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Impacts of climate and synoptic fluctuations on dust storm activity over the Middle East

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Abstract

Dust events in the Middle East are becoming more frequent and intense in recent years with impacts on air quality, climate, and public health. In this study, the relationship between dust, as determined from Aerosol Optical Depth (AOD) and meteorological parameters (precipitation, temperature, pressure and wind field) are examined using monthly data from 2000 to 2015 for desert areas in two areas, Iraq-Syria and Saudi Arabia. Bivariate regression analysis between monthly temperature data and AOD reveals a high correlation for Saudi Arabia ($R = 0.72$) and Iraq-Syria ($R = 0.64$). Although AOD and precipitation are correlated in February, March and April, the relationship is more pronounced on annual timescales. The opposite is true for the relationship between temperature and AOD, which is evident more clearly on monthly time scales, with the highest temperatures and AOD typically between August and September. Precipitation data suggest that long-term reductions in rainfall promoted lower soil moisture and vegetative cover, leading to more intense dust emissions. Superimposed on the latter effect are more short term variations in temperature exacerbating the influence on the dust storm genesis in hot periods such as the late warm season of the year. Case study analysis of March 2012 and March 2014 shows the impact of synoptic systems on dust emissions and transport in the study region. Dust storm activity was more intense in March 2012 as compared to March 2014 due to enhanced atmospheric turbulence intensifying surface winds.

Keywords

Middle East; Dust storm; MODIS; TRMM; Precipitation; Temperature; Synoptic analysis

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1. Introduction

Owing to desertification and climate change, dust emissions are of increasing concern in semi-arid and arid regions that cover approximately a third of the global land area. Dust is the most abundant aerosol type globally on a mass basis and affects climate, the water cycle, public health and welfare, and vegetation (Bollen et al., 2010; Manninen et al., 2013; Gibson, 2015; Matyssek et al., 2015; Madala et al., 2016; Carugno et al., 2016; Morelli et al., 2016; Raspanti et al., 2016; Youn et al., 2016; Soltani et al., 2017). Large deserts in the Middle East, such as those in Saudi Arabia, Iraq, and Syria, are major sources of dust where in recent years dust storm frequency and intensity has increased (Alam et al., 2014a; Boloorani et al., 2014; Jish Prakash et al., 2015; Shalaby et al., 2015; Gharibzadeh et al., 2017). Consequently, the need to understand the spatiotemporal characteristics and meteorological dependencies of dust storms is increasing.

Aerosol optical depth (AOD) is an important remote sensing parameter that serves as a columnar proxy variable representing aerosol abundance. AOD data are commonly retrieved from space and from the surface such as through the AERONET network (Holben et al., 1998). Satellite images of AOD are useful for studying dust storms owing to the large spatial nature of such plumes (Alam et al., 2011a; YuLei et al., 2013; Namdari et al., 2016). Because of the broad spatiotemporal coverage of the Moderate Resolution Imaging Spectroradiometer (MODIS), its AOD data have been widely used for examining spatial and temporal distribution of dust (Song et al., 2008; Schaap et al., 2009; Alam et al., 2010, 2011b; Huang et al., 2010; Sorooshian et al., 2011; Namdari et al., 2016; Sehatkashani et al., 2016). Several studies have addressed the relationship between dust and meteorological parameters (Zhao et al., 2004; Qu et al., 2006; Yang et al., 2007; Hui et al., 2008; Du et al., 2009; Kanniah and Yaso, 2010; Alam et al., 2012, 2014b; Yu et al., 2015; Bibi et al., 2016). Yang et al. (2007), for example, analyzed dust storm events and their relation to climate change in Northern China during the past 1000 years by using different paleoclimate archives such as ice cores, tree rings, and historical documents. Hui et al. (2008) examined the relationship between dust aerosols and rainfall in the West African Sahel, where it has been speculated that the dust-rainfall feedback contributes to sustained droughts. Du et al. (2009) used monthly dust storm data at 107 stations in North China to analyze the relationship between climate change and frequency of dust storm events. Kanniah and Yaso (2010) used regression analysis to describe AOD spatiotemporal patterns as a function of climate data (solar radiation, temperature, and relative humidity). They showed that AOD increased in the dry season months. Yu et al. (2015) considered the case of local (endogenous) dynamics within the Sahel, and analyzed precipitation-vegetation-dust interrelationships. They found a teleconnection between Sahel precipitation and exogenous (i.e., Saharan) dust emissions resulted from an increase in Saharan wind speed in years of above average Sahel precipitation. In addition to regional factors, long range transport of dust and other emissions such as from fires can also significantly impact surface dust levels in areas thousands of kilometers downwind (e.g., Crosbie et al., 2014; Lopez et al., 2016).

The role of synoptic scale atmospheric circulation systems in generating dust storms has been highlighted in past works (Prezerakos et al., 2010; Bastan et al., 2013; Hamidi et al., 2013; Al-Jumaily and Ibrahim, 2013; Awad and Mashat, 2014; Boloorani et al., 2014; Wang

et al., 2015; Sehatkashani et al., 2014). Prezerakos et al. (2010) assessed synoptic scale atmospheric circulation systems associated with the rather frequent phenomenon of coloured rain and the very rare phenomenon of dust or sand deposits from a Saharan sandstorm triggered by a developing strong depression. Al-Jumaily and Ibrahim (2013) used satellite images, aerosol index data, and synoptic weather charts to link synoptic patterns to formation of dust storms in Iraq. Using MODIS satellite images and data for soil, land cover, and wind, Boloorani et al. (2014) identified the synoptic patterns responsible for dust storms that entered Iran. Hamidi et al. (2013) synoptically analysed 12 dust storms between 2003 and 2011 using NCEP-NCAR reanalysis data. Sehatkashani et al. (2014) showed that the prevailing synoptic systems leading to dust genesis in the west and southwest of Iran during the warm season are characterized by the domination of the Saudi Arabia and Pakistan thermal low and the sub-tropical high in the region. That study confirms that the Shamal dust storm incorporates with anticyclones over north of Africa to the east of Europe and the monsoon trough over Iraq, south of Iran, Pakistan, and the India subcontinent. Wang et al. (2015) examined the correlation between African dust and Sahel rainfall on a decadal scale. They revealed that as the Saharan heat low warms, an anomalous tropospheric circulation develops that reduces wind speeds over the Sahara and displaces the monsoonal rainfall northward, thus simultaneously increasing Sahelian rainfall and reducing dust emission from the major dust “hotspots” in the Sahara.

The aforementioned works have provided much-needed information about the nature of dust storms while recognizing the complexity of predicting airborne dust concentration at a given time. The present study aims to continue unraveling details about dust emissions in the Middle East. The objectives of the present study are the following: (a) to analyze the relationship between dust concentration and both temperature and precipitation; and (b) to provide an overview of synoptic characteristics of passive and active dust periods using monthly MODIS AOD and synoptic charts from the European Centre for Medium-Range Weather Forecasts (ECMWF).

2. Methodology

2.1. Study region

There are several desert areas in the Middle East, especially in Saudi Arabia, Iraq, and Syria with Rub’ al Khali in Saudi Arabia being the largest. Construction of dams on main rivers in Iraq and Syria have led to significant desertification in recent years, which has promoted an increase in dust storms. To distinguish between the Rub’ al Khali and the influence of factors such as dams in other areas, the study domain is divided in two sections consisting of desert areas in (i) Saudi Arabia and (ii) Iraq-Syria (Fig. 1).

2.2. Datasets

This study uses AOD, temperature, and precipitation data between 2000 and 2015. AOD data are obtained from MODIS Collection 6 aerosol products over land and ocean from the combined Dark Target and Deep Blue algorithm (Giglio et al., 2016; Yan et al., 2016; Floutsi et al., 2016). MODIS is chosen as the source of AOD data owing to a significant correlation between values retrieved in relationship to those at an AERONET station in the

nearby city of Zanjan, Iran (36.705° N, 48.507° E) (Khoshshima et al., 2013). Updates in the Collection 6 have improved globally accuracy and coverage (Levy et al., 2013), and a number of other studies have relied on MODIS AOD retrievals for bright surfaces based on reasonable levels of agreement with sun photometers (e.g., Bayat et al., 2011; Hsu et al., 2006).

Monthly AOD data from the MOD08 Level 3 product (<http://ladsweb.nascom.nasa.gov/data>) at a resolution of $1^\circ \times 1^\circ$ are used to investigate the spatiotemporal distribution of dust in the study region. This study focuses on AOD at 550 nm over land, as this is close to the peak of the solar spectrum and is, therefore, associated with major radiative effects (Papadimas et al., 2009). Precipitation data are obtained from the Tropical Rainfall Measuring Mission (TRMM; <https://pmm.nasa.gov/index.php>) 3B43 V7 product, which provides monthly precipitation at 0.25° spatial resolution (Fisher, 2004; Waldo, 2009; Duan et al., 2012). Monthly mean temperature data are derived from the Global Historical Climate Network (GHCN; <http://www.esrl.noaa.gov/psd/data/gridded/data.ghcncams.html>) of the NCDC/NOAA at spatial resolution of $0.5^\circ \times 0.5^\circ$ (Kalnay et al., 1996; Kistler et al., 2001).

Synoptic data are examined to identify how well geopotential height, temperature, and wind field at various levels (i.e., sea level, 850/500/250 hpa isobaric levels) are related to both AOD and dust activity. Meteorological data used are obtained from the ECMWF archived operational initialized analyses at a resolution of $2.5^\circ \times 2.5^\circ$ (Bou Karam et al., 2010; <http://apps.ecmwf.int/datasets/data/interim-full-moda/levtype=sfc>). Visibility data are obtained from the Iran Meteorological Organization (IMO) to compare with AOD values (<http://www.irimo.ir/eng/wd/720-Products-Services.html>). The NOAA HYSPLIT model (Stein et al., 2015; Rolph, 2016) is used to compute forward trajectories at various altitudes with a resolution of 500×500 m and a horizontal grid of $1.5^\circ \times 1.5^\circ$ (Ashraf et al., 2013).

The focus of the ensuing discussion is on the relationship between AOD and meteorological parameters using both monthly and annual mean values to identify potential differences in relationships as a function of time scale. Quantitative relationships are examined between variables based on correlations and regression functions. Also, detailed case studies of specific months are presented during active and passive periods of dust activity as another way of identifying how synoptic patterns relate to dust emissions. Relationships that are reported as being statistically significant correspond to when p value < 0.05. We caution that the significant correlations presented are not direct proof of causality and that with the current dataset the most that can be done is to speculate about underlying mechanisms at play.

3. Results and discussion

Surface conditions such as soil moisture influence dust emission fluctuations. Temperature and precipitation are two parameters that directly determine soil moisture and indirectly change the threshold friction velocity for a dust outbreak on bare soil. Soil moisture increases as a function of precipitation leading to a reduction of dust emissions and thus reduced values of AOD. Also when temperature rises, relative humidity decreases, leading to a decrease in threshold wind speed to initiate dust emissions. So this study investigated the

relationship between dust concentration and both temperature and precipitation based on statistical analyzes.

3.1. Temporal interrelationships (AOD, T, precipitation)

Monthly mean values of AOD, temperature, and precipitation for different months during the study period are summarized in Figs. 2–3. There are two time periods in each year for both deserts in which there is a noteworthy relationship between AOD and either precipitation or temperature. The first period is in the months of February, March, and April where there is a rising trend in AOD (Fig. 2). The AOD-temperature relationship in the February–April months is significant over the study period ($R = 0.23$), while the correlation between precipitation and AOD is negative and significant ($R = -0.43$) (Fig. 3).

The second period includes the months of June, July, and August (Fig. 4). Since the amount of precipitation is reduced in these warmer months and temperature exhibits a wide range, this period of year is suitable to study the relationship between temperature and AOD. Unlike with precipitation, the relationship between temperature and AOD is shown to be significant and expectedly positive ($R = 0.48$) (Fig. 5). Conversely, precipitation and AOD exhibit an insignificant relationship ($R = 0.16$). These results show that precipitation exhibits a stronger relationship with AOD at the beginning of dust storm activity (February–April), while in subsequent warm summer months (June–August) temperature is better related to AOD.

Over the study period (2000–2015), temperature exhibited relatively little change in terms of annual mean values (26.64–27.75 °C for Iraq-Syria and 22.28–24.31 °C for Saudi Arabia) (Fig. 6). What is striking though is how AOD increases between 2007 and 2012, concurrent with reductions in precipitation relative to preceding and subsequent years.

Fig. 7 shows the same interrelationships from Figs. 3 and 5 but now for all months rather than specific months. AOD exhibits a stronger relationship with temperature ($R = 0.64$ – 0.72) as compared to precipitation ($R = -0.26$ to -0.42) based on monthly mean values.

Due to the simultaneous effects of temperature and precipitation on AOD, multivariate regression analysis was conducted to examine influences of these two parameters simultaneously. Table 1 shows the Pearson's correlation coefficients between monthly mean values of AOD, temperature, and precipitation.

The multiple regression model is as follows:

$$y_t = \beta_0 + \beta_1 x_{1,t} + \beta_2 x_{2,t}$$

Where y_t is mean monthly AOD, $x_{1,t}$ is mean monthly temperature, and $x_{2,t}$ is total monthly precipitation. Also β_1 and β_2 are coefficients of each independent parameter. The results indicate that the relationship between precipitation and AOD in the Iraq-Syria desert is insignificant, in contrast to the significant positive relationship between temperature and AOD. The AOD-temperature relationship is stronger for Saudi Arabia owing to the higher β_1 coefficient, which is expected based on Fig. 7. In Saudi Arabia there is a positive

relationship between AOD and precipitation ($\beta_2 = 0.21$), which is counter-intuitive since more precipitation promotes higher soil moisture and less tendency for dust emissions. It is likely that the increased precipitation co-varies with increasing temperature in the region, with higher temperatures having a more important effect on dust emissions (Singh and Oh, 2007; Almazroui et al., 2012). Based on R^2 value, the multivariate regression based on temperature and precipitation to predict AOD can be significantly improved by applying more parameters such as wind speed, relative humidity, and surface properties such as soil moisture content and other soil properties. Also positive relationship between AOD and precipitation is because of monsoon rainfall occurs in Saudi Arabia polygon. Monsoon rainfall in the southern of Saudi Arabia desert start in July. The impact of Monsoon rainfall was barely seen in reducing AOD as one of the reasons for this issue is small geographical location range of precipitation (Singh and Oh, 2007; Almazroui et al., 2012).

3.2. Synoptic analysis of dust storms: case study of March 2012 and March 2014

The synoptic pattern influencing dust genesis over the region is analyzed for the month of March in the two years of 2012 and 2014, representing periods of active and passive dust activity, respectively. Past work has examined so-called “super dust storms” over the Middle East and southwest Asia in March 2012 (Alam et al., 2014a). Fig. 2 shows that in March 2012, despite a significant decline in temperature and relative increase in rainfall (compared to 2011), especially in the desert of Iraq-Syria, there has been a significant increase in the amount of AOD. Moreover, in March 2014, despite no change in temperature compared to preceding years, AOD values were significantly reduced. Precipitation had substantially increased in the Iraq-Syria desert in 2014. These findings qualify these two months as useful cases to study in order to determine the role of synoptical patterns over the Middle East in affecting dust emissions.

Fig. 8a shows that in addition to the difference in the amount of dust storm intensity, the location of dust storm activity changed. Dust storms in 2012 exist over the total area of Iraq-Syria and Saudi Arabia deserts, while in 2014, dust storms are limited to the eastern part of the Arabian Peninsula. Subsequent discussion focuses on synoptic charts for monthly means and anomalies (compared to 30-year period 1981–2010) at sea level pressure, near surface levels (850 hPa), and upper levels.

3.2.1. Case study of March 2012—The evaluation of 500–250 hPa chart in March 2012 and its anomaly indicates that the polar jet stream core, when compared to normal conditions (23–28° N), has moved to latitudes of 28–33° N (Fig. 8b). There is a trough with low geopotential height centered over the Caspian Sea, extending to the northern parts of the Arabian Peninsula accompanied by atmospheric turbulence at upper levels; consequently dust storms at the surface.

Wind speed of the jet stream core increased by 25–30 m s⁻¹. The enhanced speed is especially evident on the eastern part of the Iraq and Saudi Arabia Deserts. The upper-level anomaly chart shows a core of Arabian sub-tropical high geopotential height over southeast Saudi Arabia. Analysis of 500 hPa geopotential height in March 2012 (Fig. 8c) indicates that

the Mediterranean wave was more active in the Middle East in March 2012, which is evident from the negative geopotential anomalies.

Increased atmospheric turbulence and wind speed in the Middle East, especially in the Tigris and Euphrates basin, can be explained by the following: (i) polar jet stream core translocation to the northeast and its establishment in Syria, Iraq, Iran, and North Arabia; (ii) more Mediterranean wave activity in the Middle East; and (iii) Saudi Arabia subtropical high pressure activities.

The mean sea level pressure chart (Fig. 8d) indicates there was high pressure over Scandinavia with central pressure of 1020 hPa and temperature of 5 °C extending to Turkey. In southeast Saudi Arabia, the average of air pressure was 1013 hPa and the average air temperature was 25 °C. The considerable pressure and temperature gradients over the region promoted blowing of northerly winds (and thus dust storms), originating from surface vortices causing the intensification of wind velocity over Iraq and the Persian Gulf, known as Shamal winds (Abdi Vishkaee et al., 2011). This wind is recognizable in the Persian Gulf and east Arabian Peninsula.

Analysis of the 850 hPa anomaly chart for March 2012 shows that in the desert areas of Syria and Iraq, wind speed increased by $\sim 3 \text{ m s}^{-1}$ (Fig. 8e). Moreover, the 850 hPa Chart of March 2012 reveals the effect of the Mediterranean trough (as low pressure in the north of Caspian Sea) and the role of a subtropical high pressure area over the southeastern part of the Arabian Peninsula in creating dust storms (Fig. 8f).

3.2.2. Case study of March 2014—Mean synoptic charts at different levels have been analyzed for March 2014 as well. Middle and upper levels synoptic charts (500 and 250 hPa) show that the polar jet stream core was in its typical geographical location, but wind speed increased by 25–30 m s^{-1} (Fig. 8b). According to the jet stream core position on the Arabian Peninsula, the causes of the relative increase in AOD over the Saudi Arabia Desert, as compared to the Iraq-Saudi Desert, becomes clear. However, despite the prevailing jet stream core and low rainfall and maximum temperature in the deserts of Saudi Arabia at this time, the reason of significant reduction in AOD in comparison with previous years is uncertain. Fig. 8c shows there was a small core of a subtropical high level system over Yemen and Sudan. The mean level of 500 hPa was reduced to the range of 20–80 geopotential m rather than normal state (Fig. 8b). At near surface level (850 hPa), with the exception of the central region of Saudi Arabia, in most desert areas of the Middle East no noticeable high wind speed is observed; furthermore, the 850 hPa anomaly chart shows there is no significant change in weather conditions compared to normal conditions in most regions (Fig. 8e) in March 2014.

At sea level pressure (SLP), the domination of 1014 hPa high pressure center near the east coast of the Arabian Peninsula and the formation of a 1011 hPa low pressure center over the southwest of the Arabian Peninsula caused increased wind speed and divergence of wind flow streamlines from the sea to the southern coast of the Arabian Peninsula (Fig. 8d). These factors resulted in limited dust activity in central and eastern regions of the Arabian Peninsula. This event occurred while normal atmospheric conditions governed the Tigris and

Euphrates basin, and mean wind speeds in all areas were less than 5 m s^{-1} . In order to investigate atmospheric turbulence fluctuations at the surface, the omega map was used at 850 hPa (Fig. 8g) and the mean and anomaly of omega values were compared between March 2012 and March 2014. As shown in the maps, both the mean and anomaly in omega in the study area in March 2012 were significantly higher than in March 2014. This provides support for there being more significant turbulence in March 2012.

Considering the important role of water vapor content near the surface layer during dust storm activity, the mean and anomaly of relative humidity were investigated at 850 hPa (Fig. 8h). Based on these maps, in March 2014, the relative humidity in study area was between 30% and 50%, which is $\sim 10\%$ higher than the long-term average. In contrast, in March 2012, the average relative humidity was between 20 and 40%, which is about $\sim 10\%$ lower than the long-term average. The governance of drier air in March 2012 over Iraq and the Arabian Peninsula is one of the factors contributing to the intensification of dust storm activity.

Forward-trajectory analysis was conducted for several altitudes to identify the trajectory of air masses originating over Middle East deserts for the two March periods. There was an intense dust storm on 18 March 2012 with less than 100 m horizontal visibility. For comparison of that event with 18 March 2014, HYSPLIT forward trajectory analysis was conducted (Fig. 9). Although daily synoptic maps are needed to determine more precisely dust emission factors in the selected days, but comparing the results of the HYSPLIT model with the synoptic monthly maps (as the prevailing atmospheric conditions per month), shows that in 2012 the wind direction at sea level pressure (Fig. 8d), as compared to other levels of the atmosphere, had the highest compliance with the direction of dust emissions. Conversely, in the March 2014 case, dust intensity was very low, concurrent with low wind speed, and the wind direction did not show a dominant pattern.

4. Conclusion

To understand the causes of trend variations in dust intensity over the Iraq-Syria and Saudi Deserts between 2000 and 2015, this study investigated parameters influencing dust genesis including rainfall, temperature, and wind fields, which are shown to be impacted by synoptic patterns. The analysis focused on examining interrelationships between AOD, temperature, and precipitation. Results indicate that AOD is better related to precipitation in late cold season and early warm season (March and April), while temperature is related more considerably to AOD in the late warm season (August and September).

Mean-annual temperature is shown to have a weak relationship with AOD leading to development of dust storms. Unlike temperature, the correlation between annual rainfall and AOD is significant and the two parameters are inversely related. Thus, variability of precipitation on annual scales is a chief determinant in dust storm activity through its role in impacting soil moisture.

Bivariate regression analysis of monthly temperature and precipitation data, unlike the comparative trend figures, yield an improved relationship between temperature and AOD (R

> 0.63) as compared to rainfall and AOD ($R = < |-0.41|$). The effects of temperature on AOD are more easily observed at monthly time scales as compared to precipitation, the effect of which is more easily gleaned over annual time scales.

To investigate the impact of synoptic systems on factors influencing dust genesis in the study region, two months (March 2012 and March 2014) were compared showing that the movement of the polar jet stream core (from 23 to 28° N to 28–33° N and 15–45° E to 45–65° E) and its establishment in the Middle East desert promotes strong winds at surface level. Atmospheric turbulence near the surface and at the middle level and drier air in March 2012 play an important role on the intensification of dust storm activities. In March 2014, the synoptic conditions in the Middle East were similar to normal conditions. The long term rainfall decline has had a significant impact on soil moisture and the amount of vegetation in study area, promoting more dust emissions. These factors have provided conditions that temperature increase in short-term intensifies the dust storm activity in the region in the late warm season of the year.

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Fig. 1.
Geographic display of the study region.

Fig. 2.
Variations in monthly mean MODIS Terra AOD, TRMM precipitation, and temperature for the months of February–April between 2000 and 2015.

Fig. 3. Correlations between AOD-Precipitation and AOD-Temperature for the entire region between February–April of 2000–2015. Each marker represents a single month.

Fig. 4. Variations in monthly mean MODIS Terra AOD, TRMM precipitation, and temperature for the months of June–August between 2000 and 2015.

Fig. 5. Correlations between AOD-Precipitation and AOD-Temperature for the entire region between June–August of 2000–2015. Each marker represents a single month.

Fig. 6. Interannual variation in annual mean MODIS Terra AOD, TRMM precipitation, and temperature.

Fig. 7. Correlations between AOD-Precipitation and AOD-Temperature for the entire region for all months between 2000 and 2015. Each marker represents a single month.

C

March 2012 500 and 250 Geopotential Level

March 2014 500 and 250 Geopotential Level

D

March 2012 Mean Sea Level Pressure

March 2014 Mean Sea Level Pressure

E

March 2012 850 Geopotential Level Anomaly

March 2014 850 Geopotential Level Anomaly

F

March 2012 850 Geopotential Level

March 2014 850 Geopotential Level

G **H** **Fig. 8.**

a. Monthly mean AOD in study region for March 2012 (left) and March 2014 (right). **b.** Composite anomaly chart at 250 and 500 hPa. Colors denote wind speed anomaly (m s^{-1}) and violet solid lines represent geopotential contour anomalies at 500 hPa. Vectors signify velocity magnitude of wind anomaly (m s^{-1}) and direction. **c.** Composite mean chart at 250 and 500 hPa. Colors denote wind speed (m s^{-1}) and violet solid lines represent geopotential contours at 500 hPa. Vectors signify the velocity magnitude of wind (m s^{-1}) and direction. **d.** Composite sea level pressure chart. Colors denote wind speed (m s^{-1}) at 10 meter. Red

dotted lines represent air temperature (centigrade). Solid lines represent geopotential contours at mean sea level pressure, while vectors show the velocity magnitude of wind (m s^{-1}) and its direction. **e.** Composite anomaly chart at 850 hPa. Colors denote wind speed anomaly (m s^{-1}). Dotted lines represent air temperature anomaly at 850 hPa (centigrade). Violet solid lines represent geopotential contour anomalies at 805 hPa, while vectors show the velocity magnitude of wind anomaly (m s^{-1}) and its direction. **f.** Composite chart at 850 hPa. Colors denote wind speed (m s^{-1}). Dotted lines represent air temperature at 850 hPa (centigrade). Violet solid lines represent geopotential contours at 850 hPa, while vectors show the velocity magnitude of wind (m s^{-1}) and its direction. **g.** Composite chart of the mean and anomaly of omega (Pascal/sec) at 850 hPa. Colors denote omega anomaly, dotted lines represent monthly mean of omega, and black solid lines represent geopotential contours at 850 hPa. **h.** Composite chart of the mean and anomaly of relative humidity (%) at 850 hPa. Colors denote relative humidity anomaly, dotted lines represent monthly mean of relative humidity, and black solid lines represent geopotential contours at 850 hPa. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Multivariate regression results comparing AOD versus temperature and precipitation. p value and Pearson's correlation coefficient are reported.

Table 1

	p value		Coefficient (β)		R ²	
	Temperature	Precipitation	Temperature	Precipitation	Overall Model	Overall Model
Iraq-Syria	0.00	0.66	0.57	-0.03	0.35	
Saudi Arabia	0.00	0.00	0.80	0.21	0.51	