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Simulating global horizontal irradiance in the Arabian Peninsula: Sensitivity to explicit treatment of aerosols

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ABSTRACT

Global horizontal irradiance (GHI) is simulated using a three-dimensional atmospheric meteorology-chemistry model and a triple-nesting configuration over the Middle East with a focus on the hot desert climate of Qatar. The model performance was assessed with measurement data of solar radiation from a ground monitoring station in Doha (Qatar) collected over a three-month period, of representative and distinct meteorological regimes. We have examined the ability of the model to reproduce GHI values under two different shortwave downward radiation parameterizations, and assessed the sensitivity of our results to the presence of aerosols. The introduction of an advanced treatment of aerosols greatly improves the model performance in predicting GHI. Explicitly including aerosol processes and its emissions in the model significantly reduces the relative root mean square error for GHI from 25% to 13% in May and from 20% to 12% in August. A significant improvement of the systematic bias was achieved (from up to 30% to approximately 2%) when aerosols are fully considered during all three seasons. The RRTM (Rapid Radiative Transfer Model) shortwave radiation scheme performs somewhat better than the Goddard scheme both with and without aerosols. This work suggests that GHI predictions in regions that experience high aerosol loadings can benefit significantly from a detailed and explicit treatment of aerosols and their physicochemical processes. This offers a novel approach to better manage the fluctuating nature of solar radiation originating from variable weather and air pollution conditions.

1. Introduction

The Middle East and North Africa (MENA) region has a plethora of solar resources and has recently started adopting plans for renewable energy (Nematollahi et al., 2016). The demand for electricity keeps rising in large urban environments of MENA and the need for diversification from conventional energy production is now pushing for methods to reduce carbon emissions towards a more sustainable development (Munawwar and Ghedira, 2014). Within that context, Qatar has developed an ambitious plan to establish solar energy applications that will produce 2% of the country's electric energy demands by 2020 and 20% by 2030. Several solar resource assessment and feasibility studies for concentrated solar power plants (CSP) and photovoltaic plants (PV) have recently been carried out in the Middle East (Liqreina and Qoaider, 2014; Zell et al., 2015; Mokri et al., 2013; Charabi and Gastli, 2010). For Qatar a comprehensive analysis of the long term potential for solar electricity production has shown that PV systems offer the most reliable and stable solution for this mostly hot and humid environment (Martín-Pomares et al., 2017; Sanfilippo et al., 2016). Therefore, accurate predictions of GHI in the region are of fundamental importance for efficient grid-connected PV establishments.

Accuracy in determining the future expected solar irradiance is essential for reducing grid integration costs and for a more effective management of the electricity grid. Unlike wind power, solar radiation predictive capabilities are still at an early stage. GHI forecasting is traditionally conducted using various modeling approaches including statistical models, models based on satellite data and sky cameras, and numerical weather prediction (NWP) models. The forecasting target horizon and spatial and temporal resolution determines the optimum modeling approach. For forecasts over the first minutes up to approximately 1–2 h ahead of time (nowcasting), time series of solar irradiance can be provided by statistical approaches based on measured solar radiation data at a specific location (Pedro and Coimbra, 2017; Mellit and Pavan, 2010). For forecasts from ∼2 h up to ∼5 h ahead (short-term forecasting), approaches based on detection of cloud motion derived from satellite remote sensing are used to infer intra-hour solar irradiance with often high spatial and temporal resolution (Heinemann et al., 2006; Perez et al., 2010; Chow et al., 2011). The most valuable tool for GHI forecasting from 6 h up to several days ahead is an NWP model.

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NWP models inherently include a radiative transfer model that is used to predict GHI through dynamic modeling of the troposphere (Heinemann et al., 2006). Zamora et al. (2003, 2005) evaluated the hourly GHI predictions of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5) (Grell et al., 1998) and the National Center for Environmental Prediction (NCEP) Eta Model in certain locations in the USA and reported model errors on the order of 100 W m^{-2} for high aerosol loadings. The ability of MM5 to predict hourly solar irradiance was also studied by Heinemann et al. (2006) who found a relative root mean square error (rRMSE) of about 50% in Germany. Perez et al. (2007) showed an rRMSE of 38% after applying a correction function estimating the hourly-averaged GHI by the NDFD (National Digital Forecast Database) as published by NCEP (Lorenz et al., 2009; Perez et al., 2013). Mathiesen and Kleissl (2011) conducted a comprehensive analysis of hourly GHI forecasts from three NWP models (NAM, GFS and ECMWF) over continental USA and found biases of up to 150 W m^{-2}. The capability of the Weather Research and Forecasting (WRF) model to predict hourly averaged solar irradiance in Andalusia, Spain was examined by Lara-Fanego et al. (2012) who found an rRMSE ranging between 10% (for clear-skies) and 50% (for cloudy conditions). Ruiz-Arias et al. (2013) using WRF, validated various shortwave radiation parameterizations in the US and found a superiority of the RRTMG scheme (Rapid Radiative Transfer Model for Global climate models), as long as reliable aerosol data are provided as input to the model. More recently, Zempila et al. (2016) focused on the sensitivity of WRF to shortwave irradiance schemes while following a simple approach for investigating the impact of aerosol variations. They found that hourly averaged GHI over Greece is overestimated with all schemes (by 40–70% in terms of relative bias) for all-sky conditions while for clear skies an RMSE ranging between 90 and 110 W m^{-2} was found. Gleeson et al. (2016) studied the effect of aerosols on clear sky solar radiation predictions using the Aire Limitee Adaptation dynamique Developpement InterNational – High Resolution Limited Area Model (ALADIN-HIRLAM) numerical weather prediction system for the August 2010 Russian wildfire case while testing three shortwave radiation schemes. They showed a reduction of error in global shortwave irradiance from 15% at midday to 10% when standard climatological aerosols were used.

One of the advantages of mesoscale NWP models is that they can cover a limited (urban to regional) geographical area and thus can be computationally inexpensive while their physics can include additional details compared to global large-scale NWP models. Furthermore, NWP models are well-suited for solar irradiance predictions as they include advanced shortwave solar radiation parameterizations (Ruiz-Arias et al., 2013). However, the fluctuating nature of solar irradiance reaching the surface, caused by highly variable weather and air pollution patterns, is currently a major challenge in cost-effective management, operation and integration of solar energy into existing electricity supply systems. More specifically, the subgrid-scale variability of clouds and the high temporal and spatial variability of atmospheric aerosol concentrations are the main sources of uncertainty in the prediction of GHI and DNI (direct normal irradiance). Complex cloud microphysics (e.g. calculation of total cloud water content) and non-deterministic aerosol patterns are not well represented by NWP models (Heinemann et al., 2006). Traditionally, NWP models either neglect the presence of particles in the atmosphere or (more often) include a simplified aerosol approach (e.g. use of climatological data), while often miscalculating the location and lifetime of clouds resulting in large biases in solar irradiance forecasting (Zamora et al., 2003, 2005; Zempila et al., 2016; Lara-Fanego et al., 2012; Thompson et al., 2016).

In the MENA region, high temperatures during most of the year often result in cloud-free atmospheric conditions due to rapid cloud dissipation. Aerosol concentrations, on the other hand, are high throughout the year due to frequent dust events and other emission sources in urban centers (Kalenderski et al., 2013; Prakash et al., 2015; Tsiouri et al., 2015). Therefore, consideration of the effect of aerosols in radiation models is crucial in order to reduce solar irradiance prediction errors in this region. Contrary to ozone, carbon dioxide and water vapor, the temporal and spatial variability of aerosols is larger and more difficult to predict. In this work, we simulate GHI in Qatar and the Middle East using a three-dimensional meteorology-chemistry model including a state-of-the-art prognostic treatment of aerosols. We evaluate our model performance against in-situ measurements and test the sensitivity of our predictions to (i) the presence of aerosols (by running separately WRF and WRF-Chem), and (ii) different shortwave radiation parameterizations that have been coupled to the aerosol processes. To the best of our knowledge, this is the first study considering an advanced aerosol representation in the calculation of GHI for this region. The suggested modeling framework offers a novel approach that can be applied in any region that suffers from variable aerosol concentrations.

In the following section we describe the measurement data collection method as well as provide details regarding the application of our modeling system. In Section 3 we analyze and discuss results of the different modeling configurations in comparison to the measured data and introduce the clearness index followed by conclusions.

2. Methodology

2.1. Measurement site and regional atmospheric conditions

The solar radiation measurements used in this study were recorded using the Qatar Environment and Energy Research Institute's (QEERI) high-precision monitoring station in Doha (25.33°N, 51.43°E), Qatar. Qatar experiences a hot desert climate with warm winters, long summers, frequent dust storms and a shortage of rainfall. Three main meteorological regimes prevail throughout the year in the country. A cool period covering November through March with average temperatures varying between 17 and 24 °C, a hot and dry period in April-June with average temperatures of 30–35 °C and relative humidity (RH) ranging between 26 and 32% and a particularly hot and humid period extending from July to September with average temperatures between 35 and 38 °C and RH of 45–55%. Long-term measurements of solar irradiance in Qatar (Bachour and Perez-Astudillo, 2014a, b; Perez-Astudillo and Bachour, 2015, 2014) have shown a maximum average daily GHI of 7 kW h m^{-2} during the month of June in Doha and a maximum interannual variability of 6.5%. The geographical variability of monthly averages of GHI was found to be low with a relative standard deviation of up to 4% with respect to the country's average.

2.2. Instrumentation and observational data

QEERI's monitoring station is equipped with Kipp and Zonen thermoelectric sensors, each mounted on a Solys2 sun tracker, which also has a sun sensor kit for improved tracking accuracy. Two CMP11 secondary standard pyranometers, fitted with CVF 3 ventilation units, are used for measuring GHI and DHI (diffuse horizontal irradiance) (http://www.kippzonen.com/?downloadcategory/551/Pyranometers.aspx), and one CHP1 first class pyrheliometer is used for DNI measurements (http://www.kippzonen.com/?downloadcategory/19,192/Pyrheliometers.aspx). A shading ball assembly is also mounted on the tracker for measuring DHI. All data from the station are collected as one-minute averages in W m^{-2}. Quality checks and routine maintenance are conducted at high frequency (daily or every other day) and involve detailed cleaning of all sensor domes/windows, replacement of the desiccant of sensors when needed, and checking of the sensor shading, sensor tracking and level/alignment, as well as offline data validation. Additionally, QEERI's air quality monitoring station, located next to the solar radiation station, is equipped with a Thermo-hygrometer (DMA867-875) and an Anemometer (DNA827) and continuously measures (every 1 min) ambient relative humidity, temperature, wind velocity and wind direction at 5 m altitude.