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Bias correction of global irradiance modelled with weather and research forecasting model over Paraguay

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ABSTRACT

The estimation of solar irradiance is performed by means of numerical weather prediction (NWP) models that include all the necessary information to solve the temporal, geographical and atmospheric conditions variability being this the basis of solar energy applications. However, the radiative transfer schemes implemented in meteorological models show systematic errors in the simulation of global horizontal irradiance (GHI). In this contribution, we present a post-process analysis of Weather and Research Forecasting (WRF-ARW) model which combines a Kalman Filter with Model Output Statistics (MOS) for bias correction in order to improve the overall predicted values of GHI simulations over Paraguay. The hourly GHI is simulated at $4 \times 4\,\text{km}^2$ of spatial resolution. The annual evaluation of the hourly WRF model without post process shows relative mean bias error (rMBE) of 21% and relative root mean square error (rRMSE) of 81%. The results using several ground stations and combinations of post-process show an annual correction of systematic errors with rMBE of -0.7% and rRMSE of 70%.

1. Introduction

The increased contribution of solar energy to power generation sources requires an accurate estimation of global horizontal irradiance (GHI) conditioned by geographical, temporal and meteorological conditions. The knowledge of the variability of these factors is necessary for estimating solar energy production and increase its reliability in the global energy participation. The prediction of GHI is performed by means of numerical weather prediction models (NWP).

NWP models simulate the earth-atmosphere system by solving fluid mechanics and thermodynamic equations, which describe weather processes based on initial values and boundary conditions in a nonlinear computing environment (Kimura, 2002). Although NWP models have been advancing rapidly along with the development of modern computing technology, numerical prediction errors are inevitable due to the following (Liang et al., 2007): (1) NWP models cannot exactly describe all the physical processes of the atmosphere (e.g. complex cloud formation); (2) There are random errors in the initial values (observations); (3) Rounding errors accumulate during computing processes; (4) The spatial coverage of observed input is incomplete, especially above the surface.

Specifically, systematic errors of simulations of radiative transfer schemes of NWP models are mainly due to: (1) Miscalculation of the location of the clouds and total cloud water content in the layers of the atmosphere; (2) Incorrect specification of the optical thickness of aerosols; and (3) Decrease of atmospheric water vapor absorption for clear skies conditions. Therefore, the use of statistical post-processing methods may have the potential to satisfy the requirements of solar irradiance forecasting for up to several days ahead and its application in solar devices (Heinemann et al., 2006b). These post-processing methods seek to improve the accuracy of the forecast by reducing both systematic and random errors, while preserving or improving the correlation with observations (Wilks, 2006).

The MOS proposed by Glahn and Lowry (1972) and developed by the National Weather Service of the United States, is often used to forecast weather variables at specific locations near the surface, which are related to NWP model output in a historic dataset by multiple linear regression. In solar irradiance forecasting, Lorenz et al. (2009a) and Mathiesen and Kleissl (2011) applied a multivariate fourth-order regression to derive the MOS correction function of solar irradiance in NWP models. Mathiesen and Kleissl (2011) applied the methodology proposed by Lorenz et al. (2009a) to improve US forecasts of the NAM,

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Table 1
Parameterizations schemes used in WRF-ARW model (v3.7.1) for the annual simulation in Paraguay of 2015.

Parameterization	Scheme	Short description
Microphysics	WRF Single-Moment 3-class (Hong et al., 2004)	A simple, efficient scheme with ice and snow processes suitable for mesoscale grid sizes
Longwave Radiation	RRTM scheme (Mlawer et al., 1997)	Scheme using lookup tables for efficiency. Accounts for multiple bands and microphysics species
Shortwave Radiation	Dudhia scheme (Dudhia, 1989)	Simple downward integration for clouds and clear-sky absorption and scattering
Surface Layer	MM5 surface layer scheme (Fairall et al., 2003)	The scheme is sped up to give similar timing as with the old MM5 scheme. The thermal and moisture roughness lengths over the ocean are changed to COARE 3 formula
Land Surface	Unified Noah land-surface model (Niu et al., 2011)	Scheme with soil temperature and moisture in four layers, fractional snow cover and frozen soil physics
Planetary Boundary layer	Yonsei University scheme (Hong et al., 2006)	Scheme with the analysis of the interaction between the boundary layer and precipitation physics, explicit treatment of the entrainment layer at the PBL top and an enhanced stable boundary-layer diffusion algorithm. Allows deeper mixing in windier conditions
Cumulus	Kain-Fritsch scheme (Kain, 2004)	Deep and shallow convection sub-grid scheme using a mass flux approach with downdrafts and removal time scale

GFS and ECMWF models with spatial resolutions from 11 km^2 to 50 km^2 and relative bias errors from 0.1 to 1.9%. Lorenz et al. (2009b) presented a comparison between MOS and others post-processes to improve forecast of ECMWF, GFS, Skiron/GFS, AEMET/HIRLAM and WRF-ARW models for twenty-four European stations. The authors found a strong climatic dependence of the accuracy of the irradiance forecast with relative bias errors that varied from −4% to 16%.

Cornaro et al. (2014) developed two models to predict hourly solar irradiance with 24 h of anticipation based on ensemble of Artificial Neural Networks (ANN) in Italy. The first is a statistical model that uses only soil measurement data and the second ECMWF-MOS-NN model that corrects ECMWF-NWP data from the European Center of Medium Weather Forecast using ground stations. The accuracy of the models was compared with the persistence model as a reference, where the ECMWF-MOS-NN model showed the best result with an improvement of 30% of relative error with respect to persistence. Porrini et al. (2015) applied MOS techniques on WRF simulations of surface irradiance using three different physics schemes of microphysics, cumulus parametrization, land-surface model, planetary boundary layer and atmospheric radiation in a Uruguay domain. The authors found that MOS technique halves the relative error with respect to raw data of WRF model for forecasts in cloudy and partially cloudy conditions. Improvements were also found for clear sky conditions and the atmospheric radiation scheme of Hong et al. (2006) proved to be the most accurate. Finally, Pierro et al. (2015) presented a MOS based in Neural Networks in Italy, that reduces the relatives bias errors of the WRF-ARW model to 1.1%.

The Kalman Filter method (Kalman, 1960) provides a linear dynamic relationship by estimating the previous error and a correction factor proportional to the forecast error with minor computational cost and easy adaptation to any changes in the observations. The Kalman has been used to correct NWP variables (e.g. Monache et al., 2011; McCollor and Stull, 2008; Galanis et al., 2006; Roeger et al., 2003). Pelland et al. (2011) presented an adjustment of solar irradiance in an NWP model using the Kalman algorithm with relative errors that varied from −0.8% to 40%. Diagne et al. (2014) presented the latest work using Kalman method to improve the hour-ahead forecasted irradiance algorithm with relative errors that varied from 0.3% to 35%.

Among different statistical post-processes, the Model Output Statistics (MOS) and the Kalman Filter are the most extensively used within the atmospheric community. Unlike MOS, the Kalman method only needs a short training period and puts more weight on recent data than older observations. However, the Kalman Filter is not likely to predict sudden changes in the forecast error caused by rapid transitions from one weather regime to another. Thereby, the Kalman Filter is unable to predict a large bias when all the biases for the past few days have been small. Therefore, in this contribution, we present a combination of MOS-Kalman techniques to reduce their limitations when applied separately. The MOS-Kalman post-process has been applied for bias-correction on an annual simulation of GHI computed with Weather and Research Forecasting (WRF-ARW) meteorological model (Skamarock et al., 2008). The post-process MOS-Kalman is easier to apply than other methods such as Artificial Neural Networks, Bayesian model averaging or analog methods (Zhang et al., 2015). Thus, we use the MOS-Kalman post-process to improve the accuracy of GHI simulated by the WRF model, significantly reducing the systematic model error for all sky conditions and full range of Sun's vector positions when compared to ground stations in Paraguay.

2. Methodology

2.1. WRF-ARW meteorological model

The WRF-ARW meteorological mesoscale model (v3.7.1/2015) has been used to compute the GHI over the geographic area of Paraguay. It is a fully compressible and nonhydrostatic Eulerian model with the latest advances in meteorological mesoscale modelling; it incorporates state-of-the-art physical parameterizations (microphysics, longwave radiation, shortwave radiation, land-surface model, planetary boundary layer and cumulus parameterization). Furthermore, it is a worldwide reference model used as a research tool and operational weather prediction.

Table 1 summarizes the main characteristics of the parameterizations used by the WRF-ARW model as applied in this contribution. The radiation schemes provide atmospheric heating due to radiative flux divergence and surface downward longwave and shortwave radiation for the ground heat budget. The longwave radiation (RRTM scheme) includes infrared or thermal radiation absorbed and emitted by gases and surfaces, while the shortwave radiation scheme of Dudhia (1989) explicitly considers extinction by Rayleigh atmosphere and water vapor only. The Dudhia scheme consists of a simple broadband parameterization of GHI that includes visible and surrounding wavelengths that make up the solar spectrum. It is a downward integration efficiently allowing clouds and clear-sky absorption and scattering, but it does not account for multiple scattering effects. Extinction by ozone, aerosols, and other molecular absorbers are considered through a bulk scattering parameter that was empirically set to represent average turbidity conditions (Zamora et al., 2005).

The WRF-ARW model is run in diagnostic (hindcast mode) over the South American continent with 30 vertical layers and three nested domains centered over Paraguay having 36 km, 12 km and 4 km horizontal grid resolution, respectively. The outputs are stored at hourly temporal resolution. Initialization and boundary conditions are provided by the dataset DS090.0 Reanalysis with information available at 6 h intervals (NCEP/NCAR, 1994). The GHI hourly simulations consist of 365 daily runs to simulate the entire year 2015. The choice of this specific year is based on the availability of ground stations of GHI for this year (see Section 3).