Dust sources over the Arabian Peninsula

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Abstract

This study explores the characteristics of crucial dust sources and changes in their emissions over the Arabian Peninsula (AP) over the 2000–2022 period using high-resolution dust aerosol optical depth (DOD) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol measurements onboard Terra and Aqua platforms. The MODIS dust retrievals successfully unravel the hitherto-unexplored key dust source regions and spatial heterogeneity in dust emissions. Critically, MODIS-defined dust sources display a robust geomorphological signature. In Iraq, the Tigris and Euphrates River basins contain extensive dust sources; the Euphrates dust sources are stronger and more widespread. Localized dust sources are noticed over Syria. In the Kingdom of Saudi Arabia (KSA), the eastern province particularly facilitates extensive dust activity. Oman is the prominent dust source in the southern AP due to the presence of intruding sand dunes.

Dust emissions in the Iraq and KSA regions exhibit a significant negative correlation with the Standardized Precipitation-Evapotranspiration Index (SPEI), a drought index, establishing that the local droughts enhance the dust emissions in these regions. The recent sustained droughts from 2008–2013 caused a remarkable escalation in the dust emissions in these regions through the modification of land surface conditions.

Key words: Dust sources, dust emissions, drought, SPEI index, MODIS, and Arabian Peninsula.
1. Introduction

The Arabian Peninsula (AP) is a global hotspot of dust activity, and according to modeling studies AP emits nearly 17% of global dust emissions (e.g., Zhao et al., 2022). The dust activity over the AP starts from early spring and reaches its peak during summer due to extreme dry conditions and northerly winds, known locally as Shamal winds (e.g., Dasari et al., 2022; Kunchala et al., 2018). The abundant dust present in the atmosphere potentially impacts the regional climate. Dust aloft in the atmosphere strongly modulates the radiation budget due to its scattering and absorption properties (e.g., Saleeby et al., 2019). The attenuation of incoming shortwave radiation due to the atmospheric dust, and deposition of dust over solar panels cause significant losses to the rapidly growing solar energy industry (e.g., Dasari et al., 2019). Dust alters the precipitation efficiency of clouds by actively contributing to the formation cloud condensation nuclei (e.g., Padmakumari et al., 2012; Harrison et al., 2015). Dust deposition further provides a vast amount of iron ore for the ocean fertilization and abnormal productivity of the ocean biomass (e.g., Mahowald et al., 2005). Therefore, iron-rich dust emitted over AP is considered as a primary source of nutrients to marine microorganisms in the neighboring Red Sea, Arabian Gulf, and the Arabian Sea (e.g., Rait sos et al., 2013; Guieu et al., 2019). Dust events over the AP cause multi-fold increase in the regional particulate pollution levels, and often deteriorate the ambient air quality (e.g., Harikishan et al., 2020; Karumuri et al., 2022). These events also favor the widespread distribution of the killer allergic bacteria and microplastic pollution (e.g., Griffin, 2007; Abbasi et al., 2022). Violent winds and poor visibility associated with dust storms could be a severe threat to the ground, air, and marine traffic. In particular, the disruption of ship traffic due to the dust storms in the central shipping lane in the Red Sea results in considerable losses to the shipping industry (e.g., Forti et al 2021).
The above-mentioned dust effects primarily depend on the dust emission processes. Accordingly, accurate knowledge of dust source areas, their geomorphological features, and critical controllers of dust emission variability is essential for a better understanding and quantification of the dust effects on regional climate. Two seminal studies delineated features of dust source regions over AP (Prospero et al., 2002; Ginoux et al., 2012) based on satellite measurements. While these studies have identified several dust spots, however, they were unable to locate quite a few key dust sources (refer to supplementary information Text S2). Therefore, an in-depth examination is still required to obtain the detailed picture of dust source activity over AP. Consequently, and critically, no studies, so far, exhaustively showcased the spatial dissimilarities in AP dust sources by addressing these limitations. To add to the complexity, dust emissions not only vary spatially but also temporally, and are controlled by wide range of factors such as soil or land use type, vegetation cover, topography, seasonality, and prevailing meteorological conditions (e.g., Ginoux et al., 2012). For example, several regions in the AP contain wadis (referred to as riverbeds) and playas (dry lakebed) get flooded only during rainy seasons and become dry in the following dust season to become a source of dust. Droughts are suggested to be an important potential driver of dust variability around the world (e.g., Prospero and Nees, 1986; Achakulwisut et al., 2018; Javadan et al., 2019; Aryal and Evans, 2021; Zhang et al., 2022). Earlier studies using ground-based measurements have tried to ascertain the relationship between drought and dust over the AP (e.g., Notaro et al., 2013; Al Ameri et al., 2019). However, the potential pertinence of the dust-drought relationship to the dust-rich AP region has not been thoroughly examined.

Here, using the long-term and high-resolution ($0.1^\circ \times 0.1^\circ$) MODIS-DOD datasets of Harikishan et al. (2020) available for the 2000–2022 period, we analyze the Dust Activation Frequency (DAF) over the AP region in order to locate and accurately characterize dust source
regions. Further, we describe the improvements shown in the present study through a qualitative
collection of MODIS’s DAF with the MISR and OMI DAFs. In the end, we analyze the trends
in dust emissions over AP, and explore their potential association with drought intensity,
vegetation cover, etc.

The manuscript is organized as follows. Section 2 details the data and methodology.
Section 3 investigates characteristics of the key dust source regions over AP using MODIS dust
observations. Variability in the dust emission activity and its association with droughts in the AP
is analyzed in Section 4. The main conclusions, and a general discussion, are provided in Section
5.

2. Data and Methodology

2.1 MODIS Dust aerosol optical depth

The MODIS onboard Terra (~10:30 LST) and Aqua (~13:30 LST) aerosol measurements are being
increasingly used around the world to monitor dust activities. Ginoux et al. (2012) implemented a
dust retrieval algorithm on MODIS-deep blue aerosol observations with highest quality assurance
flag (QA=3) and developed a DOD dataset, which was later used for dust source mapping.

Recently, Baddock et al. (2016) have included the aerosol pixels with a lower quality assurance
flag (QA=1) in the DOD retrievals, and rigorously tested the modified DOD datasets over
Chihuahuan Desert. Their results have shown that the revised DOD dataset thoroughly resolves all
the dust sources. Interestingly, Baddock et al. (2016) also show that modified DOD datasets
conform well with the local geomorphological signatures. Importantly, there have not been any
dedicated efforts to prove the reliability in the geomorphological signatures of the dust sources
identified by the other satellite sensors (OMI and MISR). We use the Harikishan et al. (2020)’s
high resolution (0.1° × 0.1°) DOD dataset for the AP region, discussed in supplementary
information Text S2, for the period 2000–2022. The local monthly dust activity is represented by the corresponding DAF, which is the number of days in a month when the DOD exceeds the threshold value of DOD > 0.75 suggested by Baddock et al. (2016). The DAF for the dust seasons over the 2000–2019 period is obtained by the accumulated monthly DAF over the March through August months of each of these years. Furthermore, we delve into the constraints related to identifying dust sources using MODIS-DOD in supplementary information Text S4.

2.2 MISR Dust plume measurements

Yu et al. (2018, 2020) highlighted the potential capabilities of MISR sensor in capturing dust storm areas and estimating the transport potential of dust over north Africa and Middle East regions. The present study uses Level–3 Version F02_0002 Cloud Motion Vector Product (CMVP) on Terra platform for the period 2000–2019 at a horizontal resolution of 17.6 km. The MISR-CMVP product is suggested to be suitable for the regions like Middle East and north Africa (Yu et al., 2018) owing to the very low cloud occurrences. The dust plume identification is based on a geometrical technique using multiple cameras of MISR, with relatively high spatial resolution compared to any geostationary sensors. The derived characteristics of dust plumes, such as height and motion, are independent of the dust microphysical and optical properties or any retrieval constraints (Nelson et al., 2013). A dust activation is identified when dust plumes move at speed greater than 10 m s$^{-1}$, with a top height within 2 km of the ground (Yu et al. 2018). Here, we prepare monthly DAF maps by aggregating frequency of dust activations over 0.75° × 0.75° grid over the 2000–2019 period.

2.3 OMI Absorbing Aerosol index (AAI)

AAI gives a semi-quantitative representation of the dust columnar loading, which is widely used to identify and characterize the dust sources around the world (e.g., Prospero et al., 2002). We
utilize the daily AAI retrievals (e.g., Torres et al., 2007) from Ozone Monitoring Instrument (OMI), a successor to the TOMS sensor, available at a spatial resolution of $1^\circ \times 1^\circ$ over the 2005–2019 period. Following Schepanski et al. (2012), we implement a threshold $AAI > 2$ for the preparation of DAF monthly maps.

2.4 SPEI

In order to identify the drought activity, we use the Standardized Precipitation Evapotranspiration Index (SPEI), which is a comprehensive index that considers both precipitation, and potential evapotranspiration a derivative of temperature (e.g., Vicente-Serrano et al., 2022), while computing the drought index. Further details of the advantages of the SPEI are detailed in Saharwardi and Kumar, (2021) and Saharwardi et al. (2022). This study uses the SPEI data, derived from the ERA5 reanalysis products, to represent drought activity at different time scales (1, 3, 6, 9, 12, and 24 months). In this study, we mostly use SPEI-24 (24-month scale) to understand the impacts of mega-droughts and dust emissions. Details about additional data sets used in our study can be found in the supplementary information (Text S1).

In our study, we compute various parameters, including bare soil area, monthly percentage anomaly (%) of DAF and its rolling sums across different time scales, and drought area. The supplementary information (Text S3) provides a comprehensive overview of the methods and considerations involved in estimating these parameters. We employ the least-squares linear trend technique to estimate the trends in both dust emissions and the associated meteorological drivers. Additionally, we utilize a two-tailed Student’s t-test to estimate the statistical significance of trends and correlations. In this exercise, we consider the autocorrelation while computing the significance of correlation. Based on the annual precipitation cycle (e.g., Dasari et al., 2022), we refer to June–August months as summer, and November–April as extended winter. On the other hand,
studies show that the dust activity is prominent during March–August (e.g., Yu et al., 2013; Harikishan et al., 2020), which we refer to as the dust season.

3. Results and Discussion

3.1 Dust source activity over the AP

This sub-section analyzes the DAF distributions of the major dust regions of the AP. For convenience, we denote the dust sources that we identify through a nomenclature containing a letter representing the broad region, followed by a number that denotes the source number in the region. For example, I1 refers to the first source region in Iraq. We broadly distinguish sources mainly based on the prominent associated contiguous geomorphological signatures (e.g., Ginoux et al., 2012).

Iraq

Most of the rainfall in Iraq is received during the extended winter (Figure 1a), with a strong spatial variability. In general, the Tigris basin receives more rainfall (~300 mm) than the Euphrates basin (~100 mm). Iraq does not experience any significant summer rainfall (Figure 1b). In this season, co-occurrences of extreme surface temperature and frequent shimal wind episodes facilitate dust emissions over Iraq (e.g., Yu et al., 2015).

Figure 1c represents the climatological DAF distribution during the dust-season from MODIS datasets across Iraq. The figure overlays the course of rivers Tigris (dark grey; solid line) and that of Euphrates (dark grey; dashed line). The boundary of the greater Tigris-Euphrates basin, also known as Shatt al-Arab, is marked in dark orange (solid line). The basin contains several wadis, ephemeral, i.e., semi-permanent, lakes. These locations, along with those of several dams on the Tigris and Euphrates rivers and their tributaries, have been also indicated in Figure 1c. From an analysis of MODIS datasets, we identify a source region I1, which covers over a broad area of
~45,000 km² between northwest of Baghdad and Iraq–Syria borders (Figure 1c). This prime dust source experiences a high dust activity with the maximum DAF of > 60. It encompasses local sources such as the wadi-Tharthar, beds of Qadisiyah lake (lake 1) and several playas (e.g., Parajuli and Zender, 2017). The wadis and playas, which are mostly ephemeral in nature, contain significant amounts of erodible soil (e.g., Mahowald et al., 2003; Boloorani et al., 2021). The Euphrates is the longest river in west Asia; its wadi system is mainly confined to the west side of the river (UN–ESCWA and BGR, 2013) and bereft of significant vegetation. The MODIS-derived DAF distribution (Figure 1c) indeed unravels widespread dust activity vastly concentrated over the west side of the river course. This dust emission zone, which we refer to as dust source region I2, spreads from the west Najaf city through Nasiriyyah region to the mouth of the Euphrates. This area is also occupied by the dry soil from ephemeral drainages and playas. In addition, the outstretch of the wadi system (UN–ESCWA and BGR, 2013) from Nasiriyyah to the northern border off the Kingdom of Saudi Arabia (KSA) contribute to yet another dust source of remarkable dust emissions (region I3). The dust activity over the Tigris basin is comparatively lower than that over the Euphrates basin, except over a valley region between Naft-Shahr and Badra district located near the east of Baghdad (region I4), which often receives alluvium deposits through fluvial drainage processes from the higher elevated regions.

Interestingly, the corresponding dust-season climatological DAFs from the other two datasets (MISR and OMI) show a spatial shift in the dust hotspots. While the MISR (Figure S1a) records high DAF over the wadi-Tharthar, it misses the dust plumes, captured between the Euphrates and wadi-Tharthar (Figure 1c). In short, the MISR datasets contain only vague signatures of the spatial contrast in the dust emissions between the Euphrates and Tigris basins, and completely underestimate the strength of the dust sources over southern Iraq. The conventional
AAI observations (Figure S1b) also underestimate the dust activity, likely due to the limitations in the AAI retrievals. The AAI is less sensitive to the ambient dust within 1.5 km height (e.g., Schepanski et al., 2012). However, the dust plumes are mostly confined to a height of 1.5 km during the dust emission events over the Iraq region (e.g., Harikishan et al., 2020). For this reason, AAI retrievals may have failed to identify the persistent dust emissions detected by MODIS. The AAI observations (Figure 1c) reasonably distinguish the dust emissions over the Tigris and Euphrates basins, particularly over southern Iraq (that is, between south Baghdad and the Iraqi marshes). Although previous studies (e.g., Prospero et al., 2002; Ginoux et al., 2012; Xi, 2021) had recognized that the Tigris–Euphrates River system is the hotspot of dust storms, the current analysis more accurately depicts the dust sources and their spatial heterogeneity.

**Syria**

The analysis of MODIS data (Figure 1c) reveals, for the first time, a localized dust source over Syria. In northern Syria, isolated dust activity is found between Damascus and east of Ar-Raqq (region S1), with a maximum dust activity placed at the ancient oasis city of Palmyra. Li et al. (2022) indicated that the ongoing civil war and frequent droughts have drastically reduced agricultural productivity in Syria, including the area around the oasis of Palmyra. These conditions likely favored the rapid development of bare lands and led to significant increase in dust emissions from the Palmyra region. The agricultural lands connected to both sides of the southern Khabur river, a tributary to the Euphrates, are active dust areas. It is important to note that the MISR and OMI datasets do not show the signatures associated with the dust sources over Syria (Figures 1c).

Our result is similar to Ginoux et al. (2012), who suggest that that the area east of Ar Raqq is the dominant dust source in Syria.

**The Kingdom of Saudi Arabia (KSA)**
The KSA experiences arid (semi-arid) conditions over its eastern (southwest) region throughout the year (Almazroui M, 2011, Viswanadhapalli et al., 2017). Winter rainfall of ~150 mm mostly occurs over the north and northeastern parts of the KSA (Figure 2a). In summer, only the southwest regions, in particular the windward side of the Asir mountains, experience rainfall (Figure 2b). The monsoon-desert mechanism favors considerable dryness throughout the summer (e.g., Rodwell and Hoskins, 1996).

The MODIS-derived distribution of the DAF (Figure 2c) shows a predominant number of discrete dust sources positioned over the low-lying flat areas of the KSA. Elevated dust emissions are mainly observed over the eastern KSA and stretch to the south and southwest regions. Interestingly, a major hotspot region (K1), is located in the southeast of KSA, and contains lake beds (Figure 2c). The strongest dust activity within this hotspot is seen over the ‘Sabkha Matti’ region, the largest dry lake in the KSA (Schulz et al., 2015), and is marked in a solid gray polygon in Figure 2c. This lake extends southwards from the southern Arabian Gulf up to the sand dunes of the eastern Rub’ al Khali desert. Another enhanced hotspot is observed within the K1 region (dotted gray polygon in Figure 2c), west of Sabkha Matti.

The Rub’ al Khali region, the dust source region K2, is famous for the frequent occurrence of localized dust storms known as haboobs (e.g., Miller et al., 2008; Francis et al., 2021). Surprisingly, the DAF values over the Rub’ al Khali (region K2) are relatively lower than the neighborhood dust sources (Figure 2c). Another prominent hotspot region in the KSA (K3) located is in the east-central parts of the KSA (Figure 2c). This region consists of poorly managed agricultural lands and alkali flats along with clay deposits. Further, the east central parts of the KSA accommodate a prominent dust source region (K4), comprising an ephemeral wadi system (e.g., Scerri et al., 2018), that facilitate dust emissions. The analysis of the DAF from the MODIS
dataset shows that the northwest KSA contains no discernible dust sources. The dust sources in
neighboring Kuwait and United Arab Emirates (UAE) also show dust activity, though not as strong
and widespread as compared to other dust source regions.

The DAF distribution from the MISR reproduces the spatial distribution of MODIS-
observed dust activity with considerable limitations (Figure S1a). Crucially, it underestimates the
strong dust activity over the eastern province of KSA. The OMI-based DAF climatology does not
capture the spatial distinction in the dust emissions in KSA, particularly between the Sabkha Matti
and Rub al' Khali (Figure S1b).

Oman and Yemen

Rainfall over Oman is confined to the northeastern regions, particularly near the foothills of the
Hajar mountains. The accumulated winter rainfall in these regions is ~120 mm (Figure 3a), while
the summer rainfall is less than half of winter rainfall (Figure 3b). Central Oman receives no
appreciable rainfall throughout the year. Dust emissions over Oman, with peak DAF > 60, stretch
parallel to the Gulf of Oman (O1), from its southwest corner to the north-central region (Figure
3c). Peak dust activity is seen over this region due to the local sand dunes and the ephemeral wadis.

Overall, Oman is an appreciable dust source in the southern AP. Furthermore, existing atmospheric
circulation patterns during the dust season limit the northward transport of dust from Oman sources
into the AP (e.g., Notaro et al., 2013). Figure 3c also shows a dust source region (Y1) in the Yemen,
which is spread between Hadhramaut Governorate and the eastern gulf of Yemen (near Al
Ghaydah), with an underlying landform mostly comprising of wadis (e.g., Mahrat, al Jiz, Kidyut).

Unlike the MODIS dataset, the MISR dataset is unsuccessful in discriminating the dust
source activity over Oman and Yemen (Figure S1a), whereas the dust distribution, and hotspots,
from the OMI dataset qualitatively conform to those from MODIS (Figure S1b). Our results for
Oman agree well with Prospero et al. (2002) and display a good association with the local geomorphology of the sources.

4. Recent changes in the dust emissions over the AP

We present time series of the monthly percentage anomaly of DAF (black line) over the regions of Iraq, KSA, Kuwait, UAE, Oman, and Yemen in Figure 4. We note that all the regions have experienced an increase in dust emissions since 2000, with the highest positive trend seen over UAE (31% per decade) followed by Oman (28% per decade), and the lowest trend recorded over Iraq (5% per decade). These trends are statistically significant at a 95% confidence level (p-value < 0.05) over all regions except for Iraq, for which the trend is not significant. Interestingly, all the time series of percentage anomalies of dust emissions indicate a quasi-decadal variability (Figure 4).

Here, we begin by examining the recent changes in the overall climatic conditions that have created a conducive environment for the observed dust emission trends across the AP. Subsequently, we conducted a thorough analysis of potential local meteorological factors and presented our findings in Figure S3. Firstly, we observe a substantial and statistically significant (at 95% confidence level; p-value < 0.05) rising trend in maximum surface air temperatures across the AP region, particularly exceeding 0.6°C per decade in Iraq and eastern AP regions (Figure S3a). Rainfall has shown no significant trend across most of the AP region, except for northeast Iraq (Figure S3b). However, the soil moisture trend is mostly negative throughout the region (Figure S3c), likely due to the rising surface air temperatures, which in turn, lead to increased evaporation rates. The identified dust sources predominantly consist of bare land areas, except for Iraq. Moreover, analysis of NDVI from MODIS data reveals a decreasing trend in vegetation coverage in northwestern Iraq (Figure S3d). These conditions collectively favor the development
and persistence of arid soil conditions. We have also noticed a significant increasing trend in “dusty wind occurrences” (refer to supplementary information Text S3) over the AP, particularly in the KSA (Figure S3e). Overall, these prevalent environmental conditions probably mediated the observed positive changes in dust emissions across the AP.

Furthermore, we have provided area-averaged yearly time series of all these meteorological drivers for each dust source region (Figure S4, Figure S5, and Figure S6), offering a clear insight of their temporal variations. Considering these insights, a thorough examination reveals that an escalation of dust emissions observed over UAE (31% per decade) and Oman (28% per decade) were intricately linked to a concurrent and consistent decrease in soil moisture levels. This decline is most pronounced in the UAE (Figure S5h), followed by Oman (Figure S6c). Conversely, a nominal change in dust emissions observed in Iraq (5% per decade) could potentially be attributed to the sudden and well-noticed increase in local soil moisture levels, particularly evident and consistent since 2009 (Figure S4c), accompanied by a simultaneous and noticeable growth in vegetation (Figure S4d). This combined influence serves to effectively counterbalance the otherwise expected significant rise in dust emissions within the Iraq region. These trends occur in the context of the rising surface temperatures, which remain a consistent factor across all the mentioned regions.

4.1 Drought controls on the variability of dust emissions

The dust emissions from Iraq and KSA dominate the interannual variability of regional dust activity over the AP (e.g., Notaro et al., 2013; Klingmüller et al., 2016). Earlier studies have explored the potential roles of circumglobal wave train, ENSO teleconnections and associated atmospheric conditions on the variability of dust emissions over the AP region (e.g., Yu et al., 2015; Banerjee et al., 2016; Kalendarski and Stenchikov, 2016; Almazroui et al., 2018; Kunchala
et al., 2019; Sun and Liu, 2020; Huang et al., 2021; Thanh Le and Deg-Hyo Bae, 2022). However, to date, there is a notable dearth of scientific literature that explicitly investigates the intricate relationship between drought occurrences and the subsequent dust emissions in the AP region. Recent studies analyzing AOD/dust storm measurements (Notaro et al., 2015; Boororani et al., 2020, 2021, Xi, 2021) have qualitatively accredited these dust activities to the influence of droughts. However, neither the relationship nor the potential variations in the dust sources during droughts were quantified. To this end, we present the time series DAF-24 over Iraq and KSA regions, which are plotted against the corresponding time series of SPEI over 24 months (referred to as SPEI-24) in Figures 5a and 5b, respectively. Over Iraq (Figure 5a), the DAF-24 anomalies display a strong negative association with the SPEI-24, with a correlation of 0.6 at 99% confidence level. Interestingly, such a relationship between the dust emissions and droughts is also prevalent at time scales of 12 months (please refer Table S1). This suggests that slow variations in drought activity are more important for variations of dust emissions over the Iraq region. In fact, increasing (decreasing) dust emissions can be associated with strengthening (weakening) of droughts on these time scales during the study period. Notably, when prolonged drought conditions were recorded during the period 2008–2013 over the AP region (e.g., Notaro et al., 2015), dust emissions over the Iraq region rose by more than 200% relative to their climatological values (Figure 4a). Furthermore, the bare soil area in Iraq increased with drought area and drought intensity (Figure 5c). We observe a strong association between the drought-affected area and bare soil area during the persistent drought period, when extremely dry conditions prevailed (Figure 5a). The situation in the KSA differed significantly. As depicted in Figure 5d, no significant association was found between the bare soil fraction and the drought-affected areas in the KSA, likely due to the predominantly bare nature of its land. Spatially, the dust sources of Iraq exhibit the highest
anomalous positive emissions during 2008–2013 in the AP (Figure 6c). Within Iraq, the region I1 (Figure 1c) was the epicenter of high dust activity. Further, dust sources (I2 to I4) situated along Tigris and Euphrates River, and the desiccated lakes therein, also showed a significant enhancement in dust emissions during the period.

Indeed, desiccation of lakes due to prevailing drought conditions can also lead to bare soil conditions and could contribute to the regional dust emissions (e.g., Mahowald et al., 2003; Rashki et al., 2013; Jin et al., 2017). Satellite mosaic images of the annual lake regions, obtained from google time-lapse tool for the years 2006, 2009, and 2013 indicate a significant expansion of dry soil beds surrounding these lakes during the persistent drought period of 2008–2013 (Figure S2), with the maximum change over the lake Razazza region. The resultant extra soil availability may have also contributed to the observed exacerbation of the regional dust emissions shown in Figure 6c. Overall, it is understandable that persistent hydrometeorological drought conditions during 2008–2013, which likely evolved initially as a meteorological drought, favored abnormal dust emissions. Dust emissions drastically reduced during a few ensuing years post-2013 due to a relative increase of wet periods. While a rapid enhancement of the dust emissions coincident with drought conditions is apparent during the year 2018, we do not see these conditions persist beyond that year (Figure 5a).

Henceforth, we examine the potential relationship between drought and dust emissions over the KSA. The DAF-24 anomalies over the region exhibit a correlation of 0.45 with the SPEI-24, which is significant at 99% level. Our analysis (Figure 5b) indicates a strong increase in KSA dust emissions also during the protracted drought period of 2008–2013, followed by a long hiatus in dust activity until 2018. Critically, unlike Iraq, the KSA does not contain a significant vegetation cover. However, KSA has many wadis (Scerri et al., 2018), which, when dry, potentially contribute
to the dust emissions because of their inherent geomorphology. We notice a marked enhancement
in the dust emissions from the dust sources associated with the wadi ad Dawasir and wadi Sabha
during the persistent drought period of 2008–2013 (Figure 6c); the intense drought apparently
dried up the wadi system over the KSA leading to abnormal dust emissions. Furthermore, the dust
sources in north-east KSA also showed enhanced dust activity during that protracted drought.
Importantly, Notaro et al. (2015), through a back trajectory analysis, suggested that the anomalous
dust loading over KSA during this period was due to the influence of dust emissions from Iraq.
Nevertheless, backward trajectory analysis simply follows wind patterns, which in this season are
dominated by the Shamal winds coming from Iraq. Due to this limitation, the contribution from
the local sources cannot accounted for in the trajectory analysis.

5. Conclusions

This study examined the major dust sources, their characteristics and recent dust emission changes
over the AP using MODIS dust aerosol optical depth (DOD) observations for the period
2000–2022. The key findings of this work are summarized as follows:

- The MODIS dust retrievals have fairly reproduced the fine scale features of the widespread
dust sources over the AP. Essentially, a visual comparison with the google earth images
(e.g., Ginoux et al., 2010) indicates that the MODIS-defined dust sources display strong
geomorphological signatures (Figures not shown). Our analysis detected unexplored dust
activity over Iraq for the first time. The intense dust hotspots are positioned in the
northwestern parts of Iraq between northwest Baghdad and Iraq-Syria borders. The land
areas of the Tigris-Euphrates River systems in Iraq also contribute to the major dust activity
over the northern AP, with the Euphrates basin dust sources dominating in intensity and
spread. Over Syria, localized and isolated dust activity is observed.
• The eastern province of KSA accommodates the prominent dust sources, and among them the largest dry lake ‘Sabkha Matti’ is the foremost contributor to dust activity.

• The dense wadi system and intrusion of sand dunes from the south Rub al’ Khali have made Oman a prominent dust source region in the southern AP.

• Although MISR dataset successfully identifies a crucial hotspot in Iraq, the overall performance is inferior to the other two sensors. To some extent, OMI dataset discriminates the dust sources, and broadly replicates most of the spatial features seen in MODIS.

• Trend analysis of dust emissions suggest a strong increase in the dust emission activity over UAE (31% per decade) followed by Oman (28% per decade), while the lowest trend is noted over Iraq (5% per decade).

• We further investigated the relationship between dust-drought for key dust sources in Iraq and KSA. Our examination showed a significant correlation of −0.6 (−0.45) between dust emissions and SEPI–24 in Iraq (KSA). The results further suggest that the extended drought circumstances favored the development of barren lands over Iraq during the protracted drought period of 2008–2013, likely favoring the abnormal emissions.

Further, we established a strong association of regional dust emissions with drought. This information is useful to constrain the dust-drought relationship in the regional and dust–climate models.

Data Availability

The MISR monthly cloud motion vectors were obtained from the ASDC data center (https://asdc.larc.nasa.gov/data/MISR/M13MCMVN.002/). MODIS-Terra NDVI was downloaded from the Giovanni web site (https://giovanni.gsfc.nasa.gov/giovanni/). The daily MODIS Deep-blue aerosol measurements were obtained from the LAADS server.
Daily gridded OMI-AAI was downloaded from the TEMIS website (https://www.temis.nl/airpollution/). Monthly accumulated precipitation is obtained from gloh2o server (http://www.gloh2o.org/mswep/). High resolution regional satellite mosaics were obtained from google earth (https://earth.google.com). Monthly surface maximum temperatures were acquired from the CRU website (https://crudata.uea.ac.uk/cru/data/hrg/). Lastly, hourly gridded 10m windspeeds were downloaded from CDS server (https://cds.climate.copernicus.eu/#!/home).

**Code availability**

Analysis was performed using the NCAR Command Language (https://www.ncl.ucar.edu), Climate Data Operators (CDO) command line tool (https://code.mpimet.mpg.de/projects/cdo/) and MATLAB-Climate data tool (Chad et al., 2019). The data and codes used for the analysis are available from the corresponding author.

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Figure Captions:

Figure 1. Rainfall and dust activity over Iraq and Syria. Climatology of accumulated rainfall over the 2000–2019 period for a) winter (November through April), b) summer (June to August), and c) dust season climatology of DAF maps for MODIS over the 2000–2019 period. The locations of the dams in Iraq are shown with cross symbols and the locations of ephemeral lakes are indicated by numbers (1-Qadisiyah, 2-Tharthar, 3-Habbaniyh, 4-Razza, 5-Najaf, 6-Hammer). The course of the Tigris River (solid gray) and Euphrates River (dotted gray) and the boundaries (orange line) of the Tigris-Euphrates basins are also shown.

Figure 2: Rainfall and dust activity over the Kingdom of Saudi Arabia. Climatology of accumulated rainfall over the period 2000–2019 for a) winter (November through April), b) summer (June to August), and c) dust season climatology of DAF maps for MODIS over the same period.

Figure 3: Rainfall and dust activity over Oman and Yemen. Climatology of accumulated rainfall over the 2000–2019 period for a) winter (November through April), b) summer (June to August), and c) dust season climatology of DAF maps for MODIS over the same period.

Figure 4: Recent trends (2000–2022) in the dust emissions activity over a) Iraq, b) Kingdom of Saudi Arabia, c) Kuwait, d) UAE, e) Oman, and f) Yemen. The trend values (per decade) are shown in the blue text. Monthly and yearly average of dust emissions are shown in gray and red lines respectively.

Figure 5. Recent variations (2000–2022) in 24–month rolling aggregate of DAF percentage anomalies (DAF–24) and their association with the evolution of drought (SPEI–24) over a) Iraq, b) KSA, and variations of drought area and bare soil area for the same period over c) Iraq and d) KSA.

Figure 6. Spatial distribution of dust season DAF mean composite for a) drought period (2008–2013), b) climatology (2000–2019), and c) the difference between drought and climatology. The locations of ephemeral lakes are shown in blue triangles.
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