Long-Term Variability of Aerosol Optical Depth, Dust Episodes, and Direct Normal Irradiance over Kuwait for CSP Applications

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Abstract

Two sources of aerosol data (from ground-based sunphotometry and long-term reanalysis), as well as irradiance data (from ground-based radiometric measurements) are investigated here. The daily, seasonal and interannual variability of aerosol optical depth is evaluated over Kuwait. Based on the MERRA-2 reanalysis, long-term aerosol trends are also established over the period 1980–2016, showing a slight increase in aerosol optical depth (AOD) since about 2000. This is conducive to a concomitant decrease in the direct normal irradiance (DNI) resource of ≈2% per decade, which can affect concentrating solar power (CSP) projects over the long-term. When compared with sunphotometer data from two AERONET stations located at a distance of only 90 km, but in somewhat differing environments, shortcomings are found in the aerosol data from the MERRA-2 reanalysis. Both bias and scatter are found in the hourly and daily AOD data, as well as occasional mismatch in the prediction of the more-or-less frequent AOD spikes caused by dust storm episodes. The use of MERRA-2 aerosol data for the prediction of clear-sky DNI with a high-performance irradiance model results in underestimation (of ≈13% on average) and substantial scatter on a 1-min basis, based on a comparison with co-located, high-quality DNI data.

Keywords: Aerosol optical depth (AOD), direct normal irradiance (DNI), CSP, dust storms, MERRA2.

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1. Introduction

Many large solar projects involving various kinds of Concentrating Solar Power (CSP) technologies are being built in regions such as the Middle East. These arid or desert regions benefit from a low overall cloudiness, and thus overall high solar resource, but are also impacted by significant background aerosol loads and somewhat frequent dust episodes. These can be detrimental to the operation and yield of CSP plants for various reasons: (i) Intense atmospheric attenuation, leading to significant loss in incident direct normal irradiance (DNI); (ii) Increased slant atmospheric attenuation between mirrors and central receiver of solar tower power plants; (iii) Concomitant strong winds that may force an emergency shutdown of the plant; and (iv) Extreme dust soiling on concentrators or mirrors. The present study focuses on the first topic. A related study (López et al., 2017) explores the second one.

Ideally, dust storm episodes should be forecasted a few days early so that the plant and electric utility operators can take all necessary measures to prepare the plant and the electric grid for any potential disruption. Research has now started toward the development of an integrated forecasting system to help the development of CSP and other renewable energy technologies in Kuwait, where significant solar power is being built or projected. Solar forecasts need to focus on both clouds and dust episodes at various time scales.

Before construction, the solar resource needs to be well established in terms of both magnitude and temporal variability. Under arid conditions, DNI's variability directly depends on that in aerosol optical depth (AOD), as discussed elsewhere (Gueymard, 2012b; Polo et al., 2016). DNI also depends on the quantity of atmospheric water vapor, measured in the form of precipitable water (PW), albeit to a much lesser extent than AOD (Gueymard, 2014). More generally, the quality of the AOD data is a major factor that directly affects the accuracy of derived DNI predictions using current modeling techniques (Cebecauer et al., 2011), which in turn can negatively impact the bankability of the solar resource data used by the solar industry (Gueymard, 2011).

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Multi-site measurements conducted over Kuwait during the last five years have confirmed that DNI's solar resource is indeed highly variable on a daily and seasonal basis (Al-Rasheedi et al., 2014). This is particularly true during summer when the potential for solar electricity generation reaches its peak, thanks to virtually permanent cloud-free conditions during longer days and high-sun conditions. Until now, the specific link between the magnitude and variability of DNI and of its AOD counterpart had not been precisely defined over Kuwait. In the present contribution, various sources of DNI and AOD data are used to establish (i) the long-term variability in both quantities over Kuwait; (ii) the modeled effects of high-AOD conditions on DNI; and (iii) possible long-term trends in those two quantities.

2. Data sources

The present analysis focuses on both modeled and observed aerosol data, and on observed solar irradiance data. NASA's MERRA-2 reanalysis model provides historical estimates of the hourly AOD at 550 nm (hereafter, AOD550), Ångström exponent (AEX), and total scattering AOD (SAOD) since 1980, among many other atmospheric variables (such as PW), at a spatial resolution of 0.5x0.625°. Although this resolution is relatively coarse, it is not a serious limitation here because of the absence of strong topographic features over Kuwait. Moreover, MERRA-2's consistent evaluation of AOD550, SAOD, and AEX at hourly resolution over more than three decades is a highly desirable feature, which is unique among all reanalysis models currently available.

In parallel, shorter-term ground observations of spectral AOD and AEX from two AERONET sunphotometric stations are also available. The older one is located at the Kuwait University campus in the coastal urban area of the capital, Kuwait City, and has reported Level-2 (L2) data for 2006–2010 and Level-1.5 (L1.5) since 2006, albeit with many long data breaks in both datasets. The newer station is located in the Shagaya solar park, where PV, CSP and wind installations already exist. Shagaya is located 90 km to the west from the capital, in a remote and drier desert area. This AERONET station was commissioned in August 2015, after its installation alongside the existing radiometric station (whose data are also used in this study, see below). Thus far, this station has provided L2 aerosol data for the period August 2015 to July 2016, as well as L1.5 data since February 2017.

The L1.5 data record is much longer than the L2 record at both sites. It is therefore worthwhile to examine the difference in AOD when retrieved with version 2 (V2) of the algorithm applied to L2 data (V2L2) relative to the more elaborate version 3 applied to L1.5 data (V3L1.5). Based on 5000 instantaneous data points at Kuwait University, the distribution of differences shown in Fig. 1 reveals that all older AOD values (from V2L2) are slightly larger than those produced by the newer algorithm. Nevertheless, the difference virtually never exceeds 0.01, which is the typical uncertainty of AOD at that wavelength (Holben et al., 1998). This agreement is remarkable, which confirms information found on AERONET's website (https://aeronet.gsfc.nasa.gov/new_web/Documents/AERONET_V3_AOD.pdf) to the effect that V3L1.5 offers similar results to V2L2. Since V3L1.5 has a more complete historical record than V2L2, the former is exclusively used here in all what follows.

In any case, these observation periods, being relatively short, cannot be used for a long-term analysis of variability or trend, but can still be helpful to validate other sources of aerosol data (such as MERRA-2) and to provide the necessary inputs for short-term irradiance predictions with radiative-transfer models. These applications are discussed below.

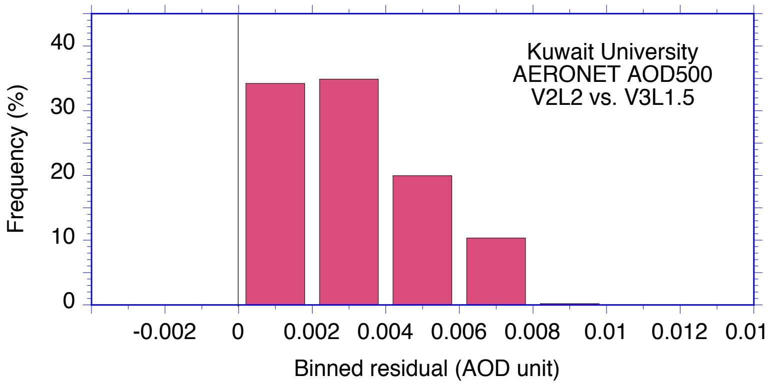

Fig. 1: Binned frequencies of difference between AOD at 500 nm retrieved from AERONET's V2L2 vs. V3L1.5 algorithms at Kuwait University.

The Shagaya sunphotometer is collocated with a well-maintained radiometric station. It monitors all irradiance components (including DNI) with both thermopile and photodiode instruments, thus providing redundancy. Details on the instrumentation, data quality control, early results, and comparisons between measured and satellite-derived modeled data were provided in a previous report (Al-Rasheedi et al., 2014). The Shagaya station has provided high-quality irradiance data since September 2012. Another radiometric station, Kabed, also provides redundant observations of DNI. The DNI resource of Kabed is similar to that of Shagaya, due to the short distance between them (≈65 km), so will not be discussed further here.

3. Results

3.1 Aerosol optical depth: MERRA-2 vs. AERONET

It is desirable to compare the AOD550 data predicted by MERRA-2 to those observed at AERONET stations. This constitutes the conventional way of validating modeled AOD data, and is also important in the context of discriminating high-AOD periods caused by dust storms of various strengths, or evaluating the historical frequency and seasonal variability of such events. This kind of study also prepares for the longer-term goal of qualifying the suitability of NASA's GEOS-5 research forecasting model (from which MERRA-2 is derived) to correctly forecast future dust-storm events over Kuwait.

A first comparison is done for daily-mean AOD data. Since AOD550 is not observed directly by AERONET sunphotometers, it is calculated here from Ångström's law using AOD at 500 nm and AEX evaluated between 440 and 870 nm. The daily-mean AOD550 is then obtained for all days that produce at least 3 instantaneous measurements (per standard AERONET procedures). This removes only a limited number of days (or periods during any day) since cloudiness is generally low or absent, particularly in summer. Observations, however, are only done for a sun zenith angle lower than 82°. To make things as comparable as possible, the MERRA-2 daily means are thus calculated for all hours for which the mid point corresponds to a zenith angle less than 80°.

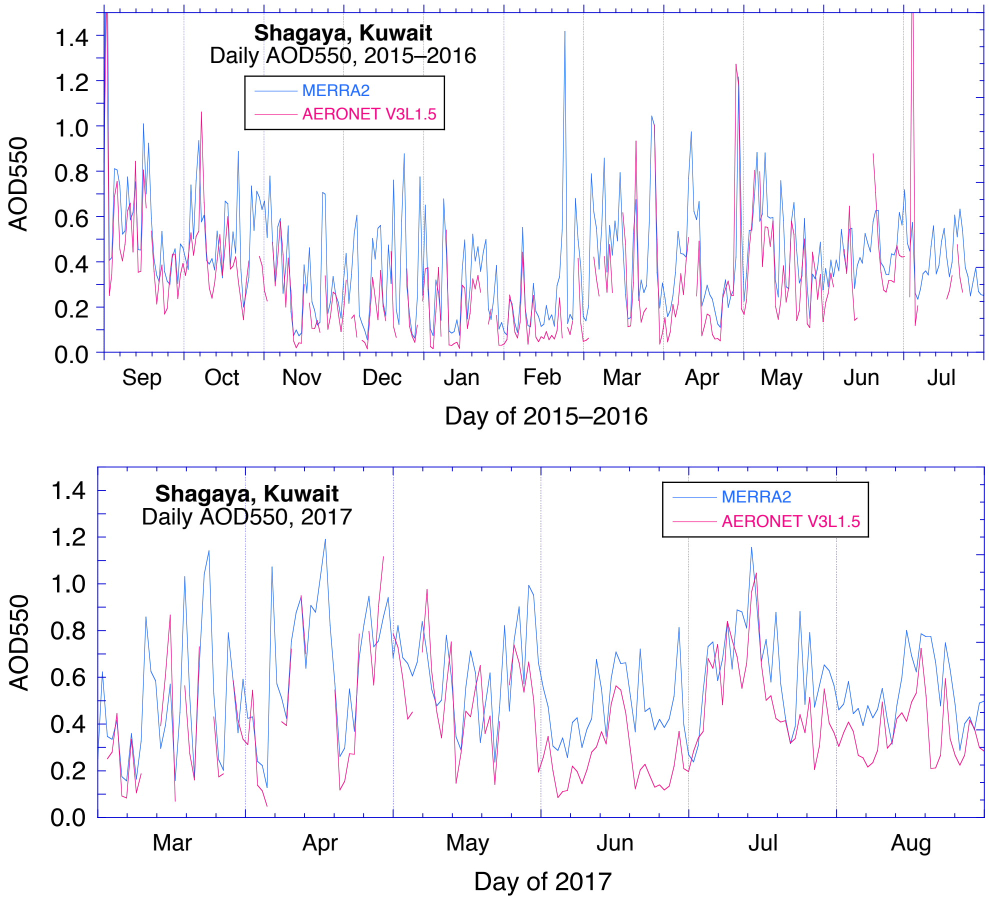

Fig. 2: Time series of daily AOD550 from both modeling by the MERRA-2 reanalysis and ground observations at the Shagaya AERONET station during 9/2015–7/2016 (top) and 3/2017–8/2017 (bottom).

Figure 2 shows the time series of daily-mean AOD550 obtained from MERRA2 and the Shagaya AERONET station during the 12-month period when the latter was operational before it was sent back for repair and calibration, and also for a more recent 6-month period of 2017. The MERRA-2 and AERONET sources of data show similar high daily and seasonal variability, with however occasional differences in magnitude or phase. It is clear that MERRA-2 tends to predict higher AOD than the ground observations. This is confirmed in Fig. 3a, which compares the *hourly* AOD550 data from MERRA2 and the corresponding *instantaneous* data from AERONET's V3L1.5. An additional characteristic is that MERRA2's overestimation is accompanied by significant scatter. A similar scatterplot appears in Fig. 3b, but for AEX. It shows large scatter too, but also a lack of similitude, due to generally too low predictions at high AEX. Figure 4 shows the frequency distributions of the differences between MERRA-2 estimates of AOD550 or AEX and matching AERONET observations. Interestingly, the two distributions of MERRA-2 deviations are skewed in opposite ways. The mean and median errors are ≈0.1 for AOD550. Hence, it can be expected that DNI simulations based on MERRA-2 AOD data should be too low by ≈10%.

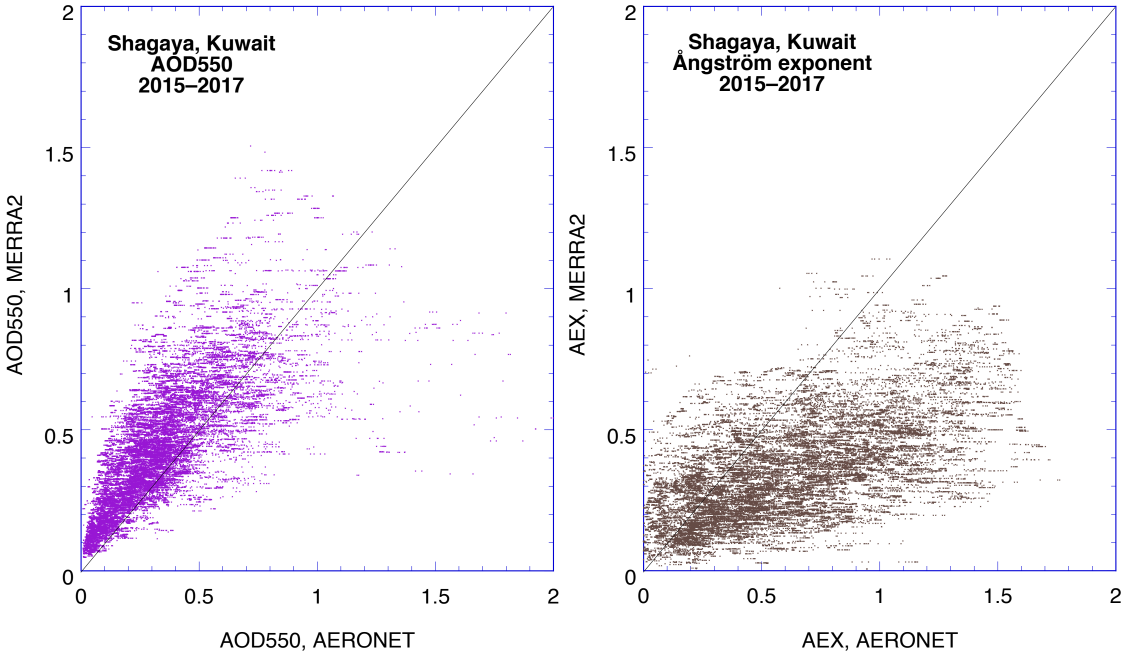

Fig. 3: Scatterplots of AOD550 (left) and AEX (right) comparing MERRA-2's predictions to ground observations from the Shagaya AERONET station.

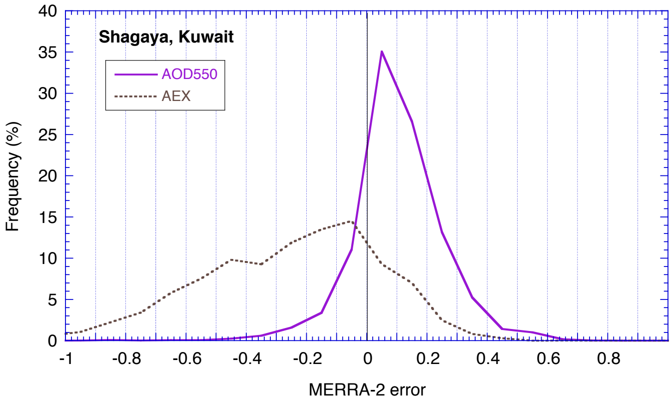

Fig. 4: Frequency distributions of MERRA-2's errors in AOD550 and AEX (compared to AERONET reference data) at Shagaya.

The difference between the predicted and observed AOD550 is reflected in their temporal frequency distribution over the period of record, as illustrated in Fig. 5. It is found that the daily AOD550 frequency distribution obtained from MERRA-2 better match that of AERONET at Kuwait University than at Shagaya. This can be explained, at least in part, by a statistical artifact caused by the lower number of days in the latter case. It is also possible that the variability of the aerosol loading is more difficult to predict in a pure desert environment such as Shagaya's, or that the (older) Kuwait University data points are assimilated into the GEOS-5 forecasting model, which would improve the aerosol modeling there.

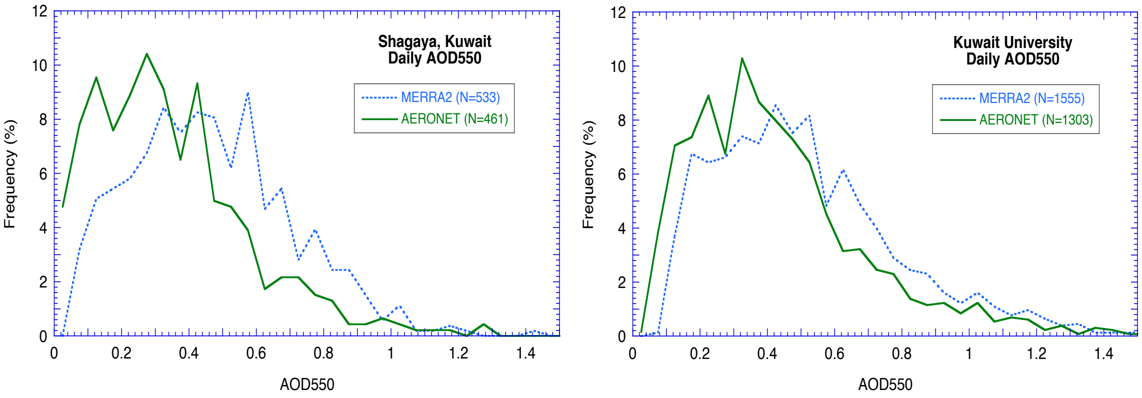

Fig. 5: Frequency distribution of daily AOD550 from MERRA-2 and AERONET for Shagaya (left) and Kuwait University (right). N is the number of days. Periods with 7 or more consecutive days of missing AERONET data were eliminated from the analysis.

Figure 5 also suggests that very hazy days (AOD550 > 0.6) are more frequent in Kuwait City than over Shagaya. For instance, the probability of days with a mean AOD550 higher than 1.0 is ≈2% at Shagaya and ≈5% in Kuwait City, based on AERONET data. At Shagaya, the maximum daily-mean AOD550 of 1.86 was observed on 2016-07-04 according to the 461-day record of AERONET V3L1.5 until end of 8/2017. In comparison, the daily mean for that day was much lower (1.17) at Kuwait University. At the latter site, the record maximum daily-mean value (2.39) was reached on 2017-04-29, while Shagaya simultaneously experienced only less than half of that value (1.06). These differences in peak AOD values and frequency distribution are remarkable, considering the relatively short distance between the two locations. Spatial variability in AOD is thus to be considered in addition to its temporal variability, which will require further study.

3.2 Aerosol optical depth: Historical time series

Based on MERRA2's 1980–2016 time series, the annual average AOD550 remained in the range 0.35–0.50 during that period, with significant interannual variability and possible decadal cycles (Fig. 6). Linear trends are evaluated separately over two distinct periods of similar duration: 1980–1996 and 1997–2016. The former is considered less certain than the latter because of the lack of satellite or AERONET data to constrain the aerosol transport model before 1997. The two last decades experienced an increasing trend in AOD, at the rate of 0.0024 AOD unit per year. This in turn translates into a likely decrease in the DNI resource of ≈2% per decade, based on the analysis of Gueymard (2012b). This positive trend in AOD is consistent with results from Hsu et al. (2012), which were based on AERONET and satellite data, and with the solar radiation dimming experimentally observed over Iran (Jahani et al., 2017; Rahimzadeh et al., 2015). Since a negative trend in DNI is likely to have a notable impact on the performance of CSP plants (many of which being built or planned in the region), more studies will be needed to better quantify this trend, and delineate its geographical extent.

Still using the whole 37-year MERRA-2 dataset currently available, the frequency distribution of AOD550 at Shagaya is shown in Fig. 7. Results are displayed for three important time scales: Hourly, daily, and monthly. The hourly and daily results are remarkably similar, much smoother than the short-term daily distribution in Fig. 5 (as could be expected, considering the much longer period), and show the characteristics of the anticipated log-normal distribution (Ruiz-Arias et al., 2016a). The monthly frequency distribution is substantially different in shape, which results in a lower median than the two other distributions. This statistical feature, in turn, has consequence on the modeling of DNI, and, ultimately, on the bankability of the DNI resource for CSP applications if monthly-mean AOD data are used as input of solar radiation models (Ruiz-Arias et al., 2016b, 2016c).

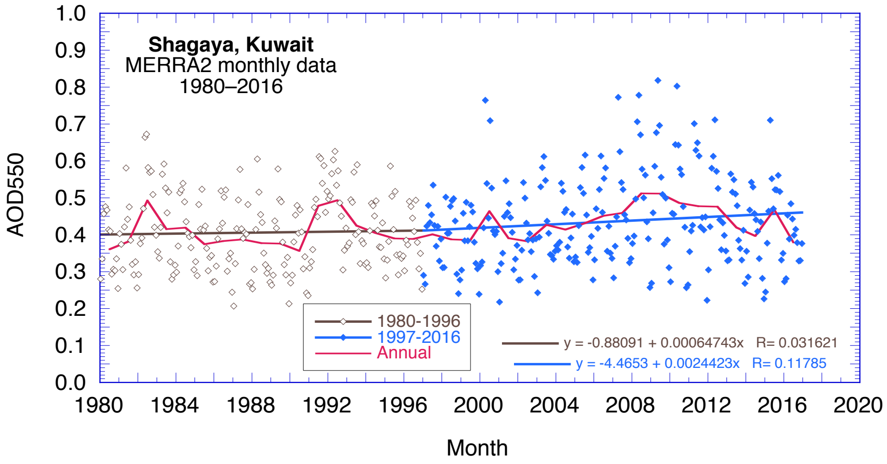

Fig. 6: Time series and trends of mean monthly and annual MERRA2's AOD550 separated into two periods.

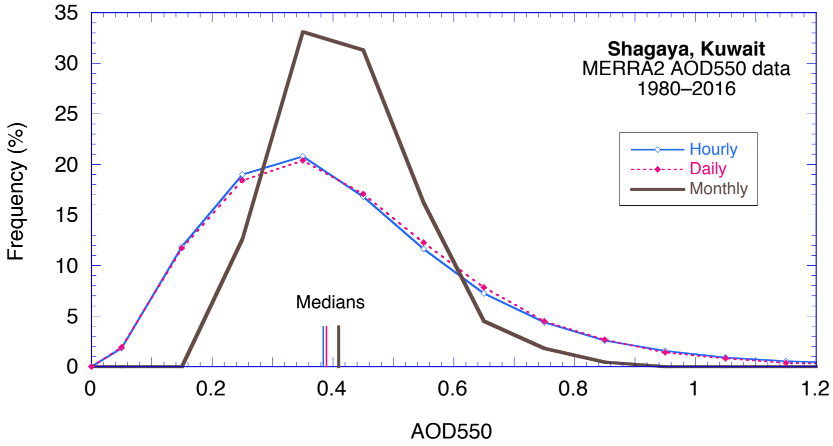

Fig. 7: Hourly, daily, and monthly frequency distributions of MERRA2's AOD550 over the period 1980–2016.

Figure 8 compares the daily variability in MERRA-2's AOD550 and in the measured DNI at Shagaya during summer 2015. Such a period being virtually cloudless (except in early May), the temporal variability in DNI is expected to be essentially due to that in AOD. Nevertheless, the two signals are not exactly in phase due to the shortcomings in the MERRA-2 AOD data discussed above. The daily-integrated DNI reached its maximum of ≈10 kWh/m^2 during a few days only, when the AOD was relatively low for the season at that location. Conversely, the strong aerosol-induced extinction makes DNI reach only 4–5 kWh/m^2 during high-AOD days.

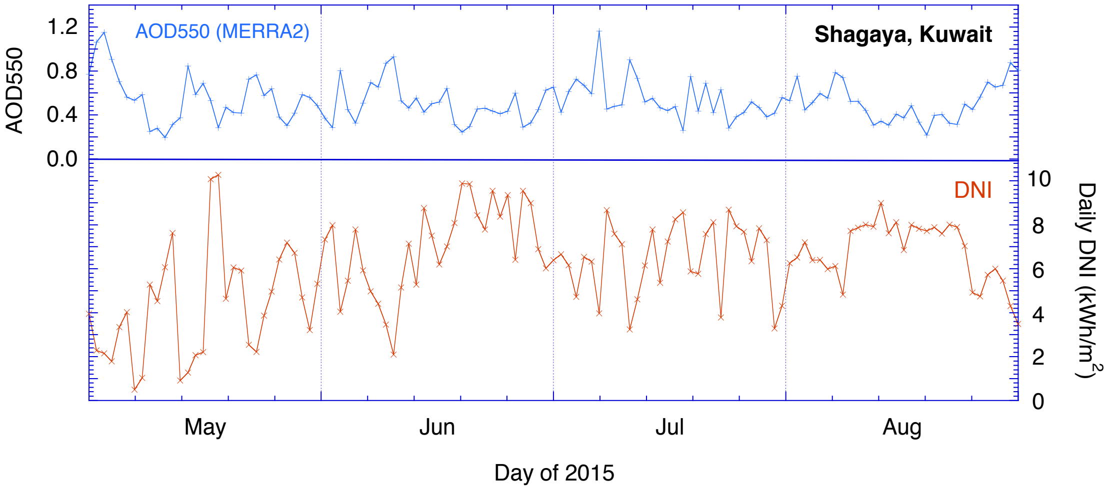

Fig. 8: Daily variability in MERRA2 AOD (top) and in DNI measured at Shagaya (bottom) during summer 2015.

3.3 Direct normal irradiance prediction

Solar irradiance is sensitive to the amount and optical characteristics of aerosols at any instant. This is most particularly true for DNI, which decreases substantially when AOD increases (e.g., Gueymard, 2005, 2012b). This also means that potential errors in AOD data used as input to a radiative transfer model necessarily result in errors (of opposite sign) in DNI. This, in turn, is important for the simulation of the power production of CSP systems before construction, since typically no long-term local DNI observations are then available. CSP systems are strongly non-linear, which makes their energy output sensitive to the quality and representativeness of the DNI resource data. The latter is actually the major source of uncertainty in the modeling of CSP plants (Ho et al., 2011). Even the use of conventional hourly Typical Meteorological Years (TMYs) may result in seasonal and annual errors (Polo et al., 2017). Simulations performed by Hirsch et al. (2010) showed that non-linearity impacts can be avoided, but this requires that calculations be done at high temporal resolution, with irradiance data time steps in the order of 1–10 minutes, which is highly demanding.

Evaluating clear-sky DNI can be done accurately if collocated instruments (e.g., sunphotometers) provide the most important aerosol and water vapor inputs at the required high temporal resolution (Gueymard, 2012a; Gueymard and Ruiz-Arias, 2015). The specialized stations reporting such data are still very scarce, which constitutes a serious limitation. Other sources of aerosol data do exist and are more readily available on a global scale (e.g., on a gridded basis), but their lower quality typically results in substantially biased or distorted DNI time series (Polo and Estalayo, 2015).

In this context, it is important to evaluate whether the MERRA-2 reanalysis data can provide accurate DNI estimates over Kuwait at sub-hourly resolution. To that effect, the latest version of the high-performance REST2 model (Gueymard, 2008) is used to simulate DNI at Shagaya. The best possible modeling of DNI is obtained when using observations of the main inputs (AOD550, AEX and PW) from AERONET V3L1.5. Secondary inputs (hourly ozone amount and station pressure) are obtained from MERRA-2. The (low) columnar amount of nitrogen dioxide is provided by spaceborne observations from the Ozone Monitoring Instrument (OMI) radiometer. The observational DNI dataset comes from a thermopile pyrheliometer and a silicon-based rotating shadowband irradiometer (RSI) that are installed side-by-side at Shagaya. The pyrheliometer observations are used preferably, but are replaced by RSI data in case of tracker malfunction or data not passing the tests of an elaborate quality control procedure, itself based on the method described by (Long and Shi, 2008). A related study has shown that the DNI observations from RSI and thermopile are in close agreement (Al-Rasheedi et al., 2017).

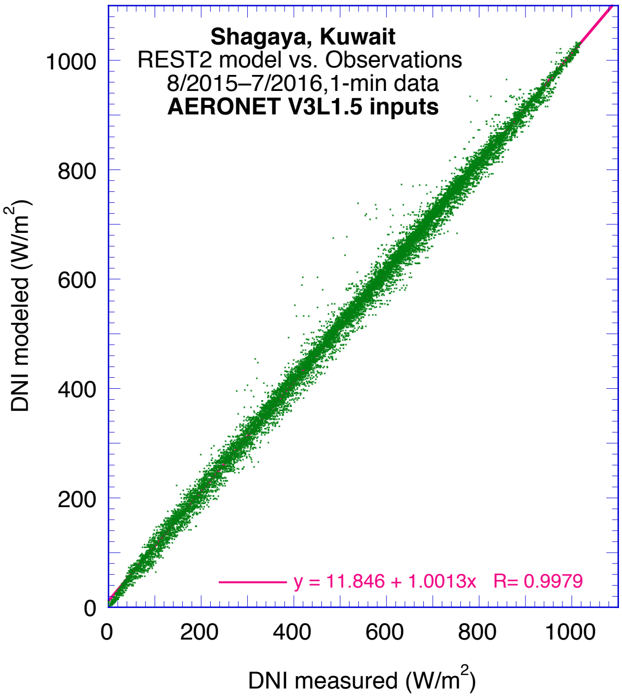

Fig. 9: Scatterplot of REST2-predicted DNI vs. ground observations using aerosol and water vapor input data from AERONET V3L1.5.

Figure 9 shows a scatterplot of the AERONET-based modeled DNI in comparison with its measured counterpart. As expected, the match is excellent, with only a few outliers caused by the passage of clouds during the irradiance observation. (Irradiance is integrated over a 1-min period, whereas AERONET observations are instantaneous, and are allowed to be as much as one minute away from the center of the 1-min period.) In comparison, this simulation is repeated with the main inputs (AOD550, AEX and PW) alternatively provided by MERRA-2 for the matching hour. The comparison of the modeled DNI thus obtained with the same measured data as in Fig. 9 shows a strong underestimation of DNI (≈13% on average) and large scatter (Fig. 10). These results can be directly traced back to the large bias and scatter in AOD (and possibly AEX) shown in Figs. 3 and 4. The difficulties of using the MERRA-2 reanalysis to simulate DNI corroborate previous findings (Polo and Estalayo, 2015), even though those were obtained with a different reanalysis model.

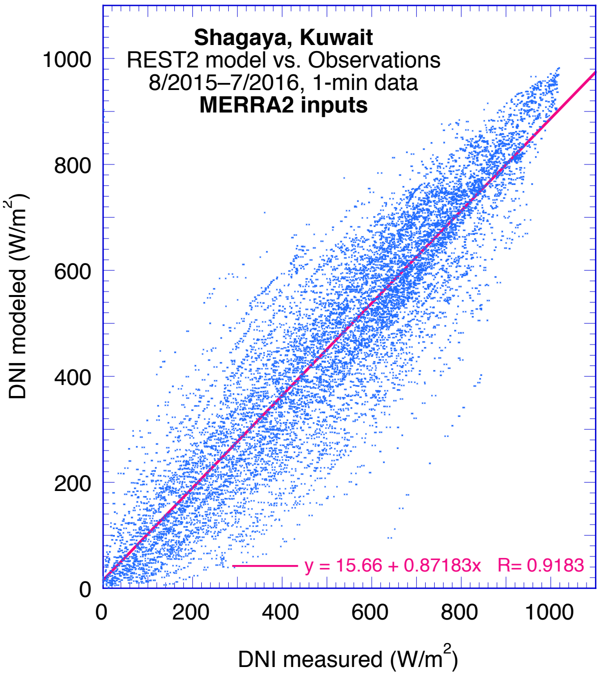

Fig. 10: Scatterplot of REST2-predicted DNI vs. ground observations using aerosol and water vapor input data from MERRA-2.

4. Conclusion

This investigation brings new information on the temporal variability in aerosol optical depth (AOD) and direct normal irradiance (DNI) under the arid conditions of Kuwait. Using data from two AERONET stations and from the MERRA-2 reanalysis, it is found that AOD is highly variable on a daily basis, and can reach very high values during any season, due to the incidence of dust storms. Some spatial variability is also apparent, even over relatively short distances. This significantly impacts the DNI solar resource in particular, and may limit the performance of CSP installations. Further investigation is needed to better characterize the spatio-temporal variability in AOD over Kuwait.

The MERRA-2 reanalysis predictions show a slight positive trend in AOD during the last two decades, signaling that a concomitant downward trend in DNI was likely. A continuation of this trend is possible in the near future, which would impact CSP projects in the region. The long-term MERRA-2 historical data has great value for, such trend analyses, but is found not accurate enough for the unbiased DNI resource evaluation required for the computerized simulation of CSP systems at high temporal resolution. Clear-sky modeled DNI predictions using MERRA-2 aerosol and water vapor data as inputs to a high-performance solar irradiance model are found noisy and too low by ≈13% on average, in comparison with actual high-quality irradiance observations with a 1-min time step.

Although the MERRA-2 aerosol transport-modeling module is still far from perfect, its main features (long time series at hourly frequency) are still unique among all other reanalysis models currently available. It is suggested that further research be carried out to compare the historical estimates of AOD from MERRA-2 or the forecasts from its parent model, GEOS-5, to those from other similar sources, in an effort to evaluate and improve the uncertainty of modeled DNI over arid areas.

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