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Evaluation of MERRA-2 data for aerosols patterns over the Kingdom of Saudi Arabia

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ABSTRACT

Aerosol is one of the major climate-forcing parameters which affect the Kingdom of Saudi Arabia in particular. The most relevant consideration that characterizes the aerosol properties and distribution is the Aerosol Optical Depth (AOD). In this study Modern Era Retrospective Analysis for Research and Applications (MERRA-2) AOD product from the year 1980–2021 is used to investigate aerosols pattern over the Kingdom of Saudi Arabia. The validation of the MERRA-2 AOD product is made by using AOD data retrieved from Aerosol Robotic Network (AERONET) stations located at Solar Village (SV) and at King Abdullah University of Science and Technology (KAUST). Various statistical analyses are performed to test the reliability of MERRA-2 data in the study region. The results of the statistical analysis indicate that MERRA-2 is highly correlated with both AERONET stations data. Thus, annual and seasonal aerosol climatology maps based on 41 years of MERRA-2 data are prepared and analyzed over the study region. The annual and seasonal aerosol climatology analysis of MERRA-2 data shows high density of AOD at southern and eastern regions while the low density emerges over the western and northern regions of the country during the study period. The results of the study are very encouraging, which increases our confidence level to use historical MERRA-2 AOD product to improve the knowledge on aerosols distribution over the region in future.

1. Introduction

Aerosols are small suspended solid or liquid particles in the atmosphere with radius ranges from 0.001 to 100 μm. Aerosols have a great impact on global climate, environment, agriculture, water cycle, human health, and ecosystem [1]. For example, atmospheric aerosols directly or indirectly influence the radiation balance, by affecting the optical properties (scattering and absorption of solar radiation) thereby altering the solar radiation budget. In addition, aerosols are a key player to change the cloud microphysics affecting the rainfall patterns [2–6]. Similarly, aerosols are also associated with the several allergic and respiratory diseases in humans [7–9]. Numerous studies discussed the aerosol characteristics and its behavior over various regions of the globe [10–22]. The Intergovernmental Panel on Climate Change (IPCC) has pointed out the role of dust in the climate change variations. Therefore, it is essential to evaluate long term variability and trends of aerosols both at global and regional scales to understand the climate variability.

The Kingdom of Saudi Arabia is vulnerable to climate change [23–25] and high concentration of aerosols are one of the key factors that can play a vital role in it [26–28]. The large deserts (for example, Rub Al Khali, An Nafud, Ad Dhana) in the country as well as

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frequent sand and dust storm activities are the major contributors in the atmospheric aerosols in the region [29–33]. Recently [28], reported that the frequency of sand and dust storm activities is highest in the eastern part of the Kingdom of Saudi Arabia while [34] in their study concluded that eastern region of the Kingdom of Saudi Arabia in the spring season exhibits the highest concentration of aerosols. Studies have also exhibited the constrained due to the limited number of ground stations for in situ data in the Kingdom of Saudi Arabia [35–38]. This gap is filled by various sources including satellite observation data [39–42] and reanalysis products [30, 43–46].

Studies have shown that AOD measurement can efficiently depicts concentration of aerosols in the atmosphere using ground based, satellite based, and reanalysis datasets [28,34,47,48]. However, several data sets to investigate the AOD behavior have certain regional impacts and thereby the data reliability over the target region is not guaranteed with great authenticity. For example, a major limitation with ground-based data is that it is not available at all grid points. Aerosol Robotic Network (AERONET) is one of the well-known ground-based (more than thousand stations around the world) AOD data [49] which however, suffer due to the sparsity of the datasets as well as due to the nonoperational of various instruments at different geographical locations from time to time. Thus, the continuity of the data both in terms of spatial and temporal scale is uncertain. On the other hand, various satellite instruments can provide AOD products over land and ocean. Although satellites provide continuity, uncertainties associated due to data gaps with respect to specific sensor as well as sparse spatial and temporal coverage due to cloud coverage cannot be ignored. Furthermore, aerosols models experience additional uncertainties in aerosol retrieval which are associated with the emission and physical parameterization. Recently, the data assimilation technique that incorporates ground and satellite data has shown to potentially provide a better characterization of atmospheric aerosols. Several research groups have developed aerosols data assimilation techniques both on a global [50–57] and regional [58–62] scales. MERRA-2 (Modern Era Retrospective Analysis for Research and Applications-2) AOD product has also been the focus of study by researchers in recent years [45,63]. Thus, in the present study, our main AOD data source is MERRA-2 reanalysis data and AERONET station data.

In this study, the inter-annual and seasonal variability of aerosol for a period of 41 years over the Kingdom of Saudi Arabia is analyzed using MERRA-2 AOD product. Thus, the assessment of the efficiency of the MERRA-2 AOD product for the study region with respect to ground based AERONET AOD product therefore is very essential. As a first step the AOD product from MERRA-2 is validated using data from two AERONET stations, one at Solar Village (SV) and other at King Abdullah University of Science and Technology (KAUST), in the country. Statistical techniques including standard deviation, linear regression, Pearson Correlation Coefficient, Index of Agreement (IOA), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Relative Mean Bias (RMB) methods are used to test the reliability of MERRA-2 data in the study region. The inter-annual and seasonal variability of aerosols using MERRA-2 AOD product over the Kingdom of Saudi Arabia is then analyzed. The uniqueness of the current study is that the ground-based dust data retrieved from National Centre for Meteorology (NCM) is also used to analyze the long-term aerosol variability (41 years MERRA-2 AOD product) over the study region. This study is organized as, the section one belongs to the introduction, second section discussed the study area, section three is related to material and method, section four highlights the results and discussions and last section describes the summary and conclusions.

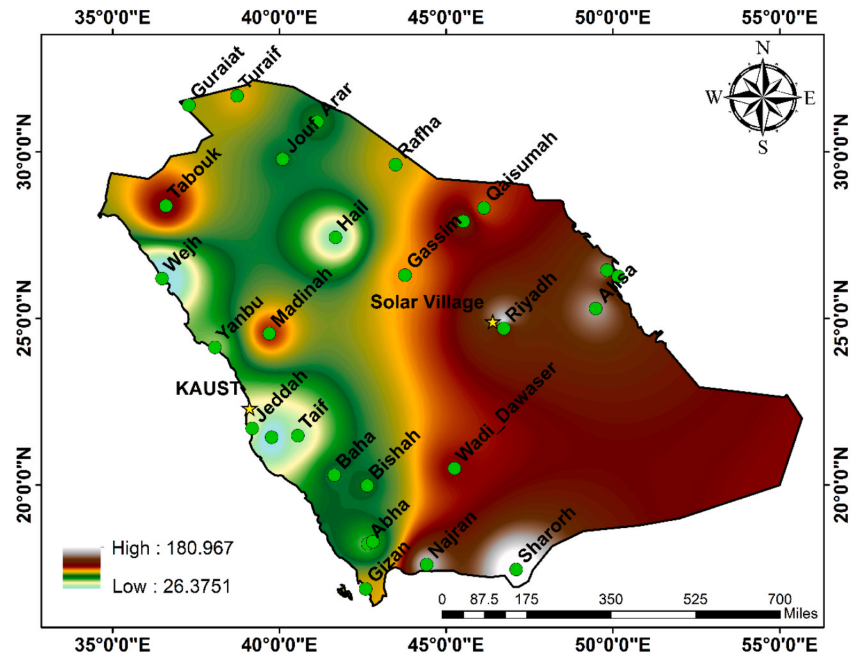


Fig. 1. Study area depicting aerosols concentration based on 25 ground stations in the country. The location of AERONET stations is also shown in the figure.

2. Study area

The Kingdom of Saudi Arabia with an area of 2,150,000 km^2 is the largest country in the Middle East. It is located in the geographical domain ranges from 34.57° W, 55.66° E, 16.37° S, and 32.15° N as shown in Fig. 1. The NCM administered ground stations (shown with circle sign) as well as location of two AERONET stations (shown with star sign) are also shown in Fig. 1. The major neighboring countries of the Kingdom of Saudi Arabia are Kuwait, Yemen, United Arab Emirates, Oman, and Qatar. The country is bordered by Arabian sea in the southeast and Red sea in the west. Large deserts (Najd, An Nafud, Rub Al Khali, Ad Dhana) are the main surface features and most of the surface is unsuited for irrigation thus making the way for research related with land reclamation. The climate of the country is mostly hot and dry with summer temperatures as high as 54 °C in some places however the mountains in the southwest receive greater rainfall amount compared to the other regions. The drought, heat waves, extreme rainfall events and dust storms are therefore the common climatic features of this region [64]. Such ingredients make the country vulnerable for sand and dust storm events thereby prominent region affected due to aerosols concentration in the atmosphere and their related studies.

3. Material and method

3.1. MERRA-2 data

The MERRA-2 is an upgraded version of MERRA reanalysis data set and is a blended product of MERRA reanalysis data, GSI (Gridpoint Statistical Interpolation) assimilation system, and the GEOS (Goddard Earth Observing System) model. This AOD product is based on bias corrected AOD from the AVHRR, MODIS, and MISR satellite sensors along with the ground observations of AERONET AOD data [43,65]. The aerosol fields from MERRA-2 can serve as initial conditions for air quality forecasting and for regional modeling [48,66,67]. In addition, MERRA-2 aerosol fields have also been used as a tool to study aerosol climate interactions [68,69]. Furthermore, researchers have also utilized MERRA-2 aerosol fields as a priori profiles in satellite retrievals of other atmospheric constituents [70,71]. Similarly, in the environment of Observing System Simulation Experiments (OSSEs) MERRA-2 aerosol fields have been used for optimal network/satellite sensor design. Further details about MERRA-2 product can be found in Refs. [45,63]. In the present study, hourly and monthly MERRA-2 AOD reanalysis product from 1980 to 2021 at a spatial resolution of 0.5° × 0.625° is acquired from NASA Giovanni interface website (https://giovanni.gsfc.nasa.gov/giovanni/). Annual and seasonal mean maps from MERRA-2 monthly data of the study region are prepared using Grads software. The prepared maps are very useful to analyze the aerosols distribution over the study region.

3.2. AERONET data

AERONET is a ground based Cimel sky radiometer network working in collaboration with NASA (National Aeronautics and Space Administration). The instrument is a spectral radiometer (eight spectral bands in the 340 nm, 380 nm, 440 nm, 500 nm, 675 nm, 870 nm, 940 nm, and 1020 nm) with a 15 min temporal resolution working robotically to point towards sun and sky powered by solar energy and is weather hardened. All the measurements are performed by using the instrument whilst the data processing is performed within AERONET standard procedures. An algorithm is used to obtain AOD values (with an absolute error between 0.01 and 0.02) from the acquired data from Cimel sun photometer directly pointed towards sun observations. An additional AERONET standard cloud screening algorithm is used in case of cloud cover during the measurements hours [72]. The detail description of Cimel Sun photometer, which is the integral instrument of AERONET setup has been discussed in detail by Ref. [49]. AERONET station data from SV (from 1993 to 2013) and KAUST (from 2012 to 2021) is retrieved from official website at http://aeronet.gsfc.nasa.gov in the current study.

3.3. NCM data

We have also used meteorological data (dust activities that include WMO codes 6–9, 30–35, and 98) retrieved from 29 ground-based stations administered by NCM in the country to prepare the annual average dust distribution map (Fig. 1). In addition, the NCM dust distribution data is also used to validate the 4 categories that is, extremely high, high, moderate, and low concentration of AOD in the study region as explained in the next section.

3.4. Statistical methods

In the current study MERRA-2 AOD product are validated with two AERONET AOD stations data using various statistical techniques in the Kingdom of Saudi Arabia. First, MERRA-2 AOD hourly values are averaged and extracted over the two AERONET sites. For this, we match AERONET (SV and KAUST) and MERRA-2 points in space and time window. We have applied the method given in Wei et al., 2020 which is based on average value of a 3 × 3 window grid centered on the ground site. The dates for which MERRA-2 co-register with AERONET station data are extracted from the entire data set and analyzed using statistical methods. For example, standard deviation is used to see the closeness of the entire dataset to the mean value of the total number of data, linear regression is applied to see the association between MERRA-2 and AERONET (SV and KAUST) AOD datasets, and Pearson Correlation Coefficient is applied to calculate the relationship between MERRA-2 AOD products and ground based AERONET (SV and KAUST) AOD measurements. Additionally, we have used the Index of Agreement (IOA) method (ratio of mean square error and potential error), as given in Eq. (1), in order to measure the degree of MERRA-2 prediction error (varies between 0 for no agreement and 1 for best agreement). Finally, Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) as given in Eqs. (2) and (3) respectively are used to calculate the errors whilst robustness of the MERRA-2 AOD product is tested using the Relative Mean Bias (RMB) method as given in Eq. (4) [15, 34].

$$IOA = 1 - \frac{\sum_{i=1}^{n}(A_i - M_i)^2}{\sum_{i=1}^{n}\left(\left|M_i - \overline{M}\right| + \left|A_i - \overline{A}\right|\right)^2} \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(A_i - M_i)^2}{n}} \quad (2)$$

$$MAE = \frac{1}{n} \times \sum_{i=1}^{n}\left|A_i - M_i\right| \quad (3)$$

$$RMB = \frac{\overline{M}}{\overline{A}} \quad (4)$$

where A is AERONET data, M is MERRA-2 data, and N is total number of pairs of AERONET and MERRA-2 values.

4. Results and discussions

4.1. Validation of MERRA-2 with AERONET data

The reliability of the MERRA-2 AOD data is tested by comparing it with AERONET data retrieved from SV and KAUST stations and is presented in Fig. 2a and b respectively. The total number of observations used from AERONET stations at SV are 3741 between the year 1999–2013 while at KAUST the total number of observations used are 1469 between the year 2012–2021. The correlation coefficient, RMSE, MAE, IOA, Pearson correlation, and RMB between MERRA-2 and AERONET data at SV are 0.82, 0.08, 0.05, 0.95, 0.91, and −0.001 respectively while between MERRA-2 and AERONET data at KAUST are 0.75, 0.11, 0.08, 0.90, 0.86, and 0.058 respectively. These results clearly indicate that MERRA-2 is not only highly correlated with AERONET based AOD values but also there is a high Index Of Agreement between model predicted AOD (MERRA-2) and measured AOD (AERONET). Similarly, small values in error analysis indicate that the AOD predicted accuracy of model (MERRA-2) is very high. MERRA-2 AOD however has high tendency of AOD agreement at SV as compared to at KAUST in the study region.

4.2. Spatio-temporal variability of AOD from MERRA-2

In order to investigate the AOD variability over the Kingdom of Saudi Arabia we analyzed the annual and seasonal mean from MERRA-2 datasets. The Annual and seasonal AOD climatology of MERRA-2 data for the period 1980 to 2021 is presented in Figs. 3 and 4(a–d) respectively. The pattern of spatial distribution indicates nature of the dynamics of aerosols concentration over the Kingdom of Saudi Arabia. For the discussion purpose we have grouped concentration of AOD in the atmosphere into 4 categories that is, extremely high (greater than 0.5), high (between 0.35 and 0.5), moderate (between 0.25 and 0.35), and low (less than 0.25) concentration of AOD. The resultant 4 categories are validated using NCM data retrieved from 29 ground stations in the Kingdom of Saudi Arabia. A similar technique has also been adopted by Ref. [38]. It is evident from the annual AOD climatology of MERRA-2 data (Fig. 3) that high concentration of aerosols is present over the central region stretching towards eastern, northeast, and southern regions while low concentration of aerosols is visible over the western coastal regions. The remaining area of the study region highlights the moderate concentration of aerosols during the study period. Generally, it can be depicted from the results of annual AOD climatology (Fig. 3) that

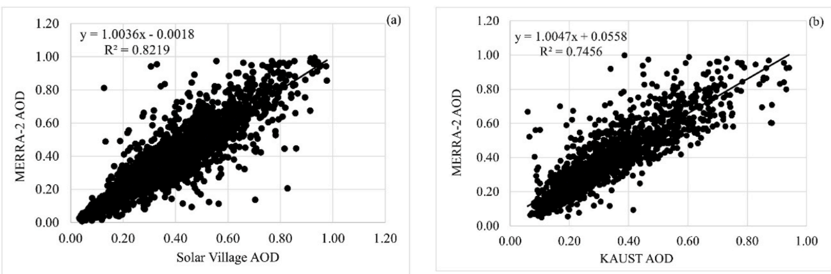


Fig. 2. Validation of MERRA-2 AOD against ground-based AERONET measured AOD at 550 nm (a) Solar Village and (b) KAUST.

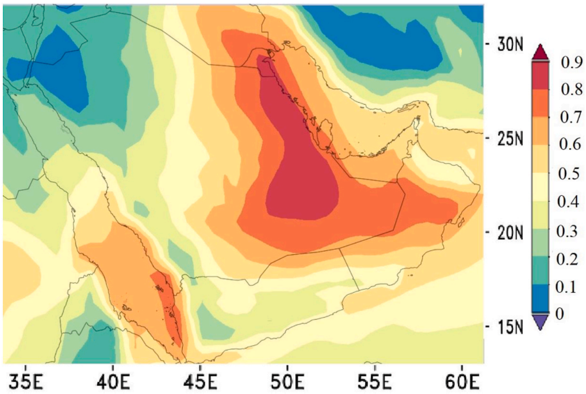


Fig. 3. Mean annual aerosol spatial distribution from MERRA-2 AOD for the years 1980–2021 over Kingdom of Saudi Arabia (KSA).

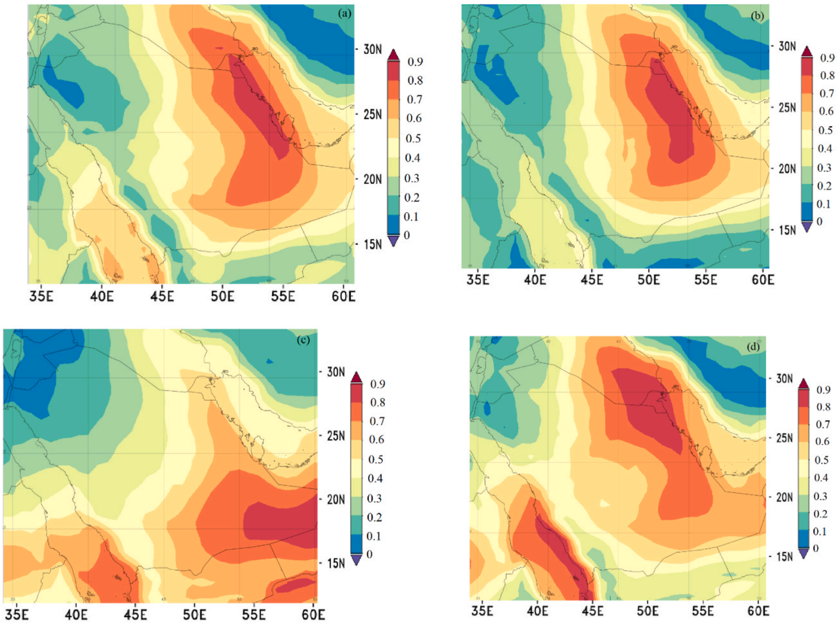


Fig. 4. Mean seasonal aerosol spatial distribution from MERRA-2 AOD for the years 1980–2021 over Kingdom of Saudi Arabia (KSA).

the northern, central, and eastern regions of the study area are highly affected due to the high concentration of aerosols in the atmosphere.

4.3. Validation of MERRA-2 spatio-temporal variability with NCM data

Ground based dust data from NCM meteorological stations were used to validate study results. For this, we have grouped NCM stations in the study area (Table 1) into north (Rafha, Arar, Jouf, Turaif, Guriat, and Tabuk), west (Wejh, Yanbo, Jeddah, Makkah, and Taif), south (Baha, Basha, Abha, Gizan, Khamis Mushat, Najran, Sharorah, and Wadi Al Dawaseer), east (Qaisumah, Haf Al Batin, Ahsa, Dammam, and Dhahran), and central (Hail, Gassim, Madinah, and Riyadh) regions. The assessment of the ground data indicates that on average around 25% days of the total study period (1980–2021) the ground stations in the KSA reported dust events. Further analysis indicates that ground stations in the east region of the KSA reported the highest percentage (46%) of the total study period followed by central (32%), southern (26%), northern (24%), and western (9.8%) regions of the KSA. This is in agreement with the MERRA-2 mean annual AOD climatology (Fig. 3) over the KSA that indicates high concentration of aerosols over the eastern, central, and southern region of the country during the study period. This also agrees well with the result of the other researchers who found that the eastern and central regions of the study areas are highly vulnerable due to sand and dust storm activities and thereby resulting in high concentration of atmospheric aerosols [30,38,73,75,78].

On the other hand, seasonal AOD climatology of MERRA-2 (Fig. 4(a–d)) indicates that for winter (December, January, February) season (Fig. 4a) eastern region of the study area has moderate to high concentration of aerosols while central region (stretching

Table 1
Geographical location of NCM stations in the study area.

Station Name (WMO ID)	Latitude-Longitude	Percentage	Location
Wejh (40400)	26.2000N-36.4833E	7.4571918	West
Yanbu (40439)	24.1333N-38.0667E	17.659491	
Jeddah (41024)	21.7000N-39.1833E	15.727193	
Makkah (41030)	21.4333N-39.7667E	7.2260274	
Taif (41036)	21.4833N-40.5500E	13.931798	
Jouf (40361)	29.7833N-40.1000E	21.060766	North
Rafha (40362)	29.6167N-43.4833E	24.820437	
Guraiat (40360)	31.4000N-37.2833E	23.912671	
Tabouk (40375)	28.3833N-36.6000E	31.275026	
Turaif (40356)	31.6833N-38.7333E	25.261679	
Arar (40357)	30.9000N-41.1333E	20.259553	
Khamis_Mushate (41114)	18.3000N-42.8000E	19.702711	South
Baha (41055)	20.3000N-41.6500E	21.361301	
Wadi_Dawaser (41061)	20.5000N-45.2500E	30.387476	
Abha (41112)	18.2333N-42.6500E	17.513172	
Gizan (41140)	16.8833N-42.5833E	24.966482	
Bishah (41084)	19.9833N-42.6333E	20.647042	
Najran (41128)	17.6167N-44.4167E	42.559932	
Sharorh (41136)	17.4667N-47.1000E	49.580479	
Riyadh (40438)	24.7000N-46.7300E	37.481045	Central
Hail (40394)	27.4333N-41.6833E	12.258817	
Gassim (40405)	26.3000N-43.7667E	26.489726	
Madinah (40430)	24.5500N-39.7000E	29.221801	
Dammam (40417)	26.4500N-49.8167E	39.908676	East
Dahran (40416)	26.2667N-50.1667E	29.327811	
Qaisumah (40373)	28.3167N-46.1333E	27.782534	
Ahsa (40420)	25.3000N-49.4833E	40.453767	
Hfr_batin (40377)	27.9167N-45.5167E	33.399751	

towards south and north) has low to moderate concentration of aerosols during the study period. Similarly, the seasonal AOD climatology of MERRA-2 for spring (March, April, May) season (Fig. 4b) indicates extremely high concentration of aerosols in the eastern region of the study area during the study period. In addition, high concentration of aerosols is also visible in center that

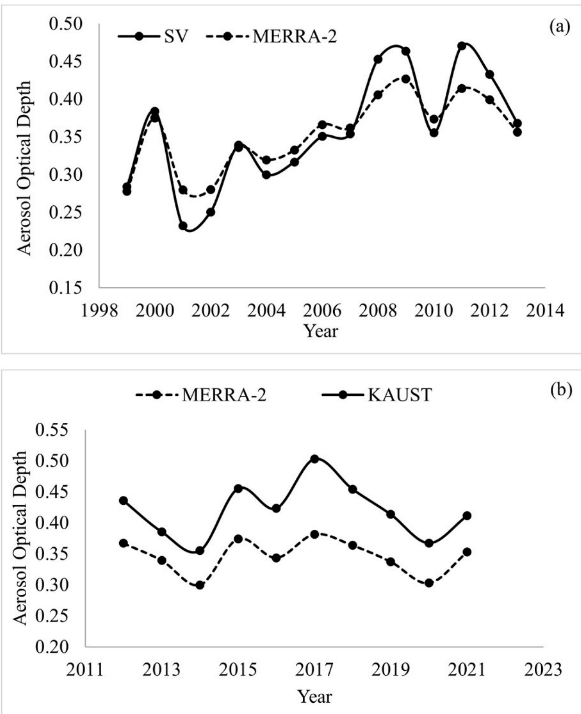


Fig. 5. Inter-annual variations of MERRA-2 AOD product and AERONET AOD over (a) Solar Village for the year 1998–2013 and over (b) KAUST for the years 2012–2021.

stretches towards north and south of the country while the remaining portion (apart from northwest and western coastal region which are under low concentration of aerosols) is under moderate concentration of the aerosols in the atmosphere. The seasonal AOD climatology of MERRA-2 for summer (June, July, August) season (Fig. 4c) indicates extremely high concentration of aerosols in southern and southeast regions of the county. The remaining area of the study region is under moderate to high concentration of aerosols while a small portion of northwest is under low concentration of atmospheric aerosols during the study period. Finally, the concentration of aerosols over the Kingdom of Saudi Arabia for the autumn (September, October, November) season (Fig. 4d) between the year 1980–2021 is almost identical to that of the winter season for MERRA-2 (Fig. 4a) datasets. The only difference is the concentration of aerosols is slightly higher during the autumn season as compared to winter season.

The analysis of the NCM data shows once again that the highest percentage of dust events days for spring, summer, autumn, and winter seasons are reported by ground stations situated in the eastern, central, and southern regions of the country. Yet again, the NCM ground based data complemented MERRA-2 AOD product over the study region for the seasonal climatology (Fig. 4a–d). Analogous to annual AOD climatology our results of seasonal climatology for all four seasons also agree with the outcomes of other researchers who demonstrated that spring and summer seasons are highly affected due to concentration of aerosols followed by autumn and winter seasons [28,74,76–78].

4.4. Annual and seasonal statistical analysis of MERRA-2 with AERONET data

For further validation of our results, we have used AERONET station data in the current study. Thus, mean annual MERRA-2 AOD products over the SV and KAUST are compared with ground based AOD data retrieved from AERONET stations in the SV and KAUST and are shown in Fig. 5a and b respectively. It is clear from Fig. 5a and b that MERRA-2 AOD exhibits similar variations as that from AERONET AOD from SV and KAUST. The inter-annual variability of AOD for SV (KAUST) data is increasing for the years 2000, 2002, 2003, 2005, 2006, 2008, 2009, and 2011 (2015, 2017, and 2021) and decreasing for the years 2001, 2004, 2007, 2010, 2012, and 2013 (2013, 2014, 2016, 2018, 2019, and 2020). It is also evident from these figures that MERRA-2 overestimates mean annual AOD values for the years 2001, 2002, 2004, 2005, 2006, 2007, and 2010 over SV. A similar increasing and decreasing inter-annual pattern is also reported by the NCM ground stations (Riyadh for SV and Jeddah for KAUST) except for the year 2016 in Riyadh and 2018 in Jeddah. Overall, MERRA-2 underestimates the mean annual AOD values at both SV and KAUST AERONET stations. However, the value of underestimation at KAUST is much higher than at SV. In addition, the MERRA-2 AOD is highly correlated with SV AOD as compared with KAUST.

Similarly, mean annual AOD values and standard deviation of AERONET stations and MERRA-2 data at SV and KAUST are given in Table 2. The highest (lowest) value of AOD at SV by AERONET and MERRA-2 is for the year 2011 (2017) while at KAUST is for the year 2002 (2017). The results in Table 2 also indicate that the highest (lowest) value of SD at SV by AERONET and MERRA-2 is for the year 2008 (2001) while at KAUST is for the year 2012 (2019). The results in Table 2 clearly depict that the lowest (highest) AOD values for MERRA-2 data follows a similar pattern as that from AERONET stations AOD data from SV and KAUST.

In the current study a comparison is also made between mean monthly MERRA-2 AOD product with the AERONET station data at SV and KAUST and are shown in Fig. 6a and b respectively. Similarly, mean monthly AOD values and standard deviation of AERONET

Table 2
Inter-annual AERONET and MERRA-2 AOD over the SV and KAUST.

Year	AOD		SD		AOD		SD	
	SV	MERRA-2	SV	MERRA-2	KAUST	MERRA-2	KAUST	MERRA-2
1999	0.28	0.28	0.11	0.11				
2000	0.38	0.38	0.15	0.14				
2001	0.23	0.28	0.10	0.10				
2002	0.25	0.28	0.11	0.12				
2003	0.34	0.34	0.18	0.12				
2004	0.30	0.32	0.16	0.14				
2005	0.32	0.33	0.15	0.13				
2006	0.35	0.37	0.17	0.15				
2007	0.35	0.36	0.15	0.13				
2008	0.45	0.41	0.24	0.17				
2009	0.46	0.43	0.21	0.16				
2010	0.36	0.37	0.18	0.14				
2011	0.47	0.41	0.22	0.17				
2012	0.43	0.40	0.19	0.14	0.44	0.37	0.25	0.16
2013	0.37	0.36	0.22	0.14	0.39	0.34	0.17	0.13
2014					0.36	0.30	0.16	0.11
2015					0.46	0.37	0.23	0.15
2016					0.42	0.34	0.20	0.12
2017					0.50	0.38	0.20	0.12
2018					0.45	0.36	0.17	0.16
2019					0.41	0.34	0.13	0.11
2020					0.37	0.30	0.14	0.14
2021					0.41	0.35	0.16	0.11

stations and MERRA-2 data at SV and KAUST are also calculated and given in Table 3. It is clear from Fig. 6a that both MERRA-2 and SV data show similar intra-annual variability during the study period. For example, MERRA-2 and SV AOD have an increasing intra-annual variability from January to May and then decreasing intra-annual variability until December during the study period. On the other hand, both MERRA-2 and KAUST (Fig. 6b) show completely different intra-annual variability. For example, MERRA-2 has an increasing intra-annual variability from January to September and then decreasing up until December during the study period while KAUST has increasing intra-annual variability from January to March, decreasing in April, increasing in May and June, decreasing in July, increasing in August and September, and finally decreasing from October to December during the study period.

Similarly, from the results given in Table 3 it is evident that the highest (lowest) value of AOD at SV by AERONET and MERRA-2 is for the month of May (December) while at KAUST is for the month of September (December). The results in Table 3 also indicate that the highest (lowest) value of SD at SV by AERONET is for the month of May (October and December) while the highest (lowest) value of SD at SV by MERRA-2 is for the month of March (October).

5. Conclusions

Atmospheric retrieval of AOD has always been considered a demanding task due to the number of reasons associated with environmental and climate change issues. The significance becomes further important if the AOD monitoring is over world's one of the highly affected region due to aerosols like the Kingdom of Saudi Arabia. Considering the importance of the region, researchers in the past few years have been utilizing various datasets including ground-based data, satellite data, and model-based product in order to predict/measure AOD in various parts of the world. However, a very little research has been conducted in the past even though Kingdom of Saudi Arabia is highly vulnerable due to sand and dust storm activities and thereby due to large amount of aerosols in the atmosphere. The current study is an endeavor to utilize reanalysis data from MERRA-2 over the Kingdom of Saudi Arabia between the year 1980–2021. In addition, AERONET station data as well as NCM dust data from ground based meteorological stations are utilized in order to perform various statistical analysis including time series analysis, the annual and seasonal climatology, bias, standard deviation, root mean square error (RMSE), and regression analysis.

The analysis of the annual AOD climatology for MERRA-2 data for the period 1980 to 2021 over the Kingdom of Saudi Arabia depicted that high concentration of aerosols are present in the central, northern, and eastern region of the study area. The annual AOD climatology analysis also depicted low concentration of aerosols over the western coastal regions while the remaining area is under moderate concentration of aerosols in the atmosphere. Similarly, seasonal AOD climatology of MERRA-2 for the study period depicted that for the autumn and winter seasons the central region is under high concentration of aerosols, for the spring season central, northern, and eastern regions are under high concentration of aerosols, and for the summer season central, southern, eastern, and northeast regions are under high concentration of aerosols. This clearly indicates that eastern, southern, and central regions of the Kingdom of Saudi Arabia are under high concentration of aerosols during the study period.

The current study concluded that MERRA-2 data are well suited for the AOD product over the Kingdom of Saudi Arabia. The results from the entire datasets conclude that eastern, northern, and central regions of the Kingdom of Saudi Arabia are under high concentration of aerosols during the period of study. However, from the annual and seasonal climatology, bias pattern, RMSE, and trend analysis MERRA-2 appears to be more reliable as compared to its counterparts. In addition, the current study also concluded that MERRA-2 strongly coincides with AERONET station data at SV and KAUST however, the degree of agreement is more at SV than at KAUST. Thus, it is concluded that MERRA-2 data is highly suitable and reliable for the studies related with aerosols concentration over the Kingdom of Saudi Arabia.

Author contribution statement

Conceived and designed the experiments; Mohsin Jamil Butt and Abdulhaleem H. Labban.
Performed the experiments; Abdulhaleem H. Labban.
Analyzed and interpreted the data; Mohsin Jamil Butt and Abdulhaleem H. Labban.
Contributed reagents, materials, analysis tools or data; Mohsin Jamil Butt.
Wrote the paper; Mohsin Jamil Butt and Abdulhaleem H. Labban.

Data availability statement

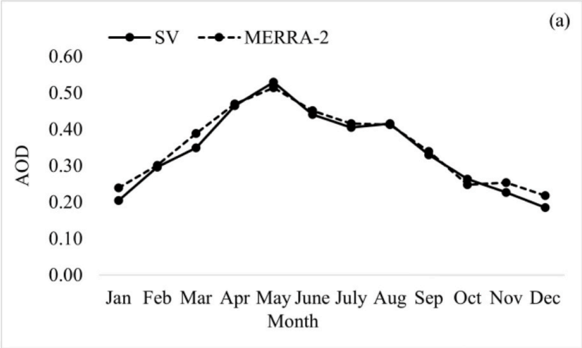
Data included in article/supp. material/referenced in article.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



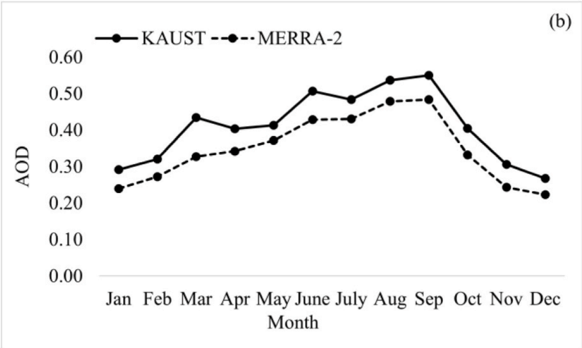


Fig. 6. Monthly mean variations of MERRA-2 AOD product and AERONET AOD over (a) Solar Village and over (b) KAUST.

Table 3
Monthly AERONET and MERRA-2 AOD over the SV and KAUST.

Year	AOD		SD		AOD		SD	
	SV	MERRA-2	SV	MERRA-2	KAUST	MERRA-2	KAUST	MERRA-2
Jan	0.20	0.24	0.12	0.12	0.29	0.24	0.17	0.11
Feb	0.30	0.30	0.18	0.14	0.32	0.27	0.17	0.12
Mar	0.35	0.39	0.22	0.20	0.44	0.33	0.30	0.17
Apr	0.46	0.47	0.24	0.17	0.40	0.34	0.19	0.15
May	0.53	0.51	0.26	0.19	0.41	0.37	0.18	0.14
Jun	0.44	0.45	0.20	0.16	0.51	0.43	0.27	0.17
Jul	0.40	0.42	0.15	0.14	0.48	0.43	0.21	0.17
Aug	0.42	0.41	0.15	0.13	0.54	0.48	0.21	0.16
Sep	0.33	0.34	0.12	0.10	0.55	0.48	0.14	0.12
Oct	0.26	0.25	0.10	0.08	0.40	0.33	0.14	0.09
Nov	0.23	0.25	0.11	0.12	0.31	0.24	0.13	0.08
Dec	0.19	0.22	0.10	0.10	0.27	0.22	0.12	0.08

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References

[1] A.S. Goudie, N.J. Middleton, Desert dust in the global system, Desert Dust Glob. Syst. (2006) 1–287, https://doi.org/10.1007/3-540-32355-4/COVER.
[2] I.N. Tang, Chemical and size effects of hygroscopic aerosols on light scattering coefficients, J. Geophys. Res. Atmos. 101 (1996) 19245–19250, https://doi.org/10.1029/96JD03003.
[3] M.Z. Jacobson, Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols, Nature 409 (2001) 695–697, https://doi.org/10.1038/35055518.

[4] X.A. Xia, H.B. Chen, P.C. Wang, W.X. Zhang, P. Goloub, B. Chatenet, T.F. Eck, B.N. Holben, Variation of column-integrated aerosol properties in a Chinese urban region, J. Geophys. Res. Atmos. 111 (2006) 5204, https://doi.org/10.1029/2005JD006203.
[5] Y. Shao, M. Klose, K.-H. Wyrwoll, Recent global dust trend and connections to climate forcing, J. Geophys. Res. Atmos. 118 (11) (2013) 107–111, https://doi.org/10.1002/jgrd.50836.
[6] J.X.L. Wang, Mapping the global dust storm records: review of dust data sources in supporting modeling/climate study, Curr. Pollut. Reports 1 (2015) 82–94, https://doi.org/10.1007/s40726-015-0008-y.
[7] K. Gyan, W. Henry, S. Lacaille, A. Laloo, C. Lamsee-Ebanks, S. McKay, R.M. Antoine, M.A. Monteil, African dust clouds are associated with increased paediatric asthma accident and emergency admissions on the Caribbean island of Trinidad, Int. J. Biometeorol. 49 (2005) 371–376, https://doi.org/10.1007/s00484-005-0257-3.
[8] Y.S. Chen, P.C. Sheen, E.R. Chen, Y.K. Liu, T.N. Wu, C.Y. Yang, Effects of Asian dust storm events on daily mortality in Taipei, Taiwan, Environ. Res. 95 (2004) 151–155, https://doi.org/10.1016/j.envres.2003.08.008.
[9] A. Kar, K. Takeuchi, Yellow dust: an overview of research and felt needs, J. Arid Environ. 59 (2004) 167–187, https://doi.org/10.1016/J.JARIDENV.2004.01.010.
[10] H. Che, X. Zhang, H. Chen, B. Damiri, P. Goloub, Z. Li, X. Zhang, Y. Wei, H. Zhou, F. Dong, D. Li, T. Zhou, Instrument calibration and aerosol optical depth validation of the China Aerosol Remote Sensing Network, J. Geophys. Res. Atmos. 114 (2009) 3206, https://doi.org/10.1029/2008JD011030.
[11] Y. Gu, K.N. Liou, W. Chen, H. Liao, Direct climate effect of black carbon in China and its impact on dust storms, J. Geophys. Res. 115 (2010), https://doi.org/10.1029/2009jd013427.
[12] K.M. Markowicz, I.S. Stachlewska, O. Zawadzka-Manko, D. Wang, W. Kumala, M.T. Chilinski, P. Makuch, P. Markuszewski, A.K. Rozwadowska, T. Petelski, T. Zielinski, M. Posyniak, J.W. Kaminski, A. Szkop, A. Pietruczuk, B.H. Chojnicki, K.M. Harenda, P. Poczta, J. Uscka-Kowalkowska, J. Struzewska, M. Werner, M. Kryza, A. Drzeniecka-Osiadacz, T. Sawinski, A. Remut, M. Mietus, K. Wiejak, J. Markowicz, L. Belegante, D. Nicolae, A decade of Poland-AOD aerosol research network observations, Atmosphere 12 (2021) 1583, https://doi.org/10.3390/ATMOS12121583.
[13] J. Seo, H. Choi, Y. Oh, J. Seo, H. Choi, Y. Oh, Potential of AOD retrieval using atmospheric emitted radiance interferometer (AERI), Rem. Sens. 14 (2022) 407, https://doi.org/10.3390/RS14020407.
[14] S. Lee, S. Park, M.I. Lee, G. Kim, J. Im, C.K. Song, Air quality forecasts improved by combining data assimilation and machine learning with satellite AOD, Geophys. Res. Lett. 49 (2022), https://doi.org/10.1029/2021GL096066.
[15] Y. Xie, Y. Zhang, X. Xiong, J.J. Qu, H. Che, Validation of MODIS aerosol optical depth product over China using CARSNET measurements, Atmos. Environ. 45 (2011) 5970–5978, https://doi.org/10.1016/J.ATMOSENV.2011.08.002.
[16] W. You, Z. Zang, X. Pan, L. Zhang, D. Chen, Estimating PM2.5 in Xi'an, China using aerosol optical depth: a comparison between the MODIS and MISR retrieval models, Sci. Total Environ. 505 (2015) 1156–1165, https://doi.org/10.1016/J.SCITOTENV.2014.11.024.
[17] L. Kong, J. Xin, W. Zhang, Y. Wang, The empirical correlations between PM2.5, PM10 and AOD in the Beijing metropolitan region and the PM2.5, PM10 distributions retrieved by MODIS, Environ. Pollut. 216 (2016) 350–360, https://doi.org/10.1016/J.ENVPOL.2016.05.085.
[18] B.C. Bhattarai, J.F. Burkhart, F. Stordal, C.Y. Xu, Aerosol optical depth over the nepalese cryosphere derived from an empirical model, Front. Earth Sci. 7 (2019) 178, https://doi.org/10.3389/FEART.2019.00178/BIBTEX.
[19] A. Farahat, Comparative analysis of MODIS, MISR, and AERONET climatology over the Middle East and north Africa, Ann. Geophys. 37 (2019) 49–64, https://doi.org/10.5194/ANGEO-37-49-2019.
[20] L. Palacios-Penã, P. Jiménez-Guerrero, R. Baró, A. Balzarini, R. Bianconi, G. Curci, T. Christian Landi, G. Pirovano, M. Prank, A. Riccio, P. Tuccella, S. Galmarini, Aerosol optical properties over Europe: an evaluation of the AQMEII Phase 3 simulations against satellite observations, Atmos. Chem. Phys. 19 (2019) 2965–2990, https://doi.org/10.5194/ACP-19-2965-2019.
[21] R. Mangla, J. Indu, S.S. Chakra, Inter-comparison of multi-satellites and Aeronet AOD over Indian region, Atmos. Res. 240 (2020), 104950, https://doi.org/10.1016/J.ATMOSRES.2020.104950.
[22] J. Li, X. Ge, Q. He, A. Abbas, Aerosol optical depth (AOD): spatial and temporal variations and association with meteorological covariates in Taklimakan desert, China, PeerJ 9 (2021), e10542, https://doi.org/10.7717/PEERJ.10542/SUPP-1.
[23] IPCC, Climate Change 2007 Synthesis Report, 2007, https://doi.org/10.1256/004316502320517344.
[24] IPCC, Desertification, Encycl. Environ. Heal. (2019) 46–51, https://doi.org/10.1016/B978-0-12-409548-9.10971-6.
[25] S.H. Alsarmi, R. Washington, Changes in climate extremes in the Arabian Peninsula: analysis of daily data, Int. J. Climatol. 34 (2014) 1329–1345, https://doi.org/10.1002/JOC.3772.
[26] N. Zeng, J. Yoon, Expansion of the world's deserts due to vegetation-albedo feedback under global warming, Geophys. Res. Lett. 36 (2009), L17401, https://doi.org/10.1029/2009GL039699.
[27] Y. Ashkenazy, H. Yizhaq, H. Tsoar, Sand dune mobility under climate change in the Kalahari and Australian deserts, Clim. Change 112 (2012) 901–923, https://doi.org/10.1007/s10584-011-0264-9.
[28] A.H. Labban, M.J. Butt, Analysis of sand and dust storm events over Saudi Arabia in relation with meteorological parameters and ENSO, Arabian J. Geosci. 14 (2021) 1–12, https://doi.org/10.1007/S12517-020-06291-W/FIGURES/7.
[29] S. Engelstaedter, K.E. Kohfeld, I. Tegen, S.P. Harrison, Controls of dust emissions by vegetation and topographic depressions: an evaluation using dust storm frequency data, Geophys. Res. Lett. 30 (2003), https://doi.org/10.1029/2002GL016471.
[30] K. Yumimoto, T.Y. Tanaka, N. Oshima, T. Maki, JRAero: the Japanese reanalysis for aerosol v1.0, Geosci, Model Dev. 10 (2017) 3225–3253, https://doi.org/10.5194/GMD-10-3225-2017.
[31] P. Ginoux, J.M. Prospero, T.E. Gill, N.C. Hsu, M. Zhao, Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products, Rev. Geophys. 50 (2012), https://doi.org/10.1029/2012RG000388.
[32] A. Farahat, H. El-Askary, A. Al-Shaibani, Study of aerosols' characteristics and dynamics over the Kingdom of Saudi Arabia using a multisensor Approach combined with ground observations, Adv. Meteorol. 2015 (2015), https://doi.org/10.1155/2015/247531.
[33] S.A. Meo, M.F.A. Al-Kheraiji, Z.F. AlFaraj, N.A. Alwehaibi, A.A. Aldereihim, Respiratory and general health complaints in subjects exposed to sandstorm at Riyadh, Saudi Arabia, Pakistan J. Med. Sci. 29 (2013) 642–646, https://doi.org/10.12669/PJMS.292.3065.
[34] M.J. Butt, M.E. Assiri, M.A. Ali, Assessment of AOD variability over Saudi Arabia using MODIS deep blue products, Environ. Pollut. 231 (2017) 143–153, https://doi.org/10.1016/J.ENVPOL.2017.07.104.
[35] A.W.S. Mashat, A.O. Alamoudi, A.M. Awad, M.E. Assiri, Seasonal variability and synoptic characteristics of dust cases over southwestern Saudi Arabia, Int. J. Climatol. 38 (2018) 105–124, https://doi.org/10.1002/joc.5164.
[36] B.H. Alharbi, M.J. Pasha, N. Tapper, Assessment of Ambient air quality in Riyadh city, Saudi Arabia, Curr. World Environ. 9 (2014) 227–236, https://doi.org/10.12944/CWE.9.2.01.
[37] A. Maghrabi, B. Alharbi, N. Tapper, Impact of the March 2009 dust event in Saudi Arabia on aerosol optical properties, meteorological parameters, sky temperature and emissivity, Atmos. Environ. (2011), https://doi.org/10.1016/j.atmosenv.2011.01.071.
[38] B.H. Alharbi, A. Maghrabi, N. Tapper, The March 2009 dust event in Saudi Arabia: precursor and supportive environment, Bull. Am. Meteorol. Soc. 94 (2013) 515–528, https://doi.org/10.1175/BAMS-D-11-00118.1.
[39] D.G. Kaskaoutis, A.K. Prasad, P.G. Kosmopoulos, P.R. Sinha, S.K. Kharol, P. Gupta, H.M. El-Askary, M. Kafatos, Synergistic use of remote sensing and modeling for tracing dust storms in the mediterranean, Adv. Meteorol. 2012 (2012), https://doi.org/10.1155/2012/861026.
[40] F.A. Vishkaee, C. Flamant, J. Cuesta, L. Oolman, P. Flamant, H.R. Khalesifard, Dust Transport over Iraq and Northwest Iran Associated with Winter Shamal: A Case Study, 2012, https://doi.org/10.1029/2011JD016339.
[41] Z. Liu, D. Liu, J. Huang, M. Vaughan, I. Uno, N. Sugimoto, C. Kittaka, C. Trepte, Z. Wang, C. Hostetler, D. Winker, Airborne dust distributions over the Tibetan Plateau and surrounding areas derived from the first year of CALIPSO lidar observations, Atmos. Chem. Phys. 8 (2008) 5045–5060, https://doi.org/10.5194/ACP-8-5045-2008.

[42] P. Israelevich, E. Ganor, P. Alpert, P. Kishcha, A. Stupp, Predominant transport paths of saharan dust over the mediterranean sea to europe, J. Geophys. Res. Atmos. 117 (2012), https://doi.org/10.1029/2011JD016482.
[43] R. Gelaro, W. McCarty, M.J. Suárez, R. Todling, A. Molod, L. Takacs, C.A. Randles, A. Darmenov, M.G. Bosilovich, R. Reichle, K. Wargan, L. Coy, R. Cullather, C. Draper, S. Akella, V. Buchard, A. Conaty, A.M. da Silva, W. Gu, G.K. Kim, R. Koster, R. Lucchesi, D. Merkova, J.E. Nielsen, G. Partyka, S. Pawson, W. Putman, M. Rienecker, S.D. Schubert, M. Sienkiewicz, B. Zhao, The modern-Era Retrospective analysis for research and Applications, version 2 (MERRA-2), J. Clim. 30 (2017) 5419–5454, https://doi.org/10.1175/JCLI-D-16-0758.1.
[44] H. Che, K. Gui, X. Xia, Y. Wang, B.N. Holben, P. Goloub, E. Cuevas-Agulló, H. Wang, Y. Zheng, H. Zhao, X. Zhang, Large contribution of meteorological factors to inter-decadal changes in regional aerosol optical depth, Atmos. Chem. Phys. 19 (2019) 10497–10523, https://doi.org/10.5194/ACP-19-10497-2019.
[45] C.A. Randles, A.M. da Silva, V. Buchard, P.R. Colarco, A. Darmenov, R. Govindaraju, A. Smirnov, B. Holben, R. Ferrare, J. Hair, Y. Shinozuka, C.J. Flynn, The MERRA-2 aerosol reanalysis, 1980 - onward, Part I: system description and data assimilation evaluation, J. Clim. 30 (2017) 6823–6850, https://doi.org/10.1175/JCLI-D-16-0609.1.
[46] V. Buchard, C.A. Randles, A.M. da Silva, A. Darmenov, P.R. Colarco, R. Govindaraju, R. Ferrare, J. Hair, A.J. Beyersdorf, L.D. Ziemba, H. Yu, The MERRA-2 aerosol reanalysis, 1980 onward. Part II: evaluation and case studies, J. Clim. 30 (2017) 6851–6872, https://doi.org/10.1175/JCLI-D-16-0613.1.
[47] A. Goudie, N. Middleton, Desert Dust in the Global System, ISBN 103-540-32354-6, Springer, 2006.
[48] H. Buchard, V. da Silva, A. Randles, C. Colarco, P. Ferrare, R.D.J. Hostetler, C. Tackett, J. Winker, Evaluation of the surface PM2.5 in version 1 of the NASA MERRA aerosol Re- analysis over the United States, Atmos. Environ. 125 (2016) 100–111.
[49] B.N. Holben, T.F. Eck, I. Slutsker, D. Tanré, J.P. Buis, A. Setzer, E. Vermote, J.A. Reagan, Y.J. Kaufman, T. Nakajima, F. Lavenu, I. Jankowiak, A. Smirnov, AERONET - a federated instrument network and data archive for aerosol characterization, Remote Sens. Environ. 66 (1998) 1–16, https://doi.org/10.1016/S0034-4257(98)00031-5.
[50] T.Y. Tanaka, K. Orito, T.T. Sekiyama, K. Shibata, M. Chiba, H. Tanaka, MASINGAR, a global tropospheric aerosol chemical transport model coupled with MRI/JMA98 GCM: model description, Pap. Meteorol. Geophys. 53 (2003) 119–138, https://doi.org/10.2467/mripapers.53.119.
[51] A. Benedetti, J.J. Morcrette, O. Boucher, A. Dethof, R.J. Engelen, M. Fisher, H. Flentje, N. Huneeus, L. Jones, J.W. Kaiser, S. Kinne, A. Mangold, M. Razinger, A. J. Simmons, M. Suttie, Aerosol analysis and forecast in the European Centre for medium-range weather forecasts integrated forecast system: 2. Data assimilation, J. Geophys. Res. Atmos. 114 (2009), 13205, https://doi.org/10.1029/2008JD011115.
[52] P. Lynch, J.S. Reid, D.L. Westphal, J. Zhang, T.F. Hogan, E.J. Hyer, C.A. Curtis, D.A. Hegg, Y. Shi, J.R. Campbell, J.I. Rubin, W.R. Sessions, F.J. Turk, A. L. Walker, An 11-year global gridded aerosol optical thickness reanalysis (v1.0) for atmospheric and climate sciences, Geosci. Model Dev. 9 (2016) 1489–1522, https://doi.org/10.5194/GMD-9-1489-2016.
[53] T.T. Sekiyama, T.Y. Tanaka, A. Shimizu, T. Miyoshi, Data assimilation of CALIPSO aerosol observations, Atmos. Chem. Phys. 10 (2010) 39–49, https://doi.org/10.5194/ACP-10-39-2010.
[54] J. Zhang, J.S. Reid, D.L. Westphal, N.L. Baker, E.J. Hyer, A system for operational aerosol optical depth data assimilation over global oceans, J. Geophys. Res. Atmos. 113 (2008), 10208, https://doi.org/10.1029/2007JD009065.
[55] V. Buchard, A.M. Da Silva, P.R. Colarco, A. Darmenov, C.A. Randles, R. Govindaraju, O. Torres, J. Campbell, R. Spurr, Using the OMI aerosol index and absorption aerosol optical depth to evaluate the NASA MERRA Aerosol Reanalysis, Atmos. Chem. Phys. 15 (2015) 5743–5760, https://doi.org/10.5194/ACP-15-5743-2015.
[56] C. Pérez, K. Haustein, Z. Janjic, O. Jorba, N. Huneeus, J.M. Baldasano, T. Black, S. Basart, S. Nickovic, R.L. Miller, J.P. Perlwitz, M. Schulz, M. Thomson, Atmospheric dust modeling from meso to global scales with the online NMMB/BSC-Dust model – Part 1: model description, annual simulations and evaluation, Atmos. Chem. Phys. 11 (2011) 13001–13027, https://doi.org/10.5194/ACP-11-13001-2011.
[57] J.I. Rubin, J.S. Reid, J.A. Hansen, J.L. Anderson, N. Collins, T.J. Hoar, T. Hogan, P. Lynch, J. McLay, C.A. Reynolds, W.R. Sessions, D.L. Westphal, J. Zhang, Development of the ensemble Navy aerosol analysis prediction system (ENAAPS) and its application of the data assimilation research testbed (DART) in support of aerosol forecasting, Atmos. Chem. Phys. 16 (2016) 3927–3951, https://doi.org/10.5194/ACP-16-3927-2016.
[58] P.E. Saide, G.R. Carmichael, Z. Liu, C.S. Schwartz, H.C. Lin, A.M. Da Silva, E. Hyer, Aerosol optical depth assimilation for a size-resolved sectional model: impacts of observationally constrained, multi-wavelength and fine mode retrievals on regional scale analyses and forecasts, Atmos. Chem. Phys. 13 (2013) 10425–10444, https://doi.org/10.5194/ACP-13-10425-2013.
[59] J.P. Schwarz, B.H. Samset, A.E. Perring, J.R. Spackman, R.S. Gao, P. Stier, M. Schulz, F.L. Moore, E.A. Ray, D.W. Fahey, Global-scale seasonally resolved black carbon vertical profiles over the Pacific, Geophys. Res. Lett. 40 (2013) 5542–5547, https://doi.org/10.1002/2013GL057775.
[60] D. Chen, Z. Liu, C.S. Schwartz, J.D. Cetola, Y. Gu, L. Xue, The impact of aerosol optical depth assimilation on aerosol forecasts and radiative effects during a wild fire event over the United States, Geosci, Model Dev. 7 (2014) 2709–2715, https://doi.org/10.5194/GMD-7-2709-2014.
[61] Z. Li, Z. Zang, Q.B. Li, Y. Chao, D. Chen, Z. Ye, Y. Liu, K.N. Liou, A three-dimensional variational data assimilation system for multiple aerosol species with WRF/Chem and an application to PM2.5 prediction, Atmos. Chem. Phys. 13 (2013) 4265–4278, https://doi.org/10.5194/ACP-13-4265-2013.
[62] J.N. McHenry, J.M. Vukovich, N.C. Hsu, Development and implementation of a remote-sensing and in situ data-assimilating version of CMAQ for operational PM2.5 forecasting. Part 1: MODIS aerosol optical depth (AOD) data-assimilation design and testing, J. Air Waste Manag. Assoc. 65 (2015) 1395–1412, https://doi.org/10.1080/10962247.2015.1096862.
[63] H. Shi, Z. Xiao, X. Zhan, H. Ma, X. Tian, Evaluation of MODIS and two reanalysis aerosol optical depth products over AERONET sites, Atmos. Res. 220 (2019) 75–80, https://doi.org/10.1016/J.ATMOSRES.2019.01.009.
[64] A.Y. Kwarteng, A.S. Dorvlo, G.T.V. Kumar, Analysis of a 27-year rainfall data (1977–2003) in the Sultanate of Oman, Int. J. Climatol. 29 (2009) 605–617, https://doi.org/10.1002/JOC.1727.
[65] A. Molod, L. Takacs, M. Suarez, J. Bacmeister, Development of the GEOS-5 atmospheric general circulation model: evolution from MERRA to MERRA2, Geosci. Model Dev. 8 (2015) 1339–1356, https://doi.org/10.5194/GMD-8-1339-2015.
[66] Y. Zhang, M. Bocquet, V. Mallet, C. Seigneur, A. Baklanov, Real-time air quality forecasting, part I: history, techniques, and current status, Atmos. Environ. 60 (2012) 632–655, https://doi.org/10.1016/J.ATMOSENV.2012.06.031.
[67] L. Giordano, D. Brunner, J. Flemming, C. Hogrefe, U. Im, R. Bianconi, A. Badia, A. Balzarini, R. Baró, C. Chemel, G. Curci, R. Forkel, P. Jiménez-Guerrero, M. Hirtl, A. Hodzic, L. Honzak, O. Jorba, C. Knote, J.J.P. Kuenen, P.A. Makar, A. Manders-Groot, L. Neal, J.L. Pérez, G. Pirovano, G. Pouliot, R. San José, N. Savage, W. Schröder, R.S. Sokhi, D. Syrakov, A. Torian, P. Tuccella, J. Werhahn, R. Wolke, K. Yahya, R. Žabkar, Y. Zhang, S. Galmarini, Assessment of the MACC reanalysis and its influence as chemical boundary conditions for regional air quality modeling in AQMEII-2, Atmos. Environ. 115 (2015) 371–388, https://doi.org/10.1016/J.ATMOSENV.2015.02.034.
[68] O. Reale, K.M. Lau, A. Da Silva, T. Matsui, Impact of assimilated and interactive aerosol on tropical cyclogenesis, Geophys. Res. Lett. 41 (2014) 3282–3288, https://doi.org/10.1002/2014GL059918.
[69] N. Bellouin, J. Quaas, J.J. Morcrette, O. Boucher, Estimates of aerosol radiative forcing from the MACC re-analysis, Atmos. Chem. Phys. 13 (2013) 2045–2062, https://doi.org/10.5194/ACP-13-2045-2013.
[70] A.L. Kessner, J. Wang, R.C. Levy, P.R. Colarco, Remote sensing of surface visibility from space: a look at the United States East Coast, Atmos. Environ. 81 (2013) 136–147, https://doi.org/10.1016/J.ATMOSENV.2013.08.050.
[71] A. Inness, F. Baier, A. Benedetti, I. Bouarar, S. Chabrillat, H. Clark, C. Clerbaux, P. Coheur, R.J. Engelen, Q. Errera, J. Flemming, M. George, C. Granier, J. Hadji-Lazaro, V. Huijnen, D. Hurtmans, L. Jones, J.W. Kaiser, J. Kapsomenakis, K. Lefever, J. Leitão, M. Razinger, A. Richter, M.G. Schultz, A.J. Simmons, M. Suttie, O. Stein, J.N. Thépaut, V. Thouret, M. Vrekoussis, C. Zerefos, The MACC reanalysis: an 8 yr data set of atmospheric composition, Atmos. Chem. Phys. 13 (2013) 4073–4109, https://doi.org/10.5194/ACP-13-4073-2013.
[72] A. Smirnov, B.N. Holben, T.F. Eck, O. Dubovik, I. Slutsker, Cloud-screening and quality control algorithms for the AERONET database, Remote Sens. Environ. 73 (2000) 337–349, https://doi.org/10.1016/S0034-4257(00)00109-7.
[73] M.J. Butt, A.S. Mashat, MODIS satellite data evaluation for sand and dust storm monitoring in Saudi Arabia, Int. J. Rem. Sens. (2018), https://doi.org/10.1080/01431161.2018.1488293.

[74] S.N. Beegum, I. Gherboudj, N. Chaouch, M. Temimi, H. Ghedira, Simulation and analysis of synoptic scale dust storms over the Arabian Peninsula, Atmos. Res. 199 (2018) 62–81, https://doi.org/10.1016/j.atmosres.2017.09.003.
[75] S. Albugami, S. Palmer, J. Meersmans, T. Waine, Evaluating MODIS dust-detection indices over the Arabian peninsula, Rem. Sens. 10 (2018) 1–17, https://doi.org/10.3390/rs10121993.
[76] Y. Yu, M. Notaro, Z. Liu, F. Wang, F. Alkolibi, E. Fadda, F. Bakhrjy, Climatic controls on the interannual to decadal variability in Saudi Arabian dust activity: toward the development of a seasonal dust prediction model, J. Geophys. Res. 120 (2015) 1739–1758, https://doi.org/10.1002/2014JD022611.
[77] D. Kim, M. Chin, H. Yu, T.F. Eck, A. Sinyuk, A. Smirnov, B.N. Holben, Dust optical properties over north Africa and Arabian peninsula derived from the AERONET dataset, Atmos. Chem. Phys. 11 (2011) 10733–10741, https://doi.org/10.5194/ACP-11-10733-2011.
[78] H. Gandham, H.P. Dasari, S. Langodan, R.K. Karumuri, I. Hoteit, Major changes in extreme dust events dynamics over the Arabian peninsula during 2003–2017 driven by atmospheric conditions, J. Geophys. Res. Atmos. 125 (2020), https://doi.org/10.1029/2020JD032931 e2020JD032931.