The Aerosol Effect on Direct Normal Irradiance in a Dust-Rich Hot, Desert Climate

Christos Fountoukis, Dunia Bachour, Daniel Perez-Astudillo

Qatar Environment and Energy Research Institute (QEERI), Hamad Bin Khalifa University, Doha, Qatar

Abstract

This study investigates how the spatial and temporal variations in atmospheric aerosols impact Direct Normal Irradiance (DNI) in a region affected by desert dust intrusions. We employ a three-dimensional atmospheric meteorology-chemistry model (WRF-Chem) with a triple-nesting configuration over the Middle East, focusing particularly on the hot desert climate of the Arabian Peninsula. We analyze data of solar radiation covering five-month periods (May-September), which represent both dry and humid summertime conditions in the region. These data are used to evaluate the model's performance. By implementing an advanced prognostic treatment of aerosols, the model demonstrates significantly improved accuracy in predicting DNI. The influence of aerosols on DNI is particularly pronounced in areas affected by human activities, such as large cities, as well as those experiencing desert dust intrusions. In these regions, aerosol-induced attenuation of DNI can exceed 70%, corresponding to a reduction of nearly 6 kWh m^{-2} per day.

Keywords: WRF, WRF-Chem, anthropogenic emissions, desert particles

1. Introduction

Qatar benefits from an abundance of sunlight throughout the year, receiving about 6.1 kWh/m² of solar energy per day (Perez-Astudillo et al., 2022), making it one of the top locations worldwide for solar potential. This high level of solar irradiation throughout the year makes Qatar a prime candidate for solar PV energy projects. The country's annual Global Horizontal Irradiation (GHI), essential for solar photovoltaic (PV) applications, is approximately 2100 kWh/m². According to Qatar's National Research Strategy and Energy Development Action Plan, one of the primary objectives is to implement large-scale PV projects. By the end of 2022, Qatar had achieved 800 MW of utility-scale PV capacity, and it aims to generate over 20% of its total electricity from solar energy by 2030. This transition is expected to contribute to a reduction of up to 26 million metric tons of CO2 equivalent by that year. Considering Qatar's demographic profile and energy requirements, solar energy, especially through distributed residential and commercial PV systems, can significantly aid in meeting the country's solar adoption targets. This approach can lower infrastructure costs and boost energy security. Furthermore, incorporating distributed PV generation into smart grids can improve grid adaptability, manage the variability of renewable energy sources, and decrease peak demand via demand response programs. This not only fortifies grid resilience but also enhances national energy security. Moreover, shifting to solar energy for electricity generation can conserve natural gas, Qatar's primary electricity source, offering potential economic benefits through gas savings for international trade or downstream industrial development.

As the use of solar energy applications increases, accurate forecasting of solar irradiance is essential. Ensuring the precise forecasting of solar irradiance is paramount for reducing grid integration expenses and enhancing the management of electricity grids. Nonetheless, unlike wind power, the prediction of solar insolation still comes with significant errors. A variety of modeling techniques, such as statistical models, satellite data-based models, sky cameras, and numerical weather prediction (NWP) models, are conventionally employed for forecasting DNI. The selection of a modeling approach depends on the forecast timeframe. NWP models are the favored tool for DNI prediction from 6 hours up to several days in advance. These models integrate a radiative transfer model (RTM) to dynamically forecast DNI by simulating the troposphere. Mesoscale NWP models offer benefits as they cover smaller geographic areas (ranging from urban to regional) and are

10.18086/eurosun.2024.10.04 Available at http://proceedings.ises.org

computationally efficient while incorporating detailed physics compared to global large-scale NWP models. They are particularly suitable for solar irradiance predictions due to their advanced shortwave solar radiation parameterizations (Ruiz-Arias et al., 2013). However, the dynamic behavior of atmospheric aerosols presents a significant challenge for solar radiation forecasts due to the complex and uncertain aerosol radiative forcing. Specifically, uncertainties in the subgrid-scale variability of clouds and the high temporal and spatial variability of atmospheric aerosol concentrations complicate the accuracy of solar radiation predictions. NWPs often inadequately represent complex cloud microphysics and non-deterministic aerosol patterns.

2. Methodology

Solar radiation data utilized in this research were gathered from the high-precision monitoring station operated by the Qatar Environment and Energy Research Institute (QEERI) in Doha (25.33ºN, 51.43ºE). This station is equipped with thermoelectric sensors manufactured by Kipp & Zonen, mounted on a Solys2 sun tracker with a sun sensor kit for precise tracking. GHI and DHI are measured using two CMP11 pyranometers fitted with CVF 3 ventilation units, while DNI is measured using a CHP1 pyrheliometer. The WRF-Chem version 4.5 (Weather Research Forecasting with Chemistry, Fast et al. (2006) three-dimensional meteorology-chemistry model was utilized over the Arabian Peninsula region, with a high grid resolution specifically over Qatar (Fountoukis et al., 2022). The model simulates three fundamental components: emissions of atmospheric constituents (both gases and aerosol particles), their transport, and physicochemical transformations. Employing a two-way nesting configuration, the WRF-Chem model operates across three domains at varying grid resolutions, with information regarding species concentrations exchanged between domains throughout the model integration process. The parent domain adopts a 50 km × 50 km grid resolution, while the intermediate nested domain, focused on the Arabian Desert, employs a 10 km × 10 km resolution. The third domain is configured over the Qatar region with a resolution of 2 km × 2 km. This nesting capability enables WRF-Chem to efficiently cover large geographical areas where regional pollutant transport, such as dust, is significant, while also offering fine resolution in specific areas to capture small-scale features.

3. Results and discussion

Typically, NWPs either disregard atmospheric particles entirely or adopt overly simplified aerosol approaches, frequently resulting in inaccuracies in cloud cover location and duration and substantial biases in solar irradiance projections. In the Arabian Peninsula, elevated temperatures for much of the year lead to cloud-free atmospheric conditions owing to swift cloud dissipation. However, aerosol concentrations persistently remain high due to frequent dust events and other urban emissions (Fountoukis et al., 2016, 2020, 2022; Tsiouri et al., 2015; Prakash et al., 2015). Therefore, accounting for aerosol effects in radiation modules is imperative for mitigating solar irradiance prediction inaccuracies in this region. In this study, we employ WRF-Chem to simulate Direct Normal Irradiance (DNI) in Qatar and the broader Middle East, incorporating an advanced prognostic treatment of aerosols (Fountoukis et al., 2020). Our model's performance is assessed against in-situ measurements, and we investigate the impact of aerosol presence on our predictions.

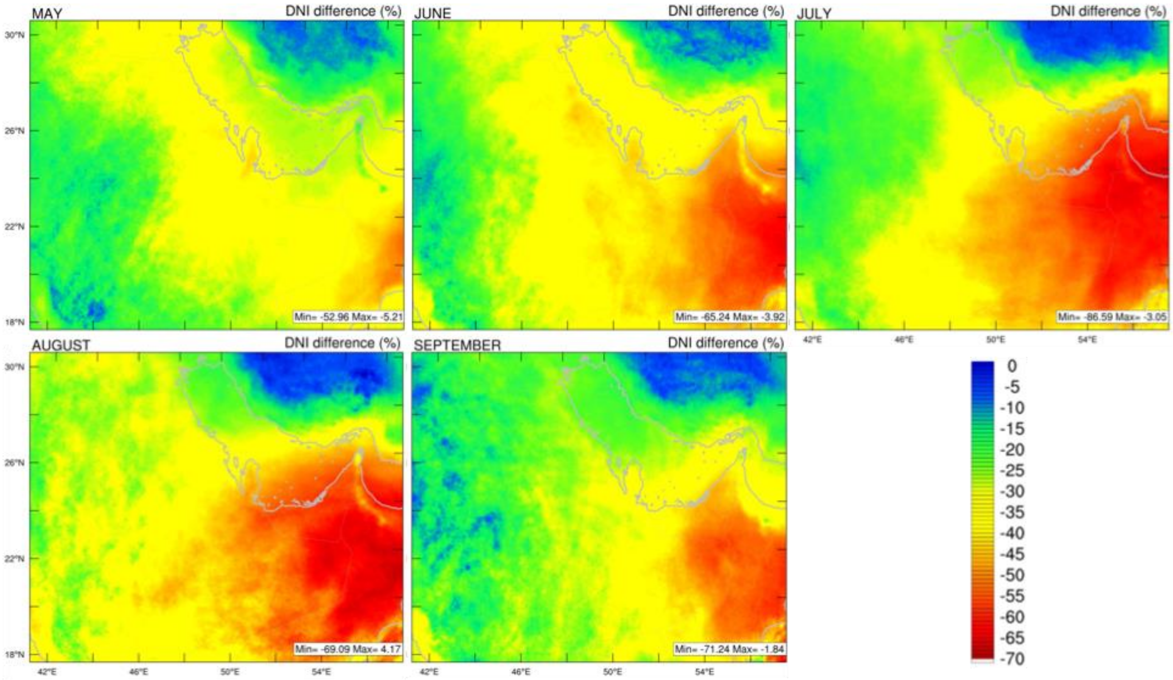

Fig. 1: Average monthly aerosol effect on DNI (%) simulated for the period May – September over the Arabian Peninsula.

Figures 1 and 2 depict the monthly average influence of aerosols on Direct Normal Irradiance (DNI) across the Arabian Peninsula and Qatar, respectively. This influence is assessed by computing the percentage (%) difference between two WRF-Chem DNI forecasts: one with detailed aerosol representation and another assuming no aerosols. The most significant percentage differences are observed in the eastern part of the Arabian Peninsula, with values decreasing by as much as -70%. This translates to a reduction of about 5-6 kWh m^{-2} per day.

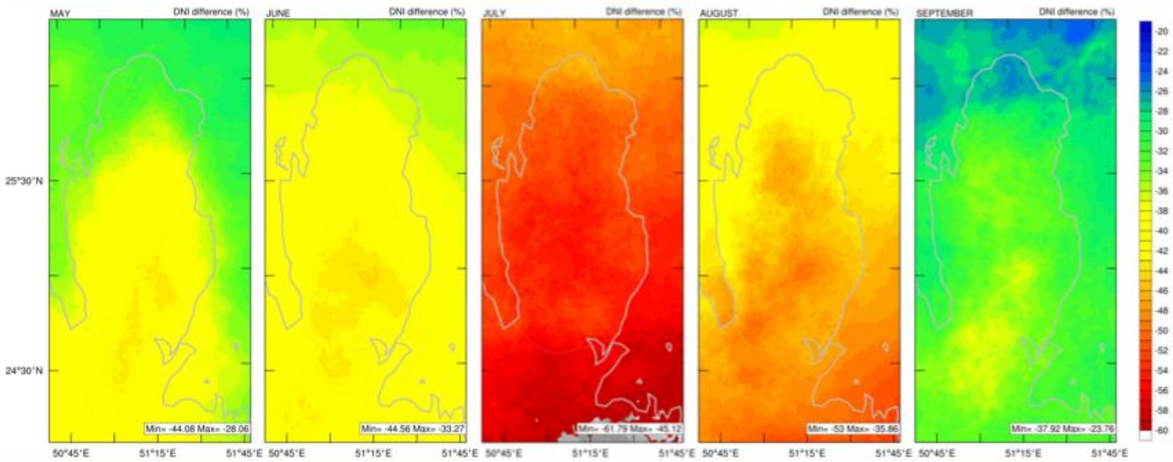

Fig. 2: Aerosol effect on DNI (%) as a monthly mean predicted for the period May – September over the state of Qatar.

This region often experiences dust storms, as noted in prior research (Roshan et al., 2019). Situated downstream of the well-known North Westerly (Shamal) winds, this area is susceptible to dust intrusions originating from the Fertile Crescent region of Iraq and Syria, as well as the deserts of Saudi Arabia, which are directed towards the Eastern Arabian Peninsula and the Arabian Gulf. The Asir Mountains in southwestern Saudi Arabia play a significant role in dust dispersal across the Arabian Peninsula. Their elevation increases the volume of dust transported over and eastward of the mountains into the Eastern Arabian Peninsula.

Notably, the most significant reductions are observed in July and August among the five months studied, coinciding with higher atmospheric relative humidity levels. This increased humidity also impacts the predicted aerosol optical depths by the model, as shown in Figure 3, which illustrates the elevated levels of AOD during the humid months in Qatar.

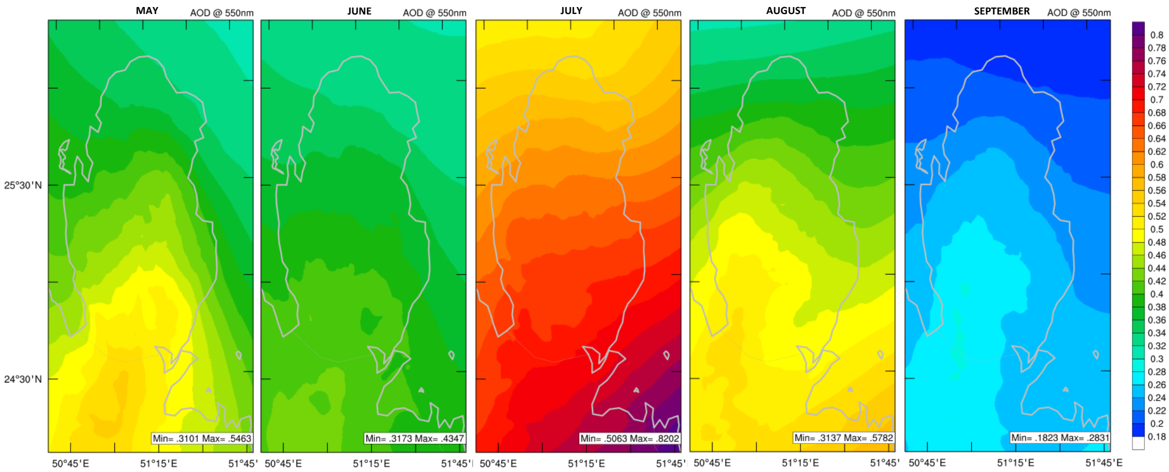

Fig. 3: Aerosol optical depth predicted as a monthly mean for the period May – September over the state of Qatar.

The model's performance significantly improves when incorporating the prognostic treatment of aerosols compared to the observed DNI values. Including comprehensive aerosol physics and chemistry enables the model to accurately replicate the observed DNI in Qatar throughout all studied months, resulting in a 30-40% reduction in the model's relative root mean square error. Figure 4 shows such a comparison for the period of June.

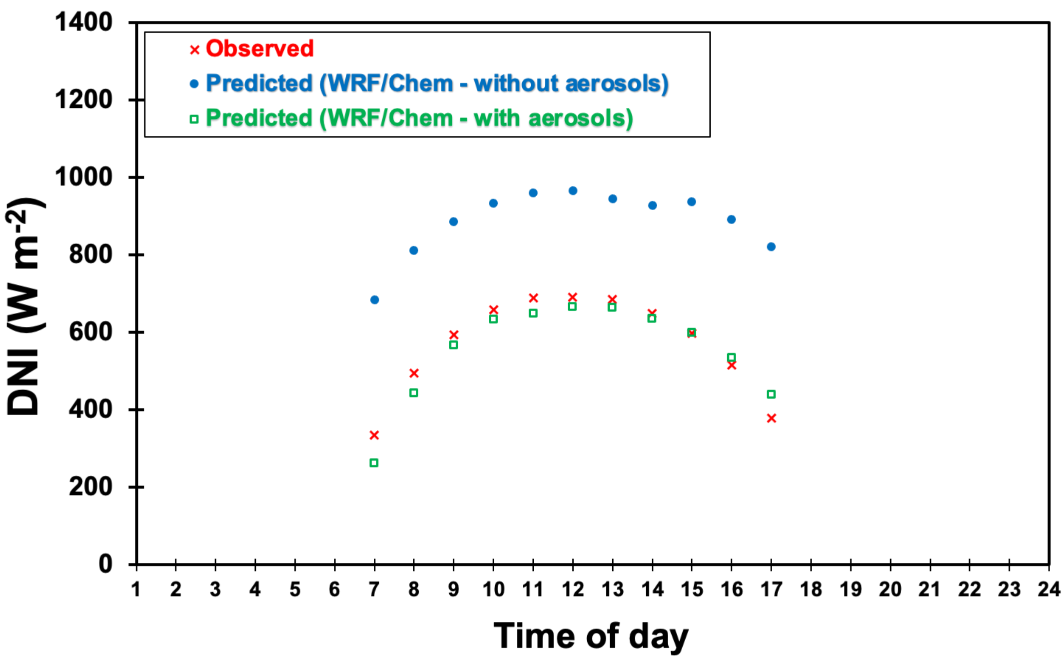

Fig. 4: Average diurnal profile of DNI (W/m^2) during the month of June for the location of QEERI's solar station in Doha, Qatar.

Acknowledgements

Research reported in this work was supported by the Qatar Research Development and Innovation Council (Grant: ARG01-0503-230061). The content is solely the responsibility of the authors and does not necessarily represent the official views of Qatar Research Development and Innovation Council.

4. References

Fast, L.D., Gustafson, Jr. W. I., Easter, R.C., Zaveri, R.A., Barnard, J.C., Chapman, E.G., Grell, G.A., 2005. Evolution of ozone, particulates, and aerosol direct forcing in an urban area using a new fully-coupled meteorology, chemistry, and aerosol model, J. Geophys. Res. (111), D21305. doi:10.1029/2005JD006721.

Fountoukis, C., Ackermann, L., Ayoub, M.A., Gladich, I., Hoehn, R.D., Skillern, A., 2016. Impact of atmospheric dust emission schemes on dust production and concentration over the Arabian Peninsula. Model. Earth Syst. Environ. 2 (115), doi:10.1007/s40808-016-0181-z.

Fountoukis, C., Harshvardhan, H., Gladich, I., Ackermann, L., Ayoub, M.A., 2020. Anatomy of a severe dust storm in the Middle East: Impacts on aerosol optical properties and radiation budget, Aerosol and Air Quality Research, 20, 155-165, doi: 10.4209/aaqr.2019.04.0165

Fountoukis, C., Mohieldeen, Y., Pomares, L., Gladich, I., Siddique, A., Skillern, A., Ayoub, M.A., 2022. Assessment of High-resolution Local Emissions and Land-use in Air Quality Forecasting at an Urban, Coastal, Desert Environment, Aerosol and Air Quality Research, 22 (6), https://doi.org/10.4209/aaqr.220001.

Perez-Astudillo, D., D. Bachour, A. Sanfilippo, H. Al-Hajri. Management and Operation of Qatar’s Solar Radiation Monitoring Network. EuroSun 2022 Proceedings. DOI: 10.18086/eurosun.2022.15.06

Prakash, P.J., Stenchikov, G., Kalenderski, S., Osipov, S., Bangalath, H., 2015. The impact of dust storms on the Arabian Peninsula and the Red Sea, Atmos. Chem. Phys. 15, 199-222. doi:10.5194/acp-15-199-2015.

Roshan, D.R., M. Koc, R. Isaifan, M.Z. Shahid, C. Fountoukis, Aerosol Optical Thickness over Large Urban Environments of the Arabian Peninsula—Speciation, Variability, and Distributions, Atmosphere, 10 (5), 228, 2019.

Ruiz-Arias, J.A., Dudhia, J., Santos-Alamillos, F.J., Pozo-Vazquez, D., 2013. Surface clear-sky shortwave radiative closure intercomparisons in the Weather Research and Forecasting model, J. Geophys. Res. Atmos. 118 (2013) 1-13, http://dx.doi.org/10.1002/jgrd.50778.

Tsiouri, V., Kakosimos, K.E., Kumar, P., 2015. Concentrations, sources and exposure risks associated with particulate matter in the Middle East Area - a review, Air. Qual. Atmos. Health 8, 67-80, doi:10.1007/s11869-014-0277-4.