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Identification of dust sources inside and outside of Iran affecting air quality in the Tehran region

Leila Mohammadian Mohammadi[1], *Sakineh Khansalari*[2,*], *Majid Gozalkhoo*[1]

[1] Tehran Meteorological Administration, Tehran, Iran
[2] Research Institute of Meteorology and Atmospheric Science, Tehran, Iran

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CORRESPONDING AUTHOR:

skhansalari@rimas.ac.ir
Tel: (+98 21) 44787651
Fax: (+98 21) 44787651

ABSTRACT

Introduction: Recent climate changes and droughts have exacerbated the impact of dust sources globally, necessitating a thorough understanding of their influence on air quality. In Tehran, the interaction between internal dust sources from Iran and external sources from neighboring countries significantly affects air quality.

Materials and methods: This study spans a 20-year period (2003-2022), utilizing satellite data and advanced algorithms to analyze dust event trends and patterns. The material and methods section outlines the use of Aqua satellite MODIS sensor data alongside two algorithms to identify dust sources, focusing on Aerosol Optical Depth (AOD) data during peak dust event seasons. Statistical analysis of dust events in 2022 supplements the investigation.

Results: The analysis reveals distinct patterns in dust particle origin and transport, highlighting the predominant contribution of internal dust sources from Iran's southern Semnan province and significant input from external sources in Iraq and northern Saudi Arabia. Examining meteorological conditions during severe dust events highlights the role of synoptic conditions, particularly the presence of a tropospheric trough, in facilitating dust transport. Increased convective motions and downburst occurrences in specific regions further exacerbate the spread of dust particles, particularly those originating from external countries and provinces.

Conclusion: The conclusion emphasizes the complex interplay between internal and external dust sources and the necessity of understanding dust emission dynamics for effective mitigation strategies. It calls for proactive measures involving local and regional cooperation to mitigate dust pollution's adverse effects on air quality in Tehran and similar urban centers.

Introduction

The phenomenon of dust storms represents a significant environmental challenge in geographically arid and semi-arid regions worldwide. Dust storms, originating from both natural and anthropogenic sources, have emerged as a global environmental concern over the past three decades [1]. The Middle East, including Iran, being situated in such areas, consistently grapples with the occurrence of dust storms. Identifying the sources of dust and sand emissions is the initial step towards managing

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this environmental issue and mitigating its adverse effects [2]. Recent climate changes and droughts have intensified the activities of internal and external dust sources. Simultaneously, the emergence of dust storms in neighboring countries and their transfer to Iran, influenced by favorable synoptic patterns, has compounded the challenge, resulting in severe and widespread dust events in the Tehran region. In addition to the activities of internal dust sources, the transport of dust particles from other provinces within the country and the long-range transport of dust from neighboring countries, such as Iraq, to the Tehran region, significantly deteriorates air quality. Consequently, the identification of factors contributing to dust storm occurrences in the Tehran region is crucial for mitigating and preventing potential environmental crises.

Regarding the necessity of using optical depth data from remote sensing to investigate dust events, it should be noted that although ground-level measurements (observation data) are employed as an exact method for data collection, these measurements mostly reflect the relatively limited environment around the observation station. By comparing satellite sensor data regarding the quantity of aerosols with ground stations in a specific region, their accuracy in precisely measuring aerosol quantities can be examined. The Moderate resolution Imaging Spectro radiometer (MODIS) sensor provides reliable data on Aerosol Optical Depth (AOD) from both land and water sectors, and numerous studies have been conducted to validate these data in various regions of Iran [3-7]. Valuable information can be obtained by conducting spatiotemporal monitoring and investigating the sources of incoming dust in different seasons and years. Taking preventive measures based on this information can reduce crises in critical regions. Furthermore, given the low and non-uniform station density network of ground-based optical measurement, satellite remote sensing becomes a principal approach for assessing temporal changes and spatial distribution of airborne particles regionally to globally [8-13]. The AOD at a wavelength of 550 nm, measured by the MODIS sensor, is a dimensionless quantity directly related to the aerosol in the atmosphere. This efficient product has been utilized in many studies in which high values of AOD indicate an excessive accumulation of aerosols in the atmospheric column [7, 14, -18]. The analysis of seasonal and regional variations in aerosol in the atmosphere in the Middle East indicates the highest AOD levels in the Arabian Peninsula, especially during the warm seasons. The second-highest AOD levels are observed in a southeastern region from Iran to western Pakistan, with higher values in summer, while the lowest AOD levels are found in northern countries of the studied region, including Turkmenistan, Uzbekistan, Kazakhstan, Armenia, Georgia, and some parts of Turkey [19]. Dust investigation using MODIS satellite data from Terra and Aqua indicate that the highest frequency of dust events in Iran occurs in the provinces of Khuzestan (in southwestern Iran) and Sistan and Baluchestan (in southeastern Iran) during the spring and summer seasons. Other regions with high occurrences of dust events are found in low-lying areas of the country, including coastal areas of the Oman Sea, the Jazmourian wetland, and the Lut Desert (in southeastern Iran), as well as the southern parts of the Dasht-e Kavir desert in central Iran [20]. The relationship between annual AOD and precipitation, soil moisture, and surface winds in the Middle East region (Saudi Arabia, Iraq, and Iran) indicates that these variables are the main factors controlling dust events in the Middle East. An increase in temperature and a decrease in soil relative humidity leads to an increase in dust events and AOD [16]. Therefore, the impact of these variables on increased dust events and AOD is expected due to climate change [21]. Additionally, in all dust sources, soil moisture reaches its minimum level, corresponding with rainfall conditions in different seasons [16, 17, 22].

In the Tehran region, [23] conducted a study investigating the influence of weather conditions on air pollution events throughout various seasons. They investigated air pollution in Tehran over the past 17 years (2004-2020), focusing on 112 events of pollution through the point of view of synoptic and thermodynamic meteorological patterns. Five distinct patterns were identified with varying frequencies. The first pattern, prevalent in autumn and winter, leads to prolonged pollution periods and high pollution indices. The second pattern, associated with high summer temperatures, intensifies the main pollutant, ozone. The third pattern, active mainly in summer and late spring, is linked to the Indian monsoon low-pressure system, causing severe dust in southeastern regions and contributing to increased pollution indices in central areas. The fourth pattern, occurring in spring and autumn, involves the development of dynamic low pressure in western regions and thermal low pressure in central areas, causing dust rise. The fifth pattern, a local one, results from the passage of a gust front and wind shear, causing dust rise in Tehran. Notably, this local pattern has the lowest occurrence frequency but triggers immediate shifts from clean to unhealthy air quality.

Several studies have been conducted on the sources of dust in Tehran; however, these studies are typically treated as case studies or cover relatively short time periods. In a study, focused on understanding the meteorological aspects, particle movement paths, and dust sources associated with dust storms affecting Tehran's air quality [24]. By identifying very unhealthy days from 2001 to 2009 in summer and autumn, the research pinpointed sources using meteorological data and trajectory modeling. The results highlighted the role of deserts near Tehran and, notably, emphasized Iraq and eastern Syria as major contributors to suspended particle production impacting the city's air quality.

In this research, it has been tried to identify the sources of dust inside and outside of Iran leading to the reduction of air quality in Tehran region from the data of weather stations, air quality index (AQI) data related to air quality control company, images Meteorological satellites and AOD data from MODIS sensor should be used for spring and summer seasons during the 20-year period when most dust events in Tehran region occur in these seasons.

Materials and methods

In this study, AOD data, obtained from the MODIS Aqua satellite sensor's 550 nm channel, were seasonally and annually analyzed for the spatial distribution of AOD values in the study area. Two deep blue and dark target algorithms were applied for bright surfaces and agricultural lands, respectively. The deep blue and dark target algorithms, vital in satellite remote sensing, retrieve AOD to quantify atmospheric aerosol levels. Crucial for air quality insight and aerosol distribution, the deep blue algorithm excels in bright regions like deserts and urban areas due to its focus on highly reflective surfaces. In contrast, the dark target algorithm is optimized for relatively darker or vegetated areas, accounting for aerosol sunlight absorption. The key distinction lies in their target surfaces, making the deep blue algorithm suitable for bright areas and the dark target algorithm optimized for darker regions. To enhance accuracy and reduce errors associated with urban and industrial dust entering during cold seasons and atmospheric stability, AOD data for spring and summer, which main periods of dust events occur in these seasons, over the past 20 years were extracted and examined. Furthermore, by examining the number of days associated with dust events during the statistical period of 2022-2003, utilizing data from synoptic stations in Tehran province for a year with the highest and most widespread occurrences of dust events in the Tehran region, 7 severe and widespread events in that year were investigated based on AQI data and four synoptic stations (illustrated these stations in Fig. 1) data in Tehran province. Subsequently, using EUMETSAT satellite images to track dust masses formed in neighboring provinces of the Tehran region and neighboring countries of Iran, their impact on the reduction of air quality in the Tehran area was investigated and, external dust sources affecting Tehran's air quality were identified. Also, Table 1, illustrates the air quality classification from the air quality control company of Tehran. The PSI (Pollutant Standard Index) serves as a gauge for assessing air pollution, with values ranging from zero to five hundred. Depending on the specific index value, air quality is categorized into five groups: clean, healthy, unhealthy, very unhealthy, and hazardous.

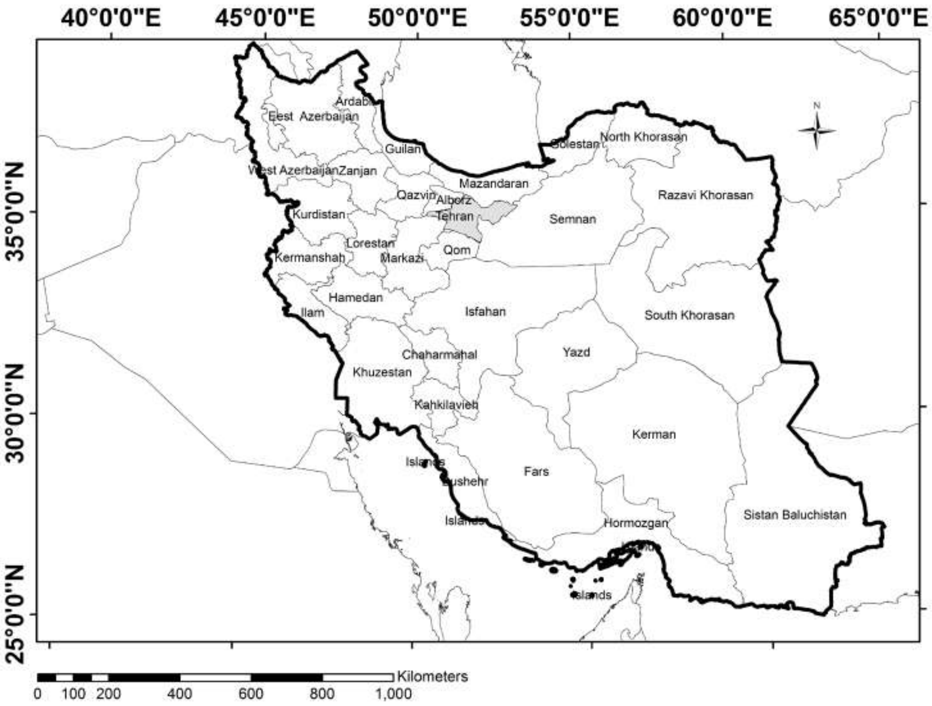
The features governing dust transport are primarily influenced by meteorological conditions. Numerous investigations have scrutinized synoptic features conducive to the onset of dust storms [26-29]. Various dust trajectories were examined by analyzing synoptic features and inspecting dust distributions using regional simulations. The influence of fronts and troughs on the vertical distribution of Asian dust was explored. Dust particles located in the frontal region of an upper-level trough may ascend to the free troposphere, whereas those situated behind the trough typically stay in the lower troposphere below 700 hPa [26]. So to examine synoptic conditions during 7 dust events gridded reanalysis data from ERA5, a product of the European Centre for Medium-Range Weather Forecasts (ECMWF), were utilized. ERA5 provides global reanalysis data with a spatial resolution of 0.25°×0.25° and a temporal resolution of 6 h (0000, 0600, 1200, 1800 UTC). The dataset includes geopotential height, three component of wind fields at 10 m' height and various pressure levels (850, 700, 500, and 300 hPa) as well as sea level pressure. Dust events were identified by applying EUMETSAT satellite images, 1-hourly METAR data, and synoptic station data. In the SYNOP code, 3-hourly present weather reports with codes 6 to 9 were employed to distinguish haze and smoke intensity, and codes 30 to 35 were used to identify severe dust storms.

Study region

The air pollution in Tehran, Iran, is a multifaceted meteorological phenomenon influenced by various atmospheric and geographical factors. Tehran's topography, surrounded by mountains, exacerbates the issue by creating a bowl-shaped terrain that traps pollutants within the urban basin. In cold seasons, temperature inversions, common in the region, further contribute to the accumulation of pollutants, as warmer air aloft traps cooler air near the surface, inhibiting vertical atmospheric mixing. The primary sources of pollution stem from anthropogenic activities, including vehicular emissions and industrial processes. Seasonal variations, particularly during winter, intensify the problem due to increased energy consumption for heating purposes. Meteorological parameters such as wind speed, atmospheric stability, and temperature inversions play crucial roles in determining the dispersion or stagnation of pollutants. In spring and summer due to increasing wind speed, the occurrence of dust events in the surrounding Tehran, the transportation of dust particles to this area, or the occurrence of dust events in Tehran reduces air quality in this area. Fig. 1 shows a geographical map of Iran and the wider region of the selected synoptic stations (Mehrabad, Imam Khomeini, Shahriar, and Varamin) in Tehran province.

Table 1. AQI values based on PSI [25]

PSI	Health importance level
0-50	Clean or good
51-100	Healthy
101-150	Unhealthy for sensitive groups
151-200	Unhealthy
201-300	Very unhealthy
300-500	Hazardous



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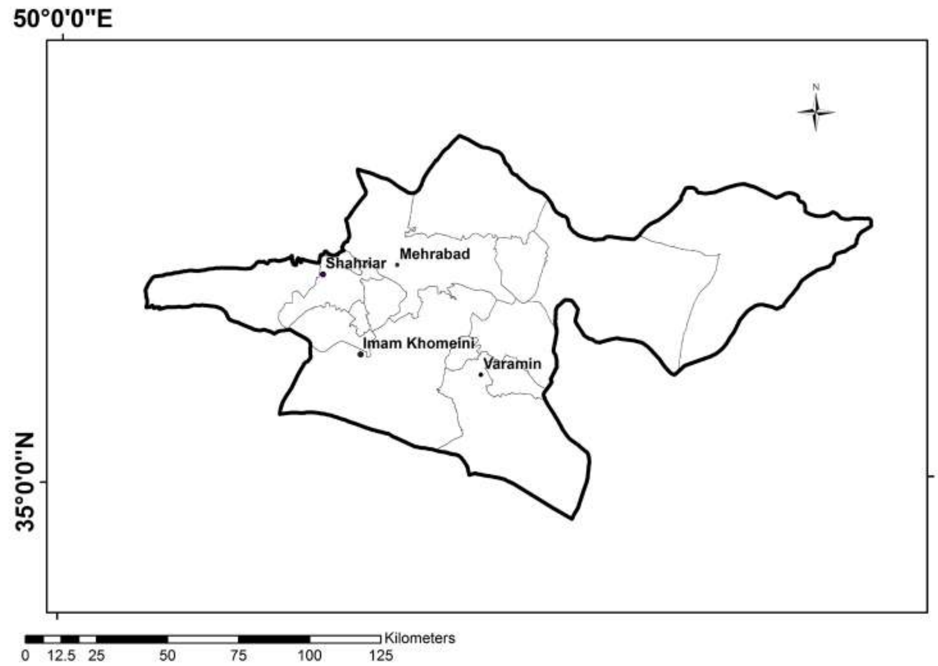


b)

Fig. 1. a) Iran map and the location of Tehran province, b) and the situation of four synoptic station in Tehran province

Results and discussion

Fig. 2 illustrates the seasonal average of AOD over a 20-year period (2003-2022) during the spring and summer, when the highest dust events occur in these seasons. As observed, the maximum AOD values are evident during the spring season. In the provinces surrounding Tehran, the highest AOD is found in the southern part of Semnan province, northern part of Isfahan province, and the northwestern part of South Khorasan province, as well as the southern coasts and islands of the country. Additionally, neighboring countries of Iran, such as Iraq and Saudi Arabia, exhibit a significant increase in AOD during the spring season.

Fig. 3 illustrates the six-month average (March to August) AOD for each year from 2003 to 2022. The spatial pattern of the AOD sources in each year's six-month average resembles the patterns observed in the spring and summer seasons in the long-term period shown in Fig. 2. In the adjacent provinces to Tehran, the highest AOD values were in 2009, 2019, and 2020, while the lowest values were recorded in 2008 and 2018. Additionally, the lowest AOD values occurred in 2004, and the highest values were observed in neighboring countries of Iran during the years 2005, 2007, and 2009. Identifying dust sources solely based on AOD values, without using observational data, may be accompanied by uncertainty [18], and human knowledge and experience are crucial factors in accurately identifying dust sources [30]. Therefore, the number of days with dust during the statistical period of 2003-2022 at the studied stations (station locations are indicated in Fig. 1) is shown in Fig. 4. As observed, there was a considerable increase in dust events in 2022. Furthermore, in this year, all four stations indicate an increase in dust, suggesting its higher prevalence in the surrounding province of Tehran. Consequently, 7 severe and widespread dust events during 2022 have been identified and investigated based on the data from the Air Quality Control Company and observational data from synoptic stations.

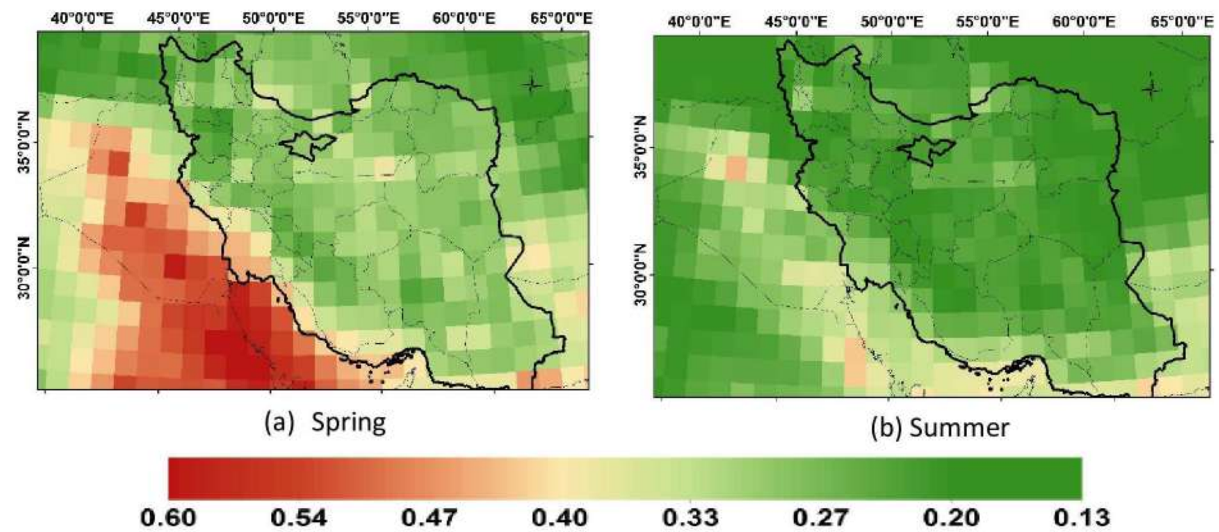
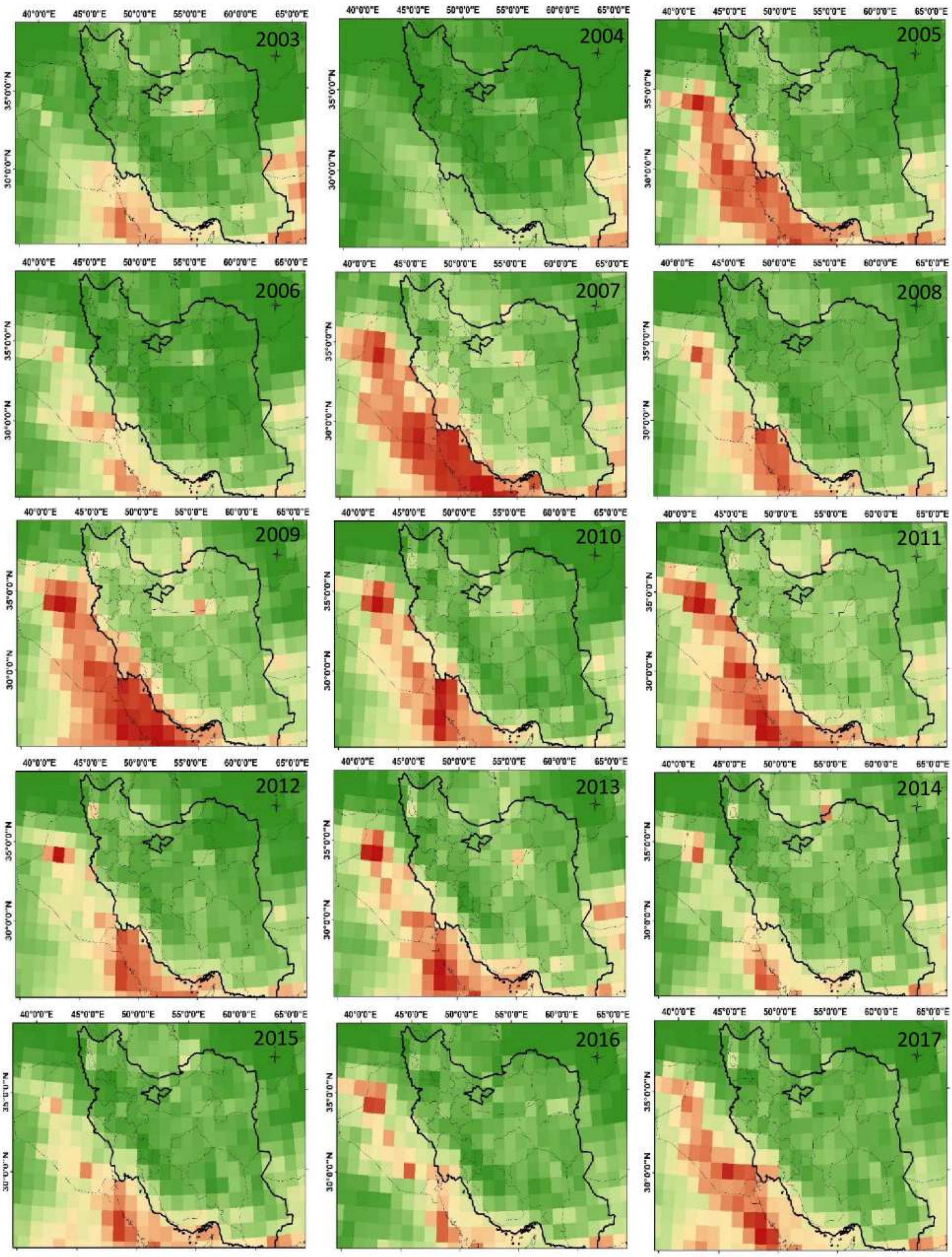


Fig. 2. Seasonal average of AOD from the MODIS Aqua satellite sensor, 550 nm channel, during the 2003-2022, a) Spring (March, April, May); b) Summer (June, July, August)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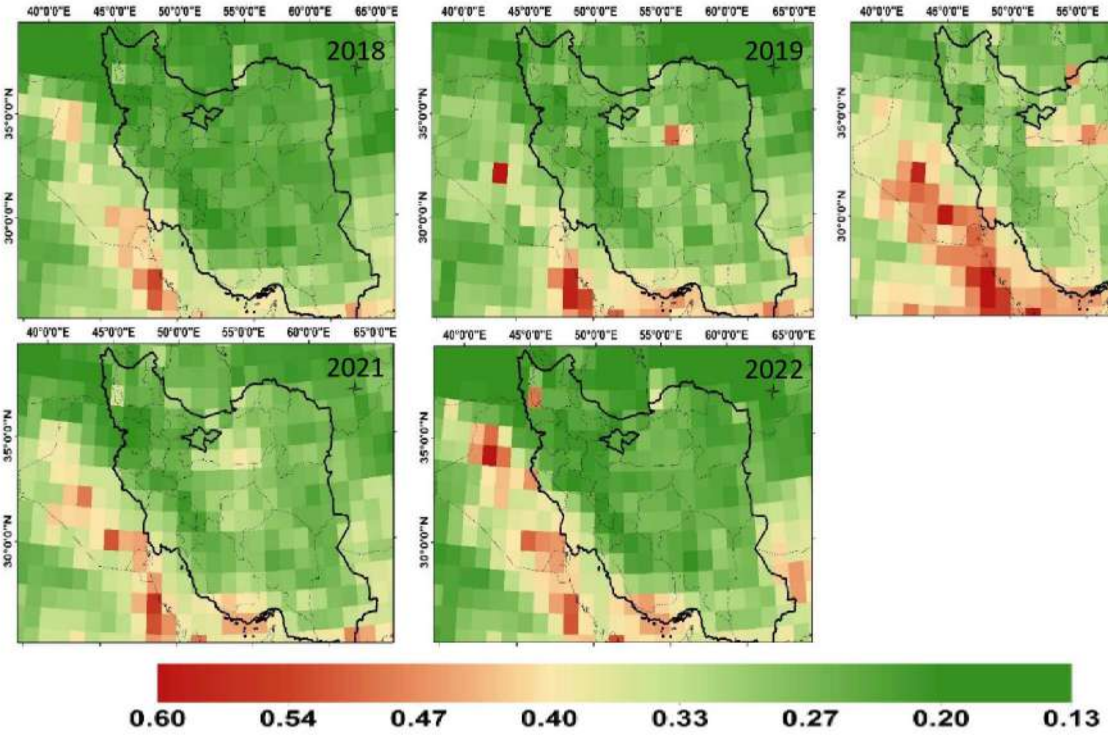

Fig. 3. 6-month average (March to August) of AOD from the MODIS Aqua satellite sensor, 550-nm channel, during the 2003-2022 for each year

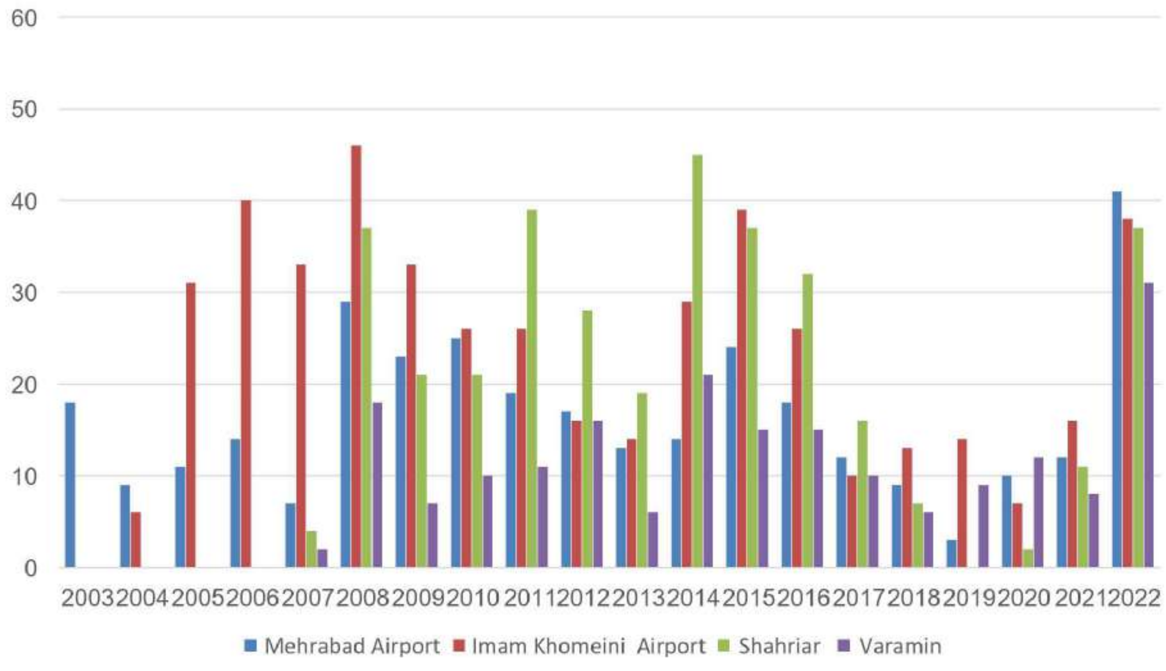

Fig. 4. Number of days with dust at Mehrabad, Imam Khomeini, Shahriar, and Varamin stations, from 2003 to 2022

Therefore, following the occurrence of 7 severe and widespread dust events in 2022, based on data from the Air Quality Control Company and synoptic station data, they were identified and examined. The characteristics of these 7 intense and widespread dust events are presented in Table 2. Furthermore, tracking the sources of dust and monitoring them in EUMETSAT satellite images is provided in Fig. 5. The analysis of these 7 events indicates that, with the passage of mid-tropospheric waves and trough over the desert regions of neighboring western countries, including Iraq, favorable conditions for upward movements and the formation of convective clouds, as well as wind convergence in the lower tropospheric levels, are created, leading to dust occurrences in the region. Subsequently, due to the strong upward movements, these dust particles ascend to higher altitudes and, propelled by the eastward movement of mid-level tropospheric waves, travel toward Iran and the Tehran region. Moreover, as the mid-tropospheric troughs move eastward, creating strong convective clouds in the Tehran region, the formation of severe dust downbursts precedes the onset of rain. One of the severe types of winds, usually accompanied by dust and sand, is known in some countries as "Haboob." The structure of this meteorological phenomenon is dependent on the formation of suitable dynamic conditions for the ascent of warm and dry air in the atmosphere. A significant portion of precipitation resulting from the ascent of air due to atmospheric warmth evaporates, taking the necessary heat for evaporation from the surrounding air. The cooler air created, having higher density compared to the warm ambient air, rapidly descends and creates secondary fronts upon colliding with the warm air within the convergence zone of the downdraft cell [31]. When this downdraft of cold air, or downburst, reaches the ground, it dusts up from the land. At all these phenomena, downbursts, and sudden and intense downward winds associated with thunderstorms, have been reported in Tehran in recent decades, contributing to localized damages.

Table 2. Average and maximum values of AQI, $PM_{2.5}$, and PM_{10} on 7 severe and widespread dust events during the 2022 year

Case Number	Date	AQI Average	AQI Maximum	$PM_{2.5}$ Average	$PM_{2.5}$ Maximum	PM_{10} Average	PM_{10} Maximum	Air Quality Level
1	2022/04/08	190	399	161	197	190	399	Unhealthy for sensitive groups
2	2022/04/09	332	500	196	266	332	500	Hazardous
3	2022/04/10	150	172	150	172	121	156	Unhealthy
4	2022/05/08	156	176	156	188	148	176	Unhealthy
5	2022/05/17	163	228	159	182	163	228	Unhealthy
6	2022/05/24	142	224	142	224	125	172	Unhealthy for sensitive groups
7	2022/05/25	435	500	229	330	435	500	Hazardous

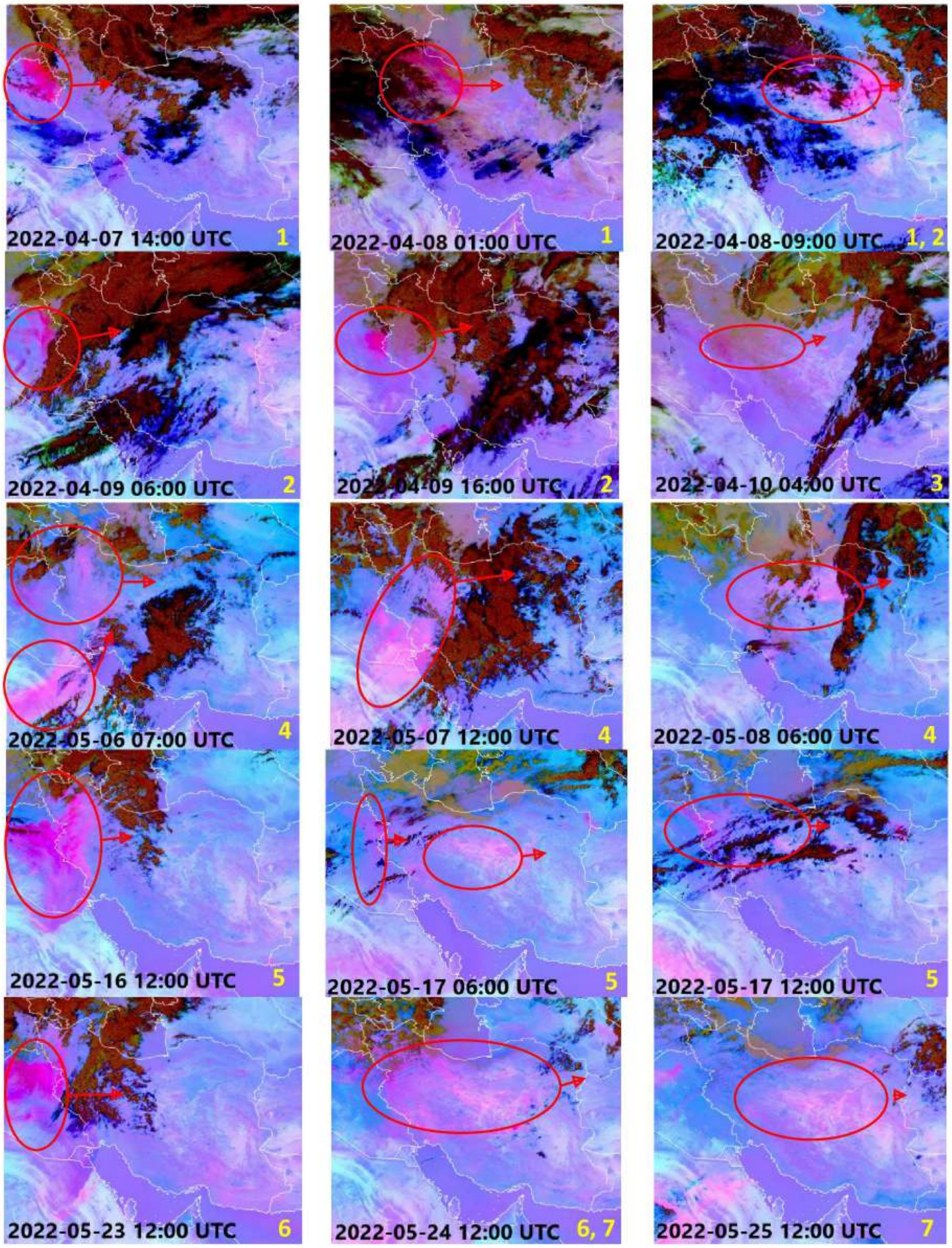

Fig. 5. Meteosat-10 dust RGB composite product for seven dust events

Meteosat-10 dust RGB composite product for seven dust events that impact the air quality of the Tehran area, the dust event areas and their direction of movement, and event number have been specified According to [26], the dust transport process involves an initial stage followed by ascending and downwind transport stages. This study introduced three types of dust trajectories that are illustrated in Fig. 6. In the ascending period of U and D type trajectories, dust is uplifted and reaches its peak height before transitioning to the downwind transport stage. In contrast, L type trajectories generally lack a distinct ascending period, with dust transported from the surface to the mixed layer by strong surface winds during the initial stage, followed by downwind movement. In U type transport, generated near a cyclonic circulation associated with a low center, contributes to dust formation, in which the surface low is more intense than in the L type. During the ascending stage, dust particles are uplifted ahead of or slightly south of the trough due to vorticity advection and temperature advection associated with the trough system. As a result, most U type cases involve upward lifting by the trough. In the downwind transport stage, U type dust particles move southeast or ahead of the trough system, allowing them to remain in the troposphere for an extended period. These particles, initially lifted from the surface, continue downwind through the upper-level system (around 500 hPa). In L-type transport, stronger surface highs, not lows, prevail. Dust particles of this type form between surface lows and highs in areas of either cyclonic or anticyclone circulation. Once generated, L-type dust particles end up behind the 700 hPa trough, limiting upward movement. As a result, these particles move downwind near the surface layer under descending or neutral flow conditions. The vertical motion shows that L-type dust particles originate in the boundary layer behind the trough and then move downwind near the surface layer. In the D-type transport, similar to the U type, dust particles undergo vertical transport up to 400 hPa facilitated by the trough's ascending motion, but downwind, they fall behind due to different speeds, descending in the lower troposphere.

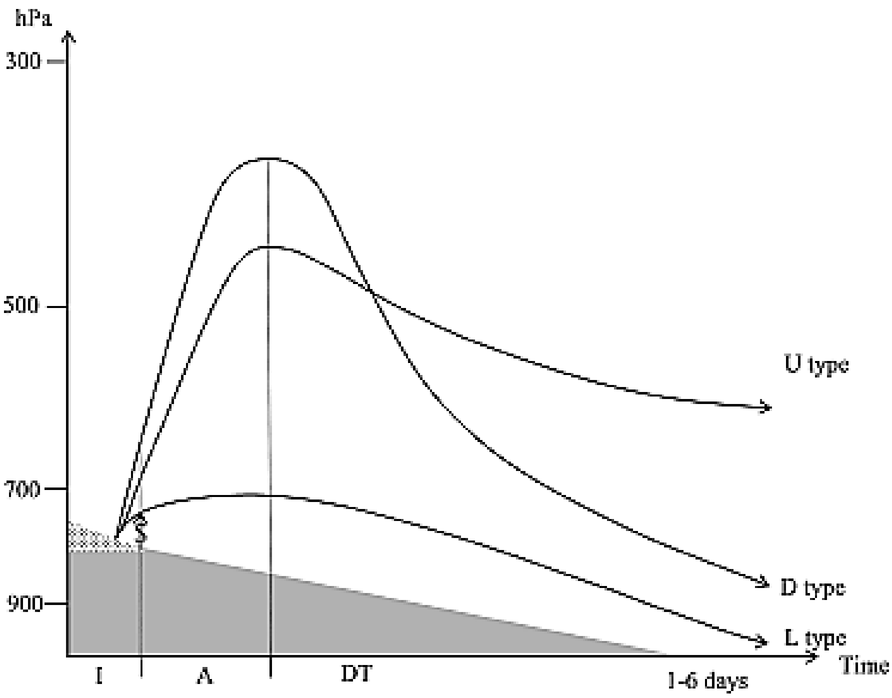

Fig. 6. Illustration of three types of dust trajectories [26]: upper-level (U type), lower-level (L type), and descending (D type) transport in the pressure–time coordinate system

Topography is shaded, and dust observations from a surface station in the desert (denoted by dots) are indicated with $. The initial (I), ascending (A), and downwind transport (DT) stages are also highlighted.

According to the result of [26], the synoptic analysis of sea-level pressure and the geopotential height at various levels was done in seven case studies. In these seven case studies, as evident from satellite images (Fig. 5), the synoptic pattern of geopotential height and sea level pressure (Fig. 7), and the 10-m wind field (Fig. 8), the occurrence of dust and sandstorms over Iraq, and occasionally over Saudi Arabia when the mid-tropospheric trough passes over. Due to dust sources being in front of the 500 hPa trough, these events are T type dust trajectories. With the eastward movement of the mentioned trough and its strong ascending movements, dust rises in the western neighboring countries of Iran to higher levels and is transported to Iran, including the Tehran region, and air quality decreases in this area. Furthermore, as the trough reaches the Tehran region, the increase in local wind speed and the convergence of surface winds in the Tehran area lead to the occurrence of local dust and a decreasing air quality. In Fig. 8 convergence of 10-m wind field over the western neighboring countries of Iran and Tehran area have been specified.

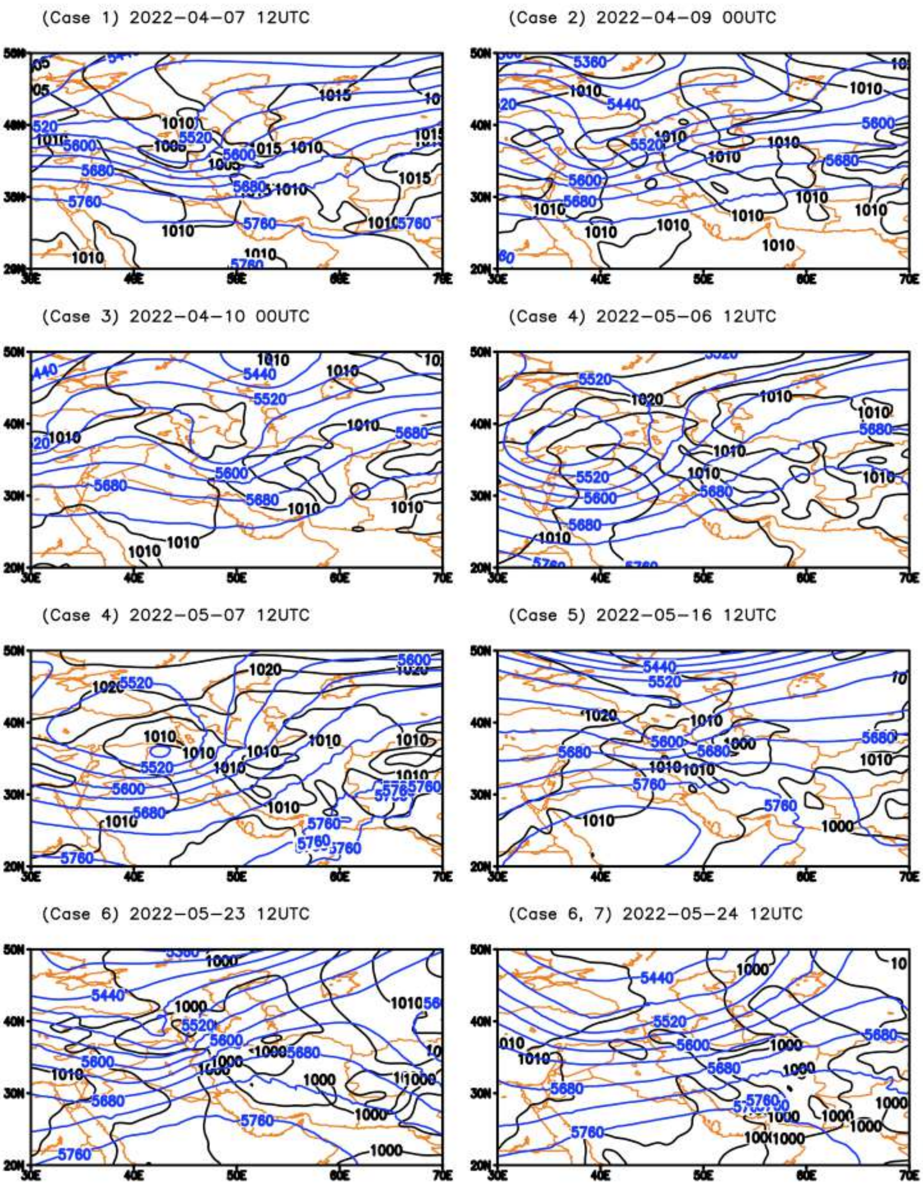

Fig. 7. Geopotential height at 500 hPa (blue lines, in geopotential meter), and sea level pressure (black lines, in hPa) for seven dust events that impact the air quality of the Tehran area

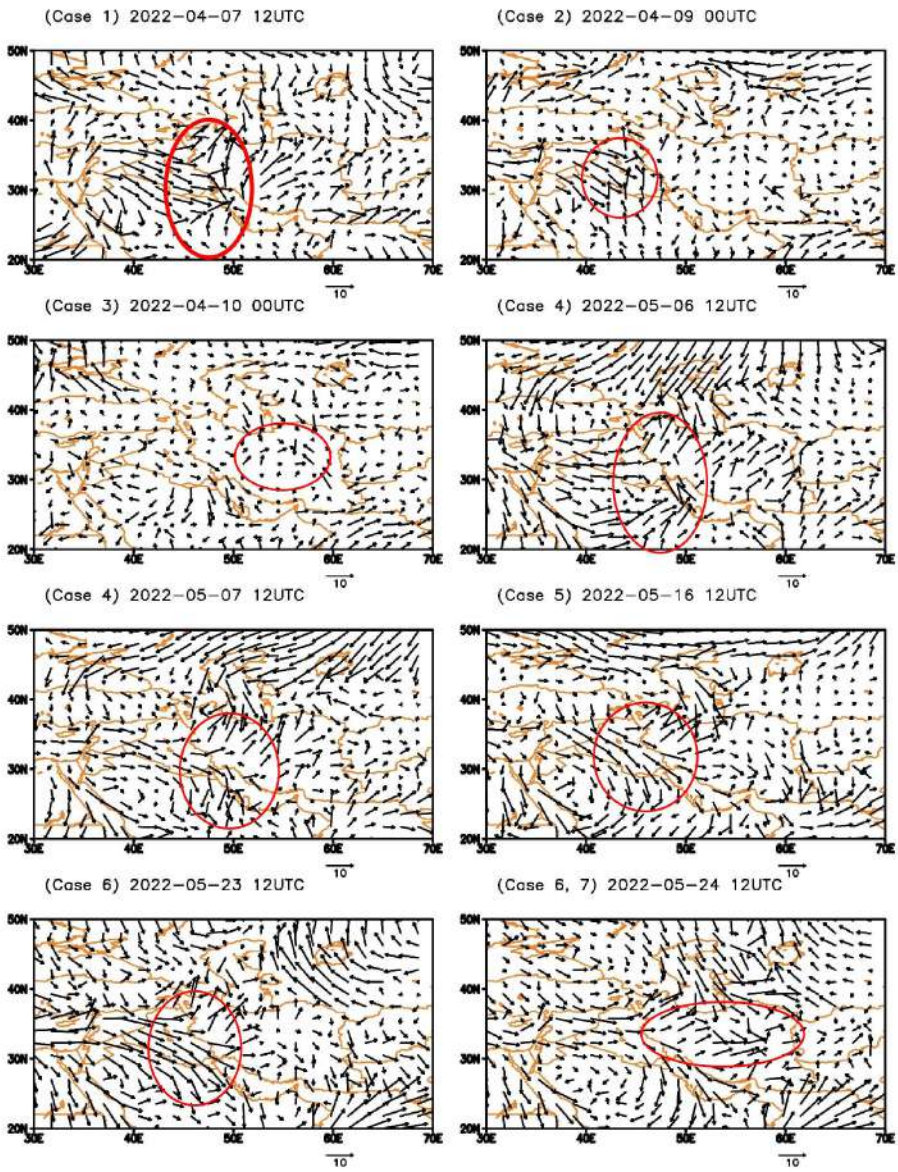

Fig. 8. 10-m winds in m/s for seven dust events that impact the air quality of the Tehran area, convergence wind over the western neighboring countries of Iran and Tehran area have been specified with red circle

Conclusion

This research discusses the use of remote sensing techniques and meteorological satellites' images in identifying dust sources and tracking dust masses. The internal activities of dust sources have intensified due to recent climate changes and droughts. On the other hand, the occurrence of dust storms in neighboring countries and their transfer to Iran, with favorable synoptic patterns, has intensified the problem of dust phenomena in recent years. In this study, to identify the internal and external dust sources affecting the air quality in the Tehran region, the AOD data from the MODIS sensor of the Aqua satellite, channel 550 nm, using the combination of two algorithms (deep blue and dark target) for bright surfaces and agricultural lands, were extracted and analyzed seasonally and annually in the study area over 20 years (2003-2022). The results indicate that most internal dust sources are concentrated in the southern province of Semnan, while external sources from countries such as Iraq and northern Saudi Arabia are observed.

In another part of the research, observation data from synoptic stations and satellite images from Eumetsat, along with tracking dust masses formed in dust sources in neighboring provinces and countries, were used to analyze the impact of identified dust sources on the air quality in the Tehran region. For this purpose, by examining data from four synoptic stations in Tehran province (Mehrabad Airport, Imam Khomeini Airport, Shahriar, and Varamin) and considering the number of days with dust during the 2003-2022 years, it was determined that there was a significant increase in dust events and the widespread of this phenomenon in the Tehran region in 2022. Based on this, 7 severe and widespread dust events in 2022 were identified, analyzed, and studied. The investigation results show that most of these events occur due to the influx of dust from Iraq and Saudi Arabia and the activation of internal dust sources in the Tehran region and neighboring western provinces (mostly due to increased convective motions and downburst occurrences. Due to the predominant westerly wind direction in Tehran province during spring and summer, dust sources in the eastern and southeastern provinces seldom result in dust events in the Tehran region. Synoptic analyses seven case studies and satellite images revealed that dust and sandstorms occur over Iraq and occasionally over Saudi Arabia when a mid-tropospheric trough passes and then this dust storm advected to Iran and Tehran. This type of dust trajectory is called T type based on [26].

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Financial assistance was not provided for the current research.

Competing interests

The authors assert the absence of any conflicts of interest related to the publication of this manuscript. Furthermore, they confirm full adherence to ethical considerations, encompassing issues such as plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, as well as redundancy.

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Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc) have been completely observed by the authors.

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