Temporal variations in the frequency and concentration of dust events over Iran based on surface observations

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ABSTRACT: Using surface meteorological records of a 20-year period from 1991 to 2010, temporal variations in the frequency and concentration of transported dust events over Iran are investigated. Five regions of frequent dust events are identified. In the order of importance, these areas are the Khuzestan Plain, the coastal plain of the Persian Gulf, west of Iran, Tabas and Sistan. The first three areas create a belt of high frequency of dust events along the western foothills of the Zagros Mountains. The Khuzestan Plain is the area with the highest frequency of dust events, over which dust laden air is almost permanently present in summer, while the coastal plain of the Persian Gulf is the second most affected area. These two areas, along with west of Iran, are mostly influenced by transported dust from sources outside of Iran, while Tabas and Sistan are mostly influenced by arid lands in the interior of Iran. In contrast, the southern coastal strip of the Caspian Sea is the area with the least frequent dust episodes. Throughout Iran, the frequency of dust events strengthens in spring, peaks in summer and significantly weakens in autumn and winter, with the least observed frequency in winter. Significant monthly variations of the frequency of dust events were also identified, with the most and least frequencies in July and December, respectively. In terms of long-term frequency of dust events, our observational analyses show an overall rising trend of the frequency of Iran’s dust events in recent years, predominantly attributed to increasingly frequent dust outbreaks in Iraq due to human intervention.

KEY WORDS frequency of dust events; arid lands; surface observations; visibility; Iran; Khuzestan Plain; Tabas; Sistan

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1. Introduction

Mineral dust is believed to be mostly originated from natural sources (Tegen et al., 2004), predominantly from the so-called ‘dust belt’ region, extending from the west coast of North Africa, over the Middle East, Central and South-Southwest Asia, to China (Prospero et al., 2002). Iran in Southwest Asia is therefore located within the Earth’s ‘dust belt’ region, suggesting that it is often significantly affected by strong dust episodes.

A majority of Iran lies in the subtropical high-pressure belt, experiencing either dry or semi-dry climate characterized by less than 260 mm annual mean precipitation (Masoodian, 1998; Hasanean, 2004) and high evaporation rates that far exceed the annual rates of precipitation. Indeed, arid and semi-arid areas occupy as much as 60% of Iran, covering about 1 million km², although in the foothills of the Alborz and Zagros mountains and the coastal strip of the Caspian Sea, a Mediterranean climate is dominated. In spite of potential sources in the interior of Iran associated with arid or semi-arid climate, it is now well established that significant quantities of dust originate from external sources (Shahsavani et al., 2012).

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frequency of dust events occurs at the borders among Iran, Pakistan and Afghanistan. This is a huge closed depression (known as Dasht-e-Margo) that comprises the Sistan Basin, the Registan Desert and northwestern Baluchistan, the areas over which the ‘wind of 120 days’ is dominated from mid-May to mid-September (Alizadeh-Choobari et al., 2013, 2014). Another high-frequency source of dust identified by Middelton (1986) is the Makran Desert along the coastal plain of the Oman Sea. Later on, temporal characteristics of dust storms in the Middle East were studied by Furman (2003) using a 21-year period synoptic data from 1973 to 1993. He found clear seasonal variations of the peak dust activity at different areas of the Middle East. Near the Mediterranean region, the peak was in winter and spring, further southeast over western Iraq and Syria and the northern Arabian Peninsula the peak was in spring, and over Mesopotamia, Iran and the southern Arabian Peninsula the peak was in summer. Using ground-based measurements, Shahsavani et al. (2012) characterized dust events in Ahwaz during a 6-month period from 1 April to 30 September 2010. They found 72 dusty days during the 6-month period, with the peak frequency of 16 dusty days in July. They also found that dust events in Ahwaz were more frequent during the afternoon, but less frequent from midnight to early morning, suggesting that thermally driven well-mixed boundary layer in the afternoon contributes to the increase of dust storms, but also highlights the contribution of the low-level Shamal wind that strengthens during the day and weakens overnight.

Over the last few decades, remotely sensed satellite data have been also extensively used to identify potential sources of dust and to understand the transport pathways of dust particles in regional and global scales. Using the Total Ozone Mapping Spectrometer (TOMS), Prospero et al. (2002) showed that dust events over Iran start in April–May, reaches to the peak in June–July, and are greatly weakened by September. They identified Dasht-e Kavir and the Sistan Basin as two major sources of dust in the interior of Iran. Their satellite analysis also showed a significant contribution of Hamun-e Mashkel and the Makran Desert, while comparatively insignificant contribution of an inter-mountain salt/dry lake of Jazmorian was noted. Using the Moderate Resolution Imaging Spectroradiometer Deep Blue (MODIS DB) aerosol products, Ginoux et al. (2012) identified a prominent source of dust along the coastal plain of the Persian Gulf, and six other internal sources, including southern shore of Lake Urumia in the northwestern corner of Iran, Hamun-e Mashkel, Dasht-e Kavir, Dasht-e Lut, ephemeral lakes around the city of Zabol in the Sistan Basin and part of the Makran Desert along the coast of the Oman Sea (location of these sites are depicted in Figure 1). Using the Multi-angle Imaging SpectroRadiometer (MISR), Alizadeh-Choobari et al. (2014) demonstrated substantial seasonal variability of Iranian dust events, with a primary peak in summer and a secondary peak in spring, while minimum dust load was observed in winter.

While these satellite analyses have provided a broad-scale view of dust sources and characterized the transport pathways of dust particles (e.g. Prospero et al., 2002; Ginoux et al., 2012; Alizadeh-Choobari et al., 2014), and progress has been made in characterizing individual dust
events over Iran (e.g. Shahsavani et al., 2012), there has been less progress in quantifying the frequency and temporal variations of dust events. Recent environmental changes in Iraq (IAU, 2012), that have already made themselves felt with a higher frequency and intensity of dust events over Iran, have exacerbated air pollution problems already existing in urban and oil production areas of Iran. This underlines the essential need not only for identifying the areas with high frequency of dust outbreaks, but also to understand temporal variations of dust activity over these areas.

This paper therefore aims to understand the frequency and temporal (including monthly, seasonal and inter-annual) variations of dust events over Iran. To this end, 3-h meteorological records of 111 meteorological stations across Iran for a 20-year period from 1991 to 2010 were used, which provides good spatial and temporal coverage of dust activities. The frequency of dust events is also examined based on the intensity of dust episodes. The paper is organized as follows: data description is presented in Section 2, while methods are described in Section 3; the spatial distribution of dust particles over Iran is discussed in Section 4, with the temporal distribution presented in Section 5; and major conclusions are summarized in Section 6.

2. Data description

Surface meteorological records of more than 300 synoptic weather stations across Iran at 3-h intervals were obtained from Meteorological Organization of Iran. Among them, 111 stations that have had at least 20-year datasets for the period of 1991–2010 were selected. These observations have already been quality controlled by the Meteorological Organization of Iran; however, they have been further examined and suspected datasets have been removed. The present weather phenomena and horizontal visibilities have been extracted, from which only those datasets that comprise the present weather code 06 and associated visibilities have been considered. This weather code represents suspended dust in the air, not raised by wind at or near the station at the time of observation, implying that it only demonstrates the transported dust.

3. Methods

As mentioned above, only transported dust has been considered (the present weather code 06), implying that dust events with the sub-local scale have not been considered. The reason for excluding dust emission is that based on remote sensing aerosol (dust) optical depth analyses, several research investigations have claimed that there are some major sources of dust in the northern tip of the Persian Gulf (over the Khuzestan Plain) and the coastal plain of the Persian Gulf (see, e.g. Ginoux et al., 2012). However, personal land-use recognition of the abovementioned regions and communications with local scientist do not support this assumption. Indeed, we believe that these areas should be significantly affected by transported dust and local emission processes have little contribution. To examine this assumption, emission processes have been excluded, and only contribution of transported dust has been considered. Accordingly, ‘dust event’ in the present study only refers to transported events, while dusty days are defined as days with at least one report of the present weather code 06 with the horizontal visibility of less than 10 km.

Dust events are classified based on visibility to three different categories: (1) severe dust storm (visibility ≤ 200 m); (2) moderate dust storm (200 m < visibility ≤ 1 km); and (3) mild dust storm (1 km < visibility). For a given station, the frequency of dust events for each category is obtained as follows:

\[ f_i = \frac{\text{Number of dust events for a specific category}}{\text{Number of meteorological records}} \times 100 \]  

The total frequency of dust events, \( f_{DE} \), regardless of their category is obtained by adding the frequency of all three categories.

Assuming that mineral dust is the determining factor during a dust event, Shao and Wang (2003) introduced an empirical relationship between dust concentration and horizontal visibility for Asian dust. They demonstrated that in relatively good visibility conditions (>3.5 km), dust concentration has a negative exponential correlation with horizontal visibility, while under relatively poor visibility (≤3.5 km), nearly an inverse correlation was identified:

\[ C = \begin{cases} 3.802 \times 10^9 D_v^{-0.84} & D_v \leq 3.5 \text{ km} \\ \exp \left( -0.11D_v + 7.62 \right) & D_v > 3.5 \text{ km} \end{cases} \]  

where \( C \) is in \( \mu g \text{ m}^{-3} \) and \( D_v \) is in km. This empirical relationship for stations at which dust events were recorded is applied to compute dust concentration.

4. Spatial distribution of dust events

Figure 2 shows distribution of total dust event frequency over Iran derived from 3-h meteorological records of the 20-year period from 1991 to 2010. Several important features have been observed: (1) five regions of frequent dust events are found, which include the Khuzestan Plain, the coastal plain of the Persian Gulf, west of Iran, Tabas and Sistan; (2) the Khuzestan Plain in southwestern Iran over the northern tip of the Persian Gulf is a region with the most frequent dust events, the area which is located near the two major sources of dust in Iraq, i.e. the Alluvial Plain of the Tigris–Euphrates basin and the Zubair Desert. Transported dust towards this region, particularly from southern Iraq (Al-Najim, 1975) and Kuwait (Abdulaziz, 1994) where the so-called Shamal wind blows, is mostly trapped due to the blockage by the Zagros Mountains; (3) the observed frequent dust events over west of Iran primarily caused by transported dust from Aljazera and the Alluvial Plain of the Tigris–Euphrates basin in Iraq (see Figure 1); (4) the high frequency of dust events over the coastal plain.
Figure 2. Total dust event frequency ($f_{DE}$, triangles) over Iran derived from 3-h meteorological records of a 20-year period from 1991 to 2010 over 111 weather stations. The triangles also show locations of the weather stations across Iran used in the present study. Topographic features of Iran are shown in colours, highlighting the Alborz Mountains in northern Iran and the Zagros Mountains extends from northwest to south of Iran. Five regions of frequent dust events, as well as surrounding countries and seas, are depicted in the figure.

of the Persian Gulf is due to the fact that this area is located close to the Ad-Dahna Desert in the Arabian Peninsula; (5) none of the last three areas discussed above are sources of dust, rather the observed frequent dust events were caused by transported dust. They create a belt of high frequency of dust events along the western foothills of the Zagros Mountains, stretching from west of Iran, passing through Khuzestan and reaching to the coastal plain of the Persian Gulf; (6) in contrast to the high-frequency areas in western Iran, Tabas in east central and Sistan in east to southeast of Iran are mostly influenced by sources of dust in the interior of Iran. Indeed, Paleozoic epicontinental marine sediments were deposited in Tabas (Berberian, 1983), while silt loads are carried by the Hirmand River to the Sistan area (Hickey and Goudie, 2007), and they can be picked up as windblown dust by the ‘wind of 120 days’ (Alizadeh-Choobari et al., 2014); and (7) significant less frequency of dust events were observed over the southern coastal strip of the Caspian Sea, over which rainfall falls throughout the year and is heavy from late summer to mid winter.

A different perspective of the frequency of dust events in terms of the three categories discussed earlier is represented in Figure 3. Again, the five regions of high frequency of dust events are clearly evident in both mild and total dust storm frequencies, while the frequency of dust events is significantly low over the southern coastal strip of the Caspian Sea. The other clear feature is that severe and moderate dust events have been hardly observed, such that they are only visible over the Khuzestan Plain. Compared to the Khuzestan Plain, less severe and moderate dust events over the coastal plain of the Persian Gulf is due to the fact that this region is located farther away from sources of dust. It is also mostly affected by transported dust from the Ad-Dahna Desert, which mostly composed of fine sand particles, while Iraq’s sources that influence the Khuzestan Plain are mostly composed of clay and silt. As fine sand particles are relatively heavier than those of clay and silt particles, less quantities of dust originated from the Ad-Dahna Desert can reach to Iran’s coastal plain of the Persian Gulf.

Using the MODIS DB Level 2 aerosol products for the period 1 January 2003 to 31 December 2009, Ginoux et al. (2012) extracted scenes of aerosol optical depth dominated by dust, thereby identified sources of dust on the global scale. As mentioned earlier, they noted seven regions of high frequent dust events over Iran: the Khuzestan Plain, the coastal plain of the Persian Gulf, Dasht-e Lut (including Tabas in its northern side), Sistan Basin, Dasht-e Kavir, part of the Makran Desert along the coast of the Oman Sea, and Lake Urmia in northwest and Jazmorian in southeast of Iran. The first four areas for which high-frequent dust activity was reported by Ginoux et al. (2012) are consistent with our ground-based measurements. However, unlike their results, Urmia and Jazmorian lakes, as well as Makran Desert along the Oman Sea coastal area of Iran are not considered as important sources of dust in our ground-based analyses. As Jazmorian was recently dried and water shrinking of Lake Urmia has been started since mid-1990s (Zarghami, 2011), and Ginoux et al. (2012) did the analysis for the period 2003–2009 compared to our longer time period from 1991 to 2010, this could be the possible explanation for the difference. The other difference is that our analyses indicate high-frequent dust events over west of Iran, mostly caused by transported dust from...
Iraq, the feature that is missed in the satellite retrievals of Ginoux et al. (2012). Furthermore, Ginoux et al. (2012) argued that Iran’s coastal plain of the Persian Gulf is a prominent source of dust. Our finding of high-frequency dust events is consistent with satellite analysis of Ginoux et al. (2012); however, as this is not an area of loose soil or fine sand, the high frequency is mostly attributed to the transported dust from external sources.

The result as the annual mean dust concentrations averaged for the period from 1991 to 2010 is shown in Figure 4. Three areas of high dust concentrations are found: the Khuzestan Plain, the coastal plain of the Persian Gulf, and west of Iran, while, similar to the frequency of dust events, the lowest concentrations were observed in the coastal strip of the Caspian Sea. The highest annual mean dust concentration over the Khuzestan Plain reaches as much as 100 μg m⁻³. The value is greater than the observed maximum 5-year mean value of 50 μg m⁻³ over the Gobi region and equal to the value of 100 μg m⁻³ over the Hexi Corridor, but is much less than the value of 800 μg m⁻³ over the Tarim Basin (Shao and Dong, 2006). Relatively lower dust concentration in Tabas and Sistan is attributed to comparatively less frequent (particularly severe and moderate) dust events.

5. Temporal variations

5.1. Seasonal and monthly variations

In late spring, thermal lows over interior Iran and Saudi Arabia begins to form, while a high-pressure ridge is located over the Mediterranean that extends into northern Saudi Arabia. The monsoon trough is also located north of the equator, crossing southeastern Iran and the southeastern Arabian Peninsula. The pressure gradient between the monsoon/thermal lows and the high-pressure ridge creates
northwesterly summer Shamal winds and subsequently dust outbreaks across Iraq, Kuwait and northern Saudi Arabia. The orientation of the Zagros Mountains tends to accelerate Shamal winds. Convective dust storms, including the haboob (Sutton, 1925) and dust devils (Sinclair, 1969), also occasionally occur in the summer months, although they last for a short period of time and are at much smaller scales than dust outbreaks caused by Shamal winds.

In autumn and winter, however, the monsoon trough backs south of the equator and the thermal lows collapse, causing Shamal winds (now known as winter Shamal winds) to be less frequent, although they are usually much more significant than that of the summer Shamal winds in terms of wind strength. The winter Shamal winds occur either following the passage of mid-latitude dynamic cold frontal systems or when very cold air masses from Turkey or Syria funnel towards the Tigris–Euphrates basin and the Persian Gulf (Walter, 1991). Dust storms over Iraq and the Arabian Peninsula in winter may also be associated with southwesterly to southeasterly prefrontal winds and shear-lines (Walter, 1991).

These seasonal changes in the frequency of Shamal winds, accompanied by corresponding changes in precipitation and evaporation (the area experiences its wet season in late autumn, throughout winter and early spring), result in the frequency of dust outbreaks over western Iran varies widely by season, as shown in Figures 5–8. The frequency of total dust events reached to the peak in summer, followed by spring. Indeed, the intensified thermal lows in summer that strengthen the intensity and frequency of northwesterly Shamal winds, maintain nearly a persistent dust layer over Iraq throughout summer, causing west of Iran and the Khuzestan Plain to be influenced more frequently by dust. In contrast, in response to the reduction of the frequency of Shamal winds in autumn and winter, during which the area also experiences its wet season, the frequency of dust events was significantly reduced, such that the least frequency was observed in winter. It should be noted that in spite of a significant reduction of the frequency of dust events in autumn and winter, dust outbreaks were still a common feature in the Khuzestan Plain and west of Iran, suggesting that these regions, that are located downwind of Iraq’s desert lands, are under the influence of mineral dust almost all year long. This is such that even severe dust events occasionally occur during these seasons (Figure 5). In contrast, dust episodes have only occasionally occurred over most other parts of Iran during dust break seasons of autumn and winter.

Similar seasonal variations of dust activity are identified over the three other high-frequency areas discussed earlier, i.e. the coastal plain of the Persian Gulf, Tabas and Sistan. A summer peak dust activity over the coastal plain of the Persian Gulf was identified, which is related to the summer peak dust outbreaks reported over the Ad-Dahna Desert (Goudie and Middelton, 2006). The second peak over this area was in spring, while again there has been a significant reduction in the frequency of dust events during autumn and winter. Similarly, the summer peak has been identified over Tabas and Sistan (Figures 5–8), which is related to the ‘wind of 120 days’ dominant over these areas from mid-May to mid-September (Alizadeh-Choobari et al., 2014). Within these areas, dust activity is also a prominent feature in spring, but is significantly weakened in autumn and winter. The seasonal variations of dust outbreaks over the Sistan Basin have been also highlighted in the recent work of Rashki et al. (2014) using different satellite datasets. Similar to the present study, they have identified a peak aerosol load in summer, but substantially lower values in winter. It should be noted that the frequency of dust outbreaks increases substantially in the Khuzestan Plain and the coastal plain of the Persian Gulf from spring to summer, but not in the other three high-frequency areas (see Figure 8). This could be related to the fact that the Khuzestan Plain and the coastal plain of the Persian Gulf are located downwind of multiple sources of dust, some of which appears to be much more active in summer, but this needs to be carefully examined.

The pattern of seasonal variations in the frequency of mild dust events is similar to the seasonality of the total dust events, while there are some differences between the seasonality of total dust events and those of severe and moderate dust events. One difference is that eastern to southeastern Iran has experienced greater severe and moderate dust events in spring compared to summer. The other discrepancy is that the frequency of moderate dust events over the Khuzestan Plain has been higher in winter than autumn, highlighting contribution of Shamal winds that are more significant in winter in terms of wind strength.

Monthly variations of the frequency of dust events averaged for the 20-year period at five stations within
the high-frequency areas and the averaged values over all 111 stations of Iran are shown in Figures 9(a) and 10(a), respectively. These stations (shown in Figure 2) are Ahwaz in the Khuzestan Plain, Kermanshah in west of Iran, Bushehr in the coastal plain of the Persian Gulf, Tabas in east central of Iran and Zahedan in the Sistan area. The frequency of dust events shows a clear substantial monthly variations, such that it has been strengthened in May, peaked in July (except in Tabas over which the peak has been observed in June), weakened in September and reached to the least frequency either in December or January. Consistent with our previous discussion, the frequency of dust events is greater in warmer months, during which the top soil is drier and strong regional winds are more frequent, including Shamal winds that occur more frequently over Iraq in late spring and throughout summer, and the ‘wind of 120 days’ that dominates over east of Iran from mid-May to mid-September. The peak dust activity over Zahedan in July is in agreement with the maximum intensity of the ‘wind of 120 days’ that has been observed in July (Alizadeh-Choobari et al., 2014).

5.2. Inter-annual variations
Inter-annual variations of the frequency of dust events over the five high-frequency areas of Iran for the period of 1991–2010 are shown in Figure 9(b). Overall, the frequency of dust events has been increasing over Ahwaz, Kermanshah and Tabas in recent years. The rising trend in Ahwaz and Kermanshah is related to the recent increase in the frequency of dust outbreaks in Iraq due to land degradation and desertification (Goudie and Middelton, 2006; IAU, 2012). The rising trend in Tabas, which began in 2008, is related to a drought that started in 2007 and has continued for the upcoming years. The frequency of dust outbreaks in Bushehr has varied substantially over

Figure 5. Seasonal variations of the frequency of severe dust events (visibility ≤ 200 m) over Iran. The data derived from 3-h meteorological records of a 20-year period from 1991 to 2010 over 111 weather stations across Iran.
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Figure 6. Seasonal variations of the frequency of moderate dust events (200 m < visibility ≤ 1 km) over Iran. The data derived from 3-h meteorological records of a 20-year period from 1991 to 2010 over 111 weather stations across Iran.

the years. It was a decreasing trend from 1991 to 1998, increased for the following 2 years, then backed to relatively lower values during the period of 2001–2006. Since 2006, similar to the other two high-frequency areas of Ahwaz and Kermanshah, the area has been experiencing a rising trend. A significant increase of the frequency of dust events is identified over Zahedan for the period of 2000–2008. This is related to long periods of drought in the Sistan area which began in 1999 (Miri et al., 2007). With an end to the drought, however, the frequency of dust outbreaks has returned back to the normal lower values for the period of 2009–2010.

Note that in early 1990s, the frequency of dust events was substantially higher in Bushehr compared to Ahwaz and Kermanshah, while it has been substantially higher throughout 2000s in Ahwaz, and in the late 2000s in Kermanshah. This implies that the coastal plain of the Persian Gulf was the area with the highest frequency of dust events in 1990s. However, following the increasingly frequent dust and sand storms in Iraq, mostly due to environmental changes by human intervention (IAU, 2012), the Khuzestan Plain has now become the most affected area by dust.

Figure 10(b) shows inter-annual variations of the frequency of dust events and the number of dusty days averaged over 111 meteorological stations of Iran from 1991 to 2010. Inter-annual fluctuations of the frequency of dust events, caused by climate variability and environmental changes, were lower from 1991 to 1998. Sincethen, higher inter-annual fluctuations of the frequency of dust events have been observed, with an overall rising trend, such that it reached from the minimum value of 0.22 in 1998 to the
maximum value of 5.27 in 2009, and quadrupled between 2006 and 2010. A sharp increase of the frequency of dust events is identified in 2008 and 2009, which is caused by 2 years of a severe drought between 2007 and 2009 in Iraq, during which 40% of Iraq’s crop coverage were reduced (IAU, 2012).

The identified significant increase of the atmospheric dust load over Iran in recent years is predominantly attributed to a prominent increase in the frequency of vast dust and sand storms over Iraq (Goudie and Middelton, 2006). The increase of dust events over Iraq was attributed to both climate and environmental changes, including substantial decrease in the annual rainfall for the former and drying of the marshes, land degradation and desertification (primarily due to military operations) for the latter. Some evidence suggests that the frequency of Iraq’s dust outbreaks will be even further increased in coming years, contributing to the further increase of the frequency of dust events over western Iran.

6. Conclusions

The frequency and seasonality, as well as monthly and inter-annual variations of dust events over Iran, were investigated using surface meteorological measurements of 111 synoptic stations across the country for a 20-year period from 1991 to 2010. Results indicate that except for the southern strip of the Caspian Sea most other parts of Iran are influenced by transported dust, often in spring and summer, but only occasionally in autumn and winter.

For the first time, five regions of frequent dust events over Iran are found. In the order of importance, they are: (1) the Khuzestan Plain in southwestern Iran over the
northern tip of the Persian Gulf; (2) Iran’s coastal plain of the Persian Gulf; (3) west of Iran; (4) Tabas in east central of Iran; and (5) Sistan in east to southeast of Iran. The first three areas constitute a regional belt of high-frequency dust outbreaks along the western foothills of the Zagros Mountains, stretching from west of Iran, passing through Khuzestan and reaching to the coastal plain of the Persian Gulf. The Khuzestan Plain is an area with the most frequent dust events, while the coastal plain of the Persian Gulf is the second most affected area by dust. These three areas are mostly influenced by transported dust from external sources. Most notable external sources that often influence western Iran are Aljazera, dry marshlands of the Alluvial Plain of the Tigris–Euphrates basin and the Zubair Desert in Iraq, as well as the Ad-Dahna Desert in the Arabian Peninsula. The arid areas of Tabas and Sistan in east of Iran, however, are mostly influenced by arid lands in the interior of Iran. A drought that began in 2008 in Tabas and particularly severe prolonged droughts for the period of 2000–2008 in the Sistan area have exacerbated the effects of an already dry climate, contributed to increasing the rates of desertification over these areas.

Seasonality of dust events over Iran was also investigated. Our analyses show that the highest frequency of dust events is in summer, during which strong Shamal winds are nearly persistent over sources of dust in Iraq and the ‘wind of 120 days’ blows almost constantly over arid lands of eastern Iran. The second dust peak season has been observed in spring. However, the frequency of dust outbreaks has been substantially declined in autumn and winter with the least frequency in winter. During these
seasons, Shamal winds only occasionally blow over Iraq and the Persian Gulf, and eastern Iran is no longer under the influence of the ‘wind of 120 days’. Seasonal variations of the frequency of dust events found here are in agreement with the results of Alizadeh-Chooobari et al. (2014) using the MISR and Furman (2003) using a 21-year period synoptic data from 1973 to 1993. Monthly variations of the frequency of dust events were also examined. Results indicate that dust outbreaks over Iran start to increase in May, peak in July and weaken in September, similar to the results of Prospero et al. (2002) using the TOMOS data.

Our observational analyses indicate that the annual variability of dust events over Iran is remarkable, which is an indicator of climate change. However, our experiment demonstrates an overall rising trend of the frequency and intensity of Iran’s dust events in recent years, which not only has exacerbated air pollution problems, but can also play a key role in climate change of the region, although this latter hypothesis requires further studies. The rising trend and associated air pollution problems are particularly remarkable over the Khuzestan Plain and west of Iran.

The rising trend of dust events over Iran highlights recent environmental changes that have been made in Iraq, including drying of marshes, shrinkage of lakes and drainage of wetland areas for agriculture. Indeed, the rising trend of dust activity over western Iran is predominantly attributed to an increase in the frequency and intensity of dust and sand storms over Iraq’s deserts (Goudie and Mid delton, 2006; IAU, 2012). Desert areas occupy as much as 31% of Iraq, but following the recent environmental changes, additional proportion has been under the threat of desertification (IAU, 2012). As Iran is mostly affected by mineral dust that is coming outside of its borders, this makes the country vulnerable to environmental changes in neighbouring countries.
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Figure 10. (a) Monthly averaged and (b) inter-annual variations of both the frequency of dust events and number of dusty days averaged over 111 weather stations of Iran. The monthly values were averaged for a 20-year period from 1991 to 2010.

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