Discrimination of aerosol types over the Tehran city using 5 years (2011–2015) of MODIS collection 6 aerosol products

Mohammad Rezaei¹ · Manuchehr Farajzadeh¹ · Tero Mielonen² · Yosef Ghavidel¹

Received: 9 March 2018 / Accepted: 4 November 2018 / Published online: 23 April 2019
© Springer Nature Switzerland AG 2019

Abstract

Purpose Tehran, Iran, is an interesting location for aerosol studies because it is affected by anthropogenic pollution and desert dust aerosols. The aim of this study was to discriminate the aerosol types using satellite data over the city.

Method The study was performed using Level-2 daily Aerosol Optical Depth (AOD) and Ångström Exponent (AE) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on board the Terra and Aqua satellites for the years 2011 to 2015. As the Deep Blue (DB) AE retrievals are more reliable than the Dark Target (DT) AE retrievals, the study was performed using DB data.

Results The number of granules with successful retrievals (at least in two pixels with AODs >0.2 over Tehran with high quality assurance) was 200, which indicates that aerosols could be observed in 5.47% (200 from 3652 of Terra and Aqua granules) of the overpasses during the study period. The maximum and minimum values of AOD occurred during May (0.32 ± 0.27) and August (0.18 ± 0.07), respectively. Based on the AOD vs. AE data, aerosols were classified into three different categories: urban/industry (UI), Desert Dust (DD) and Mixed (Mix). To improve the accuracy of the aerosol classification, the analysis was limited to retrievals with AOD values larger than 0.2. The DD, UI and Mix types had 48.5%, 30.5% and 21% contribution in the aerosol days, respectively.

Conclusions The maximum DD frequency was observed in the spring and summer seasons, while the UI type had its maximum during the cold season. The AOD of the DD type (over Tehran) correlated well with the AOD observations done at the Aerosol Robotic Network (AERONET) site in Zanzan (300 km northwest from Tehran). For the UI type, no relationship with the AERONET AOD was detected. This gives confidence in our aerosol typing as the contribution of dust in the aerosol load is mainly from long-range transport, whereas the urban aerosols originate from local sources. Back trajectories ending in Tehran show that the northeast and west trajectories are two main transport routes for the dust to the study area.

Keywords Aerosol types · MODIS · Deep blue algorithm · Back trajectory · Tehran

Introduction

Atmospheric aerosol particles have direct (by scattering and absorbing solar radiation) and indirect (by acting as cloud condensation nuclei) effect on the climate system [2, 11, 46, 58, 63]. These effects are highly variable due to variability in aerosol sources, synoptic conditions (air

mass changes), and meteorological factors (humidity, precipitation). Consequently, the concentrations and properties of atmospheric aerosol populations are highly variable in space and time [8, 35, 43, 61].

Classification of aerosols into different types is an important task since their climate effects differ considerably from one type to another [19]. Typically, aerosols have been classified into four major aerosol types: soil/desert dust, carbonaceous/biomass burning, sulfate/urban/industrial and sea salt/maritime aerosols (e.g. [19, 29]).

The discrimination of the aerosol types can be achieved by means of the widely used method of relating aerosol load (i.e. Aerosol optical depth, AOD) and particle size (i.e. Ångström exponent, AE) ([14, 27, 30, 36, 47, 49, 64]). Kaskaoutis et al. [30] separated the presence of three aerosol types over Athens

✉ Manuchehr Farajzadeh
farajzam@modares.ac.ir

¹ Department of Climatology, Tarbiat Modares University, Tehran, Iran

² Finnish Meteorological Institute, Kuopio Unit, Kuopio, Finland

on seasonal basis based on the combination of AOD at 550 nm (AOD_{550}) and fine mode fraction (FM) data. They mentioned that the AOD_{550} –FM plot qualitatively indicates the amount and dimension of the observed aerosols. However, a more robust classification of aerosol types could be done with information on the absorption capabilities of the aerosols (e.g. single scattering albedo, absorption AOD, the imaginary part of the refractive index). Unfortunately, not enough high-quality absorption data is currently available from space borne sensors.

Tehran is an interesting location for aerosol studies, due to contributions from dust from the local and neighboring desert areas [6, 16, 24, 28, 57] and the urban/industry pollutions due to rapid urbanization [21, 53]. Several studies reported the sources and temporal variations of ambient Particulate Matter (PM) over Tehran using ground-based data. Halek et al. [17, 18] showed that the monthly average of PM_{10} in Tehran is high in autumn and low in spring. PM_{10} mass concentration increases almost twofold and $PM_{2.5}$ and $PM_{1.0}$ almost three times in cold season compared to the warm season. Givehchi et al. [16] mentioned that the deserts in Iraq and Syria are the main contributing dust sources which comprise more than 90% of the dust related PM_{10} concentrations in Tehran. Arhami et al. [5] revealed that major sources of $PM_{2.5}$ over Teheran are organic matter (35%), dust (25%), non-sea salt sulfate (11%), elemental carbon (9%), ammonium (5%), and nitrate (2%). They mentioned that the contributions of different components varied throughout the year. For example dust component that varied from 7% in the cold season to 56% in the warm season.

The point to be noted is that the ground-based measurements require expensive instrumentation or permanent automatic monitoring stations [1]. However, the main advantage of satellite data is the relatively low cost of accessibility with continuous temporal and spatial coverage [51]. Satellite remote sensing data are needed to understand better the roles of the different aerosol sources [59]. Furthermore, since there is no Aerosol Robotic Network (AERONET) sunphotometer measurement site in Tehran, the satellite data provide a good opportunity for discrimination of main aerosol types (coarse and fine mode) over the city. Satellite data can be a powerful tool for aerosol monitoring [32].

The aim of this study was to identify dust and urban pollution aerosols in Tehran, Iran. We used AOD and AE from the MODIS products including both the Dark Target and the Deep Blue algorithms for the years 2011–2015. The results are presented in four main sections. First, AOD and AE from the MODIS DT and DB aerosol retrievals and AERONET observations were compared over Zanjan (the closest AERONET site to Tehran) to confirm that the MODIS retrievals are suitable for aerosol typing in this region. In the second step, temporal variation of aerosol properties was investigated over

Tehran. Next, using the AOD vs. AE comparison, all observations were classified into three aerosol types: Urban/Industry (UI), Desert Dust (DD) and Mixed (Mix). Then, each aerosol type was compared with other data sets including AERONET and monthly frequency of dust events. Finally, HYSPLIT trajectory model was used for the identification of potential sources of desert dust.

Study area

Tehran is the capital of Iran and is located in the northern part of the country. The study area covers an area within longitudes $51^{\circ} 6' - 51^{\circ} 38' E$ and latitudes $35^{\circ} 34' - 35^{\circ} 51' N$. Tehran is a mountainside city with an average altitude of 1300 m above the sea level, located on the southern slopes of the Alborz mountain range. The analyzed spatial domain includes 22 district regions in Tehran with an area of 730 km². The elevation of the city varies between 2364 m in the north and 1004 m in the south. Figure 1 represents the city's geographic location. The metropolitan area of Tehran is inhabited by 15 million people (Density = 12,896 habitant/km²; Wikipedia, 2018).

Data and methodology

In this study, we used several data sources to discriminate the aerosol types over Tehran, compared them with pollution data and identified possible dust sources in the vicinity of the city.

MODIS aerosol data

Aerosol data are available from the Moderate Resolution Imaging Spectroradiometer (MODIS; [52]) Level 1 and Atmosphere Archive and Distribution System at <http://ladsweb.nascom.nasa.gov/>. In this study, we used daily collection 6 level-2 AOD and AE data with highest quality assurance (QA = 3) from both Terra and Aqua platforms for the years 2011 to 2015 (1826 days). These data have been produced with the spatial resolution of 10×10 km² (at nadir). For the MODIS aerosol retrievals, there are three operational algorithms: the ocean algorithm [60], the Dark Target algorithm (DT; [33, 38]) and the Deep Blue (DB; [22, 23, 54]). Since the DT algorithm is designed for vegetated surfaces it is less accurate than the DB algorithm over bright surfaces such as deserts ([39]), we assume that the DB is more suitable for Tehran environment. However, we extract both DT and DB products over Tehran for the years 2011 to 2015. The DT product does not include AE data in collection 6, because the algorithm has little quantitative skill in the retrieval of aerosol size. However, the AE values can be obtained using

Fig. 1 Geographical location of Tehran in Iran along with elevation (top, right) and landscape from Google Map (bottom)

the AODs at the 460 and 650 nm wavelengths [38]. Therefore, we calculated the AE values from the DT retrievals using the Ångström power law;

$$AE_{470-650} = -\frac{\log \frac{AOD_1}{AOD_2}}{\log \frac{470}{650}} \quad (1)$$

Where, AOD_1 and AOD_2 are optical depths at 470 and 650 nm, respectively.

Regarding the Tehran area (730 km²), 7 pixels encompass the whole city. The daily AOD and AE values were calculated for the study area by averaging the pixel-level values if there were more than 2 retrievals available. Next, using the AOD vs. AE method all observations were classified into three aerosol types. The AOD vs. AE thresholds applied in this study were from the study by Kaskaoutis et al. [29].

In overall, AE value is recognized to be erroneous for small AOD. The accuracy of AOD becomes better in values higher than 0.2 [25]. Sayer et al. [54] mentioned, that the DB retrievals of AE's are reliable only for cases with high AODs ($AOD > 0.3$), thus in the present study, we

lowered the limit to 0.2 to get better statistics because the higher limit removed most of the data from the analysis. Consequently, in the DB retrievals, observations with $AOD > 0.2$ and $AE < 0.5$ were considered as desert dust (DD), observations with $AOD > 0.2$ and $AE > 1.5$ as urban/ industry aerosol (UI), and observations with $1.5 > AE > 0.5$ as mixed aerosols (Mix).

Monthly dust event frequency

The monthly frequency of the meteorological codes associated with dust (including 6, 7, 8, 9, 30, 31, 32, 33, 34, 35, and 98) was obtained from the Tehran meteorology station in the period 2011 to 2015. The Pearson correlation coefficient was used to quantify the relationship between the monthly dust events frequency from weather stations and the monthly frequency of each aerosol type. To confirm our dust type classification, the monthly frequency of the dust events should have a positive correlation coefficient with the frequency of monthly desert dust aerosols.

AERONET data

The Aerosol Robotic Network (AERONET) of sun photometers measures the spectral AOD with low uncertainty (0.01–0.02) and high temporal resolution (about 15 min) under cloud-free conditions [20]. In this study, AERONET level 2 data (AOD at 550 nm) were used for the years 2011–2013 to compare with the MODIS aerosol products by the Pearson correlation coefficient. The only Iranian AERONET station is in Zanjan city which is located in the northwest part of the country, about 300 km northwest from Tehran. Our assumption is that if the MODIS AOD and AE products are in agreement with the AERONET data in Zanjan, they will also be usable in Tehran. In addition, despite the relatively long distance between Tehran and Zanjan, both locations are affected by the same dust sources. Based on the previous studies Iraq and Syria are the main contributing dust sources over both Tehran and Zanjan [16, 34]. Therefore, we expect that for the dusty days the AOD from AERONET (at Zanjan) and MODIS (over Tehran) should be in reasonable agreement. On the contrary, we expect that during the days of urban pollution in Tehran, the agreement between AOD of MODIS (Tehran) and AERONET (Zanjan) will be low because the pollution events are limited to a smaller region.

Air mass back trajectory

The analysis of back trajectories is a widely used method for studying how atmospheric compounds and aerosols are transported from a source to receptor sites [62]. In order to identify possible desert dust sources over Tehran, five-day isentropic back trajectories were computed using the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory; [13]) model of the National Atmospheric and Oceanic Administration (NOAA).

To show the main trajectories, K means clustering method was used for the combining of similar trajectories. Following the study of Kaskaoutis et al. [32] air mass back trajectories were calculated at three different altitudes: 500 m, 1500 m and 4000 m. The lowest altitude (500 m) was selected to give representative origins of air masses near the surface. The middle altitude (1500 m) serves as a representative height for the boundary layer in which the majority of the aerosols is present, and the highest altitude (4000 m) represents the free troposphere, where the Saharan dust is usually transported. The AOD average and seasonal frequency related to the each main pathway were computed.

Results and discussion

Evaluation of the MODIS retrievals

In this section, a comparison of MODIS and AERONET AODs and AE are presented for the years 2011–2013 over Zanjan. Although there are several gaps in the AERONET data over Zanjan (for example from Feb to Jul 2012), we were able to collocate 83 granules from the DT algorithm and 41 granules from the DB algorithm with the AERONET data.

The correlation between the DT and AERONET AODs was substantial ($R^2 = 0.71$) (Fig. 2a). However, the DT algorithm shows an overestimation in comparison with the AERONET values. The average DT and AERONET AODs were $0.38 (\pm 0.17)$ and $0.24 (\pm 0.15)$, respectively, and the Root Mean Square Error (RMSE) of the DT AOD was 0.17. From the 83 DT granules, 53 were from the summer season. In addition, there were no DT data between November and March. Dust exhibits a summertime pattern in Zanjan [40] and it is the most dominant aerosol type over the Zanjan [10]. Consequently, the DT algorithm appears to be able to retrieve the dust AOD reasonably well in this region. Unlike the DT AOD, the comparison between DT and AERONET AE anomaly (Fig. 2c) does not show a substantial relationship ($R^2 = 0.02$). The average DB AOD (0.32 ± 0.32) is significantly smaller than the AERONET AOD (0.55 ± 0.40). According to Sayer et al. [55], the DB AOD is typically underestimated and the DT overestimated when compared with AERONET observations. Our comparisons showed that both DT and DB AODs were overestimated in Iran. The analysis by Sayer et al. [54] did not include any AERONET stations from Iran or the neighboring countries which might explain the difference between the results. In low-AOD conditions the uncertainties in the AERONET AE are non-negligible and the DB algorithm lacks information on AE and therefore limits the retrieved AE values to less than 1 over bright surfaces [54]. As the aim of this work is to classify aerosol types using AE retrievals, we wanted to avoid highly uncertain retrievals and limited the comparison between AERONET and DB to AERONET AOD values larger than 0.3. From 41 granules of the DB, 29 granules have AOD value less than 0.3 (red points in Fig. 2b), which have insignificant relation with AERONET AOD ($R^2 = 0.07$). This is in line with Sayer et al. [54] who also found that majority (75.4%) of the DB AOD data was from cases with low aerosol loadings. For the AERONET AODs larger than 0.3, the correlation coefficient is substantial ($R^2 = 0.77$) (blue points in Fig. 2b). Scatter plot between the DB AE versus AERONET AE (Fig. 2), shows relatively high correlation coefficient ($R^2 = 0.41$). In granules with high AOD (> 0.3), the average AE anomaly for DB and AERONET site are -0.49 ($AE = 0.115$) and -0.76 ($AE = 0.112$), respectively. Based on this comparison,

Fig. 2 Comparison between MODIS (Terra and Aqua) and AERONET aerosol properties over Zanzan. **a** DT and AERONET AOD. **b** DB and AERONET AOD. **c** DT and AERONET AE anomaly. **d** DB and AERONET AE anomaly

our analysis to discriminate aerosol types over Tehran has been done with the DB aerosol products. However, the DT AOD values are suitable for aerosol climatology over Tehran.

Monthly variation of aerosol properties in Teheran

When the frequency of observation per month from the DB and DT retrievals are compared, it is clear that the DB observations ($N=423$) are distributed over all months, while the DT observations ($N=147$) are confined to the summertime months only (Fig. 3a). During October to March, no DT retrievals are available while the maximum frequency is observed during May ($N=41$). In the DB data, the maximum and minimum frequencies of the observations occur during June ($N=59$) and September ($N=18$), respectively.

Figure 3b and c shows the monthly mean variation of the DT AOD and AE from the years 2011–2015 over the study area. For the months with data, the AOD value is higher than 0.5 and AE is lower than 0.7 (with low standard deviation) which indicates that in these retrievals the dust aerosol model was always selected.

With the DB algorithm, the maximum and minimum values of AOD were obtained in May (0.32 ± 0.27) and August (0.18 ± 0.07), respectively (Fig. 3b). Even the minimum value is larger than the satellite-based global mean AOD value of 0.12 ± 0.04 [50]. Similar temporal patterns have also been found in other regions of the world [34, 36, 59]. The monthly variation of AE (Fig. 3c) shows almost an opposite temporal pattern from the AOD. The maximum AE value (1.2 ± 0.5) was in November and the minimum (0.15 ± 0.4) in June. These characteristics indicate that the aerosols are coarse

(dust) during summer, and smaller (pollution) during autumn and winter seasons. The summer observations are most likely influenced by desert dust transport from the arid areas in the vicinity of Tehran. In addition, Iran experiences the rainy seasons in autumn and winter and due to precipitation and atmospheric circulation, the AOD values are then smaller [48]. Based on these results and the comparisons with the AERONET observations, we decided to use the DB retrievals in the aerosol classification. Although the DT AODs were in better agreement with the AERONET observations, the data set was limited to summer months only and the AE values were not as reliable as in the DB retrieval. Compared to the AERONET AODs, the DB AODs were biased high but the absolute values are not that crucial for the classification scheme because we only considered observations with AODs over 0.2 and the type classification was based solely on the AE values ($AE < 0.5$ indicates dust, $0.5 < AE < 1.5$ mixed aerosols and $AE > 1.5$ urban pollution).

Classification of aerosols over Tehran

For the years 2011–2015 we found 200 dB granules which had at least 2 pixels with AODs > 0.2 over Tehran. This indicates that aerosols could be observed only in 5.47% (200 from 3652 of Terra and Aqua granules) of the granules during the study period. All of these observations were classified into three categories using the AE limits from Kaskaoutis et al. [29], DD, UI, and Mix. The scatter plot of AOD vs. AE in Fig. 4 shows each aerosol type.

In Fig. 5 monthly frequencies of each of the three aerosol type are shown. In addition, their seasonal variations are listed

Fig. 3 Comparison of monthly variation of aerosol properties between MODIS DB and DT retrievals from 2011 to 2015 over Tehran. **a** The frequency of observations over study area. **b** The monthly mean AOD. **c** The monthly mean AE

in Table 1. The DD type was detected on 97 granules during the study period, which includes 48.5% of the aerosol observations. The peak of DD frequency occurred from April to July with more than 14 granules and its maximum was observed in May ($N=16$). While the minimum frequency was observed during February and September ($N=3$). In terms of seasonal variation, the spring season ($N=38$) had the highest frequency of DD with $AOD=0.39$, $AE=0.09$, while autumn had the lowest frequency ($N=12$) with $AOD=0.26$ and $AE=0.22$. Arhami et al. [5] showed that over Tehran dust contribution to Particulate Matter (PM) with a diameter less than $2.5\ \mu\text{m}$ ($PM_{2.5}$) reached up to 56% during the warm season, while the minimum of 7% was observed in the winter. Léon et al. [37] reported that dust events were found only in the period from March to July at Thessaloniki (Greece). Meloni et al. [41] found that the occurrence of sand dust storm

events is at its highest in summer at the Mediterranean island of Lampedusa. In addition, such seasonal pattern was observed in previous studies by Escudero et al. [15] at Spain; [9] at Italian peninsula and Antoine and Nobileau [4] over the Mediterranean Sea.

The UI aerosols are from fossil fuel combustion in populated urban/industrial regions that produced locally and play a major role in regional-scale climatic features [29, 31, 49]. The UI type was detected on 61 granules during the study period, which equals to 30.5% of the aerosol observations. Monthly frequency of the UI (see Fig. 5) show that the polluted days are more common during the cold season. The maximum UI frequencies occurred in November ($N=18$) and January ($N=11$), while there are no any days with UI type during May, July or October. In addition, UI day's frequency is higher in the winter and autumn ($N=47$) compared to the spring and

Fig. 4 AOD vs. AE (0.412–0.47 μm) retrieved from C6 Deep Blue algorithm; represents aerosol types over Tehran in the period 2011–2015

Fig. 5 Comparison of the monthly frequency of aerosol types over Tehran in period 2011–2015

summer ($N=14$). Arhami et al. [5] reported that the pollutant levels are the highest during the cold season over Tehran. A large number of highly polluting vehicles and industrial activity in the vicinity of the city are the main pollutant sources in Tehran [7, 56]. The average AOD values during the UI days are approximately 0.3. It is possible that the DD (coarse-mode particles) and UI aerosols (fine mode particles) are mixed together. In these cases, the observations not belonging to any of the DD and UI categories and characterized as mixed type or undetermined aerosols [47]. Kaskaoutis et al. [30, 31] reported the mixture of dust and local pollution aerosols over Athens in Greece and Hyderabad an urban area in central India. The mixed aerosol type was detected on 42 days, which equals to 21% of the observations. The mixed aerosol type frequency is distributed quite evenly throughout the year (Fig. 5). However, the maximum frequency is observed during December and January ($N=9$) and during August are reached to minimum frequency ($N=0$). The same temporal pattern was observed in the occurrence of the mixed aerosol type in the study of Kaskaoutis et al. [31] over Hyderabad. They mentioned that the fine mode aerosols play a more important role in the mixed-type aerosols in winter season.

Table 1 Seasonal variations of aerosol types in period 2011–2015 over Tehran

Type		Annual	Winter	Spring	Summer	Autumn
All samples	Frequency	200	61	59	41	39
	AOD	0.3	0.28	0.35	0.29	0.27
	AE	0.77	1.09	0.53	0.28	1.15
DD	Frequency	97	13	38	34	12
	AOD	0.31	0.24	0.39	0.28	0.26
	AE	0.1	0.13	0.09	0.07	0.22
UI	Frequency	61	27	11	3	20
	AOD	0.3	0.3	0.3	0.32	0.29
	AE	1.72	1.71	1.74	1.67	1.73
MIX	Frequency	42	21	10	4	7
	AOD	0.27	0.26	0.24	0.38	0.25
	AE	0.94	0.90	0.86	1.07	1.12

Evaluation of aerosol type classifications

In this section, the correlation coefficients were calculated between AOD values of each aerosol type and AERONET on a daily scale and between the AODs and dust event frequency on a monthly scale (see Table 2). Between 2011 and 2013, polluted and dusty days (at least 2 pixels) were identified over Tehran. The AOD values during these days were compared with the AERONET data in Zanjan. The comparison was done for 20 UI days, 32 days with DD and 13 Mix days. During the DD days, the correlation coefficient between DB AOD (over Tehran) and AERONET AOD (over Zanjan) is substantial ($R=0.71$) (Fig. 6b). This indicates that both locations are affected by the same dust aerosols ([40]; see section 4.6). As expected, the corresponding relationship for polluted days is insignificant ($R=-0.2$) because the sources of pollution are local [7, 56]. In addition, this relation was also very insignificant for Mix days ($R=0.08$).

In addition, the relationship between the monthly dust event frequency and the monthly frequencies of DD, UI and Mix were computed. As can be seen in Fig. 6c and Table 2 a positive relationship is observed between the dust events and DD type ($R=0.74$). Deng et al. [12] reported that the correlation coefficient for stratospheric AOD and dust event frequency was 0.315 over the Tibetan Plateau. For the UI and Mix types, the corresponding relationship is negative ($R=-0.60$ and -0.38 , respectively). This negative relationship is because that the dust events have opposite annual cycles with the UI and Mix types. Consequently, the classification of aerosols using DB retrievals appears to be capable of capturing the dust events over Tehran.

Table 2 The Pearson correlation coefficient between AOD of each aerosol type with AERONET and dust event frequency

Aerosol types	AERONET vs. AOD	Dust events vs. monthly frequency
UI	-0.2	-0.60 ^a
DD	0.71**	0.74 ^a
MIX	0.08	-0.38 ^a

^a significant at the 0.01 level

Fig. 6 The comparison between AOD of aerosol type (over Tehran) with AERONET AOD (over Zanjan); **a** MODIS AOD vs. AERONET AOD during UI type. **b** MODIS AOD vs. AERONET AOD during DD type. And comparison between monthly dust storm frequency (over Tehran)

and monthly aerosol type frequency (over Tehran); **c** Monthly frequency of UI and dust storms frequency. **d** Monthly frequency of DD and dust storms frequency

Possible DD sources

To examine potential desert dust sources we calculated 5-day back trajectories at different levels (500, 1500 and 4000 m above the surface) using the HYSPLIT model. From the DB retrievals we identified 97 aerosol dusty days over Tehran and from those days 44 had more than half of the Tehran city affected by dust aerosol (at least 4 pixels). These high dust aerosol days were selected for the trajectory analysis. Table 3

presents the average AOD, percent frequency of trajectory and seasonal frequency of each cluster at different levels. At the 500 m level, five clusters were allocated (Fig. 7a). Cluster 2 and 4 represent the airflow from the northeast sector (52%), and clusters 1, 3 and 5 describe the airflow from west sectors (48%). Local sources have the strongest impact on the cluster 1. These local sources could be dry lakes as, for example, Masoumi et al. [40] found that Qom dry lake is a small source of dust affecting Zanjan city. The AOD average

Table 3 The average AOD, percent frequency of trajectory and seasonal frequency of each cluster at different levels related to DD aerosol type

Level (Meter)	Cluster	Frequency (%)	AOD	Winter	Spring	Summer	Autumn
500	1	27	0.28	1	8	0	3
	2	20	0.25	1	1	4	3
	3	2	0.84	0	1	0	0
	4	32	0.26	0	1	13	0
	5	18	0.42	1	6	0	1
1500	1	45	0.27	1	12	1	6
	2	41	0.29	0	1	16	1
	3	5	0.21	1	1	0	0
	4	9	0.57	1	3	0	0
4000	1	36	0.32	0	6	5	5
	2	27	0.26	0	1	12	1
	3	23	0.33	2	7	0	1
	4	14	0.31	1	3	1	1

Fig. 7 The main paths relating to the widespread DD over Tehran by cluster analysis using 5 days backward trajectories in different altitude at Tehran. **a** 500. **b** 1500. **c** 4000

related to the western trajectory is 0.36 and its maximum frequency occurred during the spring season. The AOD average is lower in the northeastern trajectory (0.25) and its maximum frequency occurred during the summer season. Four clusters were calculated for the 1500 m level (Fig. 7b). Similar to the 500 m level, the contribution of western trajectories is higher than for the northeastern trajectories. Cluster 2 represents the airflow from the northeast sector (41%), while clusters 1, 3 and 4 are related to the western pathway (59%). The AOD averages for the western and northeastern trajectories are 0.35 and 0.29, respectively. The maximum frequency for the western trajectories occurred during the spring season while the maximum for the northeastern trajectories was in the summer season. For the 4000 m level (Fig. 7c), 4 clusters were obtained. At this level, the contribution of the western sources is larger than for the lower altitudes (73%, AOD = 0.32). In this level, there does not seem to be air masses coming from the northwestern path, instead the air masses circle in the vicinity of Tehran for several days. Similar to the lower levels, the AOD values in the western path (AOD = 0.32) are higher compared to the local path (AOD = 0.26). It is noteworthy that the western trajectories are observed in all seasons (the maximum in the spring), while the local and northwestern path is limited during the summer.

The AOD values for the western path are higher in comparison to the northeastern path, which confirms the importance of Iraq, Syria and northern Africa as sources of DD aerosol over the study area. According to Mohammadi et al. [42], the most severe dust over Tehran was associated with the western transport path. They showed that the Saudi Arabia, Iraq and some parts of Syria are the source regions for the most significant dust event in Tehran (in May 2000) within the period 1981–2005. In addition, Khoshshima et al. [34] reported that the most dust events at the Zanzan station happened when the wind direction was from the west or southwest. In the recent years, Iraq and Syria (western path) have become more important sources of desert dust events over the Middle East due to the recent desertification [44]. Moreover, our results suggest the importance of Karakum and Kyzylkum deserts (northeastern path) as possible sources DD aerosol observed in Tehran. Orlovsky et al. [45] found that the Karakum and Kyzylkum deserts are the main source areas for generating dust storms in central Asia. The maximum number of dust storm days in western Turkmenistan was 146. The arid climate, vast areas of sandy, sparse vegetation cover, and strong winds all favor the formation of dust storms. The Karakum desert (350,000 km², black sands desert) along the east coast of the Caspian Sea is a source of dust influencing nearby areas including north and northeastern Iran and northwestern

Afghanistan [3, 45]. Using analysis of 5-day back trajectories, Kabanov et al. [26] showed that air masses move from the Karakum desert in a westward direction to the coast, and then, over the Caspian Sea.

Conclusions

The main focus of this study was to discriminate the aerosols types using 5 years of daily Level-2 collection 6 MODIS aerosol products (2011–2015) over Tehran, Iran. Comparison of MODIS and AERONET AOD data over Zanjan showed that the Dark Target (DT) and Deep Blue (DB) algorithms have a reasonable agreement with the AERONET data. However, the DT retrievals were biased high when compared with the ground-based observations whereas the DB retrievals were biased low. As the DB AE retrievals are more reliable than the DT AE retrievals, the aerosol type classification was performed using the DB data. Dust, urban/industrial and mixed type aerosols contributed to the observed aerosols by 48.5%, 30.5% and 21%, respectively. The maximum desert dust frequency was observed in the warm seasons (spring and summer), while the urban/industrial aerosols were at maximum during the cold season. In addition, the seasonal pattern of meteorological codes related to the dust events was consistent with the monthly dust aerosol frequency from satellite data. There were two main pathways for the transport of dust to the study area, a northeastern path in which dust is transported from the Karakum desert and a western path in which the dust is transported from Iraq, Syria and North Africa. The AOD values for the western path were higher in comparison to the northeastern path. Moreover, the northeastern path was dominant in the summer while the air masses came from the west during spring. Our results demonstrate the ability of MODIS collection 6 aerosol products in discrimination of the aerosol types over Tehran. Therefore the satellite data (along with the ground-based data) can be used for air quality monitoring over Tehran.

Acknowledgements Analyses used in this paper were produced with AERONET and MODIS website (<http://ladsweb.nascom.nasa.gov>) developed and maintained by the NASA GES DISC and. We acknowledge the mission scientists and Principal Investigators who provided the data used in this research effort.

References

1. Alam K, Qureshi S, Blaschke T. Monitoring spatio-temporal aerosol patterns over Pakistan based on MODIS, TOMS and MISR satellite data and a HYSPLIT model. *Atmos Environ*. 2011;45(27):4641–51.
2. Albrecht BA. Aerosols, cloud microphysics, and fractional cloudiness. *Science*. 1989;245(4923):1227–31.
3. Alizadeh-Chooabari O, Zawar-Reza P, Sturman A. The “wind of 120 days” and dust storm activity over the Sistan Basin. *Atmos Res*. 2014;15(143):328–41.
4. Antoine D, Nobileau D. Recent increase of Saharan dust transport over the Mediterranean Sea, as revealed from ocean color satellite (SeaWiFS) observations. *J Geophys Res Atmos*. 2006;111(D12):27.
5. Arhami M, Hosseini V, Zare M, Bigdeli M, Lai A, Schauer JJ. Seasonal trends, chemical speciation and source apportionment of fine PM in Tehran. *Atmos Environ*. 2017;153:70–82. <https://doi.org/10.1016/j.atmosenv.2016.12.046>.
6. Ashrafi K, Shafiepour-Motlagh M, Aslemand A, Ghader S. Dust storm simulation over Iran using HYSPLIT. *J Environ Health Sci Eng*. 2014;12(1):9.
7. Askariyeh MH, Arhami M. Projecting emission reductions from prospective mobile sources policies by road link-based modelling. *Int J Environ Pollut*. 2013;53(1–2):87–106.
8. Balakrishnaiah G, Lingaswamy AP, Devi U, Reddy RR. Columnar-integrated aerosol optical properties and classification of different aerosol types over the semi-arid region. Anantapur, Andhra Pradesh. *Sci Total Environ*. 2015;15(527):507–19.
9. Barkan J, Alpert P, Kutiel H, Kishcha P. Synoptics of dust transportation days from Africa toward Italy and Central Europe. *J Geophys Res Atmos*. 2005;110(D7):16.
10. Bayat A, Masoumi A, Khaledifard HR. Retrieval of atmospheric optical parameters from ground-based sun-photometer measurements for Zanjan, Iran. *Atmos Meas Tech*. 2011;4(5):857–63.
11. Charlson RJ, Schwartz SE. Climate forcing by anthropogenic aerosols. *Science*. 1992;255(5043):423–30.
12. Deng ZQ, Han YX, Zhao Q, Li J. Aerosol vertical distribution characteristics over the Tibetan Plateau. In *IOP Conference Series: Earth and Environmental Science*. 2014; (Vol. 17, No. 1, p. 012004). IOP Publishing.
13. Draxler RR, Hess, GD. An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition. *Aust Meteor Mag*. 1998; 47, 295–308.m.
14. Eck TF, Holben BN, Reid JS, Dubovik O, Smirnov A, O'Neill NT, ... Kinne S. Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols. *J Geophys Res Atmos*. 1999; 104(D24):31333–31349.
15. Escudero, M., Castillo, S., Querol, X., Avila, A., Alarcón, M., Viana, M. M., ... & Rodríguez, S. Wet and dry African dust episodes over eastern Spain. *J Geophys Res Atmos*. 2005;110:1–16. 110(D18).
16. Givehchi R, Arhami M, Tajrishy M. Contribution of the middle eastern dust source areas to PM 10 levels in urban receptors : case study of Tehran, Iran. *Atmos Environ*. 2013;75:287–95. <https://doi.org/10.1016/j.atmosenv.2013.04.039>.
17. Halek F, Kavouci A, Montehaie H. Role of motor-vehicles and trend of air borne particulate in the great Tehran area, Iran. *Int J Environ Health Res*. 2004;14(4):307–13.
18. Halek F, Kianpour-Rad M, Kavousirahim A. Seasonal variation in ambient PM mass and number concentrations (case study: Tehran, Iran). *Environ Monit Assess*. 2010;169(1–4):501–7.
19. Higurashi A, Nakajima T. Detection of aerosol types over the East China Sea near Japan from four-channel satellite data. *Geophys Res Lett*. 2002;1(29):17.
20. Holben BN, Eck TF, Slutsker I, Tanre D, Buis JP, Setzer A, et al. AERONET—A federated instrument network and data archive for aerosol characterization. *Remote Sens Environ*. 1998;66(1):1–6.
21. Hosseinpour AR, Forouzanfar MH, Yunesian M, Asghari F, Naieni KH, Farhood D. Air pollution and hospitalization due to angina pectoris in Tehran, Iran: a time-series study. *Environ Res*. 2005;99(1):126–31.

22. Hsu NC, Tsay SC, King MD, Herman JR. Deep blue retrievals of Asian aerosol properties during ACE-Asia. *IEEE Trans Geosci Remote Sens.* 2006;44(11):3180–95.
23. Hsu NC, Jeong MJ, Bettenhausen C, Sayer AM, Hansell R, Seftor CS, et al. Enhanced deep blue aerosol retrieval algorithm: the second generation. *J Geophys Res Atmos.* 2013;118(16):9296–315.
24. Hui CAO, Jian LIU, Guizhou W, Guang Y, Lei LUO. Identification of sand and dust storm source areas in Iran. *J Arid Land.* 2015;7(5):567–78. <https://doi.org/10.1007/s40333-015-0127-8>.
25. Ignatov A, Stowe L, Singh R. Sensitivity study of the Ångström exponent. *Adv Space Res.* 1998;21(3):439–42.
26. Kabanov DM, Panchenko MV, Sakerin SM, Turchinovich SA, Shmargunov VP, Rostov A P, ... Lisitzyn AP. Results of the investigations of aerosol characteristics over the Caspian Sea during the 29th cruise of the research vessel rift. *Atmos Oceanic Opt.* 2009;22(6): 567–574. <https://doi.org/10.1134/S1024856009060013>.
27. Kalapureddy MC, Kaskaoutis DG, Ernest Raj P, Devara PC, Kambezidis HD, Kosmopoulos PG, et al. Identification of aerosol type over the Arabian Sea in the premonsoon season during the integrated campaign for aerosols, gases and radiation budget (ICARB). *J Geophys Res Atmos.* 2009;114(D17).
28. Karami S, Ranjbar A, Mohebalhojeh AR, Moradi M. A rare case of haboob in Tehran: observational and numerical study. *Atmos Res.* 2017;1(185):169–85.
29. Kaskaoutis DG, Kambezidis HD, Hatzianastassiou N, Kosmopoulos PG, Badarinath KV. Aerosol climatology: dependence of the Ångström exponent on wavelength over four AERONET sites. *Atmos Chem Phys Discuss.* 2007a;30(3):7347–97.
30. Kaskaoutis DG, Kosmopoulos P, Kambezidis HD, Nastos PT. Aerosol climatology and discrimination of different types over Athens, Greece, based on MODIS data. *Atmos Environ.* 2007b;41(34):7315–29.
31. Kaskaoutis DG, Badarinath KV, Kumar Kharol S, Rani Sharma A, Kambezidis HD. Variations in the aerosol optical properties and types over the tropical urban site of Hyderabad, India. *J Geophys Res Atmos.* 2009;114(D22):27.
32. Kaskaoutis DG, Nastos PT, Kosmopoulos PG, Kambezidis HD. Characterising the long-range transport mechanisms of different aerosol types over Athens, Greece during 2000–2005. *Int J Climatol.* 2012;32(8):1249–70.
33. Kaufman YJ, Tanré D, Remer LA, Vermote EF, Chu A, Holben BN. Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradiometer. *J Geophys Res Atmos.* 1997;102(D14):17051–67.
34. Khoshshima M, Bidokhti AA, Ahmadi-Givi F. Variations of aerosol optical depth and Ångström parameters at a suburban location in Iran during 2009–2010. *J Earth Syst Sci.* 2014;123(1):187–99.
35. Kinne S, Schulz M, Textor C, Guibert S, Balkanski Y, Bauer SE, et al. An AeroCom initial assessment—optical properties in aerosol component modules of global models. *Atmos Chem Phys Discuss.* 2005;5(5):8285–330.
36. Kumar TK, Gadhavi H, Jayaraman A, Suman MS, Rao SV. Temporal and spatial variability of aerosol optical depth over South India as inferred from MODIS. *J Atmos Sol Terr Phys.* 2013;1(94):71–80.
37. Léon JF, Chazette P, Dulac F. Retrieval and monitoring of aerosol optical thickness over an urban area by spaceborne and ground-based remote sensing. *Appl Opt.* 1999;38(33):6918–26.
38. Levy RC, Remer LA, Mattoo S, Vermote EF, Kaufman YJ. Second-generation operational algorithm: retrieval of aerosol properties over land from inversion of moderate resolution imaging spectroradiometer spectral reflectance. *J Geophys Res Atmos.* 2007;112(D13):16.
39. Li C, Hsu NC, Tsay SC. A study on the potential applications of satellite data in air quality monitoring and forecasting. *Atmos Environ.* 2011;45(22):3663–75.
40. Masoumi A, Khalesifard HR, Bayat A, Moradhaseli R. Retrieval of aerosol optical and physical properties from ground-based measurements for Zanjan, a city in Northwest Iran. *Atmos Res.* 2013;1(120):343–55.
41. Meloni D, Di Sarra A, Biavati G, DeLuisi JJ, Monteleone F, Pace G, et al. Seasonal behavior of Saharan dust events at the Mediterranean island of Lampedusa in the period 1999–2005. *Atmos Environ.* 2007;41(14):3041–56.
42. Mohammadi F, Kamali S, Eskandary M. Tracing dust sources in different atmosphere levels of Tehran using hybrid single-particle lagrangian integrated trajectory (HYSPLIT) model. *Geography and environ. haz.* 2016; 11–14.
43. Moorthy KK, Satheesh SK, Babu SS, Dutt CB. Integrated campaign for aerosols, gases and radiation budget (ICARB): an overview. *J Earth Syst Sci.* 2008;117(1):243–62.
44. Moridnejad A, Karimi N, Ariya PA. Newly desertified regions in Iraq and its surrounding areas: significant novel sources of global dust particles. *J Arid Environ.* 2015;31(116):1–10.
45. Orlovsky L, Orlovsky N, Durdiev A. Dust storms in Turkmenistan. *J Arid Environ.* 2005;60(1):83–97.
46. Paasonen P, Asmi A, Petäjä T, Kajos MK, Äijälä M, Junninen H, et al. Warming-induced increase in aerosol number concentration likely to moderate climate change. *Nat Geosci.* 2013;6(6):438–42.
47. Pace G, Sarra AD, Meloni D, Piacentino S, Chamard P. Aerosol optical properties at Lampedusa (Central Mediterranean). 1. Influence of transport and identification of different aerosol types. *Atmos Chem Phys.* 2006;6(3):697–713.
48. Papadimas, C. D., Hatzianastassiou, N., Mihalopoulos, N., Querol, X., & Vardavas, I. Spatial and temporal variability in aerosol properties over the Mediterranean basin based on 6-year (2000–2006) MODIS data. *J Geophys Res Atmos.* 2008; 113(D11).
49. Pathak B, Bhuyan PK, Gogoi M, Bhuyan K. Seasonal heterogeneity in aerosol types over Dibrugarh-north-eastern India. *Atmos Environ.* 2012;47:307–15.
50. Ramanathan VC, Crutzen PJ, Kiehl JT, Rosenfeld D. Aerosols, climate, and the hydrological cycle. *Science.* 2001;294(5549): 2119–24.
51. Redfern H, Williams RG. Remote sensing: latest developments and uses. *Water Environ J.* 1996;10(6):423–8.
52. Salomonson VV, Barnes WL, Maymon PW, Montgomery HE, Ostrow H. MODIS: advanced facility instrument for studies of the earth as a system. *IEEE Trans Geosci Remote Sens.* 1989;27(2):145–53.
53. Saniei R, Zangiabadi A, Sharifikia M, Ghavidel Y. Air quality classification and its temporal trend in Tehran, Iran, 2002–2012. *Geospat Health.* 2016;11(2).
54. Sayer AM, Hsu NC, Bettenhausen C, Jeong MJ. Validation and uncertainty estimates for MODIS collection 6 “deep blue” aerosol data. *J Geophys Res Atmos.* 2013;118(14):7864–72.
55. Sayer AM, Munchak LA, Hsu NC, Levy RC, Bettenhausen C, Jeong MJ. MODIS collection 6 aerosol products: comparison between Aqua’s e-deep blue, dark target, and “merged” data sets, and usage recommendations. *J Geophys Res Atmos.* 2014;119(24).
56. Shahbazi H, Reyhanian M, Hosseini V, Afshin H. The relative contributions of mobile sources to air pollutant emissions in Tehran, Iran : an emission inventory approach. 2016; 44–56. <https://doi.org/10.1007/s40825-015-0031-x>.
57. Shahsavani A, Naddafi K, Haghighifard NJ, Mesdaghinia A, Yunesian M, Nabizadeh R, et al. The evaluation of PM10, PM2.5, and PM1 concentrations during the middle eastern dust (MED) events in Ahvaz, Iran, from April through September 2010. *J Arid Environ.* 2012;77:72–83.

58. Stevens B, Feingold G. Untangling aerosol effects on clouds and precipitation in a buffered system. *Nature*. 2009;461(7264):607–13.
59. Sullivan RC, Levy RC, Pryor SC. Spatiotemporal coherence of mean and extreme aerosol particle events over eastern North America as observed from satellite. *Atmos Environ*. 2015;112:126–35. <https://doi.org/10.1016/j.atmosenv.2015.04.026>.
60. Tanré D, Kaufman YJ, Herman M, Mattoo S. Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances. *J Geophys Res Atmos*. 1997;102(D14):16971–88.
61. Textor C, Schulz M, Guibert S, Kinne S, Balkanski Y, Bauer S, et al. Analysis and quantification of the diversities of aerosol life cycles within AeroCom. *Atmos Chem Phys*. 2006;6(7):1777–813.
62. Toledano C, Cachorro VE, De Frutos AM, Torres B, Berjon A, Sorribas M, et al. Airmass classification and analysis of aerosol types at El Arenosillo (Spain). *J Appl Meteorol Climatol*. 2009;48(5):962–81.
63. Twomey S. Aerosols, clouds and radiation. *Atmos Environ Part A*. 1991;25(11):2435–42.
64. Yu X, Lü R, Kumar KR, Ma J, Zhang Q, Jiang Y, et al. Dust aerosol properties and radiative forcing observed in spring during 2001–2014 over urban Beijing, China. *Environ Sci Pollut Res*. 2016;23(15):15432–42.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.