Spatial and temporal variations of satellite-based aerosol optical depth over Iran in Southwest Asia: Identification of a regional aerosol hot spot

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\textbf{ABSTRACT}

Knowledge of spatial and temporal variations of aerosols is essential for understanding the impacts of aerosols on air quality. Using aerosol products of the Collection 6 Terra MODIS Deep Blue, regional and temporal variations of aerosol optical depth (AOD) at 0.55\,μm in sixteen locations spread over nine different regions of Iran are studied for the period 2001–2015. Monthly means of dust column mass density in three locations of Iran are also obtained from the MERRA-2 dataset. It is found that southwestern Iran experiences the highest annual mean AOD, while other regions experience significantly lower values. Indeed, southwestern Iran is identified as a regional hot spot of aerosols in Southwest Asia, significantly contributing to degrading the air quality in the nearby regions. Annual mean AOD values in most of the other studied locations are between 0.08 and 0.12. High AOD over southwestern Iran is strongly related to frequent dust outbreaks over the region all year long, although AOD values are higher from April to August, during which dust events are more frequent over Southwest Asia. In other, mostly urban populated areas, maximum AOD values occur from mid-winter to mid-spring due to significant aerosol emissions from combustion of fossil fuels, combined with shallow atmospheric boundary-layer depths, which lead to the development of a concentrated mass of aerosols near the surface. On the other hand, minimum values of AOD occur from August to November. Trend analysis indicated that none of the regions of Iran has experienced a noticeable increase or decrease in AOD during 2001–2015.

1. Introduction

Arousing from both natural and anthropogenic sources (Streets et al., 2009), suspended aerosol particles in the atmosphere are among the most important components of the Earth’s atmosphere having major impact on the Earth’s radiation balance (Kaufman et al., 2002). Aerosols also degrade the regional air quality (Fuzzi et al., 2015; Alizadeh-Choobari et al., 2016a), adversely affect human health (Pope et al., 2002; Lelieveld et al., 2015) and contribute to the reduction of visibility in urban and industrialized areas (Sabetghadam et al., 2012; Wu et al., 2012; Wang et al., 2015). Thus, understanding the regional and temporal variations of aerosol optical depth (AOD) is essential to better quantify radiative effects of aerosols (IPCC, 2013). This is particularly important over land areas due to a larger spatio-temporal heterogeneity of aerosol properties over landmasses compared to that over oceans, primarily due to a heterogeneous source distribution over land. In addition, understanding regional and temporal variations of aerosols is important for developing effective mitigation measures to reduce local and regional air quality impacts.

Due to their high accuracy, ground-based measurements constitute a reliable method for characterizing the spatial distribution of atmospheric aerosols and their variation on monthly to interdecadal time scales (Xiang-AO et al., 2005; Gerasopoulos et al., 2011). However, due to sparse and short duration of surface observing networks in many regions of the globe, satellite remote sensing is the best available tool to study the spatial distribution and temporal variation of aerosols on the global and regional scales. Indeed, since the development of satellite remote sensing over the past few decades, their aerosol products have been extensively used for many studies conducted on the global (e.g. Kaufman et al., 2002; Gupta et al., 2008; Alizadeh-Choobari et al., 2014) and regional scales (e.g. Rajeev et al., 2000; Kim et al., 2007; Ramachandran and Cherian, 2008).

Different satellite platforms are available, and their retrieved data have been widely used to characterize the distribution of aerosols and their temporal variation. Some of these satellites are the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), the Advanced Very High Resolution Radiometer (AVHRR), the Total Ozone Mapping Spectrometer (TOMS), the Multiangle Imaging SpectroRadiometer (MISR) and the Deep Blue Aerosol Retrieval System (MODIS Deep Blue) (Kaufman et al., 2002; Lelieveld et al., 2015) and provide aerosol optical depth information at various wavelengths. Among these satellite-based aerosol products, MODIS Deep Blue aerosol optical depth product at 0.55\,μm is available as a free product from the NASA’s Earth Data Gateway. MODIS Deep Blue product includes information on aerosol optical depth, aerosol optical thickness, aerosol loading, aerosol type, aerosol fine mode fraction and aerosol water content at three different wavelengths (Kaufman et al., 2002; Lelieveld et al., 2015). However, for this study, aerosol optical depth at 0.55\,μm is exclusively used.

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(MISR) and the Moderate Resolution Imaging Spectro-radiometer (MODIS). The quality of aerosol products of these satellites was reviewed by Li et al. (2009) and Wang et al. (2017). Among others, good accuracy of the MODIS aerosol products has been confirmed (Remer et al., 2005; Ramchandran, 2007; Levy et al., 2010; Zhang and Reid, 2010).

Using these satellite platforms, temporal variation of AOD in many regions of the world has been previously examined (e.g. Massie et al., 2004; de Meij et al., 2010; Zhang and Reid, 2010; Ramchandran et al., 2012; Pozzer et al., 2015; Klingmüller et al., 2016). Massie et al. (2004) used TOMS dataset and found large increases in AOD over the coastal areas of China and the Ganges River basin in India between 1979 and 2000. Using Terra MODIS, Zhang and Reid (2010) identified an increasing trend in AOD over the Indian Bay of Bengal, the east coast of Asia, and the Arabian Sea for the period 2000–2009. Recently, Ramchandran et al. (2012) found that the annual mean AOD in several areas in India increased by more than 40% during the period 2000–2009. This significant enhancement was attributed to factors such as urbanization, an increase in the combustion of fossil fuels, biomass burning and forest fires. Klingmüller et al. (2016) used the aerosol products of MODIS and found a positive trend of AOD over large parts of the Middle East during the period 2001–2012. They argued that drying of the soil during the last decade due to increasing temperature and decreasing relative humidity have led to the increase of dust emissions and AOD over the Middle East. On the contrary, significant negative trends of AOD have been reported in several regions of the Europe and Northeastern America (de Meij et al., 2010). Using AOD from MODIS, results of Koukouli et al. (2010) also indicated a negative trend of AOD over the Southern Balkan/Eastern Mediterranean region during the period 2000–2006.

In spite of the good understanding of the spatial and temporal variations of AOD on the global scale and in many regions across the globe, aerosol properties have not been well analyzed over Iran. Iran landmass covers coastal regions, inland plains, semi-arid and arid regions (Alizadeh-Chooobari and Najafi, 2018) and two big mountain ranges, and bordered by several big sources of dust (Alizadeh-Chooobari et al., 2016b). Most of the regions of Iran experience different climatic features in different seasons of the year. These features introduce a large variability in aerosol characteristics on spatial and temporal scales over Iran. In spite of the importance of the subject, only few studies have been conducted to understand aerosol loading and its temporal variation over different regions of Iran. These studies have been mostly conducted only for a very limited period of time (e.g. Nakajima et al., 1996) or in few urban areas (Masoumi et al., 2013; Crosbie et al., 2014; Khoshsima et al., 2014a,b; Rashki et al., 2014). Thus, our understanding of the aerosol distribution and its variation over time in different regions of Iran is extremely limited, emphasizing the requirement for further new investigations.

The present study, therefore, aims to investigate the spatial and temporal variations of AOD over different regions of Iran. To this end, the obtained level-3 Collection 6 MODIS Deep Blue dataset of the NASA’s Terra satellite are analyzed over sixteen different locations of Iran for the period from March 2000 to December 2015. These locations are capitals of provinces and they are spread over nine different regions of Iran. They are selected in a way that all parts of the country can be covered. The reason for choosing the capitals of provinces is that they are urban centers, industrialized in some regions and have medium to dense population, all of which contribute to the high AOD values.

2. Data and methods

Monthly means AOD over land at 0.55 μm with a 1° × 1° resolution in sixteen locations spread over nine different regions of Iran were obtained from the level-3 Collection 6 MODIS Deep Blue dataset of the NASA’s Terra satellite. These locations are Urmia and Zanjan in northwestern, Kermanshah in western, Ahwaz and Bushehr in southwestern, Sari, Tehran and Semnan in northern, Isfahan and Yazd in central, Shiraz and Bandar Abbas in southern, Mashhad in northeastern, Birjand in eastern, and Kerman and Zahedan in southeastern Iran. Geographic locations of these regions are shown in Table 1 and Fig. 1. Aerosol optical depth derived from MODIS was compared against Aerosol Robotic Network (AERONET) sun photometer observations in Zanjan by Khoshsima et al. (2013). Their comparison showed a significant correlation between the two dataset, with the correlation coefficient of 0.87. Validation of Collection 6 of the MODIS Deep Blue against AERONET observations was also recently conducted by Sayer et al. (2013, 2014).

MODIS detectors measure 36 spectral bands in a wide range between 0.405 and 14.385 μm; the measurements that are used to derive spectral AOD and several other aerosol products over both land and ocean (Remer et al., 2008). The uncertainty of the AOD products of MODIS falls between ±0.03 ± 0.05 μm over ocean and ±0.05 ± 0.15 μm over dark land, where r denotes the retrieved AOD (Remer et al., 2005). Aerosol optical depth over land surfaces in different locations of Iran was retrieved using the Deep Blue algorithm, which was developed by Hsu et al. (2004) to characterize the properties of aerosols over bright land surfaces, and recently revised by Hsu et al. (2013) to accurately retrieve aerosol properties over the entire land areas. Validation of the Collection 6 of the MODIS Deep Blue over the Mediterranean region was performed by Georgoulis et al. (2016a,b).

To examine contribution of dust outbreaks in high AOD values over the regions that are frequently affected by dust events, monthly means of dust column mass density in three locations of Iran were obtained from the second Modern Era Retrospective-analysis for Research and Applications (MERRA-2) dataset (Gelaro et al., 2017). This dataset has been produced using the Goddard Earth Observing System atmospheric model version 5 (GEOS-5) data assimilation system based on satellite observations of NASA’s Earth observing system. This dataset with the horizontal grid resolution of 0.625° × 0.5° is freely available from 1979 to the present (http://giovanni.sci.gsfc.nasa.gov/).

3. Results and discussions

3.1. Annual mean aerosol optical depth

The 15-year (2001–2015) annual averages of aerosol optical depth (AOD) at 0.55 μm and their standard deviations in sixteen locations of Iran obtained from the MODIS Deep Blue dataset of the NASA’s Terra satellite. Latitudes, longitudes and elevations (above mean sea level) of the locations are also provided.

<table>
<thead>
<tr>
<th>Region</th>
<th>Annual mean AOD</th>
<th>Std. deviation</th>
<th>Location</th>
<th>Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urmia</td>
<td>0.08</td>
<td>0.05</td>
<td>37.1</td>
<td>45.1</td>
</tr>
<tr>
<td>Zanjan</td>
<td>0.07</td>
<td>0.05</td>
<td>36.1</td>
<td>48.0</td>
</tr>
<tr>
<td>Kermanshah</td>
<td>0.1</td>
<td>0.09</td>
<td>34.0</td>
<td>47.2</td>
</tr>
<tr>
<td>Ahwaz</td>
<td>0.36</td>
<td>0.16</td>
<td>31.0</td>
<td>48.1</td>
</tr>
<tr>
<td>Bushehr</td>
<td>0.17</td>
<td>0.08</td>
<td>28.1</td>
<td>50.1</td>
</tr>
<tr>
<td>Sari</td>
<td>0.12</td>
<td>0.05</td>
<td>36.1</td>
<td>53.0</td>
</tr>
<tr>
<td>Tehran</td>
<td>0.1</td>
<td>0.04</td>
<td>35.1</td>
<td>51.0</td>
</tr>
<tr>
<td>Semnan</td>
<td>0.12</td>
<td>0.04</td>
<td>35.1</td>
<td>53.0</td>
</tr>
<tr>
<td>Isfahan</td>
<td>0.1</td>
<td>0.05</td>
<td>32.1</td>
<td>51.1</td>
</tr>
<tr>
<td>Shiraz</td>
<td>0.08</td>
<td>0.03</td>
<td>29.1</td>
<td>52.1</td>
</tr>
<tr>
<td>Bandar Abbas</td>
<td>0.16</td>
<td>0.05</td>
<td>27.0</td>
<td>56.0</td>
</tr>
<tr>
<td>Mashhad</td>
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<td>0.02</td>
<td>36.0</td>
<td>59.1</td>
</tr>
<tr>
<td>Birjand</td>
<td>0.08</td>
<td>0.03</td>
<td>32.1</td>
<td>59.0</td>
</tr>
<tr>
<td>Yazd</td>
<td>0.12</td>
<td>0.05</td>
<td>31.1</td>
<td>54.0</td>
</tr>
<tr>
<td>Kerman</td>
<td>0.13</td>
<td>0.04</td>
<td>30.0</td>
<td>56.1</td>
</tr>
<tr>
<td>Zahedan</td>
<td>0.09</td>
<td>0.04</td>
<td>29.0</td>
<td>60.1</td>
</tr>
</tbody>
</table>
emissions and burdens varies significantly over different regions of Iran. Ahwaz and Bushehr in southwestern Iran have the highest annual mean AOD of 0.36, 0.17, respectively, with standard deviations of 0.16 and 0.08. As standard deviations were calculated based on deviation of each month averaged AOD from the annual mean AOD, high standard deviations in Ahwaz and Bushehr indicate that monthly AODs are spread out over a wide range of values. In other words, monthly variations of AOD are prominent over Ahwaz and Bushehr. As previously shown and discussed by Alizadeh-Choobari et al. (2016b), high frequency of dust events over southwestern Iran is the leading contributing factor in the observed high annual mean AOD in this region, although aerosol emissions from combustion of fossil fuels have also partly contributed. In this regard, high standard deviations on the annual mean AOD can be attributed to more frequent dust events over the region from April to August (Alizadeh-Choobari et al., 2016b), as later further discussed. The 15-year annual mean AOD is also relatively high over Bandar Abbas with the value of 0.16 and standard deviation of 0.05. High AOD in this coastal region is due to the fact that in occasions of favorable wind conditions, mineral dust and sea salt are present in this location. Our argument that high AOD in southwestern Iran (Ahwaz and Bushehr) and Bandar Abbas is related to high dust loads can be clearly seen in Fig. 2. The figure shows monthly variations of AOD and dust column mass density over the three discussed locations for the period from March 2000 to December 2015, as well as correlation between AOD and dust column mass density over each of the locations. Our analysis indicate that correlations between AOD and dust outbreaks are statistically significant (at p < 0.01) at all three locations. The correlation is particularly significant in Ahwaz, such that as can be seen in Fig. 2, dust column mass density and AOD are closely overlapped during the studied period.

Annual mean AOD values over other locations of Iran are significantly lower than those observed over the three discussed locations, mostly ranging between 0.08 and 0.12. Out of the sixteen locations, Zanjan in northwestern Iran has the lowest annual mean AOD of 0.07, with the standard deviation of 0.05. This location is less densely populated and is far from major sources of dust; thus contribution of anthropogenic air pollution and natural/anthropogenic dust aerosols to AOD is minimal. Relatively high annual averages of AOD can be observed in Kerman (0.13), Yazd (0.12) and Semnan (0.12) which are partly caused by the fact that these regions are occasionally influenced by dust events that mostly originate from local sources (Alizadeh-Choobari et al., 2016b). This is particularly the case during spring when combination of dry conditions and relatively strong wind speeds favour formation of dust storms. The other location with a relatively high AOD is Sari (0.12). As Sari is close to the Caspian Sea, its relatively high annual mean AOD could have been caused by the suspended sea salt in its atmosphere.

3.2. Monthly and seasonal variations in aerosol optical depth

Seasonal variability of AOD in sixteen different locations of Iran is shown in Fig. 3. Aerosol optical depth in Ahwaz is significantly high during all seasons, with the values of 0.27 in winter (December-January-February), 0.3 in autumn (September-October-November), 0.43 in spring (March-April-May) and 0.49 in summer (June-July-August). Aerosol optical depth values in spring and summer are significantly higher than those in autumn and winter. However, even the minimum value of AOD in Ahwaz which occurred in winter is greater than the maximum AOD values observed in all other locations of Iran, suggesting that southwestern Iran is indeed a regional hot spot of aerosols. After
Ahwaz, Bushehr which is also located in southwestern Iran experienced the second highest AOD, with the peak value of nearly 0.2 in spring and summer. As mentioned earlier and can be inferred from Table 2, the high AOD over southwestern Iran is related to frequent dust events over this region.

Alizadeh-Choobari et al. (2016b) argued that from mid-spring to late summer, thermal lows develop in the interior of Iran and Saudi Arabia and a high-pressure ridge forms over the Mediterranean region that extends well into northern Saudi Arabia. A strong pressure gradient between the thermal lows and the high-pressure ridge is responsible for the establishment of northwesterly summer Shamal winds. The summer Shamal winds cause dust outbreaks to occur over the potential sources of dust in the region, including the Alluvial Plain of the Tigris-Euphrates basin and the Zubair Desert in Iraq, and some other desert lands in Syria and Kuwait (Alizadeh-Choobari et al., 2016b). The entrained dust aerosols by the summer Shamal winds are subsequently transported to southwestern Iran; thus significantly degrade the air quality and cause the observed high AOD. Contribution of dust events in high AOD values over Ahwaz and Bushehr during spring and summer can be clearly seen in Table 2 which shows that peak concentrations of dust over the region occur from March to August. Higher AOD values in spring and summer over Bandar Abbas in southern Iran compared to the values in other seasons are also attributed to more frequent dust outbreaks over the region during these seasons. As Table 2 shows, the peak dust activity over Bandar Abbas is from April to August.

The observed relatively high AOD over Ahwaz in southwestern Iran during autumn and winter is also mostly caused by dust outbreaks over some local sources and transported dust from desert lands of Syria, Iraq and Kuwait. This can be clearly seen in Table 2, which shows relatively high dust column mass density during autumn and winter. In these
seasons, the discussed pressure gradient collapses. Instead, the so-called winter Shamal winds occasionally influence the region which 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; Alizadeh-Choobari et al., 2016b). The winter Shamal winds, however, are less frequent and occasionally accompanied with precipitation, causing dust outbreaks to be less frequent in southwestern Iran compared to the more frequent dust events during the dry seasons of spring and summer. Indeed, as indicated in Table 2, minimum values of dust column mass density over Ahwaz and Bushehr have been observed from October to February. Accordingly, AOD values over southwestern Iran are significantly lower during autumn and winter. As dust outbreaks are the dominant contributing factor in Bandar Abbas too, the minimal dust column mass density over this location from October to February (Table 2) is in line with the observed lower AOD values in autumn and winter.

Aerosol optical depth over most other studied locations is generally the highest in winter and lowest in autumn (Fig. 3). As these locations are mostly urban populated areas, the observed peak AOD in winter is caused by anthropogenic air pollution. Low temperatures and shallow atmospheric boundary layer depths in winter combined with anthropogenic aerosol emissions from combustion of fossil fuels cause development of a concentrated mass of aerosols near the surface, which may partly contribute to the observed high AOD over the region. Indeed, a shallow boundary-layer depth in winter leads to trapping of the pollutants near the surface, which otherwise could have got ventilated to downwind regions. Contribution of shallow boundary-layer depth in the increase of AOD due to enhancement of aerosol concentration near the surface was shown in several previous studies (e.g. Wang and Christopher, 2003; Luo et al., 2014).

Monthly averaged variation of AOD over different locations of Iran are shown in Fig. 4. The averaged values are for the period from March 2001 to December 2015. Both regional and monthly variation in individual locations are evident. The most noticeable monthly variation of AOD occurred over Ahwaz, with values ranging from 0.21 in November and December to 0.56 in July, quite similar to the monthly variation of dust column mass density over the same location, with the minimum value in December (0.23 g m\(^{-2}\)) and the maximum value in July (0.73 g m\(^{-2}\), Table 2). On the other hand, the least monthly variation of AOD occurred over Mashhad and Birjand, with values ranging from 0.06 to 0.1.

Maximum values of AOD over Ahwaz and Bushehr occurred from March/April to August, quite similar to the monthly variation of dust column mass density for which maximum values over these locations occurred from April to August (Table 2). This reinforces our previous argument that dust events are the primary factors in the observed high AOD values over southwestern Iran during the dry months of the year. Minimum AOD values occurred from November to January over Ahwaz, in November and January over Bushehr, and in November over Bandar Abbas, in association with the minimum dust activity over these locations (Table 2). This is in line with the observational analysis conducted by Alizadeh-Choobari et al. (2016b). They indicated that the frequency of dust events over Ahwaz reaches to the least from November to January. On the other hand, maximum AOD values over most other locations of Iran, that are less affected by dust outbreaks, is from mid-winter to mid-spring during which the anthropogenic air pollution combined with relatively low temperatures and shallow atmospheric boundary-layer depths are the leading contributing factors. Minimum AOD values over these regions mostly occur from late summer (August) to late autumn (November) during which a greater development of the atmospheric boundary-layer depth allows more effective ventilation of the near-surface atmospheric pollutants.

### 3.3. Interannual variation in aerosol optical depth

Annual averages of AOD anomalies over the sixteen locations of Iran for the period 2001–2015 are shown in Fig. 5. High interannual variability of AOD is particularly evident over Ahwaz, Bushehr and Bandar Abbas, all of which are influenced by dust outbreaks. The annual means of AOD over Ahwaz, Bushehr and Bandar Abbas during the period 2001–2015 were in the range of 0.25–0.53, 0.1–0.31 and 0.12–0.21, respectively (not shown). High interannual variability of AOD over these locations can be due to the fact that frequency and intensity of dust events are highly related to the dry and wet conditions controlled by interannual natural climate variability, and this needs to be investigated. Aerosol optical depth over other locations of Iran generally show less interannual variations, which reinforces our previous argument that in these urban areas anthropogenic air pollution, which does not change significantly from year to year, is the dominant contributing factor in the observed AOD.

Annual means of AOD over both Ahwaz and Bushehr show relatively higher values from 2008 to 2012. This could have been caused by the occurrence of three La Niña events during this period (2007–08, 2010–11 and 2011–12) because La Niña is generally associated with dry conditions and more dust events over the Middle East (Kumar and Ouarda, 2014; Alizadeh-Choobari et al., 2018). A rapid reduction of AOD over Ahwaz and Bushehr from 2009 to 2010 (although anomalies have still remained positive) could have been caused by the impact of a moderate El Niño event occurred in 2009–10. El Niño is generally associated with wet conditions and less potential for the occurrence of dust outbreaks over the Middle East (Kumar and Ouarda, 2014). Further investigation is required to fully unravel the possible linkage between the El Niño-Southern Oscillation (ENSO) and variability of AOD over different locations of Iran.

Fig. 5 indicates that most of the studied locations of Iran have experienced very small positive trends in AOD during the studied period from 2001 to 2015 (except in Kermanshah and Zahedan over which small negative trends can be observed). The positive trend of AOD over Ahwaz is a bit higher than those observed in other locations, which may suggest that dust activity has increased over this region. However, the increasing and decreasing trends are very small and not statistically significant, implying that annual mean variations in AOD over different regions of Iran do not show any noticeable increase or decrease during the 15-year period. Both similar and different results have been found in some other regions nearby Iran. For example, Ramachandran and Cherian (2008) found that annual mean AOD in different regions of India did not change noticeably during the period 2001–2005. In contrast, Babu et al. (2013) used a longer time series of dataset (up to 25 years in some stations) and found that AOD significantly increased over India for the period 1988–2012. We argue that the period of the available satellite observations used in the present study is not long enough to capture long-term trends.
enough for a trend analysis. Satellite data with a longer period of time are required to undertake trend analyses and provide robust conclusions in terms of changes in the annual mean variations of AOD.

4. Conclusions

Using the MODIS Deep Blue dataset of the NASA’s Terra satellite from March 2001 to December 2015, monthly, seasonal and annual variations of AOD in sixteen populated locations spread over nine different regions of Iran are analyzed. It is found that southwestern Iran is an aerosol hot spot, which is consistent with the results of Alizadeh-Choobari et al. (2016b). Indeed, among other regions of the country, southwestern Iran experienced the highest AOD throughout the year, which caused by frequent dust outbreaks nearly all year long. As a semi-arid to arid region, southwestern Iran is influenced by large aerosol sources. Apart from some local sources of dust, this region is bordered by several important sources of dust on the northwestern, western and southwestern sides (Alizadeh-Choobari et al., 2016b). In spite of the observed high AOD values throughout the year, much more frequent dust events occur in southwestern Iran during spring and summer, causing the region to experience significant seasonal variation in AOD. This is caused by the strong Shamal winds blow over the region during the warm seasons of the year (spring and summer) during which the region experiences its dry season. A decrease in the frequency of the Shamal winds and the fact that southwestern Iran experiences its wet season in autumn and winter contribute to the observed significant reduction of AOD during autumn and winter (Alizadeh-Choobari et al., 2016b). Monthly, seasonal and annual means of AOD over other regions of Iran are significantly lower than those observed in southwestern Iran.

In these urban populated areas, maximum AOD values generally occur from mid-winter to mid-spring, whereas minimum values occur from late summer (August) to late autumn (November).

In terms of trends of AOD, none of the regions of Iran has experienced a noticeable increase or decrease in AOD during 2001–2015. Using ground-based measurements with a longer period of time, Alizadeh-Choobari et al. (2016b) found that the frequency of dust events has significantly increased over southwestern Iran in recent years of the previous decade. However, their ground-based observations were not extended beyond 2010; thus possible changes in the frequency of dust events in more recent years have remained unexplored. We argue that satellite data with a longer period of time that extend to more recent years are required to identify the possible changes in the annual mean AOD in different regions (particularly southwestern) of Iran.

The present study has examined the regional and temporal variations of AOD across Iran. However, the anthropogenic and natural fraction of aerosols in different locations of Iran is remained to be investigated. In addition, size, chemical composition and the type of aerosols over Iran have not yet been investigated. These aspects of aerosols are particularly important because radiative forcing of aerosols depends on their size, abundance and chemical composition, and differs for different aerosol species (Ramachandran et al., 2012). As there are some uncertainties in aerosol retrievals from satellites (Babu et al., 2013), dense surface aerosol observing networks are required to better examine spatio-temporal variation of aerosols over different regions of Iran.
Fig. 5. Interannual variations (solid lines) in anomalies of aerosol optical depth and their trends (dashed lines) over sixteen different locations of Iran for the period 2001–2015. Anomalies were calculated relative to the period 2001–2015. Positions of the locations are shown in Fig. 1. Note the different Y axis scales in panels (d) and (e) compared to other panels.

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