forecasts by the Lambert law are systematically underestimated. These biases are significantly reduced by implementing FARMS-DNI to account for the scattered radiation in the circumsolar region. Although the forecast errors for some individual scenes are reduced by FARMS-DNI, they are nonignorable. The negative correlations between the DNIs and their relative biases indicates that the accuracy of DNI forecasting is severely influenced by the long-term cloud coverage in the area.

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