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

Samaneh Sabetghadam[a], Masoud Khoshsima[b], Omid Alizadeh-Choobari[a,*]

[a] Institute of Geophysics, University of Tehran, Tehran, Iran
[b] Satellite Research Institute, Iranian Space Research Center, Tehran, Iran

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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

Arising 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

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* Corresponding author.
E-mail address: omid.alizadeh@ut.ac.ir (O. Alizadeh-Choobari).

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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; Ramachandran, 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; Ramachandran 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, Ramachandran 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-Choobari and Najafi, 2018) and two big mountain ranges, and bordered by several big sources of dust (Alizadeh-Choobari 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 $1^{\circ} \times 1^{\circ}$ 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).

Table 1
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.

Region	Annual mean AOD	Std. deviation	Location		Elevation (m)
			Lat. (°N)	Lon. (°E)	
Urmia	0.08	0.05	37.1	45.1	1328
Zanjan	0.07	0.05	36.1	48.0	1663
Kermanshah	0.1	0.09	34.0	47.2	1318.6
Ahwaz	0.36	0.16	31.0	48.1	22.5
Bushehr	0.17	0.08	28.1	50.1	9
Sari	0.12	0.05	36.1	53.0	23
Tehran	0.1	0.04	35.1	51.0	1190.8
Semnan	0.12	0.04	35.1	53.0	1127
Isfahan	0.1	0.05	32.1	51.1	1550.4
Shiraz	0.08	0.03	29.1	52.1	1484
Bandar Abbas	0.16	0.05	27.0	56.0	9.8
Mashhad	0.08	0.02	36.0	59.1	999.2
Birjand	0.08	0.03	32.1	59.0	1491
Yazd	0.12	0.05	31.1	54.0	1237.2
Kerman	0.13	0.04	30.0	56.1	1753.8
Zahedan	0.09	0.04	29.0	60.1	1370

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 $\pm 0.03 \pm 0.05\tau$ over ocean and $\pm 0.05 \pm 0.15\tau$ over dark land, where τ 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 Georgoulias 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. These dataset with the horizontal grid resolution of $0.625^{\circ} \times 0.5^{\circ}$ 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 AOD in sixteen different locations of Iran are summarized in Table 1. Large differences are evident in some locations, which suggest that distribution of aerosol