Major changes in extreme dust events dynamics over the Arabian Peninsula during 2003–2017 driven by atmospheric conditions

Harikishan Gandham, Hari Prasad Dasari, Sabique Langodan, Rama Krishna Karumuri, and
Ibrahim Hoteit*

*Physical Science and Engineering Division, King Abdullah University of Science and Technology,
Thuwal, Saudi Arabia.*

Key points

- Dust optical properties extracted from MODIS and CALIOP.
- Formation stages and trends of extreme dust events discussed.
- Recent decline in the dust events explained.

*Corresponding author:

Prof. Ibrahim Hoteit,

King Abdullah University of Science and Technology (KAUST),

Physical Science and Engineering Division,

Thuwal 23955-6900, Saudi Arabia.

E-mail: ibrahim.hoteit@kaust.edu.sa

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1029/2020JD032931](https://doi.org/10.1029/2020JD032931).

This article is protected by copyright. All rights reserved.

Abstract

Mineral dust emitted from the arid regions of the Arabian Peninsula (AP), in particular Kingdom of Saudi Arabia (KSA), is an important contributor to the northern hemispheric aerosol loading. Dust events over AP are frequent and persistent throughout the year, with a peak in occurrence and intensity between March and August. This study examines the variability of dust events that occurred over AP during 2003–2017 using long-term dust optical depth retrieved from MODIS satellite measurements. Dust profiles were derived from CALIOP satellite measurements to assess the vertical distributions of the dust events.

Our analysis suggests that the formation of extreme dust events is primarily associated with strong high-pressure systems that occur over AP. Northerly Shamal winds transport dust aerosols from surrounding arid regions to the AP, amplifying the dust aerosol loading across the country. CALIOP dust profiles show that the dust aerosols reach up to 4 km height above sea level, with peak concentrations at an altitude around 1.5 km. Dry deposition of dust is the dominant removal process over the Arabian Gulf, and wet deposition of dust is the dominant removal process over the Red Sea. A total of 49 extreme dust events occurred during the period between 2003–2017, over a combined total of 207 days. We observe a significant increase in the frequency of dust events between 2007 to 2012, peaking in 2012, followed by a marked decrease in the following years. We attribute this sudden decline in dust activity after 2012 to enhanced winter rainfall, after noticing increased soil moisture and vegetation coverage during the dust seasons that followed wetter winters. A strengthened Red Sea trough in the middle and the upper altitudes produced favorable conditions for strong moisture convergence and increased rainfall over AP, which may have dampened dust activity during 2013–2017.

Keywords: Arabian Peninsula, Extreme dust events, Dust Optical Depth, MODIS, CALIOP, Red Sea trough.

1. Introduction

Dust is the dominant aerosol species by mass in the Earth's atmosphere, and emissions from the deserts and arid regions across the globe range between 1000 to 4000 Tg yr⁻¹ annually (e.g., Huneus *et al.*, 2011; Urban *et al.*, 2018). Dust aerosols play an important role in the Earth's climate dynamics (e.g. Sokolik *et al.*, 2001; Kok *et al.*, 2018), affecting the Earth's radiative balance, and also rainfall (Gemma Shepherd *et al.*, 2016). Dust also enriches oceanic biological productivity by supplying micronutrients, which in turn helps the oceans to act as carbon sinks by reducing atmospheric carbon dioxide concentrations (e.g., Mahowald *et al.*, 2005; Banerjee *et al.*, 2014; Farahat and Abuelgasim, 2019). Through direct radiative effects, dust emitted from the Arabian Peninsula (AP), for instance, strengthens the large-scale southwesterly flow of the monsoon and promotes higher Indian monsoon rainfall (e.g., Mohalfi *et al.*, 1998; Vinoj *et al.*, 2014; Jin *et al.*, 2016). Recent studies suggest that dust activity over the AP has been increasing since the beginning of this century (Hsu *et al.*, 2012; Yu *et al.*, 2015b; Ravi Kumar *et al.*, 2018; 2019), which could have repercussions on the Indian monsoon in the future.

The AP is a major global hotspot of dust storm activity and a significant dust source region, both on a local and global scales (Prospero *et al.*, 2002; Yu *et al.*, 2015b; Alobaidi *et al.*, 2017). According to Prospero *et al.* (2002), dust activity over AP persists throughout the year, with a low activity during winter and reaches its peak in the spring and summer. The major dust activity concentrates over the south and south west regions of AP during the summer season. Low lying flat regions along the Arabian gulf and coast of Oman experience dust activity throughout the year. The AP region includes three major desert regions: (a) Rub Al-Khali in the southeast, (b) Ad-Dahna in the east, and (c) An-Nafud deserts in the northwest, with Rub-Al Khali being the largest dust source region of these deserts (Yu *et al.*, 2013; WMO report, 2013). The occurrence of dust storms can cause immeasurable damage to properties across AP, while disrupting air traffic and causing a wide range of health-related issues and respiratory diseases (e.g., Alharbi *et al.*, 2013; Notaro *et al.*, 2013;

UNESCAP report, 2018; Dasari *et al.*, 2019).

Several studies have described the mechanisms of formation of dust storms over AP using observations and models (e.g., Miller *et al.*, 2008; Maghrabi *et al.*, 2011; Alharbi, 2013; Miller *et al.*, 2019). The residing anticyclonic circulation in autumn and winter was suggested to be responsible for the formation of dust storms (Mashat *et al.*, 2018, 2019). Dust activity in spring is driven by Mediterranean cyclones and associated cold fronts (Notaro *et al.*, 2015). In contrast, dust storms in summer are triggered by the strong northwesterly Shamal wind flowing from the Tigris–Euphrates region, which transports dust towards AP and onwards to the Arabian Gulf. Notaro *et al.* (2015) investigated the variability of dust storms based on station observations and remotely sensed aerosol optical depth (AOD). However, previous studies based on the highly scattered and sparse ground-based measurements may not have fully captured the variability of dust events over AP. A comprehensive long-term dataset incorporating all the major desert regions of AP is required to understand the regional variability of dust activity.

Dust aerosol information from satellite observations has been widely used to study the variability of dust events over several regions around the world (Prospero *et al.*, 2002; Washington *et al.*, 2003; Ginoux *et al.*, 2012). Prospero *et al.* (2002) used the Aerosol Index measurements from the Total Ozone Mapping Spectrometer (TOMS) satellite to investigate the geographical characteristics of the dust sources and their seasonal and interannual variability. Washington *et al.* (2003) compared TOMS identified dust source regions against the surface-based observations and further estimated the sand flux. Later, Ginoux *et al.* (2012) characterized dust sources to natural, anthropogenic, and hydrological types using the high-resolution MODIS satellite measurements. Here, we use state-of-the-art dust retrieval algorithms to generate a long-term dust aerosol dataset over the AP, in order to characterize extreme dust events dynamics and their interannual variability. We quantify the mean emission and deposition rates of dust aerosols and identify the source and sink regions of dust. Furthermore, we analyze the vertical structure of the dust column during dust events using dust

aerosol profiles from Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). To the best of our knowledge, this is the first comprehensive study to use satellite-derived long-term dust data and vertical dust profiles to characterize the dust activity over AP. We examine the different stages of dust events, from initiation to maturity, for the duration of multi-day extreme dust events (≥ 3 -day), and we describe the associated atmospheric circulations observed over AP during dust seasons (from March to August) between 2003–2017. We identify the active sources and sink regions of dust using the dust products provided by the second generation Modern-Era Retrospective analysis for Research and Application (MERRA-2) reanalysis. We also analyze the observed recent declining trend in extreme dust events frequency and investigate the potential changes in different atmospheric parameters that may be driving it.

The manuscript is organized as follows. Section 2 describes the data and methodology. Section 3 discusses the formation of extreme dust events over AP and the identification of the different source and sink regions, and describe the role of atmospheric conditions in the formation of the extreme dust events using composite analysis of several atmospheric variables. Section 4 investigates the recent decline in the dust activity driven by changes in atmospheric conditions. Conclusions and a general discussion are provided in Section 5.

2. Datasets and Methodology

2.1. Dust Optical Depth from MODIS

Satellite sensors have emerged as among the most efficient and powerful tools to identify the sources of atmospheric dust (Banks *et al.*, 2013; Ginoux *et al.*, 2012; Schepanski *et al.*, 2012). The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor measures columnar aerosol properties with a cross-track resolution ~ 2330 km, onboard the National Atmospheric Space Agency (NASA) polar-orbiting Terra and Aqua satellites. MODIS crosses the equator twice per day at $\sim 10:30$ LT (local time in KSA) and $\sim 13:30$ LT and measures radiance in 36 spectral channels ranging from 0.44 to $15\ \mu\text{m}$ at 250 m to 1 km resolution. Aerosol information is retrieved at 250 and 500 m resolutions using

seven solar spectral channels (0.47–2.1 μm) (Levy *et al.*, 2005). Aerosol retrievals over bright land surfaces (such as deserts) are more difficult to determine than retrievals over oceanic surfaces. Over the land, surface reflectance at blue wavelength is much lower compared to the longer wavelengths, and this disparity allows for the development of the Deep Blue algorithm for aerosol retrievals over bright surfaces (Hsu *et al.*, 2013). Here, we use MODIS collection 6.1 (C6.1) which includes significant improvements in the aerosol retrieval algorithms and radiometric calibration (Wei *et al.*, 2019). The Level-2 (L2) spectral aerosol properties are derived at $10\text{ km} \times 10\text{ km}$ resolution by implementing the Deep Blue algorithm over the calibrated Level 1B spectral reflectance.

We first interpolated the Aerosol Optical Depth (AOD), Single Scattering Albedo (ω), and the Ångström Exponent (α) from the Deep Blue aerosol data at a $0.1^\circ \times 0.1^\circ$ resolution. Using the interpolated data, the Dust Optical Depth (DOD) was retrieved based on the methodology described by Pu and Ginoux (2018). Pu and Ginoux (2018) revised the original dust algorithm of Ginoux *et al.* (2012) to make it more suitable for the latest MODIS's-L2 deep blue aerosol products. The present version of this algorithm used to derive DOD keeps single scattering albedo (SSA) at 470 nm below one to separate dust from sea salt aerosols (Equation 1 in Pu and Ginoux, 2018). Ginoux *et al.* (2012) used the $\alpha < 0$ to identify the dusty pixels; however, the updated algorithm (i.e. Pu and Ginoux, 2018) discarded this threshold as the current MODIS-L2 deep blue aerosol products provide the α starting from 0 (Sayer *et al.*, 2013). The updated algorithm uses a continuous function (Equation 1 in Pu and Ginoux, 2018) based on the angstrom exponent to estimate the final DOD, and we followed same procedure to derive the DOD over the AP.

2.2. Identification of extreme dust events

There is no standard definition in the literature for extreme dust events. In this study, we characterize extreme dust events, as those that lasted three consecutive days or more and exhibited widespread coverage over the AP based on the following two criterions: (i) During dust events, particulate matter concentrations (PM₁₀) increases above the WHO standards for air-quality (e.g., Alharbi *et al.*, 2013;

Goudarzi et al., 2017; Khaniabadi et al., 2017). Long-term exposure to high PM10 concentrations can increase the risk of mortality through respiratory and cardiovascular diseases (e.g., Kotsyfakis et al., 2019). Multiple reports suggested that an increase in the non-accidental mortality by up to more than 10% due to prolonged (≥ 3 days) high PM10 episodes (Pizzo and Clerico, 2012; Zhou et al., 2015; Wong et al., 2017; Zhang et al., 2017; Kim et al., 2018; Wang et al., 2018), much higher than the mortality rate caused by shorter duration events (<3 days). (ii) Severe widespread prolonged dust events are triggered and maintained by persistent synoptic circulations (e.g., Knippertz and Fink, 2006; Shao et al., 2010; Hamidi et al., 2014, 2017; Knippertz and Stuut, 2014; Houssos et al., 2015; Solomos et al., 2017; Beegum et al., 2018; Dumka et al., 2019). A synoptic circulation should sustain at least 3 days to reach its persistent nature (e.g., Kysely and Domonkos, 2006; Guemas et al., 2009, 2010; Miller et al., 2020). All the identified dust events in our study are widespread in nature and affect most of the Arabian Peninsula and its surrounding regions.

To identify the extreme dust events, we used the standardized anomaly method (e.g., Rajeevan et al., 2010; Manoj et al., 2011; Jin et al., 2018). The steps involved in computing the standardized anomaly of DOD are as follows: (a) We first computed the daily mean DOD from MODIS by combining both Terra and Aqua passes, and then generated the daily time series of DOD for the period 2003 to 2017 by spatially averaging the daily mean DOD over the Arabian Peninsula. Using the resulting daily time series, we computed the corresponding climatology for each day and its standard deviation, (b) We then computed the DOD daily time series of standardized anomaly, by subtracting the daily time series from the corresponding climatology (reference period 2003-2017) and dividing by the corresponding standard deviation, (c) Standardized anomalies higher than +1.0 that persisted for three or more consecutive days are considered as extreme dust events.

2.3. CALIOP dust profiles

The 3D distribution of aerosols during day and night can be studied using CALIOP (Winker *et al.*, 2013). At present, CALIOP is the only space-based lidar that measures the vertical distributions of

aerosol and optical properties over the globe. The CALIOP aerosol classification algorithm uses surface type, location, altitude, particulate depolarization ratio, and integrated attenuated backscatter to locate the aerosol subtype (Omar et al., 2009). Here, we use the CALIOP–L2 version 4.20 standard aerosol profiles at 532 nm available at 5 km horizontal and 60 m vertical resolutions during day and night over AP from 2006 to 2017. The dust model used for CALIOP retrievals is based on the theoretical calculations of particle scattering and uses the discrete dipole approximation technique. In the present version, the updated particle depolarization ratio reduced the misclassifications of dust aerosols around the coastal regions as well in the open oceans (Kim *et al.*, 2018). Aerosol profiles under all-sky conditions were considered, and the quality control procedures applied to the data are (1) AOD at 532 nm ≤ 3 ; (2) $-100 \leq$ cloud aerosol discrimination score ≤ -20 ; (3) extinction quality control flags = 0, 1, 16, 18; (4) extinction uncertainty $< 99.9 \text{ km}^{-1}$; (5) feature type = 3 (aerosol), aerosol subtype = 2 (Dust); and (6) $0\% < \text{uncertainty in AOD } 532 \text{ nm} / \text{AOD } 532 \text{ nm} \leq 100\%$, as used in earlier studies (Koffi *et al.*, 2012; Tian *et al.*, 2017). The dust aerosol lidar ratio, a key parameter for the dust extinction retrieval, is determined based on modeling, measurements, and the cluster analysis of AERONET dataset (Omar et al., 2009). The dust lidar ratios in version 4.20 are modified to 44 ± 9 sr at 532 nm and 44 ± 13 sr at 1064 nm.

2.4. MERRA–2 Reanalysis

MERRA–2 from the NASA Global Modelling and Assimilation Office (GMAO) is a global long-term reanalysis developed via the Goddard Earth Observing System (GEOS–5) version 5.12.4 model (Gelaro *et al.*, 2017). MERRA-2 simulates the aerosol properties using the Goddard Chemistry, Aerosol, Radiation, and Transport (GOCART) model (Buchard *et al.*, 2017; Randles *et al.*, 2017). GOCART computes the sources and sinks of dust in five non-interactive dry size bins 0.1–1 μm , 1–1.8 μm , 1.8–3.0 μm , 3–6 μm , and 6–10 μm with corresponding effective radii of 0.73 μm , 1.4 μm , 2.4 μm , 4.5 μm , and 8 μm , respectively. Dust emissions mainly constrained by wind-driven erosion over the source locations are identified based on the topographic depression map (Ginoux *et al.*,

2001). The dust emissions and dry/wet deposition rates in MERRA-2 are estimated by summing the emissions/deposition rates from all five bins. We use the gridded data with a spatial resolution of $0.625^{\circ} \times 0.5^{\circ}$ during 2003–2017. The usage of the three-dimensional variational data assimilation (3DVar) and Grid point Statistical Interpolation analysis system with the GOCART aerosol model improved the aerosol properties (Randles *et al.*, 2017). Generally, MERRA-2 tends to show similar vertical structure as CALIOP over the aerosol source regions, with peak attenuated backscatter values at about the same altitude (Buchard *et al.*, 2017). More importantly, MERRA-2 successfully reproduces the interannual variability of north-Atlantic dust transport. The aerosol assimilation methodology (2D analysis combined with LDE methodology) has an overall positive influence on the representation of dust aerosol distribution and transport. Despite the considerable improvements in the dust related products, uncertainties still arise due to the static dust source functions and physical process parameterizations such as hygroscopic growth, transport, and aerosol–cloud interactions (Randles *et al.*, 2017).

2.5. Other datasets

We analyze various atmospheric parameters to understand the variability in the activity of extreme dust events over AP. We use the tropical rainfall measuring machine (TRMM) 3B43 version 7 rainfall data available at $0.25^{\circ} \times 0.25^{\circ}$ horizontal resolution (Huffman *et al.*, 2007; Huffman and Bolvin, 2015), soil moisture data from the Climate Prediction Center available at a spatial resolution of $0.5^{\circ} \times 0.5^{\circ}$ (Fan and van den Dool, 2004), the normalized difference vegetation index (NDVI) from the MODIS–Terra sensor available at $0.05^{\circ} \times 0.05^{\circ}$, the geopotential height, and winds from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR, Kalnay *et al.*, 1996) to investigate the influence of these parameters on the accumulation of dust in the atmosphere over AP. We also use Level 2.0 AERONET (Holben *et al.*, 1998) coarse mode aerosol optical depth at 500 nm measured at Solar Village (24.906°N ; 46.397°E) during 2003–2013 to validate the DOD derived from MODIS.

3. Results

We first evaluate the DOD from Terra and Aqua against the available AERONET observations at the Solar Village, KSA, and then use the validated DOD datasets to study the formation and variability of the dust events and associated meteorological conditions. We also explain the potential mechanisms behind the recent decrease in dust events observed over AP.

3.1. Comparison of MODIS derived DOD with AERONET

We compared the DOD retrievals against the coarse mode aerosol optical depth at 500 nm from AERONET observations collected at the Solar Village, KSA, during 2003–2013, and used the spatiotemporal approach (Pu and Ginoux, 2018; Wei *et al.*, 2019) to collocate the MODIS and AERONET measurements. We considered at least two AERONET measurements within ± 30 mins by centering the Terra and Aqua overpass times, and the DOD measurements were averaged within a spatial radius of 30 km by centering the AERONET location. Figure 1 presents the individual comparisons of Terra and Aqua retrieved DOD against the AERONET measurements. The scatter plot suggests that the DOD retrievals from MODIS agree well with AERONET measurements. Aqua shows a higher correlation (0.83) than Terra (0.74) against the ground-based measurements with more than 99% statistical significance. The slopes in the range 0.86 (Aqua) – 0.86 (Terra) and low values of intercept suggest the validity of the assumptions made for the dust retrievals. The low RMSE and high correlations further suggest good agreement between the DOD retrievals from Aqua and Terra with AERONET observations, thus giving us confidence in utilizing these for the analysis of the spatiotemporal variability of extreme dust events over the AP.

3.2. Extreme dust events

The total number of dust days (filled bar), number of dust events (in blue), and mean dust season DOD values (red curve) for each year are reported in Figure 2. We calculated the number of dust days by summing all dust events that occurred during a dust season. The analysis of the annual variations in dust days, the number of dust events, and the mean seasonal DOD values during each dust season

indicates a sharp increase in the frequency of dust days between 2007 and 2012, and a decrease after 2012. A total of 49 extreme dust events occurred between 2003–2017, totaling 207 days, with significant interannual variability. Among the 49 dust events, 26 events (53%) were extended dust episodes with a duration between four and ten days, and the remaining 23 events (47%) persisted for three days only. The longest dust event persisted for about ten days, between 2–11 April, 2015, and the highest dust activity occurred in 2012 with a maximum number of dusty days (35 days; 9 events). The correlation coefficient between dust season DOD and dust events is 0.91, with a statistical significance of 99%, suggests that dust events drive the interannual variability of DOD. Interestingly, no dust events occurred during 2004–2006 which was also reported by Notaro et al. (2015) using ground-based observations over AP. A significant increase in dust days of 48.3 per decade is noticeable during 2007–2012, of 48.3 dust days per decade, followed by a pronounced decreasing trend of -41 dust days per decade. Using the ground-based dust storm data, Notaro et al. (2015) and Yu *et al.* (2015b) also reported this increasing trend in dust episodes from 2006, this is further analyzed in the following sections.

3.3. Atmospheric circulation patterns during extreme dust events

We applied the widely used Lead-lag methodology, which examines the anomaly composites for Day-2 (two-day prior), Day-1 (one-day prior) and Onset-Day (starting day) of the extreme dust events to indicate their evolution stages and associated anomalous atmospheric patterns (e.g., Jones et al., 2003, 2004; Oh et al., 2015; Yu et al., 2015a; Grogan and Thorncroft, 2019; Hingmire et al., 2019; Kumar and Arora, 2019). The composite anomalies were computed as follows: (i) We first identified the extreme dust events based on the daily standardized anomalies. To determine the anomalous circulation favoring the extreme dust events, we generated spatial maps of the daily anomalies (= daily mean – corresponding daily climatology) of meteorological and DOD fields. (ii) We then computed the composite anomalies of DOD and meteorological fields for Day-2, Day-1 and Onset-day, respectively by averaging DOD and meteorological anomalies of the two-day prior, one-day

prior, and starting day for all the identified extreme dust events.

Figure 3 depicts the mean anomaly composites of geopotential height (GPH) and vector winds at 1000 hPa and 700 hPa for the onset day, Day-1, and Day-2. The changes over time in positive GPH anomalies at 1000 and 700 hPa illustrate the systematic development of synoptic conditions that favor dust accumulation over AP. On Day-2, an irregular surface high pressure appears over the eastern corridor of Libya, extending into Egypt. In contrast, the atmosphere above AP is characterized by an anomalous low pressure at lower levels that supports dust resuspension (Fig. 3c). The core of the high-pressure anomaly strengthens over Egypt and further develops over northern AP during Day-1 (Fig. 3b). The anomalous high pressure enhances the surface winds over northern AP and the nearby bordering region of Iraq. The elevated wind speeds trigger aeolian processes over the Tigris-Euphrates region, where loose clay deposits are abundant. The intrusion of northerly winds into AP facilitates an influx of dust from higher latitudes. On the onset day of the dust event, the core of the high-pressure anomaly moves to north-central AP (Fig. 3a), and the low-level subsidence (induced by the anomalous high-pressure) promotes the widespread distribution of dust aerosols emitted from different source regions. The zonal composites of vertical velocities during the onset day indicate a seesaw motion over AP (Fig. S1a). The positive (negative) values indicate subsidence (upward) motions. Subsidence dominates over most of the northern AP, whereas upward motions dominate between 15°N to 25°N. The vertical transport and entrainment of the dust aerosols above the boundary layer facilitate considerable long-range transport of dust. The presence of strong easterly wind anomalies from the lower- to mid altitude-levels over the Arabian Sea opposes the oceanic transport of dust during these events. The synoptic patterns on the onset day of the dust events replicate the anomalous sea level pressure patterns associated with the stronger Shamal winds. Here after we provide further evidence that anomalous pressure patterns increase the strength of Shamal winds, which triggers abrupt dust emissions over the central AP.

3.4. Dust aerosol distribution during extreme dust events

Figure 4 shows the mean spatial and vertical distribution of dust aerosols from MODIS and CALIOP. The AOD between MODIS and CALIOP observations over AP during 2007-2015 are compared (Figure S2) and discussed in Supplementary Material. The analysis indicates that both data sets are correlated well with the correlation of 0.5 with a statistical significance greater than 99%. During Day-2, the positive anomalies of DOD begin to spread across the north-central AP with maxima over Iraq and northeastern KSA (Fig. 4c). Central and southwest AP witness a consequent accumulation of dust, with positive DOD anomalies reaching up to 0.5 during the onset day of the dust event (Fig. 4a). Anomalous northerly winds during the extreme dust event resuspend clay deposits into the atmosphere over Iraq, transferring significant dust loads to AP. Moreover, dry riverbeds across the central-east KSA provide further dust sources that enhance the atmospheric dust loading. The strong low-level subsidence induced by the prevailing anomalous high pressure inhibits vertical and oceanic transport, resulting in higher DOD values. The zonal mean distribution of the dust backscattering coefficient over AP derived from CALIOP is presented in Figs. 4d-f. The vertical distribution of the dust backscattering coefficient on Day-2 reveals an increase of concentrations up to 2 km height above ground level and a rapid decline above 2 km (Fig. 4f). On the onset day, the dust aerosols mostly accumulate between 15°–25°N with an elevated concentration between 1-2.5 km above sea level (Fig. 4d). Dust backscatter reaches a peak of $0.015 \text{ km}^{-1}\text{sr}^{-1}$ around 1.5 km due to the uplift of fine dust aerosols, caused by the anomalous low pressure residing over the southern AP. The abnormal shortwave radiative heating induced by the dust aerosols during the daytime imposes temperature inversions above the boundary layer. These temperature inversions may limit the vertical transport of dust while further strengthening the existing anomalous high-pressure system. Radiosonde observations from King Khalid international airport (24.93°N; 46.71°E) confirm the presence of the multiple inversion layers between 1.5 to 3 km above sea level (not shown) during the onset day of the dust event.

Figure 5 shows the spatial patterns of concentrations of PM₁₀ (airborne particulate matter of

diameter 10 μm or less) and emissions for dust aerosols. Elevated PM₁₀ concentrations over extended duration can severely deteriorate ground visibility, leading to disruptions in the air-traffic and transport sectors, and induce severe complications for human health. We observe elevated PM₁₀ concentrations on the onset day of the dust events over the eastern and southern AP with values exceeding 1200 $\mu\text{g m}^{-3}$, which is about 400% higher than the air-quality limits set by the Saudi General Authority for Meteorology and Environmental Protection (GAMEP). Emissions during dust events over AP derived from MERRA2 is presented in Figure. 5d-f. Active dust sources are seen in Iraq, the coastal region of Kuwait, KSA, Bahrain, Qatar, United Arab Emirates, the coast of Oman, and the northern tip of Somalia. During the onset day, emission rates peaked at 1 $\text{g m}^{-2} \text{day}^{-1}$ in KSA and Iraq, with a slight north-south gradient in dust emissions. Substantial emissions of dust from these regions are driven by dry wind conditions that perturb coastal alluvial deposits.

Figure 6 outlines the spatial characteristics of the dry and wet deposition rates during the dust events. Dry deposition is the process of settling of atmospheric particles over time, whereby larger dust particles settle and return to the ground more rapidly than smaller particles due to gravity (Slinn and Slinn, 1980). Dust dry deposition rate in MERRA2 strongly depends on model dry deposition schemes, whereas wet deposition of (precipitation-induced) dust depends mainly on the assimilated global precipitation data (Randles *et al.*, 2017). The dust deposition rates are considerably higher over the oceanic regions than over land. On the onset day, northerly winds are dominant over the Tigris-Euphrates regions, resulting in the emission of clay deposits that contribute large dust particles to the atmosphere. Due to their shorter atmospheric lifespan, we observe high dry-deposition rates over the Arabian Gulf and adjacent regions (Fig. 6a). We also record different spatial characteristics in dry and wet deposition rates between the Red Sea and the Arabian Gulf. Both dry and wet deposition dust rates dominate over the oceanic regions compared to land regions; however, the wet deposition's intensity dominates over the dry deposition. Dry deposition dominates over the Arabian Gulf, with values up to 0.04 $\text{g m}^{-2} \text{day}^{-1}$, due to the northerly winds traversing the nearby source regions. In

contrast, high wet-deposition rates of $\sim 0.05 \text{ g m}^{-2} \text{ day}^{-1}$ dominate over the southern Red Sea and the adjacent Ethiopian highlands during the onset day (Fig. 6d). We observe significant dust wet-deposition gradients from north to south of the Red Sea, starting from Day-2 to the onset day. Easterly and northeasterly winds carry a significant amount of dust from the active source regions to the southern Red Sea. Lower dry deposition rates allow finer dust particles to be more easily transported to the southern Red Sea. Moreover, the presence of the Red Sea convergence zone (Viswanadhapalli *et al.*, 2016; Dasari *et al.*, 2018; Hoteit *et al.*, 2020) may also increase wet deposition over the southern Red Sea; this process deserves further investigation using state-of-the art numerical modeling (e.g., WRF-Chem).

4. Epochal changes in dust aerosol distribution and meteorological parameters

This section examines the seasonal mean distribution of dust aerosols, rainfall, soil moisture, normalized difference vegetation index (NDVI), winds, and geopotential height in an attempt to explain the corresponding epochal changes, as well as the role of these parameters in controlling the extreme dust activity. We divided the total study period between 2003–2017 into two epochs. The first epoch (EP1) corresponds to 2007–2012, during which time we observed an increase in dust activity, and a second epoch (EP2) that corresponds to 2013–2017 when we recorded a marked decrease in dust activity. To better represent the difference between EP2 and EP1, we estimated the percentage change observed between EP2 and EP1 by $[(\text{EP2}-\text{EP1}) \times 100/\text{EP1}]$.

We performed frequency distribution analysis (Fig. 7) to explore the differences in dust activity between EP1 and EP2. For the analysis, we computed the number of days with $\text{DOD} > 0.5$ during each dust season for the entire period and the mean values of EP1 and EP2. In general, higher frequencies are concentrated around the AP and the borders of the Arabian Gulf in both EP1 and EP2. A significant enhancement in dust activity is noticeable during EP1 over the borders of Iraq and KSA (Fig. 7a). The dust activity centered around central KSA was most likely related to the dust sources from dry wadis or riverbeds. High frequencies are spread across the Empty quarter region consisting

of salt flats in the United Arab Emirates interferers in Rub Al Khali sandy desert, providing a sand source to generate the dust emissions through sandblasting. The west coast of Iran has been identified as a prominent source of dust during the dry season (Ginoux *et al.*, 2012; Choobari *et al.*, 2016); this region also emitted a significant amount of dust from natural and anthropogenic dust sources during EP1. A significant reduction in frequency is observed across the AP during EP2 mostly pronounced over southern KSA (Figure 7b). This reduction in dust frequency during EP2 led to a depletion in dust accumulation (Fig 7d), and most of the dust abundant regions underwent up to a 50% reduction in DOD.

Figure 8 suggest the significant changes in dust emission and deposition rates between EP1 and EP2 during the dust season. The spatial distributions of dust emissions, which also consist of fine particle sediments from ephemeral lakes, across AP were mostly concentrated along regions with low elevation ($< 200\text{m}$) (Fig. 8a). The seasonal distribution of dry and wet deposition indicates higher dry deposition over the eastern side of the AP and the Arabian Gulf (Fig. 8c) and higher wet deposition over the southern Red Sea (Fig. 8b). The wet deposition rates in EP2 were more increased than others (Fig. 8e). The percentage change of wet deposition is significantly more substantial over the mainland of KSA, coastal regions of Iran and northern Red Sea region during EP2.

We note that the primary source regions of dust had a mean seasonal (October to December) rainfall less than 50 mm month^{-1} (Fig. 9a), and the maximum precipitation occurred over the borders of eastern Iraq and western Iran. According to Banerjee *et al.* (2016), winter rainfall over the AP crucially affects levels of dust emissions in the following dust season. Our analysis suggests that most of the active dust regions in EP2 experienced an increase in the amount of rainfall by about 100% (Fig. 9d), which made the soils less susceptible to wind erosion during the following dust seasons. Rainfall increase across the AP, the northern Red Sea, and northeast Africa during EP2, caused a 100% increase in the mean soil moisture (Fig. 9b) during the dust season. NDVI analysis showed positive values over the entire AP during EP2, with a significant increase of about 50% over the

Tigris–Euphrates region (Fig. 9f). Enhanced vegetation associated with increased soil moisture also favored the suppression of wind erosion over the region and thus, the generation of dust.

Figure 10 displays the mean and epochal changes in the spatial patterns of wind speeds and geopotential height (GPH) at different pressure levels during the wet season. The mean pattern at 850 hPa shows the two semi-permanent high-pressure systems over northeast Africa and eastern AP. In this scenario, the Red Sea creates an active channel for the transport of moisture between the Mediterranean and the Arabian Sea (Langodan *et al.* 2017; Hoteit *et al.*, 2020). Dasari *et al.* (2018) studied the development of the Red Sea trough and the Red Sea convergence zone between the two semi-permanent systems, and observed that this system is responsible for moisture transport over the AP. Climatologically, moisture transport from the Red Sea to AP mediated by the mid-level westerlies from Arabian high reaches 80%. The moisture convergence facilitated by the Red Sea trough triggers the rainfall activity over AP, and meridional movement of the Red Sea trough creates a spatial variability in the wet seasonal rainfall over the AP. The difference that we observed in GPH between EP2 and EP1 have been caused by the northward movement of the East African high-pressure system and a weakening of the Arabian high-pressure system at 850 hPa (Fig. 10d). There was also a deepening of the Arabian high-pressure system in the mid to upper levels of the atmosphere from EP1 to EP2 (Fig. 10d and 10e). The eastward movement of high-pressure systems over the AP at upper levels has been shown to facilitate the formation of an elongated Red Sea trough that extends between 850 hPa to 500 hPa (Dasari *et al.*, 2018). This synoptic-scale feature resembles the conditions of the active Red Sea trough, which amplifies wave activity in the middle and upper levels of the atmosphere (De Vries *et al.*, 2013; Zolina *et al.*, 2018). These combined atmospheric conditions enhanced the moisture and associated rainfall over the AP during EP2, particularly over dust source regions. The excess rainfall is carried over to the next dust season as the soil stores moisture for a long time and further facilitates vegetation growth. The overall effect is reducing the dust production due to lower soil erodibility over the dust source regions during EP2.

5. Summary and Conclusions

This study described the annual variability of extreme dust events that occurred over AP during 2003–2017. We derived DOD from MODIS to identify extreme dust events that took place during the usual dust season (March to August). We have also used CALIOP to investigate the vertical distribution of the dust. The retrieved DOD values correlate well with ground-based AERONET measurements collected at Solar Village. A total of 49 extreme dust events occurred during the period between 2003–2017, over a total of 207 days.

A summary of the main findings of this study, which further analyzed the atmospheric processes that caused an increase or decrease in dust events, as follows:

- The composite analysis of winds and geopotential height indicated that anomalous high-pressure systems at 1000 hPa tended to form during the onset day of an extreme dust event. These anomalous surface high-pressure systems increased the strength of the Shamal winds over the northern parts of the AP, which resuspended significant loads of dust aerosols and transported them towards the AP, thus causing considerable accumulation of dust aerosols in the atmosphere.
- On the onset day of an extreme dust event, dust aerosols reached up to altitudes of 4 km, with the highest concentrations located at an altitude of around 1.5 km.
- Extreme dust events resulted in high deposition rates over the Arabian Gulf and the Red Sea. Dry deposition rates were significantly higher over the Arabian Gulf, and wet deposition rates were higher over the Red Sea. During dust events, surface PM₁₀ concentrations over KSA were more than 400% higher than the permissible environmental standards.
- We observed significant changes in dust activity over AP in the most recent decade. The frequency of $DOD > 0.5$ indicated a rapid decline in the number of dusty days during 2013–2017 relative to 2007–2012.

- We recorded an anomalously positive wet deposition rate across the AP between 2013 and 2017. The enhanced rainfall during the winters preceding the dust seasons led to increased soil moisture, which favored higher NDVI during 2013–2017.
- The increased strength of the Red Sea trough favored strong moisture convergence and gave rise to increased rainfall during 2013–2017.

This study described in detail the long-term changes in extreme dust events and associated atmospheric conditions over AP using satellite-based dust measurements. We expect that the interannual variability of dust activity is strongly influencing the region's climate through radiative feedbacks. We aim to quantify this radiative feedback in a future study using an advanced atmospheric-chemistry model such as Weather Research Forecasting model coupled with Chemistry (WRF-Chem).

Acknowledgments

This study was financially supported by King Abdullah University of Science and Technology (KAUST) under the research grant “Virtual Red Sea Initiative (Award # REP/1/3268-01-01)”. The research made use of the Supercomputing Laboratory resources at KAUST. The datasets used in the present study are freely available and are properly acknowledged. MODIS-Level 2 Deep Blue Aerosol products are download from LAADS-DAAC website (https://ladsweb.modaps.eosdis.nasa.gov/search/order/1/MOD04_L2--61,MYD04_L2--61). CALIOP-Level 2 standard V4.20 aerosol profile products are obtained from ASDC data center (https://asdc.larc.nasa.gov/project/CALIPSO/CAL_LID_L2_05kmAPro-Standard-V4-20_V4-20). MERRA-2 dust products are download from GES-DISC data server (<https://disc.gsfc.nasa.gov/datasets?keywords=%22MERRA-2%22&page=1&subject=Aerosols>). TRMM monthly mean precipitation products are available at Giovanni data hosting site (<https://giovanni.gsfc.nasa.gov/giovanni/>), and AERONET daily Level-2.0 products are accessed from AERONET website (<https://aeronet.gsfc.nasa.gov/>).

References

1. Alharbi BH, Maghrabi A, Tapper N. 2013. The march 2009 dust event in Saudi Arabia: Precursor and supportive environment. *Bulletin of the American Meteorological Society*, 94(4): 515–528.
2. Alobaidi M, Almazroui M, Mashat A, Jones PD. 2017. Arabian Peninsula wet season dust storm distribution: regionalization and trends analysis (1983–2013). *International Journal of Climatology*, 37(3): 1356–1373.
3. Banerjee P, Kumar SP. 2014. Dust-induced episodic phytoplankton blooms in the Arabian Sea during winter monsoon. *Journal of Geophysical Research: Oceans*, 119(1): 6121–6139.
4. Banerjee P, Kumar SP. 2016. ENSO modulation of interannual variability of dust aerosols over the northwest Indian Ocean. *Journal of Climate*, 29(4): 1391–1415.
5. Banks JR, Brindley HE, Flamant C, Garay MJ, Hsu NC, Kalashnikova O V., Klüser L, Sayer AM. 2013. Intercomparison of satellite dust retrieval products over the west African Sahara during the Fennec campaign in June 2011. *Remote Sensing of Environment*. The Authors, 136(June 2011): 99–116. <https://doi.org/10.1016/j.rse.2013.05.003>.
6. Beegum SN, Gherboudj I, Chaouch N, Temimi M, Ghedira H. 2018. Simulation and analysis of synoptic scale dust storms over the Arabian Peninsula. *Atmospheric Research*. Elsevier, 199(December 2016): 62–81. <https://doi.org/10.1016/j.atmosres.2017.09.003>.
7. Buchard V, Randles CA, da Silva AM, Darmanov A, Colarco PR, Govindaraju R, Ferrare R, Hair J, Beyersdorf AJ, Ziemba LD, Yu H. 2017. The MERRA-2 aerosol reanalysis, 1980 onward. Part II: Evaluation and case studies. *Journal of Climate*, 30(17): 6851–6872.
8. Choobari Alizadeh O, Ghafarian P, Owlad E. 2016. Temporal variations in the frequency and concentration of dust events over Iran based on surface observations. *International Journal of Climatology*, 36(4): 2050–2062.
9. Dasari HP, Langodan S, Viswanadhapalli Y, Vadlamudi BR, Papadopoulos VP, Hoteit I. 2018. ENSO influence on the interannual variability of the Red Sea convergence zone and associated rainfall. *International Journal of Climatology*, 38(2): 761–775.
10. Dasari HP, Srinivas D, Sabique L, Raju A, Ravikumar K, Yesubabu V, Omar K, Hoteit I. 2019: High-resolution assessment of solar energy resources over the Arabian Peninsula. *Applied Energy*. 248, 354–371.

- Accepted Article
11. De Vries AJ, Tyrlis E, Edry D, Krichak SO, Steil B, Lelieveld J. 2013. Extreme precipitation events in the Middle East: Dynamics of the Active Red Sea Trough. *Journal of Geophysical Research Atmospheres*, 118(13):7087–7108. <https://doi.org/10.1002/jgrd.50569>.
 12. Dumka UC, Kaskaoutis DG, Francis D, Chaboureau JP, Rashki A, Tiwari S, Singh S, Liakakou E, Mihalopoulos N. 2019. The Role of the Intertropical Discontinuity Region and the Heat Low in Dust Emission and Transport Over the Thar Desert, India: A Premonsoon Case Study. *Journal of Geophysical Research: Atmospheres*, 124(23): 13197–13219. <https://doi.org/10.1029/2019JD030836>.
 13. Fan Y, van den Dool H. 2004. Climate Prediction Center global monthly soil moisture data set at 0.5° resolution for 1948 to present. *Journal of Geophysical Research D: Atmospheres*, 109(10): 1–8.
 14. Farahat A, Abuelgasim A. 2019. Role of atmospheric nutrient pollution in stimulating phytoplankton growth in small area and shallow depth water bodies: Arabian Gulf and the sea of Oman. *Atmospheric Environment*. Elsevier Ltd, 2019(March): 117045. <https://doi.org/10.1016/j.atmosenv.2019.117045>.
 15. Gelaro R, McCarty W, Suárez MJ, Todling R, Molod A, Takacs L, Randles CA, Darmenov A, Bosilovich MG, Reichle R, Wargan K, Coy L, Cullather R, Draper C, Akella S, Buchard V, Conaty A, da Silva AM, Gu W, Kim GK, Koster R, Lucchesi R, Merkova D, Nielsen JE, Partyka G, Pawson S, Putman W, Rienecker M, Schubert SD, Sienkiewicz M, Zhao B. 2017. The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). *Journal of Climate*, 30(14): 5419–5454.
 16. Gemma Shepherd, et al., 2016. Global Assessment of Sand and Dust Storms. UNEP.
 17. Ginoux P, Chin M, Tegen I, Prospero JM, Holben BN, Dubovik O, Lin S-J. 2001. Sources and distributions of dust aerosols simulated with the GOCART model. *Journal of Geophysical Research*, 106: 20255–20273.
 18. Ginoux P, Prospero JM, Gill TE, Hsu NC, Zhao M. 2012. Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. *Reviews of Geophysics*, 50(3): 1–36.
 19. Goudarzi G, Daryanoosh SM, Godini H, Hopke PK, Sicard P, De Marco A, Rad HD, Harbizadeh A, Jahedi F, Mohammadi MJ, Savari J, Sadeghi S, Kaabi Z, Omid Khaniabadi Y. 2017. Health risk assessment of exposure to the Middle-Eastern Dust storms in the Iranian megacity of Kermanshah. *Public Health*. Elsevier Ltd, 148: 109–116. <https://doi.org/10.1016/j.puhe.2017.03.009>.

20. Grogan DFP, Thorncroft CD. 2019. The characteristics of African easterly waves coupled to Saharan mineral dust aerosols. *Quarterly Journal of the Royal Meteorological Society*, 145(720): 1130–1146. <https://doi.org/10.1002/qj.3483>.
21. Guemas V, Salas-Mélia D, Kageyama M, Giordani H, Voldoire A, Sanchez-Gomez E. 2009. Winter interactions between weather regimes and marine surface in the North Atlantic European region. *Geophysical Research Letters*, 36(9): 1–6. <https://doi.org/10.1029/2009GL037551>.
22. Guemas V, Salas-Mélia D, Kageyama M, Giordani H, Voldoire A, Sanchez-Gomez E. 2010. Summer interactions between weather regimes and surface ocean in the North-Atlantic region. *Climate Dynamics*, 34(4): 527–546. <https://doi.org/10.1007/s00382-008-0491-6>.
23. Hamidi M, Kavianpour MR, Shao Y. 2014. Numerical simulation of dust events in the Middle East. *Aeolian Research*. Elsevier B.V., 13: 59–70. <https://doi.org/10.1016/j.aeolia.2014.02.002>.
24. Hamidi M, Kavianpour MR, Shao Y. 2017. A quantitative evaluation of the 3–8 July 2009 Shamal dust storm. *Aeolian Research*. Elsevier B.V., 24(July 2009): 133–143. <https://doi.org/10.1016/j.aeolia.2016.12.004>.
25. Hingmire D, Vellore RK, Krishnan R, Ashtikar N V., Singh BB, Sabade S, Madhura RK. 2019. Widespread fog over the Indo-Gangetic Plains and possible links to boreal winter teleconnections. *Climate Dynamics*. Springer Berlin Heidelberg, 52(9–10): 5477–5506. <https://doi.org/10.1007/s00382-018-4458-y>.
26. Holben BN, Eck TF, Slutsker I, Tanré D, Buis JP, Setzer A, Vermote E, Reagan JA, Kaufman YJ, Nakajima T, Lavenu F, Jankowiak I, Smirnov A. 1998. AERONET - A federated instrument network and data archive for aerosol characterization. *Remote Sensing of Environment*, 66(1): 1–16.
27. Hoteit, I., Abualnaja, Y., Afzal, S., Ait - El_Fquih, B., Akylas, T., Antony, C., Dawson, C., Asfahani, K., Brewin, R., Cavaleri, L., Cervero, I., Cornuelle, B., Desametti, S., Attada, R., Dasari, H., Sanchez - Garrido, J., Genevieve, L., Gharamti, M.E., Gittings, J., Elamurugu, G., Gopalakrishnan, G., Guo, D., Hadri, B., Hadwiger, M., Hammoud, M.A., Hendershott, M., Hittawe, M., Karumuri, A., Knio, O., Kohl, A., Kortas, G., Kunchala, R., Issa, L., Lakkis, I., Langodan, S., Lermusiaux, P., Luong, T., Ma, J., Maitre, O.L., Mazloff, M., Mohtar, S.E., Papadopoulos, V.P., Platt, T., Pratt, L., Raboudi, N., Racault, M.F., Raitsos, D., Razak, S., Sanikommu, S., Sathyendranath, S., Sofianos, S., Subramanian, A., Sun, R., Titti, E., Toye, H., Triantafyllou, G., Tsiaras, K., Vasou, P., Viswanadhapalli, Y., Wang, Y., Yao, F. and Zhan, P., (2020). Towards an end-to-end analysis and prediction system for weather, climate, and

- marine applications in the Red Sea. *Bulletin of the American Meteorological Society*, 1-61, <https://doi.org/10.1175/BAMS-D-19-0005.1>
28. Houssos EE, Chronis T, Fotiadis A, Hossain F. 2015. Atmospheric circulation characteristics favoring dust outbreaks over the solar village, Central Saudi Arabia. *Monthly Weather Review*, 143(8): 3263–3275. <https://doi.org/10.1175/MWR-D-14-00198.1>
29. Hsu NC, Gautam R, Sayer AM, Bettenhausen C, Li C, Jeong MJ, Tsay SC, Holben BN. 2012. Global and regional trends of aerosol optical depth over land and ocean using SeaWiFS measurements from 1997 to 2010. *Atmospheric Chemistry and Physics*, 12(17): 8037–8053.
30. Hsu NC, Jeong MJ, Bettenhausen C, Sayer AM, Hansell R, Seftor CS, Huang J, Tsay SC. 2013. Enhanced Deep Blue aerosol retrieval algorithm: The second generation. *Journal of Geophysical Research Atmospheres*, 118(16): 9296–9315.
31. Huffman GJ, Adler RF, Bolvin DT, Gu G, Nelkin EJ, Bowman KP, Hong Y, Stocker EF, Wolff DB. 2007. The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *Journal of Hydrometeorology*, 8(1): 38–55.
32. Huffman GJ, Bolvin DT. 2015. TRMM and Other Data Precipitation Data Set Documentation. doi:10.1111/fcre.12141.
33. Huneus N, Schulz M, Balkanski Y, Griesfeller J, Prospero J, Kinne S, Bauer S, Boucher O, Chin M, Dentener F, Diehl T, Easter R, Fillmore D, Ghan S, Ginoux P, Grini A, Horowitz L, Koch D, Krol MC, Landing W, Liu X, Mahowald N, Miller R, Morcrette JJ, Myhre G, Penner J, Perlwitz J, Stier P, Takemura T, Zender CS, 2011. Global dust model intercomparison in AeroComPhase-I: *Atmospheric Chemistry and Physics*, 11(15): 7781–7816. <https://doi.org/10.5194/acp-11-7781-2011>.
34. Jin Q, Wei J, Pu B, Yang ZL, Parajuli SP. 2018. High Summertime Aerosol Loadings Over the Arabian Sea and Their Transport Pathways. *Journal of Geophysical Research: Atmospheres*, 123(18): 10,568–10,590. <https://doi.org/10.1029/2018JD028588>
35. Jin Q, Yang ZL, Wei J. 2016. Seasonal responses of Indian summer monsoon to dust aerosols in the middle East, India, and China. *Journal of Climate*, 29(17): 6329–6349.
36. Jones C, Mahowald N, Luo C. 2003. The role of easterly waves on African desert dust transport. *Journal of Climate*, 16(22):3617–3628.[https://doi.org/10.1175/1520-0442\(2003\)016<3617:TROEWO>2.0.CO;2](https://doi.org/10.1175/1520-0442(2003)016<3617:TROEWO>2.0.CO;2).

37. Jones C, Mahowald N, Luo C. 2004. Observational evidence of African desert dust intensification of easterly waves. *Geophysical Research Letters*, 31(17): 13–16. <https://doi.org/10.1029/2004GL020107>.
38. Kalnay E. *et al.*, 1996. The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society*, 437–471.
39. Khaniabadi YO, Daryanoosh SM, Amrane A, Polosa R, Hopke PK, Goudarzi G, Mohammadi MJ, Sicard P, Armin H. 2017. Impact of Middle Eastern Dust storms on human health. *Atmospheric Pollution Research*. Elsevier Ltd, 8(4): 606–613. <https://doi.org/10.1016/j.apr.2016.11.005>.
40. Kim MH, Omar AH, Tackett JL, Vaughan MA, Winker DM, Trepte CR, Hu Y, Liu Z, Poole LR, Pitts MC, Kar J, Magill BE. 2018. The CALIPSO version 4 automated aerosol classification and lidar ratio selection algorithm. *Atmospheric Measurement Techniques*, 11(11): 6107–6135.
41. Kim SE, Bell ML, Hashizume M, Honda Y, Kan H, Kim H. 2018. Associations between mortality and prolonged exposure to elevated particulate matter concentrations in East Asia. *Environment International*. Elsevier, 110(May 2017): 88–94. <https://doi.org/10.1016/j.envint.2017.10.010>.
42. Knippertz P, Fink AH. 2006. Synoptic and dynamic aspects of an extreme springtime Saharan dust outbreak. *Quarterly Journal of the Royal Meteorological Society*, 132(617): 1153–1177. <https://doi.org/10.1256/qj.05.109>.
43. Knippertz P, Stuut J-BW. 2014. Mineral Dust - A Key Player in the Earth System.
44. Koffi B, Schulz M, Bréon FM, Griesfeller J, Winker D, Balkanski Y, Bauer S, Bernsten T, Chin M, Collins WD, Dentener F, Diehl T, Easter R, Ghan S, Ginoux P, Gong S, Horowitz LW, Iversen T, Kirkevåg A, Koch D, Krol M, Myhre G, Stier P, Takemura T. 2012. Application of the CALIOP layer product to evaluate the vertical distribution of aerosols estimated by global models: AeroCom phase-I results. *Journal of Geophysical Research Atmospheres*, 117(10): 1–26.
45. Kok JF, Ward DS, Mahowald NM, Evan AT. 2018. Global and regional importance of the direct dust-climate feedback. *Nature Communications*. Springer US, 9(1).

- Accepted Article
46. Kotsyfakis M, Zarogiannis SG, Patelarou E. 2019. The health impact of Saharan dust exposure. *International Journal of Occupational Medicine and Environmental Health*, 32(6): 749–760. <https://doi.org/10.13075/ijomeh.1896.01466>.
 47. Kumar S, Arora A. 2019. On the connection between remote dust aerosol and Indian summer monsoon. *Theoretical and Applied Climatology*. 137(1–2): 929–940. <https://doi.org/10.1007/s00704-018-2647-6>.
 48. Kysely J, Domonkos P. 2006. Recent increase in persistence of atmospheric circulation over Europe: Comparison with long-term variations since 1881. *International Journal of Climatology*, 26(4): 461–483. <https://doi.org/10.1002/joc.1265>.
 49. Langodan S, Cavaleri L, Vishwanadhapalli Y, Pomaro A, Bertotti L, Hoteit I. 2017. The climatology of the Red Sea–part 1: the wind. *International Journal of Climatology*, 37(13):4509–4517.
 50. Levy RC, Remer LA, Martins J V., Kaufman YJ, Plana-Fattori A, Redemann J, Wenny B. 2005. Evaluation of the MODIS aerosol retrievals over ocean and land during CLAMS. *Journal of the Atmospheric Sciences*, 62(4): 974–992.
 51. Maghrabi A, Alharbi B, Tapper N. 2011. Impact of the March 2009 dust event in Saudi Arabia on aerosol optical properties, meteorological parameters, sky temperature and emissivity. *Atmospheric Environment*. Elsevier Ltd, 45(13): 2164–2173.
 52. Mahowald NM, Baker AR, Bergametti G, Brooks N, Duce RA, Jickells TD, Kubilay N, Prospero JM, Tegen I. 2005. Atmospheric global dust cycle and iron inputs to the ocean. *Global Biogeochemical Cycles*, 19(4). doi:10.1029/2004GB002402.
 53. Manoj MG, Devara PCS, Safai PD, Goswami BN. 2011. Absorbing aerosols facilitate transition of Indian monsoon breaks to active spells. *Climate Dynamics*, 37(11–12): 2181–2198. <https://doi.org/10.1007/s00382-010-0971-3>.
 54. Mashat AWS, Alamoudi AO, Awad AM, Assiri ME. 2018. Seasonal variability and synoptic characteristics of dust cases over southwestern Saudi Arabia. *International Journal of Climatology*, 38(1): 105–124.
 55. Mashat AWS, Awad AM, Alamoudi AO, Assiri ME. 2019. Monthly and seasonal variability of dust events over northern Saudi Arabia. *International Journal of Climatology*, (March): 1–23.
 56. Miller DE, Wang Z, Trapp RJ, Harnos DS. 2020. Hybrid Prediction of Weekly Tornado Activity Out to Week 3: Utilizing Weather Regimes. *Geophysical Research Letters*, 47(9): 1–10. <https://doi.org/10.1029/2020GL087253>.

57. Miller SD, Grasso LD, Bian Q, Kreidenweis SM, Dostalek JF, Solbrig JE, Bukowski J, Van Den Heever SC, Wang Y, Xu X, Wang J, Walker AL, Wu TC, Zupanski M, Chiu C, Reid JS. 2019. A Tale of Two Dust Storms: Analysis of a complex dust event in the Middle East. *Atmospheric Measurement Techniques*, 12(9): 5101–5118.
58. Miller SD, Kuciauskas AP, Liu M, Ji Q, Reid JS, Breed DW, Walker AL, Mandoos A Al. 2008. Haboob dust storms of the southern Arabian Peninsula. *Journal of Geophysical Research Atmospheres*, 113(1): 1–26.
59. Mohalifi S, Bedi HS, Krishnamurti TN, Cocke steven D. 1998. Impact of Shortwave Radiative Effects of Dust Aerosols on the Summer Season Heat Low over Saudi Arabia. *Monthly Weather Review*, 126:3153–3168.
60. Notaro M, Alkolibi F, Fadda E, Bakhrjy F. 2013. Trajectory analysis of Saudi Arabian dust storms. *Journal of Geophysical Research Atmospheres*, 118(12): 6028–6043.
61. Notaro M, Yu Y, Kalashnikova O V. 2015. Regime shift in Arabian dust activity, triggered by persistent Fertile Crescent drought. *Journal of Geophysical Research Atmospheres*, 229–249.
62. Oh HR, Ho CH, Kim J, Chen D, Lee S, Choi YS, Chang LS, Song CK. 2015. Long-range transport of air pollutants originating in China: A possible major cause of multi-day high-PM10 episodes during cold season in Seoul, Korea. *Atmospheric Environment*. Elsevier Ltd, 109: 23–30. <https://doi.org/10.1016/j.atmosenv.2015.03.005>.
63. Omar AH, Winker DM, Kittaka C, Vaughan MA, Liu Z, Hu Y, Trepte CR, Rogers RR, Ferrare RA, Lee KP, Kuehn RE, Hostetler CA. 2009. The CALIPSO automated aerosol classification and lidar ratio selection algorithm. *Journal of Atmospheric and Oceanic Technology*, 26(10): 1994–2014.
64. Pizzo G, Clerico M. 2012. Safety health impacts of particulate matter from excavation work sites. *American Journal of Environmental Sciences*, 8(4): 466–472. <https://doi.org/10.3844/ajessp.2012.466.472>.
65. Prospero JM, Ginoux P, Torres O, Nicholson SE, Gill TE. 2002. Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. *Reviews of Geophysics*, 40(1): 1–31. <https://doi.org/10.1029/2000RG000095>.
66. Pu B, Ginoux P. 2018. How reliable are CMIP5 models in simulating dust optical depth? *Atmospheric Chemistry and Physics*, 18(16): 12491–12510.

67. Rajeevan M, Gadgil S, Bhate J. 2010. Active and break spells of the Indian summer monsoon. *Journal of Earth System Science*, 119(3): 229–247.
68. Randles CA, da Silva AM, Buchard V, Colarco PR, Darmenov A, Govindaraju R, Smirnov A, Holben B, Ferrare R, Hair J, Shinozuka Y, Flynn CJ. 2017. The MERRA-2 aerosol reanalysis, 1980 onward. Part I: System description and data assimilation evaluation. *Journal of Climate*, 30(17): 6823–6850.
69. Ravi Kumar K, Attada R, Dasari HP, Vellore RK, Sabique L, Abualnaja YO, Hoteit I. 2018. Aerosol Optical Depth Variability over the Arabian Peninsula inferred from satellite measurements. *Atmospheric Environment*. 187, 346–357.
70. Ravi Kumar K, Attada R, Dasari HP, Vellore RK, Abualnaja YO, Ashok K, Hoteit I. 2019. On the Recent Amplification of Dust Over the Arabian Peninsula During 2002–2012. *Journal of Geophysical Research: Atmospheres*, 124(23): 13220–13229.
71. Sayer AM, Hsu NC, Bettenhausen C, Jeong MJ. 2013. Validation and uncertainty estimates for MODIS Collection 6 “deep Blue” aerosol data. *Journal of Geophysical Research Atmospheres*, 118(14): 7864–7872. <https://doi.org/10.1002/jgrd.50600>.
72. Schepanski K, Tegen I, Macke A. 2012. Comparison of satellite based observations of Saharan dust source areas. *Remote Sensing of Environment*. Elsevier Inc., 123: 90–97. <https://doi.org/10.1016/j.rse.2012.03.019>.
73. Shao Y, Fink AH, Klose M. 2010. Numerical simulation of a continental-scale Saharan dust event. *Journal of Geophysical Research Atmospheres*, 115(13): 1–19. <https://doi.org/10.1029/2009JD012678>.
74. Slinn, SA, Slinn WGN. 1980. Predictions for particle deposition on natural waters. *Atmospheric Environment*, 14, 1013–1016.
75. Sokolik IN, Winker DM, Bergametti G, Gillette DA, Carmichael YJ, Kaufman YJ, Gomes L, Schuetz L, Penner JE. 2001. Introduction to special section: Outstanding problems in quantifying the radiative impacts of mineral dust. *Journal of Geophysical Research Atmospheres*, 106(16): 18015–18027. <https://doi.org/10.1029/2000jd900498>.
76. Solomos S, Ansmann A, Mamouri RE, Biniotoglou I, Patlakas P, Marinou E, Amiridis V. 2017. Remote sensing and modelling analysis of the extreme dust storm hitting the Middle East and eastern Mediterranean in September 2015. *Atmospheric Chemistry and Physics*, 17(6): 4063–4079. <https://doi.org/10.5194/acp-17-4063-2017>.
77. Tian P, Cao X, Zhang L, Sun N, Sun L, Logan T, Shi J, Wang Y, Ji Y, Lin Y, Huang Z, Zhou T, Shi Y, Zhang R. 2017. Aerosol vertical distribution and optical properties over China from

- long-term satellite and ground-based remote sensing. *Atmospheric Chemistry and Physics*, 17(4): 2509–2523.
78. UNESCAP report, 2018. Sand and Dust Storms in Asia and the Pacific: Opportunities for Regional Cooperation and Action. 2018.
79. Urban FE, Goldstein HL, Fulton R, Reynolds RL. 2018. Unseen Dust Emission and Global Dust Abundance: Documenting Dust Emission from the Mojave Desert (USA) by Daily Remote Camera Imagery and Wind-Erosion Measurements. *Journal of Geophysical Research: Atmospheres*, 123(16). 8735–8753. <https://doi.org/10.1029/2018JD028466>.
80. Vinoj V, Rasch PJ, Wang H, Yoon JH, Ma PL, Landu K, Singh B. 2014. Short-term modulation of Indian summer monsoon rainfall by West Asian dust. *Nature Geoscience*, 7(4): 308–313.
81. Viswanadhapalli Y, Hari Prasad D, Sabique L, Srinivas CV, Hoteit I. 2016. Climatic features of the Red Sea from a regional assimilative model. *International Journal of Climatology*, DOI: 10.1002/joc.4865.
82. Wang X, Dickinson RRE, Su L, Zhou C, Wang K. 2018. PM_{2.5} pollution in China and how it has been exacerbated by terrain and meteorological conditions. *Bulletin of the American Meteorological Society*, 99(1): 105–120. <https://doi.org/10.1175/BAMS-D-16-0301.1>.
83. Washington R, Todd M, Middleton NJ, Goudie AS. 2003. Dust-storm source areas determined by the total ozone monitoring spectrometer and surface observations. *Annals of the Association of American Geographers*, 93(2): 297–313. <https://doi.org/10.1111/1467-8306.9302003>.
84. Wei J, Li Z, Peng Y, Sun L. 2019. MODIS Collection 6.1 aerosol optical depth products over land and ocean: validation and comparison. *Atmospheric Environment*. Elsevier, 201(October 2018): 428–440.
85. Winker DM, Tackett JL, Getzewich BJ, Liu Z, Vaughan MA, Rogers RR. 2013. The global 3-D distribution of tropospheric aerosols as characterized by CALIOP. *Atmospheric Chemistry and Physics*, 13(6): 3345–3361.
86. WMO report, 2013. Establishing a WMO Sand and Dust Storm Warning Advisory and Assessment System Regional Node for West Asia: Current Capabilities and Needs. 2013. WMO-NO. 1121.
87. Wong MS, Ho HC, Yang L, Shi W, Yang J, Chan TC. 2017. Spatial variability of excess mortality during prolonged dust events in a high-density city: A time-stratified spatial regression approach. *International Journal of Health Geographics*. BioMed Central, 16(1): 1–14. <https://doi.org/10.1186/s12942-017-0099-3>.

- Accepted Article
88. Yu Y, Notaro M, Kalashnikova O V, Garay MJ. 2015a. Climatology of summer Shamal wind in the Middle East. *Journal of Geophysical Research Atmospheres*, 289–305. <https://doi.org/10.1002/2015JD024063>.
 89. Yu Y, Notaro M, Liu Z, Kalashnikova O, Alkolibi F, Fadda E, Bakhrjy F. 2013. Assessing temporal and spatial variations in atmospheric dust over Saudi Arabia through satellite, radiometric, and station data. *Journal of Geophysical Research Atmospheres*, 118(23): 13253–13264.
 90. Yu Y, Notaro M, Liu Z, Wang F, Alkolibi F, Fadda E, Bakhrjy F. 2015b. Climatic controls on the interannual to decadal variability in Saudi Arabian dust activity: Toward the development of a seasonal dust prediction model. *Journal of Geophysical Research: Atmospheres*, 5780–5792.
 91. Zhang J, Liu Y, Cui LL, Liu SQ, Yin XX, Li HC. 2017. Ambient air pollution, smog episodes and mortality in Jinan, China. *Scientific Reports*. Springer US, 7(1): 1–8. <https://doi.org/10.1038/s41598-017-11338-2>.
 92. Zhou M, He G, Fan M, Wang Z, Liu Y, Ma J, Ma Z, Liu J, Liu Y, Wang L, Liu Y. 2015. Smog episodes, fine particulate pollution and mortality in China. *Environmental Research*. Elsevier, 136: 396–404. <https://doi.org/10.1016/j.envres.2014.09.038>.
 93. Zolina O, Dufour A, Gulev SK, Stenchikov G. 2017. Regional hydrological cycle over the Red Sea in ERA-Interim. *Journal of Hydrometeorology*, 18(1): 65–83.

Figure 1. Scatter plots of DOD from MODIS (a) Terra and (b) Aqua sensors against the AERONET coarse mode aerosol optical depth measurements from solar village, Saudi Arabia during the period 2003–2013. The DODs from Terra and Aqua agree well with the AERONET coarse mode optical depth, with more than 99% confidence level. The color bar represents the normalized density of observations.

Figure 2. The annual variability of number of dust days (Filled bar) occurred in a dust season (March to August) and seasonal mean dust optical depth (Red line) during the period 2003–2017. The numbers in blue indicate the number of extreme dust events observed in a dust season.

Figure 3. Composite of anomalous geopotential height (shaded, m) and vector winds at 1000 hPa (a to c) and 700 hPa (d to f) on the onset day (upper panel), day-1 (middle panel) and day-2 (lower panel) of the extreme dust events.

Figure 4. Composite of anomalous dust optical depth (a to c) and zonal mean composite of CALIOP back scatter ($\text{km}^{-1} \text{sr}^{-1}$) (d to e) on the onset day (upper panel), day-1 (middle panel) and day-2 (lower panel) of the extreme dust events.

Figure 5. Mean composites of dust PM10 ($\mu\text{g m}^{-3}$) concentrations (a to c) and dust emissions ($\text{g m}^{-2} \text{ day}^{-1}$) (d to f) on the onset day (upper panel), day-1 (middle panel) and day-2 (lower panel) of the extreme dust events.

Figure 6. Mean composites of dust dry deposition rates ($\text{g m}^{-2} \text{day}^{-1}$) (a to c) and wet deposition rates ($\text{g m}^{-2} \text{day}^{-1}$) (d to f) on the onset day (upper panel), day-1 (middle panel) and day-2 (lower panel) of the extreme dust events.

Figure 7. Distribution of DOD > 0.5 frequency during dust season for (a) EP1, (b) EP2 periods. (c) mean dust optical depth (2003–2017), and (d) percentage change between EP2 relative to EP1.

Figure 8. Spatial distributions of different dust aerosol parameters for EP2 relative to EP1 during the dust season (March to August) during 2007–2017. Top panel presents mean emissions (g m⁻²day⁻¹) and percentage changes (%). Middle panel presents mean wet deposition (g m⁻²day⁻¹) and percentage changes (%). Bottom panel presents mean dry deposition (g m⁻²day⁻¹) and percentage changes (%).

Figure 9. Spatial distributions of different meteorological parameters for EP2 relative to EP1 during 2007–2017. Top panel presents mean wet season rainfall (mm month⁻¹) and percentage changes (%). Middle panel presents mean soil moisture (mm) and percentage change (%). Bottom panel presents the mean NDVI and percentage change (%) during the dust season.

Figure 10. Mean seasonal (October–December) winds (ms^{-1}) and geopotential height (shaded, m) (a) to (c) and epochal changes (d) to (e) at different pressure levels. Top panel is for 850 hPa, middle panel is for 700 hPa and bottom panel is for 500 hPa during 2007–2017.

Figure S1. Zonal mean composite of anomalous vertical velocities (Pascal/s) averaged between 35°E and 55°E on the onset day (upper panel), day-1 (middle panel) and day-2 (lower panel) of the extreme dust events.

Figure S2. Comparison of AOD between MODIS-Aqua and CALIOP daytime for the period from 2007 to 2015 over the Arabian Peninsula region. The color bar represents the number of coincident observations.