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Spatio-Temporal Distribution of Various Types of Dust Events in the Middle East during the Period 1996-2015

Fattahi Masrour, P.[1] and Rezazadeh, M.[2*]

1. Ph.D. Student, Department of Marine and Atmospheric Science (Non-Biologic), Faculty of Marine Science and Technology, University of Hormozgan, Bandarabbas, Iran
2. Assistant Professor, Department of Marine and Atmospheric Science (Non-Biologic), Faculty of Marine Science and Technology, University of Hormozgan, Bandarabbas, Iran

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Abstract
In recent years, an increase in the frequency of dust storms in the Middle East has been experienced. Identifying the potential sources of dust is essential to manage the hazardous consequences of dust storms. In addition, the relation between dust events and meteorological factors such as wind speed and horizontal visibility in the Middle East is lacking. The relation between dust events and topographical features such as soil texture in the Middle East is also unclear. In this study, dust events in the Middle East were classified based on horizontal visibility and the present weather reports during the period 1996-2015. Frequencies of different types of dust events, including blowing dust, dust in suspension, dust storm and severe dust storm, were estimated. The average concentrations of dust particles in the Middle East were also estimated based on horizontal visibility. Wind speed makes a critical contribution to dust events in the Middle East, thus wind speeds were also analyzed over the regions with relatively high frequency of dust events. In addition, maps of soil texture, elevation of landforms and the vegetation cover percentage, which have been obtained by the Weather Research and Forecasting (WRF) preprocessing system (WPS), were evaluated. The highest frequency of dust events is observed in five domains, which include Sudan, Saudi Arabia, Iraq, the United Arab Emirates (UAE), Afghanistan, Pakistan and Iran. Dust in suspension has the highest frequency among all types of the dust events studied here, particularly in southeastern Iran and central and eastern Iraq. Seasonal variations in dust event activity are directly related to wind speed, such that the frequency of dust events is the highest in June and July when winds are strongest, and lowest in January when winds are weakest. Maximum dust concentrations are observed in Saudi Arabia, Yemen and Iraq. The maximal frequency of dust storms in the Middle East occurs in May, June and July. Due to the differences in soil texture, elevation and vegetation cover, the dust emission in the Middle East is characterized by significant spatial heterogeneity. Our numerical analysis shows that sources of dust in the Middle East are mostly topographical lows with heights below 400 m, including sources in Sudan, northeastern and eastern Saudi Arabia, Iraq and Pakistan. Nevertheless, in the southwestern Arabian Peninsula, the height of sources of dust reaches to approximately 1200-2400 m. The upper surface texture of soil in region A (northeastern Sudan) is loam and sandy loam, in region B (Yemen and the southwestern Arabian Peninsula) is loamy sand and loam, in region C (northeastern Saudi Arabia, eastern Iraq and western Iran) is clay loam and loam, in region D (the UAE) is sand, sandy loam and loam, and in region E (Afghanistan, Pakistan and southeastern Iran) is loam clay and loam. The upper surface texture of soil in areas with the highest dust frequency is sandy loam and clay loam. The spatial distributions of the vegetation cover percentage show a sharp decline (below 1%) in Sudan, Saudi Arabia, Iraq, Central and Southern Iran and Pakistan.

Keywords: Dust events, Dust distribution, Dust frequency, Dust concentration, Middle East.

1. Introduction
Dust storms play an important role in the Earth system (Goudie and Middleton, 2006; Ravi et al., 2011; Shao et al., 2011). Dust storms are both natural and anthropogenic events, influencing meteorological and climatic conditions on local to global scales (Prospero and Lamb, 2003; Rodriguez et al., 2015; Solmon et al., 2015), radiation and energy budget (Antón et al., 2011; Prakash et al., 2015; Kumar et al., 2015; Valenzuela et al., 2015), ocean bio-geochemistry (Jickells et al., 2005; Jickells and Moore, 2015), ecosystems (Lin, 2002), human health (Pope, 2003; Martiny and Chiapello, 2013; García-Pando et al., 2014). Thus, they have diverse socio-economic impacts (Kurosaki and

*Corresponding author: rezazadeh@hormozgan.ac.ir

Mikami, 2003; Sharifikia, 2013). Inhalation of small dust particles in dry weather may create favorable conditions for bacterial infections (Dukic et al., 2012). The first step towards controlling the harmful effects of dust storms is accurate detection of sources of dust. The Middle East Dust Index (MEDI) was introduced by Ackerman (1997), in which sources of dust can be detected based on the analysis of thermal emissive bands with wavelength ranges of 8.40–8.70 μm, 10.78–11.28 μm and 11.77–12.27 μm at the spatial resolution of 1000 m. In this approach, airborne dust and desert surfaces are differentiated. Based on the MEDI, a significant relationship is reported between deserts and dust sources during the period 2001-2012 (Moridnejad et al., 2015). The largest deserts of the Middle East, such as those in Saudi Arabia, Iraq, and Syria, are primary sources of dust, over which an increase in the frequency and intensity of dust storms has been reported in recent years (Alam et al., 2014; Boloorani et al., 2014; Shalaby et al., 2015; Gharibzadeh et al., 2017).

Many studies have investigated the frequency and distribution of dust storms in the Middle East. Kutiel and Furman (2003) analyzed relevant data during the period 1973-1993 and identified the Middle East as one of the most affected areas by dust. The Arabian Peninsula is considered as one of the most important sources of dust in the Middle East (Barkan et al., 2004). It is also recognized as one of the five regions in the world where the occurrence of severe dust storms and the transport of dust particles significantly contribute to degradation of the air quality of other regions around the world (Idso, 1976; Goudie and Middleton, 2001). Ozdemir et al. (2018) investigated meteorological conditions that contribute to dust storms in the Arabian Peninsula. They detected dust storms in Bahrain, Kuwait, Saudi Arabia and the United Arab Emirates (UAE). Prospero et al. (2002) showed that the Rub' al Khali desert and the drylands around the Tigris-Euphrates river and the coasts of Oman are the primary sources of dust in the Middle East. The source region of the dust observed at Dubai Airport in UAE is the eastern regions of the Rub’al Khali Desert located between Saudi Arabia, Oman, and UAE. The observed dust at Dubai Airport in the UAE originates from the eastern regions of the Rub’al Khali Desert located between Saudi Arabia, Oman, and the UAE. Yassin et al. (2018) studied dust storms over Kuwait using the HYSPLIT model with MODIS satellite observations during the four seasons; winter, spring, summer and fall. He noted significant reduction of visibility by dust storm. Other regions that are highly influenced by dust storms are Iraq and Iran (Middleton, 1986) due to the significant dust emission from the Tigris-Euphrates Basin (Hamidi et al., 2013). Each year, particularly in spring and summer, huge amounts of desert dust originate from semi-arid and arid regions of Southwest and Central Asia and are transported towards the Arabian Sea, Tibetan Plateau and eastern China Sea (Irino and Tada, 2000; Orlovsky et al., 2013; Rashki et al., 2015; Ge et al., 2016; Guan et al., 2015; Moridnejad et al., 2015; Xi and Sokolik, 2016).

Based on the analysis of horizontal visibility data of synoptic stations, Rezazadeh et al. (2013) identified the regions in the Middle East and Iran that are mostly affected by dust events. Their results indicated that Khuzestan Province in southwestern Iran and the Sistan Basin in southeastern Iran on the border with Afghanistan are the most affected regions by dust. Some dust events in the UAE may originate from Iran and Central Asia (de Villiers and van Heerden, 2011).

Rashki et al. (2017) studied dust activity in Jazmourian, southwestern Iran during the period 1990-2013 using observations of five local weather stations. They found that the maximal frequency of dust storms occurs in June and July, while the least frequency of dust storms is in autumn and winter. They found that severe dust storms in Jazmourian usually occur in March-April-May. Dust storms originated from Jazmourian affect most of the coastal areas in the northern Arabian Sea (Makran Mountains), Oman Sea, northeastern parts of the Arabian Peninsula and West Pakistan. On the other hand, air masses from the arid and desert regions of the central and eastern parts of Iran and Saudi Arabia increase the dust load in Jazmourian (Rashki et al., 2017).

Several studies have also been conducted to understand the relationship between dust storms and meteorological conditions. Fengmei and Chongyi (2010) analyzed the correlation between the frequency of dust storms on the one hand and temperature, humidity, and wind speed of four neighboring stations in China from 1988 to 1998 on the other hand. They concluded that dust storms had a strong correlation with monthly averaged wind speed.

Tan et al. (2012) analyzed daily observations from 43 meteorological stations in the Inner Mongolia Autonomous Region, China, during the period 2000-2007. They concluded that interannual and seasonal variations of dust storms were firmly related to weather conditions, especially wind speed.

Since the Middle East has been recognized as an important source of dust in recent years, accurate analysis of dust events in terms of their spatio-temporal distribution is essential. In this study, the spatio-temporal distribution of various types of dust events in the Middle East is studied using ground-based observations for a 20-year period from 1996 to 2015. To this end, the observed data at 253 meteorological stations in the Middle East are analyzed. In particular, spatial distribution, frequency and seasonal variation of different types of dust events in the Middle East are discussed. To our knowledge, sources of dust over the Middle East based on a relatively long period of 20 years have not been identified yet. In addition, the relation between dust events and meteorological factors such as wind speed and horizontal visibility in the Middle East is lacking. The relation between dust events and topographical features such as soil texture in the Middle East is also unclear. Thus, this study can fill these gaps in the Middle East.

2. Materials and Methods

2-1. The study region

The study region is the Middle East (10°- 45° N, 25°- 65° E).

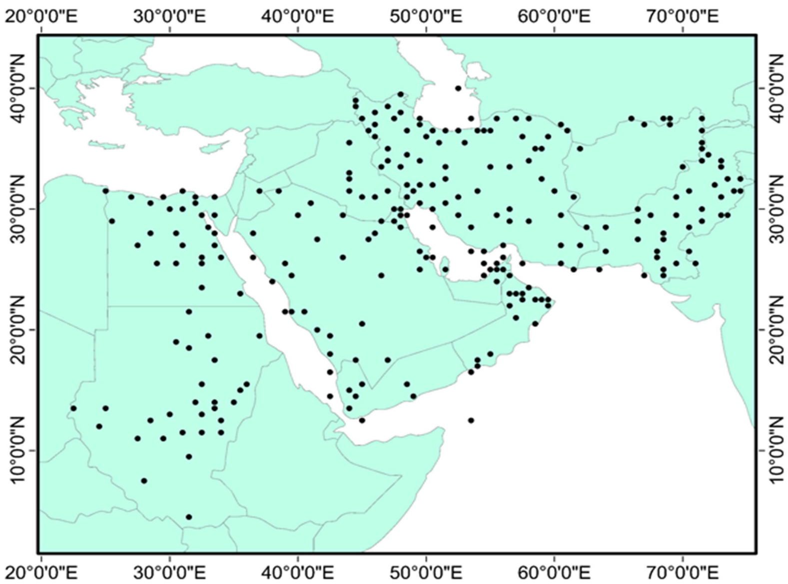


Figure 1. Locations of the ground-based weather stations whose data are used in this study

Table 1. The number of countries and stations

countries	Sudan	Egypt	Saudi Arabia	Kuwait	Iraq	United Arab Emirates	Yemen	Oman	Qatar	Iran	Afghanistan	Pakistan
number of stations	26	27	31	5	7	8	8	17	1	77	11	35

Most parts of the Middle East are covered by large deserts, high mountains and dry plateaus. Important deserts in the Middle East include the Sahara in North Africa, the Arabian Desert in West Asia, Syrian Desert, Thar Desert in South Asia (in India and Pakistan), Dasht-e Margo and Registan Desert in Afghanistan and Dasht-e Kavir and Dasht-e Lut in Iran. Climatologically, most parts of the Middle East are characterized by hot desert climate, among which Saudi Arabia is the warmest and driest region in the world (Shao, 2008). Nevertheless, orographic regions in northern Iraq, northwestern Iran and eastern Turkey have mostly experience either semi-dry cold or the Mediterranean warm climate (Figure 1).

2-2. Spati-temporal distribution of dust events

Dust events are classified based on the combination of the horizontal visibility and the present weather codes reported in synoptic weather stations. Based on the World Meteorological Organization (WMO) protocol, dust events are classified according to the horizontal visibility into four categories (International Cloud Atlas, Manual on the Observation of Clouds and Other Meteors; World Meteorological Organization: Geneva, Switzerland, 1975; Volume 1, WMO No. 407):

1. Dust in suspension: Widespread dust in suspension in the air that is not raised by the wind, either at or near the station at the time of observation; horizontal is typically no higher than 10 km, SYNOP WW code for this event is 07.
2. Blowing dust: Dust or sand raised by the wind at the time of observation, decreasing horizontal visibility to 1–10 km, SYNOP WW code for this event is 06.
3. Dust storm: Strong winds lift large amounts of dust particles, decreasing horizontal visibility to between 200 and 1000 m, SYNOP WW codes for this event are 09, 30, 31 and 32.
4. Severe dust storm: Extreme winds lift large amounts of dust particles, decreasing horizontal visibility to less than 200 m, SYNOP WW codes for this event are 33, 34 and 35.

The frequency of dust events can be assessed based on the type of events. The four different types of dust events discussed above can be used to identify sources of dust particles. As dust in suspension and blowing dust do not require strong wind speeds, relatively high dust concentrations associated with either of these phenomenon indicates that the affected region is a source of dust (WMO reports). On the other hand, dust storms and severe dust storms can only occur when wind speeds are strong. In areas where these two phenomenon occur, dust particles from remote source regions are transported.

In this section, the observed data from ground-based stations on 3-hour intervals for the period 1996-2015 are obtained. These data are available as a Global Weather Observation Data on Centre for Environmental Data Analysis (CEDA) (https://catalogue.ceda.ac.uk/uuid/0ec59f09b3158829a059fe70b17de951) website for 253 stations in the Middle East. These stations located in Sudan, Egypt, Saudi Arabia, Kuwait, Iraq, the UAE, Yemen, Oman, Qatar, Afghanistan, Pakistan and Iran. Spatial distribution of the stations is shown in Table 1.

The dataset comprises hourly and daily weather measurements, such as wind speed and direction, maximum and minimum air temperature, soil temperature, sunshine duration and the incoming radiation. In addition, daily, hourly and sub-hourly rain measurements, some climatological data and marine observations (including sea surface temperature (SST), swell and wave-associated parameters) are also available. The global weather observation data contain meteorological values observed at 3-hourly intervals by non-UK stations, as reported in SYNOP and METAR codes. There was no data for African stations in 2005 and 2006, so we did not consider these years in our calculations for North Africa. We used the 3-hourly global weather observation data to obtain monthly mean dust frequency and concentration. The 3-hourly data for each month over the 20-year period are averaged. Each value is an average of about 600 values (30 days × 20 years).

Using Fortran programing, dust events are classified based on the horizontal visibility and synoptic codes for the present weather.

Based on the observed data, we filter those horizontal visibility reports that are less than 10 km due to the dust, as previously discussed.

The approach of Shao and Wang (2003) is used to determine the frequencies of all types of dust events, including blowing dust, dust in suspension, dust storm and severe dust storm. In this approach, the following equation is used to estimate the frequency of blowing dust in the Middle East:

$$f_{DIS} = N_{DIS}/N_{obs} \quad (1)$$

where N_{obs} denotes the total number of SYNOP reports and N_{DIS} denotes the number of blowing-dust events reported at each station. The total number of dust events at each station is equal to:

$$f_{DE} = f_{DIS} + f_{BD} + f_{DS} + f_{SDS} \quad (2)$$

where:

f_{DE} = the total frequency of dust events

f_{BD} = the total frequency of blowing-dust events

f_{DIS} = the total frequency of dust in suspension events

f_{DS} = the total frequency of dust storms

f_{SDS} =the total frequency of severe dust storms

We also calculated the percentage of dust storms at each station:

$$f_{DE} = N_{DE(each\,station)}/N_{DE(total)} \quad (3)$$

2-3. Estimation of dust concentration from horizontal visibility

According to Shao and Wang (2003), the horizontal visibility can be used to determine the four types of dust events. Shao and Wang (2003) obtained an empirical relationship to estimate dust concentration Northeast Asia using horizontal visibility. They fitted the degree of horizontal visibility to the concentration level of dust suspended in the atmosphere near the Earth's surface. In the present study, the same approach is used to estimate the concentration of dust at meteorological stations in the Middle East. These values are then analyzed to identify maximum dust concentrations in the Middle East. In addition to different types of dust phenomenon as the present weather, horizontal visibility is available in Global Weather Observation Data on Centre for Environmental Data Analysis (CEDA) (https://catalogue.ceda.ac.uk/). For the four types of dust events, namely blowing dust, dust in suspension, dust storm and severe dust storm, which are defined based on the horizontal visibility, the distribution of the dust concentration for each month in the study region is obtained. Shao and Wang (2003) obtained the dust concentration based on the horizontal visibility as the following equations:

$$C_V = 3802.29\, D_V^{-0.84} \qquad D_V < 3.5$$
$$C_V = \exp(-0.11 D_V + 7.62) \quad D_V \geq 3.5 \quad (4)$$

where C_V and D_V represent dust concentration in μg m^{-3} and horizontal visibility in km, respectively. Here, Equations (3) and (4) are used to estimate the dust concentration at stations where dust events were reported.

The above relationship indicates that the dust concentration rapidly increases with decreasing horizontal visibility.

Spatial analysis can be conducted based on various techniques, including statistics and using the geographical information systems (GIS). A GIS facilitates the attribute interaction with geographical data in order to enhance the accuracy of interpretation and prediction of spatial analysis (Gupta, 2005).

Geostatistical interpolation consists of ordinary Kriging interpolation, simple Kriging interpolation, universal Kriging interpolation, indicator Kriging, probability Kriging, disjunctive Kriging and topo to raster (Hengl et al., 2007; Setianto and Triandini, 2013). With interpolation, we predict unknown values at other locations. Kriging is a geostatistical interpolation technique that considers both the distance and the degree of variation between known data points when estimating values in unknown areas (Paramasivam and Venkatramanan, 2019).

This study is carried out using GIS and simple Kriging methods to reveal the spatial variation of the dust concentrations using the observed data at 253 stations in the Middle East.

2-4. Characteristic of wind

Analyzing winds is important to determine synoptic conditions of dust events in the Middle East. Five regions in the Middle East with the maximum frequency of dust events are diagnosed the period 1996-2015, which over the stations of each, wind speed and direction are analyzed during dust events (Figure 7).

Table 2 shows the geographic characteristics of selected stations in the Middle East and the frequency of dust events in these stations during the study period. Due to the statistical flaw at all stations in the region C (Iraq) and a high frequency of dust events in this region, limited data for the period 2013-2015 is used for this region.

3. Results and Discussion

3-1. Spatio-temporal distribution of dust events

Figure 2 shows the distribution of the frequency of dust events in the Middle East for the period 1996-2015.

According to the map guidance in the left side, the frequency of dust events from the lowest to highest values are shown by yellow to red circles.

- Region A (Sudan): Sudan's North and North East, where dust particles are derived from the Sahara Desert in Africa. It is an area where the most frequent of all types of dust events occurred. The highest frequency of dust events (22.3%) in this region is observed at Abu Hamed Station (33 °N,19.5 °E) in northern Sudan.

-Region B (Saudi Arabia and Yemen): South West Saudi Arabia and West Yemen are other areas with the highest frequency of dust events. The highest frequency of dust events (17.8%) in this region is reported at Wadi Al Dawasir Station (45 °N, 20.5 °E) in Rub' Al Khali desert.

-Region C (Saudi Arabia, Iraq and Kuwait): In this area, a belt of dust events with the highest frequency is stretching from central Iraq to western Iran. Also, Kuwait and central and northeastern Saudi Arabia experienced high frequency of dust events. The highest frequency of dusty events (27.5%) in the region is reported at the Al-Amarah Station (31.5°N, 47°E) in southeastern Iraq.

-Region D (the UAE and Iran): This area is located in south of Iran and the northeastern UAE and the Rub' Al Khali desert. The highest frequency of dust events in the area is observed at Abu Dhabi Station (25°N, 55°E).

-Region E (Iran, Afghanistan and Pakistan): Southwest Afghanistan, northwestern Pakistan and southeastern Iran are also identified as regions with high frequency of dust events. The highest frequency of dust events (23.9%) in this region is observed at Nok Kennedy Station (28.5°N,62.5°E) in northwestern Pakistan.

3-2. Spatial and temporal distribution of different types of dust events

Figure 3 shows the distribution of the annual mean frequency of different types of dust events for (a) dust in suspension, (b) blowing dust, (c) dust storm and (d) severe dust storm using a 3-hour observation data from meteorological stations in the Middle East for the period 1996–2015.

The most frequent occurrence of dust events in southeastern Iran and central and eastern Iraq is dust in suspension (Figure 3a).

The highest frequency of blowing dust is observed in southern Iran, northern Sistān and Balūchestān, the UAE and northern Sudan (Figure 3b).

Dust storms with lower frequency have occurred in northern Sistān and Balūchestān (eastern Iran) and southwestern Pakistan (Figure 3c).

Dust events in southeastern Iraq and western Iran are mainly severe, but their frequency is lower than 1% (Figure 3d).

3-3. Annual cycle of dust events

Figure 4 shows the frequency of dust events on the monthly basis for the period 1996-2015.

Most of the stations in the Middle East experienced the highest frequency of dust events in April, May, June and July, particularly in stations located in regions B (southwestern Saudi Arabia), C (Iraq) and E (eastern Iran).

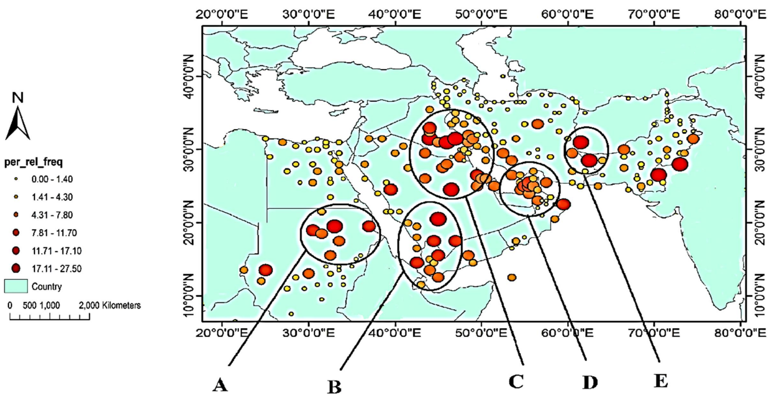


Figure 2. Distribution of the frequency of dust events in the Middle East based on analysis of three-hourly surface observation data (http://ceda.ac.uk) from meteorological stations for the period 1996-2015.

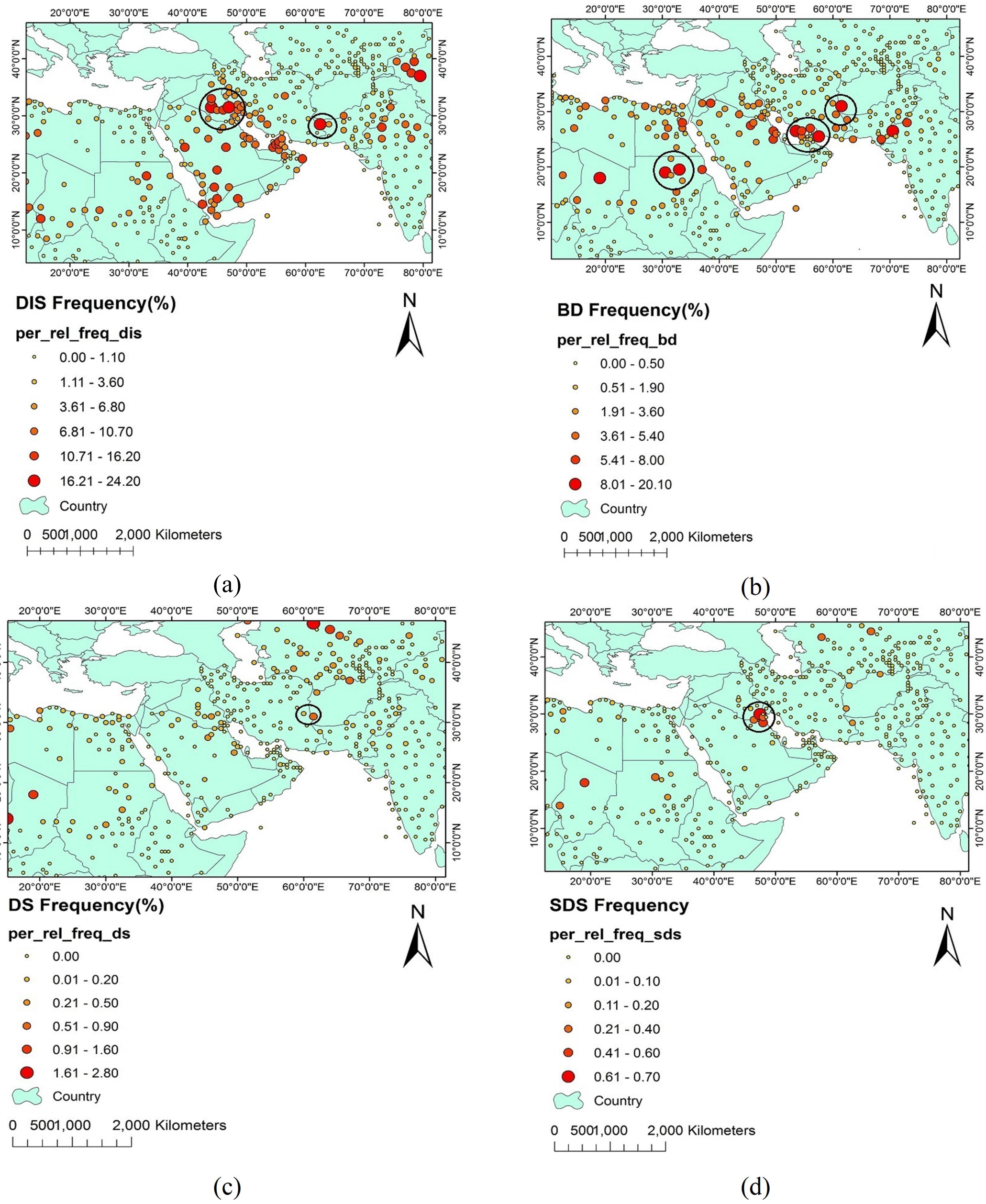


Figure 3. Distribution of the frequency of (a) dust-in-suspension (b) blowing dust (c) dust storm and (d) severe dust storm obtained based on three-hour observational data from meteorological stations in the Middle East for the period 1996-2015.

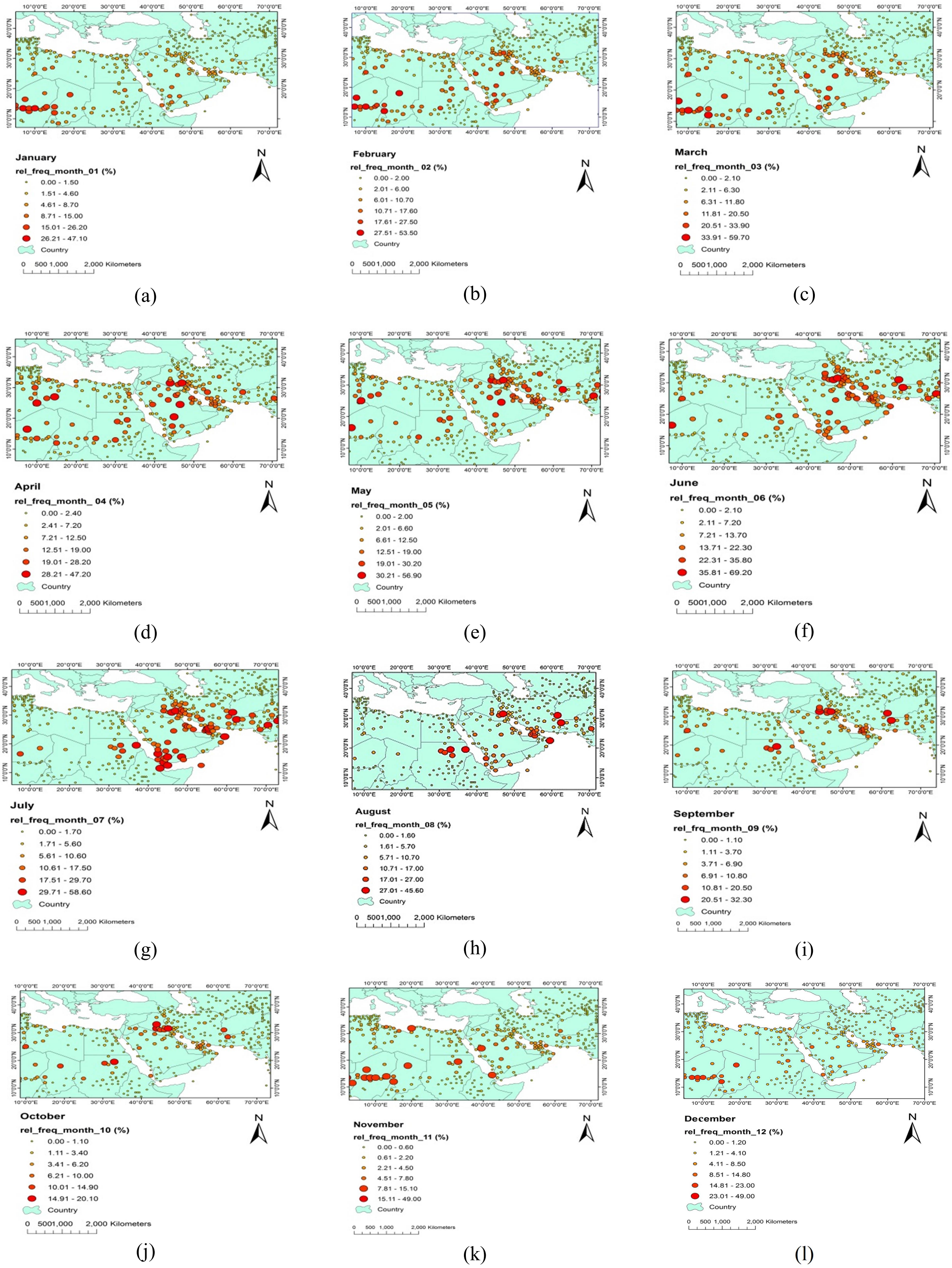


Figure 4. Frequency of dust events in (a) January, (b) February, (C) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November and (l) December using three-hour observational data from meteorological stations in the Middle East for the period 1996-2015.

Our analysis indicates that the highest frequency of dust events is observed in the center of the Middle East (Iraq and Afghanistan) in spring (Figure 4c-e), and in Iraq and eastern regions of the Middle East (Afghanistan and Pakistan) in summer (Figure 4f-h). Nevertheless, the frequency of dust events is reduced in these regions in September (Figure 4i). The maximum frequency of dust events in autumn is much less than that in spring and summer, particularly in Iraq and western regions of the Middle East (northeastern Sudan). The lowest frequency of dust events is occurred in winter (Figure 4a, b, f), although the frequency is increased in December (Figure 4l).

According to the observations, dust events occurred from western regions of the Middle East and Sudan in March (Figure 4c) to northeastern Saudi Arabia and western Iran. The highest frequency of dust events in the Middle East is in May (Figure 4e), June (Figure 4f) and July (Figure 4g), while the frequency is gradually decreased from August to January next year (Figure 4h-l and 4a), with the lowest frequency (1%) in November (Figure 4k), December (Figure 4l) and January (Figure 4a). The frequency of dust events starts to gradually increase in February (Figure 4b).

Wind speed is one of the main factors affecting the frequency and intensity of dust storms, although other factors such as the topography, soil moisture, and land cover also play significant roles. In order to obtain long-term behavior of dust storms in the Middle East, the relationship between seasonal variations of dust events and wind speed is examined.

Figure 5 shows monthly mean wind speed and the frequency of dust events averaged for the period 1996-2015. In most regions of the Middle East, dust events are most frequent in summer. Indeed, dust activity is increased in May, June and July, reaching to the peak in June and July, but starts to decrease from November.

The strongest steady wind speeds are recorded in summer (particularly in June and July), while the weakest wind speeds are recorded in winter (particularly in January). This suggests that seasonal variation of dust activity is consistent with that of wind speed.

3-4. Estimation of dust concentration based on the horizontal visibility

Wang et al. (2008) investigated changes in PM10 concentrations during dust storm events and found a strong correlation (r^2 = 0.90) between PM10 and visibility. Dust events were observed over different areas in Turkey, which decreased the visibility to less than 1 km (Ozdemir, 2019). Leys et al. (2011) classified dust events based on values of PM10 concentration and visibility, which include severe dust storm (PM10 ≤ 20.055 μg/m^3, 0 < visibility ≤ 0.2 km; moderate dust storm: PM10≤ 3.252 μg/m^3, 0.2 km < visibility ≤ 1 km; severe haze: PM10≤ 527 μg/m^3, 1 km < visibility ≤ 5 km; moderate haze: PM10≤ 240 μg/m^3, 5 km < visibility ≤ 10 km. Hence, PM10 concentration has direct relationship with visibility (Draxler et al., 2001; Escudero et al., 2006), and mineral dust is the main contributing factors to the increase of PM10 concentration. We used Equations (3) and (4) to estimate dust concentrations over the study region. For the all four types of dust events, the distribution of dust concentration in different months is obtained. As shown in Figure 6, eastern Saudi Arabia (67 μg/m^3), and Pakistan experience the highest dust concentration in November (Figure 6k). East and northeastern Saudi Arabia and southeastern Saudi Arabia and southern Iran experience the highest dust concentration in December (Figure 6l).

East and northeastern Saudi Arabia (49 μg/m^3), central regions of Iran (24 μg/m^3) and Pakistan (31 μg/m^3) experience the maximum dust concentration in January (Figure 6a). In February, the highest dust concentration (70 μg/m^3) is observed in eastern and northeastern Saudi Arabia, northern and southwestern Iraq and in Turkmenistan (Figure 6b).

Regions B (Saudi Arabia and Yemen) and C (Saudi Arabia and Iraq) experience higher dust concentrations (Figure 6a-l). Dust concentrations in regions A, D and E are less than those in the other two regions. Region C experiences the highest dust concentration, with lower concentration in summer (Figure 6f, Figure 6g and Figure 6h), as shown in Figures 3 and 4. The maximum dust concentration in region C is observed since late autumn to late winter (November to

February), while dust concentration is reduced in March (Figure 6c) and April (Figure 6d). According to Natalie et al. (2013), the suspension of dust particles in downwind regions largely depends on their sizes, so that larger particles can stay longer in the atmosphere due to their greater fragility. Thus, the higher dust concentration in region C in winter might be attributed to larger dust particles.

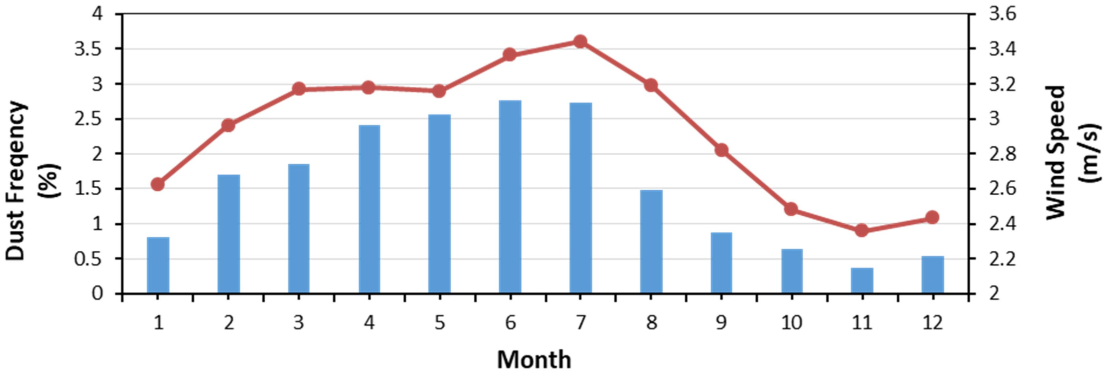
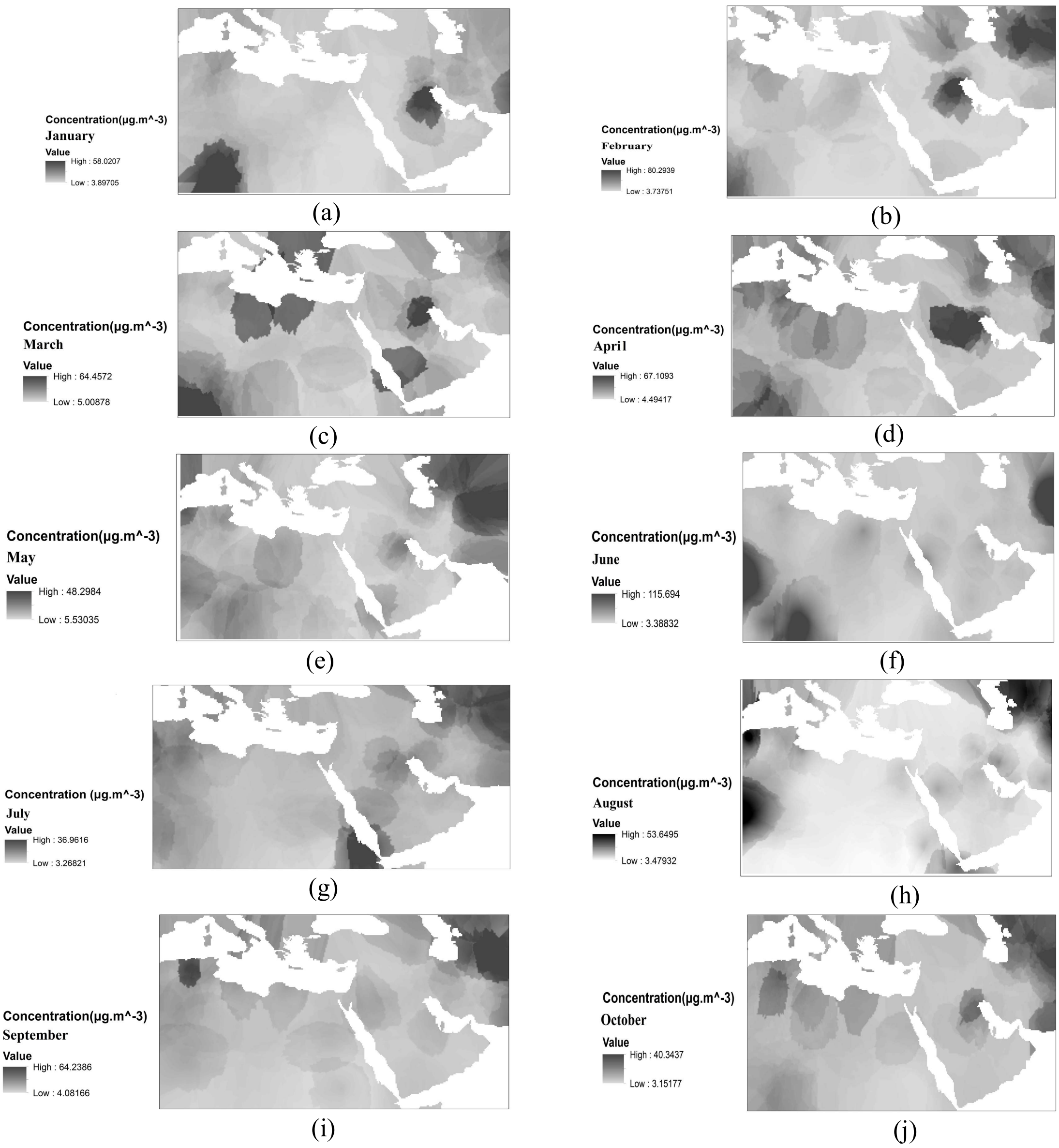
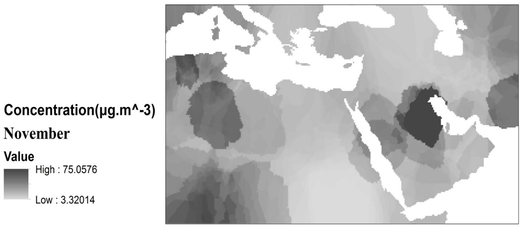
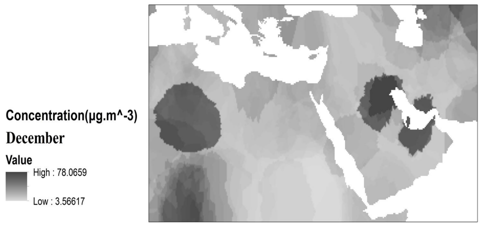


Figure 5. Monthly means of the frequency of all types of dust events (column) and wind speed (curve) in the Middle East for the period of 1996-2016.





(k)



(l)

Figure 6. Monthly mean dust concentration in the Middle East estimated based on observational data. Monthly mean values are obtained by averaging during the period 1996-2015.

Table 2. Geographical features and the frequency of dust events (percentage) in those stations in the Middle East that experienced higher frequency of dust events, based on which wind profile is determined.

Station name	latitude	longitude	Height (m)	Dust events frequency (%)
Wadi-Al-Dawaser	20.3	45.12	622	17.8
Nuok-Kundi	28.49	62.45	683	23.9
Abu-Dhabi-Intl	24.26	54.39	27	15.9
Abu-Hamed	19.32	33.19	312	22.3
Amarah	31.51	47.1	9	27.5

3-5. Relationship between wind speed and dust events

It is unlikely that dust storms occur when wind speeds are less than 4 m s^{-1}. Nonetheless, most dust events (dust in suspension) have been derived from regional sources (Shao, 2003).

All atmospheric dust-emission phenomena are accompanied with steady wind speeds exceeding the threshold winds required for dust emission.

3-5-1. Northeastern Sudan (Abu Hamed)

The highest frequency of dust in this region is occurred from August to November. At Abu Hamed station in Sudan, winds are generally stronger in June. In this region, dust events are generally associated with wind speeds higher than 4 m s^{-1} (Figure 7). As blowing dust is more frequent in this region (Figure 3), dust emission from local sources of dust mainly contribute to dust events in June. In May and July, wind speeds are often less than 4 m s^{-1} (Figure 7).

3-5-2. Southwestern Saudi Arabia (Wadi Al Dawasir)

In Wadi Al Dawasir, the dust in suspension is more frequent compared to other three classes of dust events (Figure 3). The maximum frequency of dust events in this region is observed in April (Figure 4).

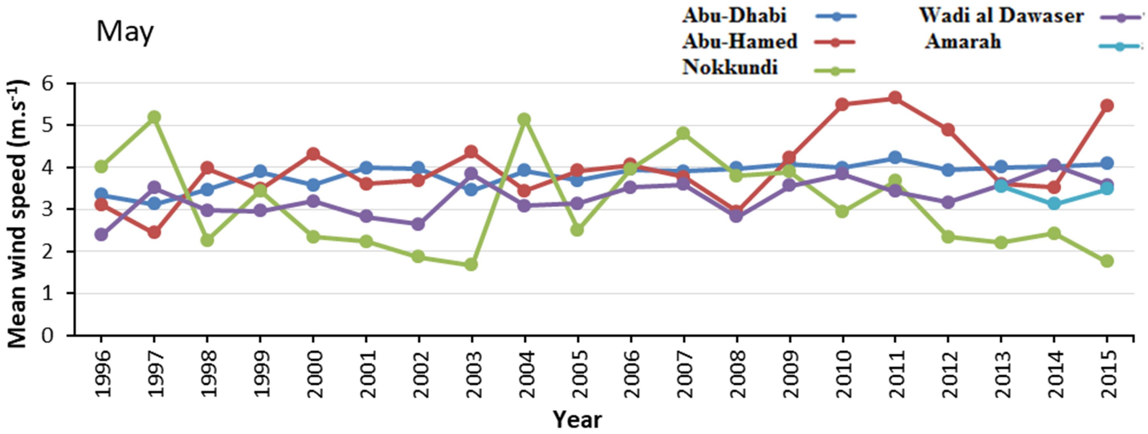
We have analyzed the observed data for those stations in southwestern Saudi Arabia (i.e., Wadi Al Dawasir) with the highest frequency of dust. Our results indicate that wind speeds are generally less than 4 m s^{-1} in this region in May and June (Figure 7), during which dust events are mainly originated from regional sources. In July, wind speeds are mainly greater than 4 m s^{-1} (Figure 7); therefore, dust is mainly emitted from local sources.

3-5-3. Eastern Iraq (Al-Amarah)

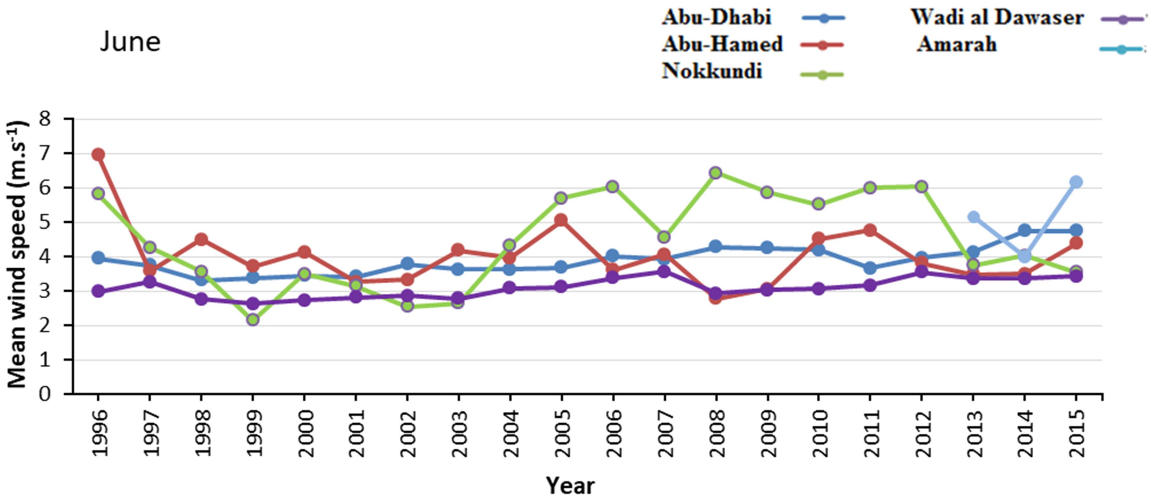
Among the four classes of dust events, dust in suspension is the most frequent event in Al-Amarah (Figure 3), over which the maximum frequency of dust events is observed in May, June and July (Figure 4). When dust events occur in Iraq in May and July, in this region winds are generally weak (less than 4 m s^{-1}) (Figure 7).

3-5-4. United Arab Emirates (Abu Dhabi)

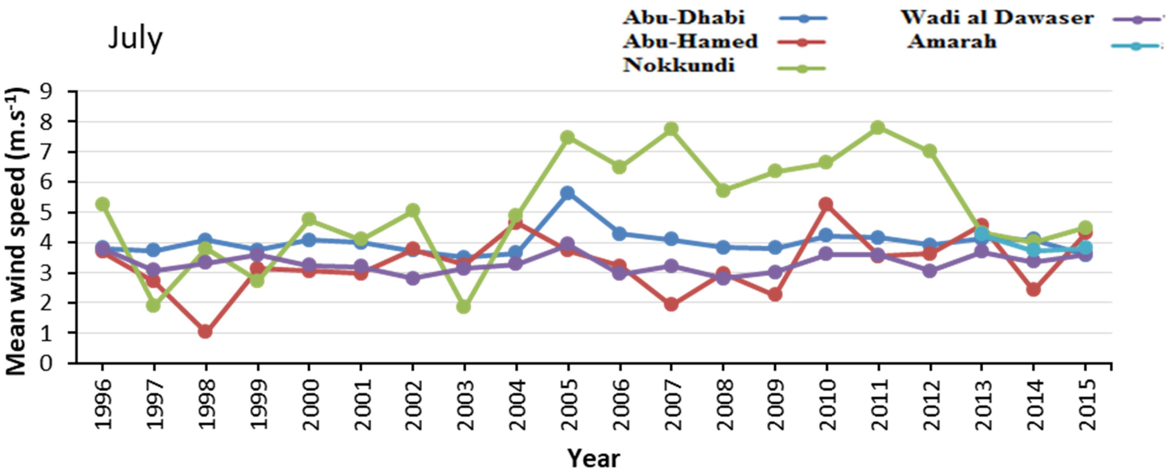
The highest frequency of dust events in Abu Dhabi was attributed to dust in suspension (Figure 3). The maximum occurrence of dust events was observed in May, June, and July (Figure 4). In the United Arab Emirates, the occurrence probability of wind speeds during dust events in May (Figure 7a) and June (Figure 7b) was less than four ms^{-1}. The occurrence probability of wind speeds was more significant than four ms^{-1} in July (Figure 7).



(a)



(b)



(c)

Figure 7. Mean wind speeds of the stations designated in (a) May, (b) June and (c) July of the statistical period 1996-2015.

3-5-5. Pakistani (Nok Kennedy)

The highest frequency of dust events in this region is related to blowing dust (Figure 3). The maximum frequency of dust events is observed between May and August (Figure 4). In Pakistan, wind speeds are often less than 4 m s^{-1} in May and June (Figure 7); therefore, dust is mainly emitted from regional sources. In July, wind speeds are often higher than 4 m s^{-1} in this region (Figure 7); hence dust is mainly emitted from local sources.

3-6. Elevation of landforms, soil type and vegetation fraction

In order to obtain topographic characteristics of the surface and determine their effects on the global distribution of dust sources, elevation of landforms, soil texture and the fraction of vegetation cover are obtained and used for running geogrid.exe in the Weather Research and Forecasting (WRF) preprocessing system (WPS).

Analysis of the elevation of landforms (Figure 8a) shows that topographic depressions are located in northeastern Sudan, deserts of Rub' Al Khali, an-Nafud and ad-Dahna, while deserts in eastern Iraq are higher than other regions, with a height of less than 600 m. Therefore, the frequency of dust events in these regions are higher. Vegetation cover is one of the most important factors affecting soil erosion, such that the soil erosion decreases with an increase of vegetation cover (Elwell and Stocking, 1976).

As shown in Figure 8b, there is a correlation between the percentage of the vegetation cover and the frequency of dust events. In Sudan, Saudi Arabia, Iraq, central and southern Iran, where the highest frequency of dust events is observed, the percentage of vegetation cover is low (less than 1%). Our results are consistent with results of Prospero et al. (2002) who indicated that the soil erosion rapidly occurs over bare surfaces with small particle sizes.

As shown in Figure 9a, southern parts of Rub' Al Khali desert, the UAE and the Kara-Kum desert in Turkmenistan are covered with sand. According to International Soil Science Society of soil classification, soils covered with sand fall into two categories (World reference base for soil resources; FAO, 2015): (1) particles with diameters ranging from 0.02 to 0.07 mm, which can be remained in suspension in the air for just a few hours, are hardly transported to several hundred miles, unless under favorable atmospheric conditions. Thus, these particles are subject to a short-term suspension; (2) particles with diameters ranging from 0.5 to 0.07 mm, are called saltation. Saltation is the skipping and bouncing movement of sand grains along the surface during erosion. This process leads to transport of a large amount of soil particles to the downwind regions; thus, sand dunes can be formed. The relatively low dust concentrations in these regions might be attributed to this feature of soil particles.

Northern Sudan, northeastern and central Saudi Arabia are characterized by sandy loam soil (Figure 9c). Northeastern and central Saudi Arabia also experience relatively high dust concentrations. Relatively high frequency of dust events in these regions are mostly due to the blowing dust and the dust in suspension. Therefore, relatively high dust concentrations in these regions might be due to the existence of larger clay particles in different types of sandy loam soils. Northern and southeastern Saudi Arabia, eastern and southeastern Iraq and southwestern Iran are characterized by sandy loam soil (Figure 9b, e). Therefore, regions that are characterized by larger clay particles are associated with higher dust concentrations compared to those regions that are characterized by smaller clay particles.

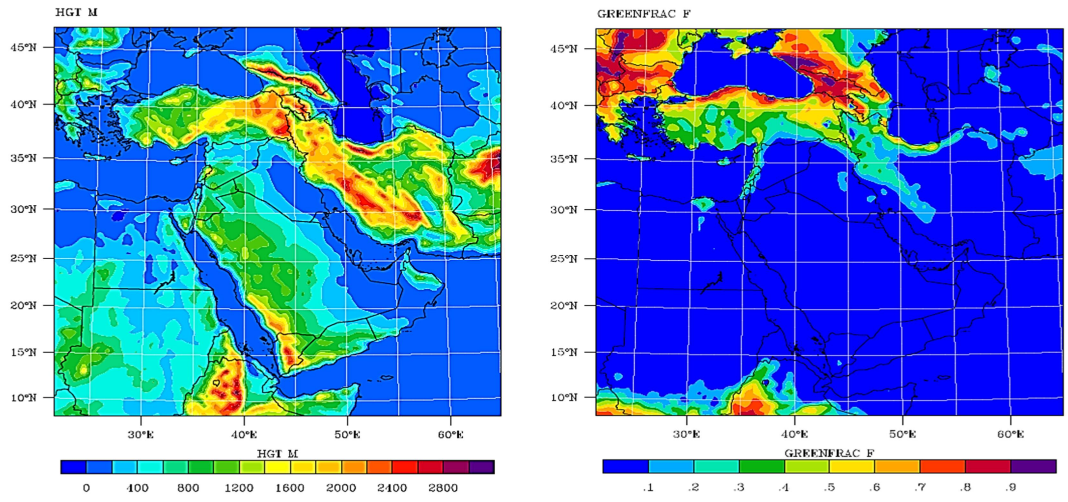


Figure 8. (a) Elevation of landforms (m) and (b) vegetation fraction in the Middle East.

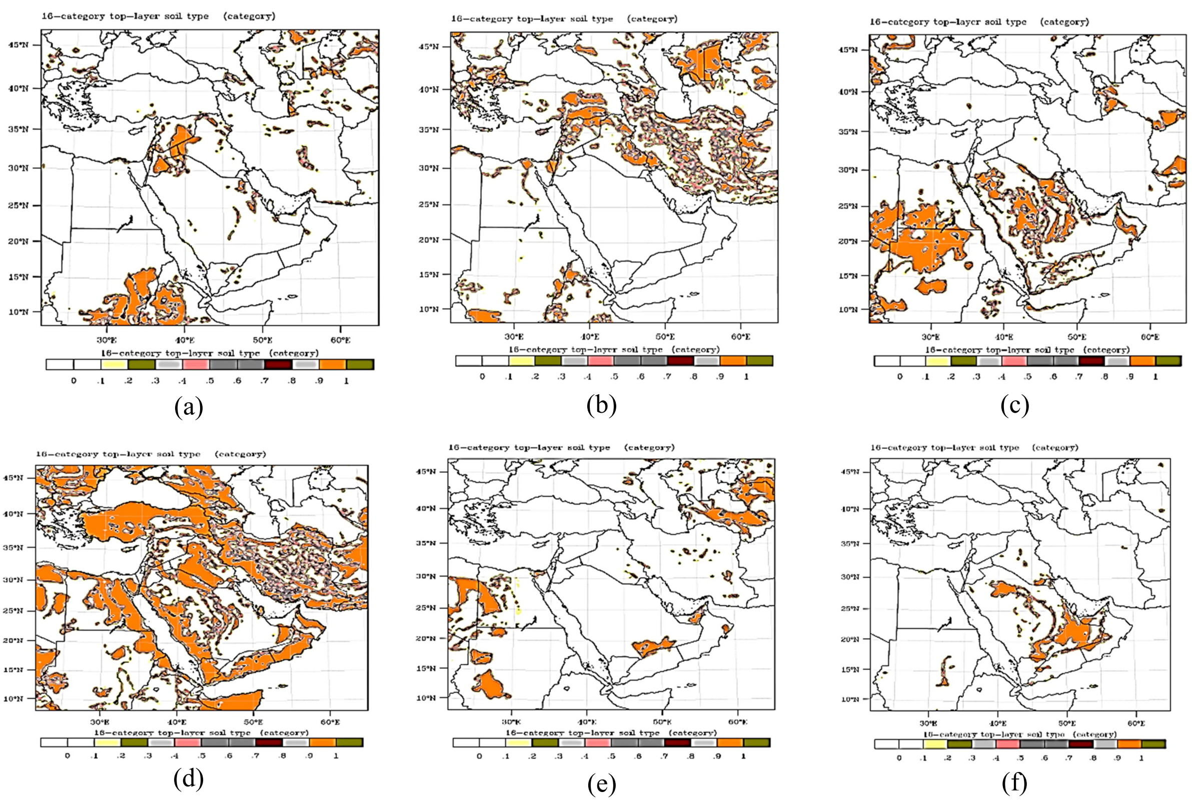


Figure 9. Percentages of different soil types in the Middle East: (a) sand, (b) loamy sand, (c) sandy loam, (d) loam, (e) clay loam and (f) Clay in the Middle East.

4. Conclusions

According to this study, the dust belt starts from northern Sudan in North Africa, extending to the Middle East, central and southern Asia and reaches western Pakistan and Afghanistan (eastern Iran).

Rezazadeh et al. (2013) demonstrated that four regions in the Middle East experience the highest dust activity during the period 1998-2003. In this study, we identified five regions as the main sources of dust by analyzing the frequency of dust events in the Middle East during the period 1996-2015. In addition to the four regions identified by Rezazadeh et al. (2013), the UAE is also diagnosed as a main source of dust in the Middle East.

Analysis of the annual cycle of dust events in this study showed a significant difference between the frequency of dust events in winter and summer.

Monthly mean frequency of dust events in the Middle East shows substantial seasonal variability. Dust events in the Middle East mostly occur in late spring and during summer, with the highest frequency in June and July. The results are in agreement with those of Prospero et al. (2002) in terms of the dust belt regions in the Northern Hemisphere. In the last month of spring, low values of geopotential height in central Pakistan and high values in the eastern Caspian Sea, the central Arabian Sea and southeastern Saudi Arabia contribute to the development of relatively strong wind speeds of 5-7 m s^{-1} in southeastern Saudi Arabia and wind speeds greater than 7 m s^{-1} in the northern Arabian Sea.

Relatively high dust concentrations are observed in regions B (Saudi Arabia and Yemen) and C (Saudi Arabia and Iraq), but dust concentrations are relatively low in region C in summer. The maximum dust concentrations in region C are observed in late autumn and during winter (November to February), after which dust concentrations are reduced in March and April. The higher dust concentration in region C in winter might be attributed to the formation of dust events with larger soil particles. The results highlight an increase of dust concentrations in winter and spring, but a decrease in autumn.

By the analysis of topographic characteristics of the study region such as soil texture, elevation of landforms and vegetation cover, we have found that sources of dust have the lowest percentage of the vegetation cover and their elevations are generally low. The threshold wind speeds for dust emission in northern Sudan, northeastern and central Saudi Arabia, eastern and southeastern Iraq and southwestern Iran are higher than those in the UAE, and southern and southeastern Saudi Arabia. Regions A and C are characterized by larger soil particles; thus, the threshold friction velocity for dust emission is higher than that in regions B and D.

In this study, spatio-temporal variations of dust events in the Middle East are investigated. The results of this study can be used to better manage sources of the dust and reduce the risk and vulnerability to dust storm hazards in the Middle East. Also, this study provides valuable information in terms of dust events in the dust belt region, which can be used in regional and global studies.

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