Long-term variation of Dust episodes over the United Arab Emirates

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Abstract:

This paper deals with the investigation of long-term variability of atmospheric dust over the United Arab Emirates (UAE). The climatology of dust episodes (dust events, dust storms, and severe dust storms) is compiled based on the hourly observations and synoptic codes recorded at four different stations over UAE between the years 1983-2014. The diurnal, temporal, monthly, and inter-annual variations of dust episodes and their relation with the mean wind speed, maximum wind speed, and temperature are discussed. Dust episodes show a clear diurnal variation in all the stations. The duration of dust storms is large compared to dust events. For instance, dust events over the UAE persist for 2-5 hours while dust storms last for about 5-11 hours. Dust storms also show clear seasonal variability with the maximum occurring during winter and the minimum during summer whereas most of the dust events occur during the months of March and April. The inter-annual variation of dust events shows a significant decrease while dust storms depict a moderate increase over the UAE. The synoptic scale climatology of all dust storms is also analysed and shows changes in wind direction to the south-west prior to 2 days of the dust storm generation. The climatology of wind direction and wind speed during the dust episode indicates that 90% of dust episodes are coming from the southwest direction. These observed results are discussed in light of the current global warming scenarios with a special emphasis on the role of dust episodes on the regional enhancement of temperature.

Keywords: Dust episode, Dust storm, UAE, Wind Speed and Temperature

1.Introduction

Dust storms (DSs) are one of the natural hazards that severely affect daily life for short time intervals (Maghrabi et al., 2011). DSs are the consequence of the air turbulence, which spreads a large mass of dust in the atmosphere and reduces the horizontal visibility to few hundreds of meters which leads to the occurrence of traffic accidents and other disturbances (Goudie and Middleton, 2006). Desert dust also has a significant impact on aviation as it affects aircraft engines and visibility (Lekas et al., 2011; WMO, 2011). Such incidents lead to rerouting aircraft, flight delays and massive cancellation of scheduled flights as well as mechanical problems such as erosion and corrosion of aircraft engines (WMO, 2011). The dust particles that are suspended in the air have several impacts on climate, hydrological cycle and human health (IPCC, 2013). Dust aerosols alter the radiative budget through absorption and scattering of long-wave and shortwave radiation. In addition, dust particles cause a serious risk to the environment and human health, particularly with patients suffering from lung diseases (Gobbi et al., 2007; Zhang et al., 2012).

The Middle East is one of the most active hotspots for the occurrence of DSs in the world. The Rub' al Khali is the largest uninterrupted sand desert in the world with dunes that reach a height of 250 m. The Rub' al Khali is also known to be one of the most arid and hottest locations in the Arabian Peninsula. Its vast area of sand and dust provides a sizeable source region to areas surrounding the Arabian Peninsula. Further, the desert acts as a fuel for the northwest originating DSs before they drift into the Arabian Sea and eventually dissipate. The major parts of Saudi Arabia, and the southern part of the United Arab Emirates (UAE) are situated in Rub' al Khali desert. The dust particles that originate in these arid regions can be transported over long distances by strong winds and convective processes (Sun et al., 2001).

The synoptic and mesoscale weather systems which are responsible for the generation of DSs vary from one region to another (Kaplan et al., 2011). Several studies noted that the changes in atmospheric circulation are related to DS frequency (Zhang et al., 1997; Yang et al., 2008). These large-scale systems (atmospheric circulations) alter the local climatic parameters such as temperature, precipitation, winds, and others (Niranjan Kumar and Ouarda, 2014; Naizghi and Ouarda, 2017; Niranjan Kumar et al., 2016; Kumar et al., 2017). Climatic variables (temperature, precipitation, and wind) significantly influence the occurrence of DSs (Gao et al., 2003; Natsagdorj et al., 2003; Ouarda et al., 2014). For example, higher temperature with strong winds help in the formation of DSs in regions like Rub' al Khali (Notaro et al., 2013). The detailed long-term variability of dust episodes can explain the past climatological and environmental changes and will help understand the controlling or responsible factors for the occurrence of DSs. Several case studies have focused on DSs and their impacts on aerosol optical and radiative properties (Miller et al., 2008; Hansell et al., 2008; Basha et al. 2015). Several studies have also been carried out on the long-term variation of dust episodes around the major parts of the desert areas in the world (Qian et al. 2002; Natsagdorj et al., 2003; Ekström et al., 2004; Hara et al., 2006; Sabbah et al., 2012; Steenburgh et al. 2012; Guan et al. 2014; Wang et al., 2017; An et al., 2018). For instance, de Villiers and van Heerden (2007) studied the variability of dust episodes over the Abu Dhabi region by considering data from 1994-2003. Unfortunately, no study exists over the whole UAE on the long-term variability of dust episodes. Hence, the present study focuses on the long-term variation of dust episodes at four stations in the UAE between the years 1983-2014. In addition, we have also attempted to investigate the responsible or controlling factors for the occurrence of DSs.

The present paper is organized as follows: Section 2 contains the description of the datasets used and the methodology adopted for the identification of dust episodes. The diurnal, temporal, monthly, and inter-annual variations of dust episodes and their relation with average wind speed, maximum wind speed, and temperature are presented in Section 3. The important conclusions drawn from the current study are summarized in section 4.

2. Data and Methods

2.1. Data sets

The data used in this study are obtained from the National Climate Data Center (https://www.ncdc.noaa.gov/cdo-web/datasets) at four different stations of UAE operational since 1983. The stations are Abu Dhabi (54.69°E, 24.29°N), Dubai (55.27°E,25.20°N), Sharjah (55.51°E, 25.32°N), and Ras Al-Khaimah (55.97°E, 25.80°N). The data includes conventional meteorological variables such as wind speed, wind direction, temperature, and visibility accompanied by visual observations of current weather on the hourly basis at UTC. The whole paper deals with UTC time only. Monthly data of temperature, maximum wind speed, and average wind speed are derived from hourly observations from all the stations for the period 1983-2014.

2.2. Methodology

A DS or sandstorm is a collection of dust or sand particles of dust or sand that are significantly lifted from the surface to higher altitude by strong turbulent wind and thus visibility reduces to few hundreds of meters (WMO 2009). The horizontal visibility is the maximum distance at which an observer can see and identify an object lying close to the horizontal plane on which he or she is standing (American Meteorological Society, Glossary). According to the WMO, the dust episodes are classified as Severe Dust Storm (SDS) (horizontal visibility lies between 0-200 m), DS (horizontal visibility lies between 200 m-1 km) and Dust Event (horizontal visibility lies between 1-5 km). Along with horizontal visibility, we also use background weather conditions, which refer to atmospheric phenomena occurring at the time of observation recorded at a given station. The synoptic codes for dust observation are 7–9 and 30–35 (WMO 2009). In this study, we considered one dust episode in a given day, even if there were two or more episodic events.

2.3. Study region

The topography of UAE and its surrounding regions is shown in Figure 1. The UAE is located in the southwestern part of Asia bordered by the Arabian Gulf to the north, the Arabian Sea and Oman to the east, Saudi Arabia to the south and Qatar and Saudi Arabia to the West. The geographical location of the UAE is between 21.5º-26.5ºN and 51.5º-56.5ºE and covers an area of about 77,700 km^2. The UAE is comprised of large sandy desert, which covers about 90% of the country's surface area, extending from the Oman Mountains in the east to the coastline of the Arabian Gulf. The mountains peak about ~1.4–1.6 km above mean sea level, and extend from the north to the southeastern part of the country as shown in Figure 1. The blue line in Figure 1 indicates the Rub' al Khali desert, which is known as the Empty Quarter. Desert is a dominant landscape in the UAE, from the massive rolling dunes in the Empty Quarter to the flat sandy and gravel plains stretching towards the mountains. The UAE lies across the Tropic of Cancer, which receives a large amount of radiation from the Sun during the summer. The wind pattern over this region is northwesterly throughout the year, known as Shamal wind (Rao et al., 2001; Ouarda et al., 2015). The climate of the UAE can be divided into two main seasons with two transition periods: Summer (Jun-Sep), fall transition (Oct-Nov), winter (Dec-Mar), spring transition (Apr-May).

3. Results and discussion

3.1. Diurnal variation in dust episodes

The diurnal frequency of dust episodes is estimated from hourly observations, which are integrated to 3 hours' timescale for all the four different stations as shown in Figure 2. Dust episodes illustrate clearly the diurnal variation over the UAE region. The frequency of occurrence of dust episodes is maximum during 9-15 hours. The diurnal variation in the frequency of dust episodes in this region is consistent with previous studies over other regions in the world (Orgill and Sehmel 1976; Natsagdorj et al. 2003; Wang et al. 2005; Guan et al. 2014). During daytime, the heating of Earth's surface takes place due to incoming solar radiation thus creating unstable conditions favoring the formation of convection (Stull, 1998; Basha and Ratnam, 2009; Ratnam and Basha, 2010). The nocturnal temperature inversion induces stability; removal of the inversion due to surface heating during the day increases the environmental lapse rate to the dry adiabatic lapse rate and increases instability. Convective sources cause the thermals of warm air to rise from the ground, which leads to strong horizontal velocities, more intense turbulence and increased dust entertainment and transport (Geiger et al., 1995). In addition, the sea breeze circulation and the maximum differential temperature between sea temperature and land temperature during the later afternoon and early evening, which, in conjunction with a Shamal, can considerably reduce visibility. Sea breezes are like clockwork and very rarely is there a day without them along the UAE gulf coast.

The climatological duration of dust episodes at four different stations is shown in Figure 3. We have considered only the dust episodes whose period is greater than 2 hours to identify its temporal variability. Almost 55% of Dust episodes' duration fall within the 2-8 hour period, and 40% of DSs were in the range of 5-11 hour period. The SDS duration varies from station to station. The SDS duration is highest over Abu Dhabi followed by Dubai, Sharjah, and Ras Al Khaimah (RAK). Over Abu Dhabi (Dubai), the maximum duration falls in 11-14 (8-11) hour period. The Sharjah station shows a maximum duration of 5-8 hours. The temporal frequency of SDS at RAK is about 15% during the period of 2-17 hours.

The monthly climatology of dust episodes at four stations in the UAE is shown in Figure 4. Significant seasonal variation is observed in dust episodes. The maximum number of Dust episodes was observed over Abu Dhabi followed by Dubai, Sharjah, and RAK. The seasonal distributions of dust events and DSs are maximum during winter followed by summer. Most of the Dust events occur during March, April, and August in all locations. The DSs start peaking during December, reach a maximum in March and then decrease reaching a minimum during August. Over the UAE, SDSs are significantly low compared to DSs. The total number of SDSs observed over the Abu Dhabi, Dubai, Sharjah, and RAK is 10, 4, 3, and 9 respectively, over the period 1983-2014. Although the four stations are separated by ~100 km distance, the impact of DSs varies significantly from station to station.

The inter-annual variation of dust episodes during the period 1983-2014 is shown in Figure 5. Dust episodes show an increasing trend at all stations with a magnitude of 0.20, 0.025, 0.16 and 0.20/year over Abu Dhabi, Dubai, Sharjah, and RAK, respectively. The increasing trends in dust events are large over Abu Dhabi, and RAK compared to the other two stations. The maximum number of dust episodes over Abu Dhabi is observed during the year 2007. This number varies from station to station. A moderate increasing trend is noticed in DSs in all stations. The dust episodes show high and low phases during the 1983-1992 and 1994-1999 phases, respectively, indicating decadal variability. Therefore, we have divided the total data series into three-decades i.e. first decade (1983-1993), second decade (1994-2004) and third decade (2005-2014), to verify the decadal variability of Dust episodes and DSs. In the first decade, the occurrence of dust episodes is very high compared to the other decades except over RAK. Compared to the first and third decades, the second decade shows a very low occurrence of dust episodes. The occurrence of DSs increases significantly in the third decade in all stations. The Abu Dhabi station shows a higher number of dust episodes compared to other stations.

3.2. Climatology of dust episodes: Synoptic scale analysis

In this section, we summarize the characteristics of synoptic scale climatology before, during and after the event in the years 1983-2014. The synoptic pattern that generates DSs is shown in Figure 6. The composite spatial and temporal distributions of Sea Level Pressure (SLP) along with wind vectors at the surface level are selected before, during and after the DS to examine its synoptic variability. The National Centers for Environmental Prediction (NCEP) reanalysis mean SLP and surface winds are utilized to study the synoptic analysis of all the DSs which occurred from 1983 to 2014 over the UAE region. The NCEP reanalysis uses a global data assimilation system on 2.5^{o} longitude and 2.5^{o} latitude (Kalnay et al., 1996). The evolution of each event is examined by extending the composite analysis to the days preceding (Days -6, -4 and -2), during (Day 0) and following (Days +2, +4) the occurrence of DS. The anomalies are acquired by removing from each DS the daily climatological mean for the reference period 1983-2014. The most pronounced feature noticed is the occurrence of low pressure over the UAE region corresponding to high pressure over north-east Africa. The strong southwesterly wind brings most of the desert dust to the UAE region from Rub' al Khali. A strong cyclonic circulation pattern clearly emerges 2 days before the occurrence of the DS. This pattern strengthens when it approaches the day during the event and dissipates slowly after the event. The composite picture indicates that the southwesterly surface winds bring dust to the UAE region.

The cyclonic circulation pattern is clearly emerging before and during the DS days, associated with the low pressure over the UAE. During dusty days, the locations of the high-speed winds (~3 ms^{-1}) shift to the Rub' al Khali, which bring most of the dust to this region. The composite wind speed and direction map shows speedy air streams during the beginning of the DSs. This circulation transports a large amount of dust from the western part to the Southern part of the Arabian Peninsula. The global pressure systems shift southward in winter. Low-pressure systems and their troughs are closer to the UAE. Cooler air from the north is entrained around the western flank of these systems, warm/hot air from the desert, to the south, along with the eastern flank of the desert, assisted by the morning land breeze (de Villiers et al., 2007).

3.3. Relationship between dust episodes and climatic parameters

In this section, we investigated the relation between meteorological parameters and dust episodes responsbile for the occurrence of dust storms. The monthly variation of dust episodes, mean wind speed, maximum wind speed, and temperature is shown in Figure 7. The main observed feature is the strong relationship between DSs and maximum wind speed with a correlation of about 0.88, 0.83,0.82, 0.86 at the Abu Dhabi, Dubai, Sharjah and RAK stations, respectively. The dust events significantly correlate with average wind speed with a coefficient value of about ~0.88 at all the stations. Therefore, DSs (dust events) correspond to the maximum (average) wind speed over the UAE. From the above results, it is clear that wind has a significant impact on the occurrence of dust episodes. The monthly mean temperature shows a maximum during August. During this month, a maximum number of dust episodes is observed at all stations except Sharjah.

The annual variations of dust episodes, wind speed, and maximum wind speed during the years 1983-2014 are shown in Figure 8. The maximum wind speed illustrates variations similar to those of DS variability at inter-annual time scales except during the years 1992-2001. The mean wind speed shows increasing (decreasing) trend over Abu Dhabi, Dubai (Sharjah and RAK). This suggests that the mean wind speed is a significant contributing factor for the occurrence of DSs compared with maximum wind speed. This might be due to the strong wind that lifts easily the dust from sand rich areas where the DSs occur. The strong wind is the direct factor for causing the DSs. The UAE is situated in an extremely dry region with a wide sandy surface and low vegetation coverage. The ecological environment is fragile, with large areas of desert and decertified land, which provide sufficient materials for the occurrence of DSs.

The annual temperature variation shows an increasing trend in all stations as shown in Figure 9. A significant increase in temperature trend of ~ 0.065^{o}C/year (averaged over all stations) is noticed from the year 1983 over the UAE. Thus, an increase in temperature of about 2.08 K is noticed in last 32 years over these stations. The relationship between temperature anomaly and dust episodes is very complex. A positive correlation is observed between temperature, dust events and DSs. A higher temperature leads to an increase in surface evaporation, which reduces precipitation. These effects give rise to the creation of drier and looser surface soil and the most frequent DSs. An increasing trend in temperature and dust episodes is observed in Figure 9. Previous work by Zhand and Reid (2010) showed the large increase of AOD over Coastal China, the Indian Bay of Bengal, and the Arabian Sea. Particularly, over the coastal part of India, the increase in AOD depicts a worsening scenario to heavily polluted air, which impacts the local regional climate. Hsu et al. (2012) observed a significant increasing trend in mineral dust over the Arabian Peninsula by considering 13-years of MODIS AOD data, which matches with our present study. The increase in Arabian dust directly influenced the Indian monsoon circulation and contributed to rainfall increase over the southern part of India as discussed by Solmon et al. (2015).

4. Summary and Conclusions

This study focuses on the climatic variability of dust episodes over a 30 year period in the UAE region. The diurnal, monthly and inter-annual variations of dust episodes and their relation with mean wind speed, maximum wind speed, and temperature are investigated. In addition, the synoptic climatology of DSs and reduction/enhancement in temperature/wind speed are also investigated. The main conclusions are summarized in the following:

1. There exists a clear diurnal variation in the occurrence of dust episodes with a peak during 9-12 hour local time.
2. The duration of dust events has a period of 2-5 hours, whereas DSs have a large period ranging between 5-8 hours.
3. The duration of the SDS is largest, over Abu Dhabi followed by Dubai, Sharjah, and RAK. Over Abu Dhabi (Dubai), the maximum duration falls in the range of 11-14 (8-11) hours. The Sharjah station shows a maximum duration of 5-8 hours. The temporal frequency of SDS at RAK is about 15% during the 2-17 hour local time.
4. The seasonal distributions of dust episodes and DSs are maximum during the winter followed by summer. Most of the dust episodes occur during March and April in all the locations except RAK. A maximum number of dust episodes is observed over Abu Dhabi followed by Dubai, Sharjah, and RAK.
5. The maximum temperature during August corresponds to the occurrence of a large number of dust episodes in all stations.
6. The occurrence of DSs increases significantly during the recent decade at all stations. The Abu Dhabi station shows a higher number of dust episodes compared to the other stations. A clear increasing trend in dust episodes of 0.20, 0.025, 0.16 and 0.20/year is noticed over Abu Dhabi, Dubai, Sharjah, and RAK, respectively.
7. The occurrence of low pressure over the UAE and corresponding high pressure over northeast Africa leads to strong southwesterly winds, which brings most of the desert dust

to the UAE from Rub' al Khali. A strong cyclonic circulation pattern emerges clearly two days prior to the occurrence of DS.

8. On the monthly time scale, dust events significantly correlate (>0.80) with mean wind speed whereas DS correlates with maximum wind speed.
9. The most common wind direction during the dust episode period is mainly from the southwest direction. This suggests that dust is brought from the Rub' al Khali region to the UAE region.

Over East Asia, the decrease in intensity and frequency of SDSs is due to the decrease in the intensity of polar vortex (An et al., 2018). Increase in extreme precipitation reduces the frequency of dust storms over China (Wang et al., 2016). However, our results suggest that the mean wind speed is a significant contributing factor to the occurrence of dust episodes. Maximum wind speed contributes to the occurrence of major DSs. During summer, the temperature over this region reaches a peak value, and the surface soil becomes drier with looser surface. Wind speed is low during the summer months over this region. As the precedence of winter, wind speed becomes higher and the particles of dust or sand are lifted to higher heights by strong and turbulent wind. The visibility is then reduced to less than few hundred meters. An interesting feature noted in the present study is that the increase in surface temperature is associatedr to an increase in dust events. Though part of the increase in surface temperature can be explained by global warming, the reported increase in global temperature was only 0.87 K during the period 1880-2015 (http://climate.nasa.gov/vital-signs/global-temperature/). The additional 1.21 K over these stations can be partly related to the increase in dust episodes. Since global temperatures are expected to increase further, dust episodes are also expected to increase in the UAE.

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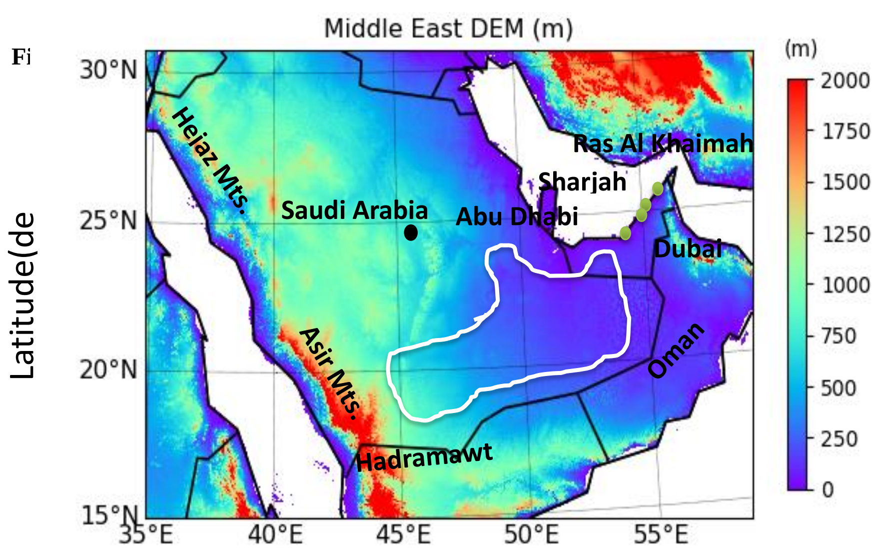

Rub' al Khali

Figure 1. Digital Elevation Map (DEM) of Middle East. Observational stations are shown by Green dots. Abu Dhabi (54.37°E, 54.37°E), Dubai (55.27°E, 25.20°N), Sharjah (55.42°E, 25.34°N), and Ras Al Khaimah (55.98°E, 25.67°N). The dark white line indicates the spatial extent of Rub' al Khali or Empty Quarters (Not to Scale) which is the largest sand desert in the world covering most of the southern third of the Arabian Peninsula.

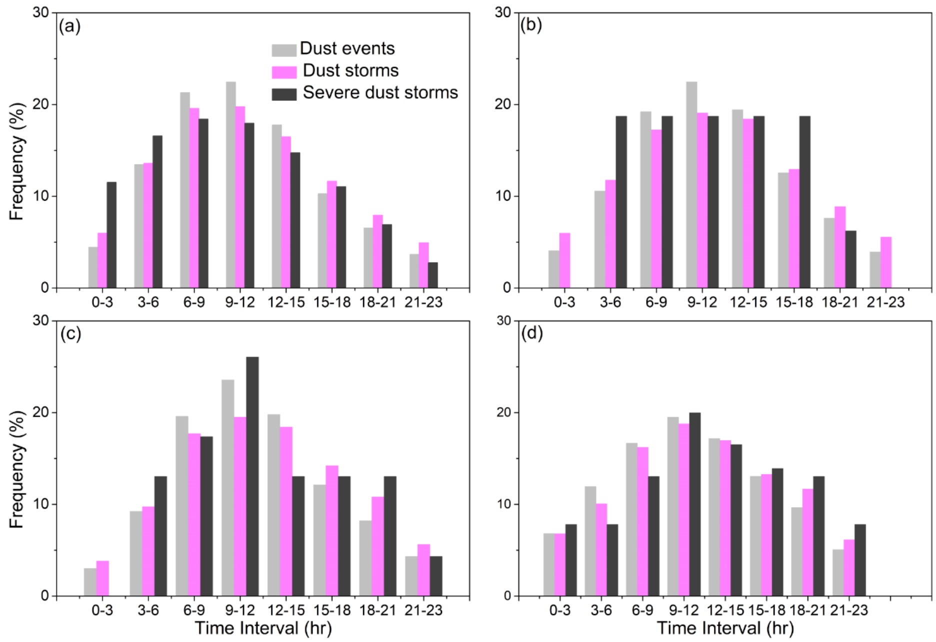

Figure 2. Diurnal variation of dust events, dust storms and severe dust storms over (a) Abu Dhabi, (b) Dubai, (c) Sharjah and (d) RAK averaged over the years 1983 to 2014.

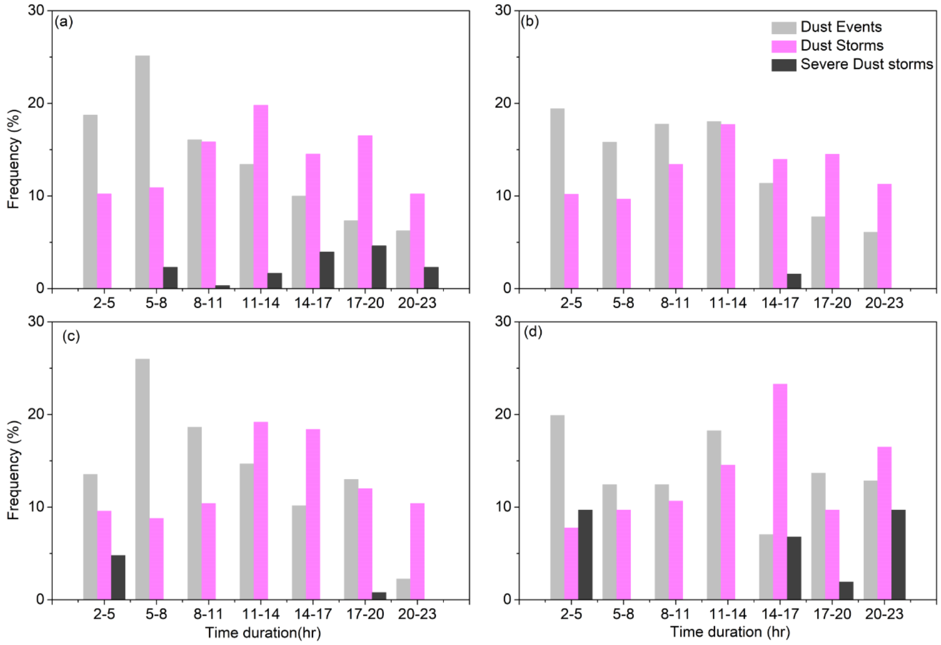

Figure 3. Duration of dust events, dust storms and severe dust storms over (a) Abu Dhabi, (b) Dubai, (c) Sharjah and (d) RAK averaged over the years 1983 to 2014.

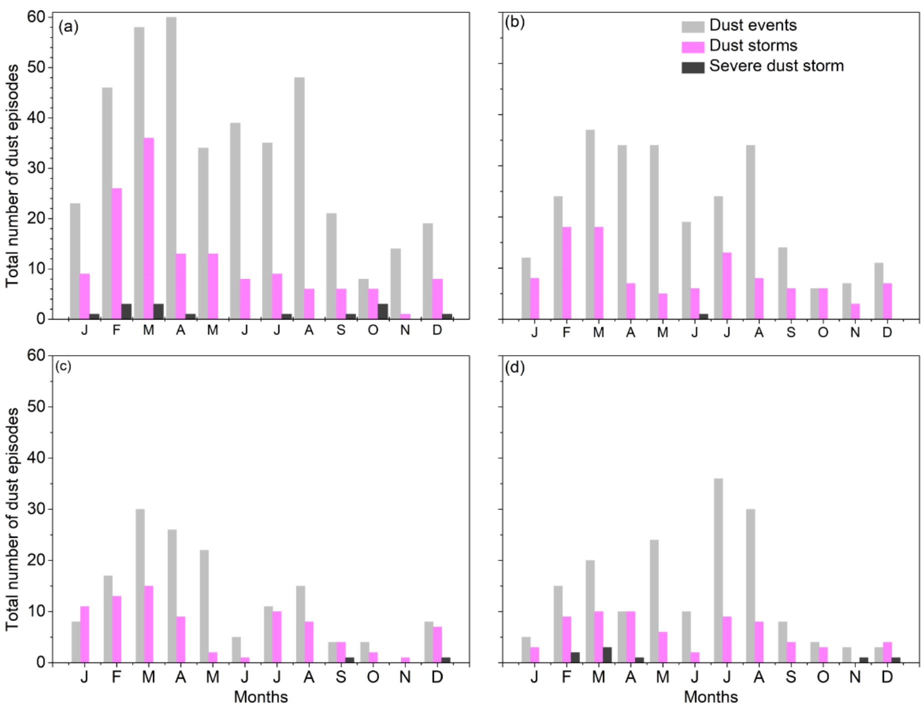

Figure 4. Monthly variation of dust events, dust storms and severe dust storms over (a) Abu Dhabi, (b) Dubai, (c) Sharjah, and (d) RAK averaged over the years 1983 to 2014.

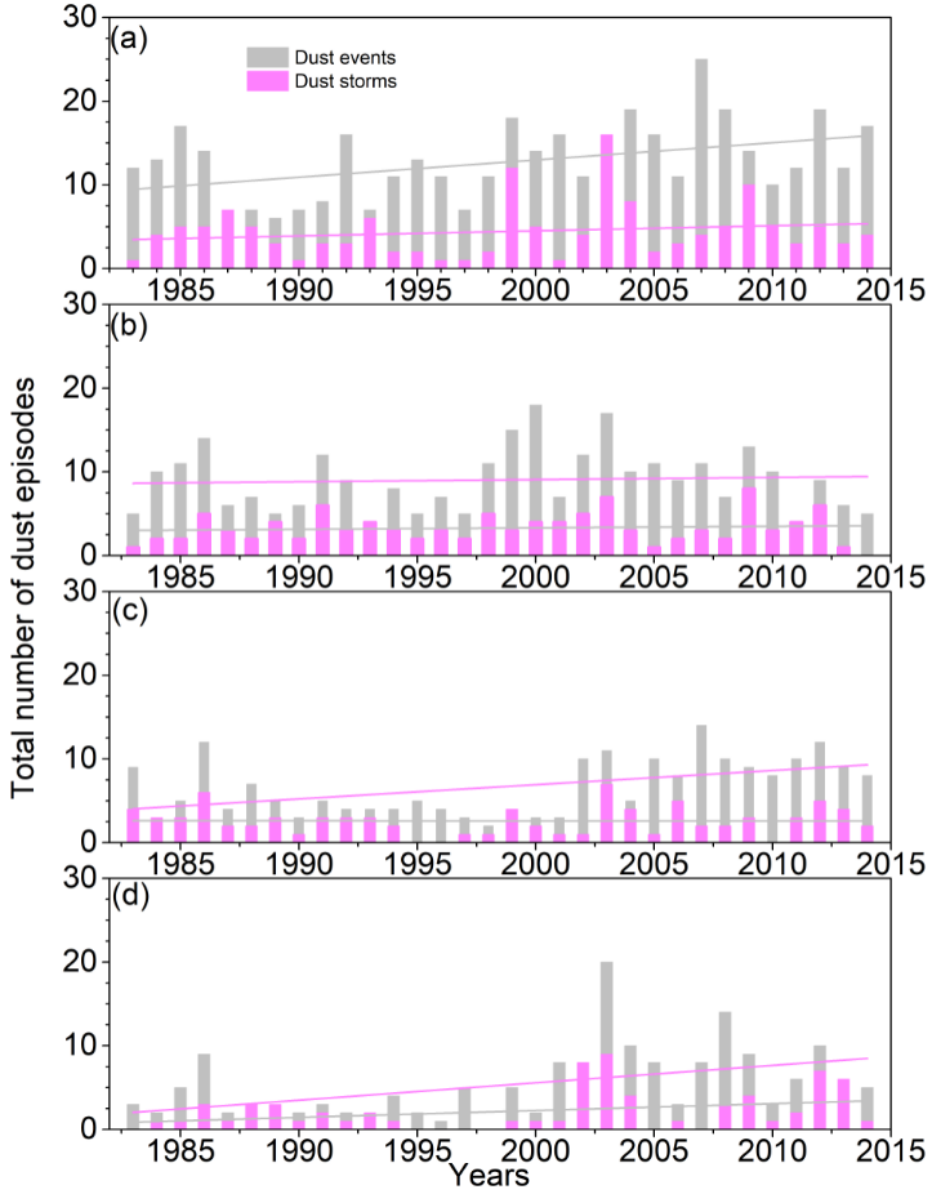
(a)
Dust events
Dust storms
(b)
(c)
(d)
Total number of dust episodes
Years
0
10
20
30
1985
1990
1995
2000
2005
2010
2015

Figure 5. Yearly variation of dust events and dust storms over (a) Abu Dhabi, (b) Dubai, (c) Sharjah, and (d) RAK ,observed during 1983 to 2014. The straight line indicates the linear trend.

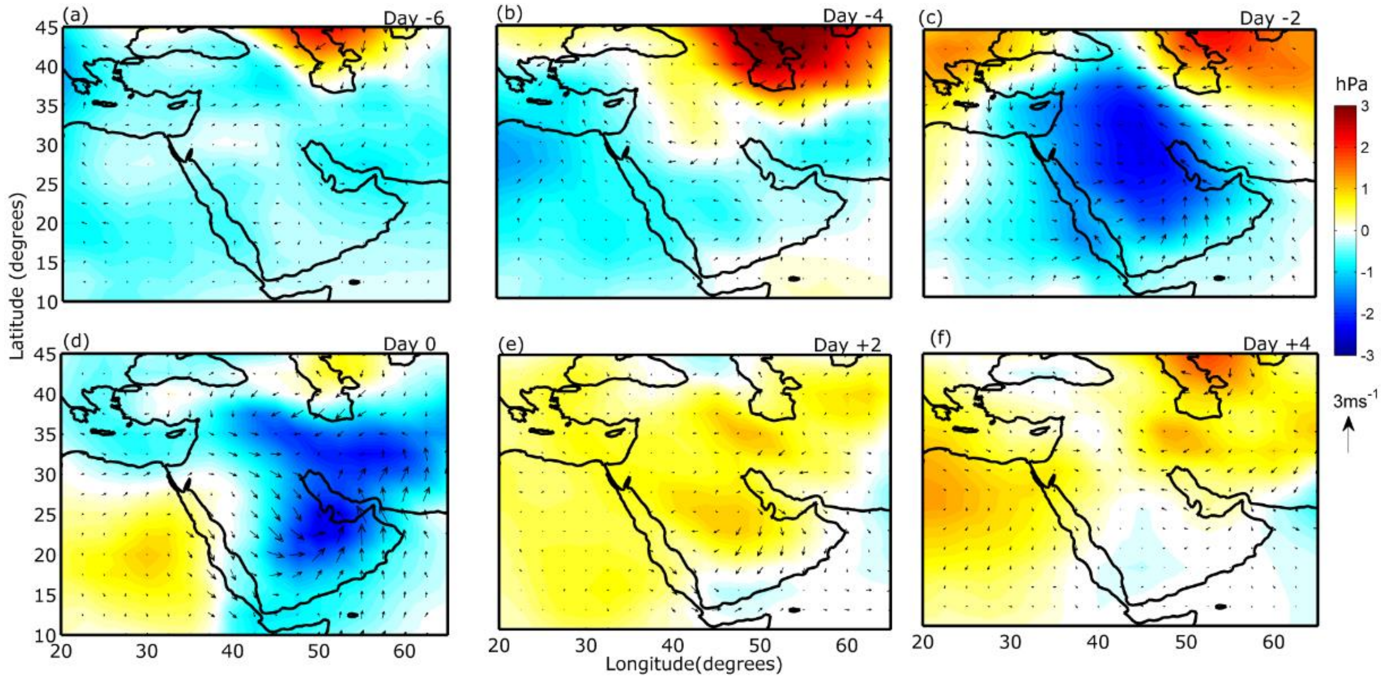

Figure 6. Temporal evaluation of composite wind vectors at 1000 hPa superimposed on Sea Level Pressure (SLP) from NCEP/NCAR reanalysis over the Arabian Peninsula. The SLP anomalies for the Days -6, -4, -2 belong to preceding events (a, b, c). Day '0' refers to the event occurrence day (d). Days 2 and 4 occur after the event.

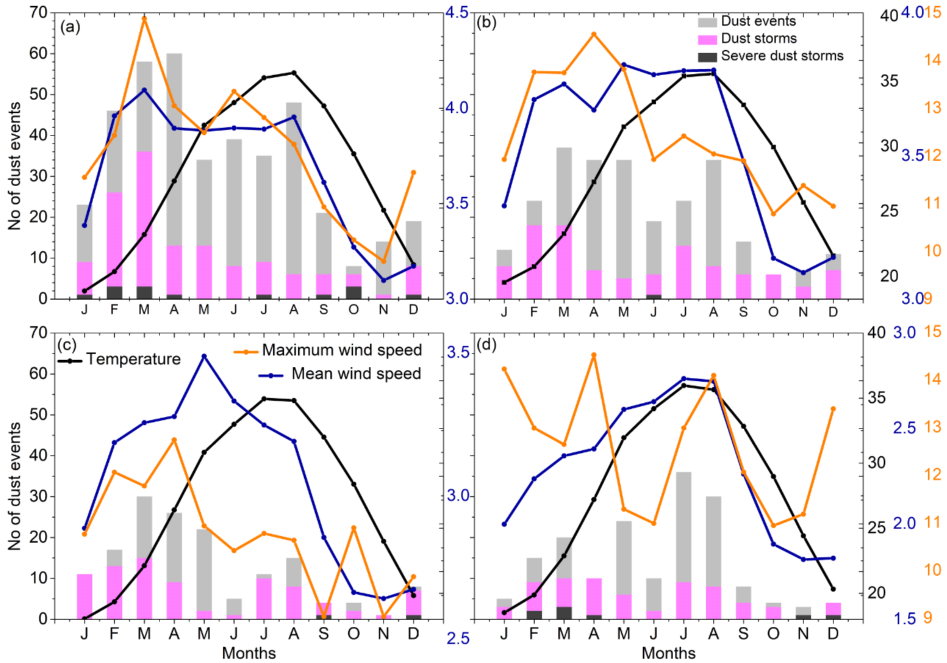

Figure 7. Monthly variation of dust events, dust storms, severe dust storms over (a) Abu Dhabi, (b) Dubai, (c) Sharjah and (d) RAK averaged over the years 1983 to 2014. The mean wind speed (ms^{-1}), maximum wind speed (ms^{-1}) and temperature (^{o}C) observed during the same period are also superimposed with the axis on the right.

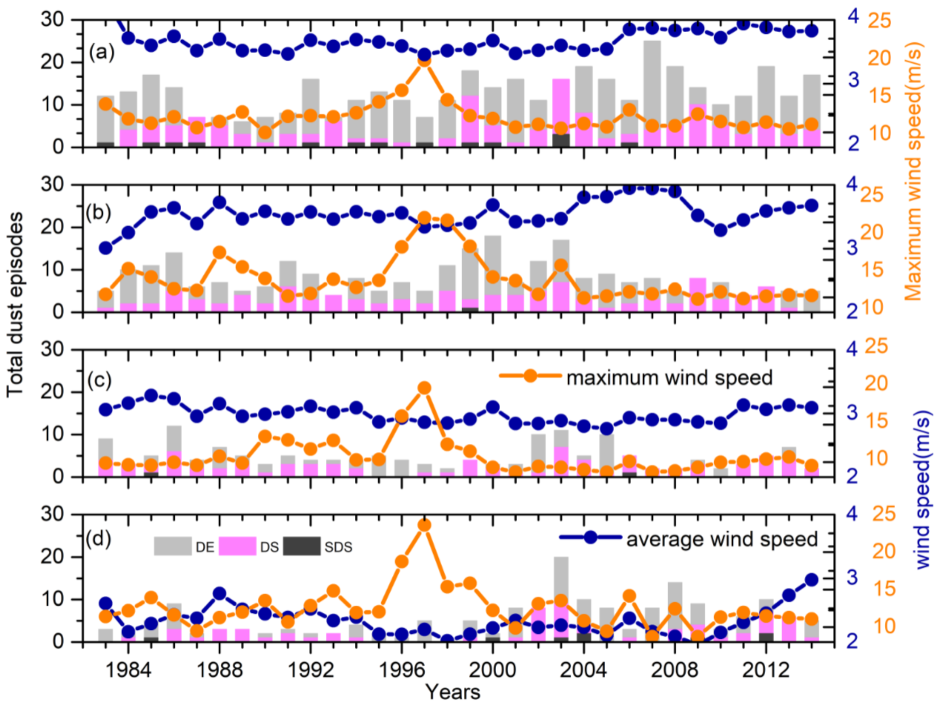

Figure 8. Annual variation of dust events, dust storms, and severe dust storms over (a) Abu Dhabi, (b) Dubai, (c) Sharjah and (d) RAK, observed during 1983 to 2014. The mean wind speed (ms^{-1}) and maximum wind speed (ms^{-1}) observed during the same period are also superimposed with the axis on the right.

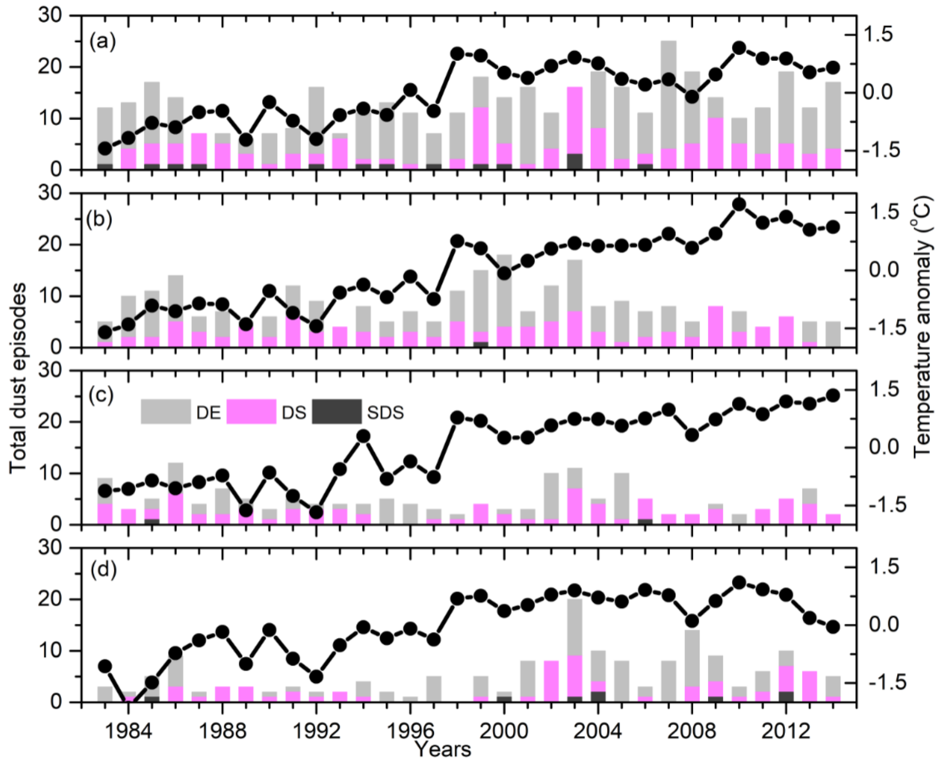

Figure 9. Annual variation of dust events, dust storms, and severe dust storms observed during 1983 to 2014 over (a) Abu Dhabi, (b) Dubai, (c) Sharjah and (d) RAK. The monthly mean temperature anomaly (°C) observed during the same period is also superimposed with the axis on the right.