DESERT 2022, 27(1): 97-114
DOI: 10.22059/JDESERT.2022.88512

RESEARCH PAPER

Variation of PM10 and its relationship with Dust and Climate in Birjand, Iran

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Received: 22 July 2021, Revised: 8 December 2021, Accepted: 10 December 2021

Abstract
Particulate matter emission is an important threat to sustainable development due to its various effects on the atmosphere. Particulate matter originates from natural sources or human activities. Since Birjand is located between Sistan plain and Karakum desert, numerous dust events have been reported in this area. In the present study, concentration of PM_{10} was divided into annual, seasonal, monthly, weekly, and hourly time scales from 2014 to 2018. HYSPLIT model and AOD products were used for examining the movement pattern and origins of the particles. Pearson correlation was calculated between the frequency of dusty days and climate variables. The results revealed that PM_{10} concentration and dusty days frequency trends were similar. Additionally, the mean temperature and wind speed had a similar trend as PM_{10} concentration. Furthermore, PM_{10} was significantly related to dust and most of the climate variables. The closest correlation of PM_{10} was with dusty days in seasonal (Pearson correlation = 0.494) and monthly (Pearson correlation = 0.619) time scales. Based on PM_{10} daily concentration, 34 unhealthy days were identified. To track the particles on unhealthy days, HYSPLIT model was employed. Except in spring, the wind roses showed that the main direction of the wind was to the west. Meanwhile, based on AOD images, the particles originated from dust sources. A big amount of PM_{10} concentration originated from the surrounding regions, and the majority of dust particles came from the north. Therefore, the local climate variables as well as dust events of the surrounding regions had crucial roles in the rise in PM_{10} concentration, which should be taken into consideration by managers so that PM_{10} concentration could be taken under control.
Keywords: Particulate Matter, Dusty days, Climate, Aerosol Optical Depth, HYSPLIT, Birjand

Introduction

Particulate matter includes soot, smoke, dust, and liquid droplets. These particles are generally classified according to their origin and size, which is called the aerodynamic diameter. There are two types of particulate matter, namely PM_{10} and $PM_{2.5}$. PM_{10} are particles with an aerodynamic diameter of 2.5 to 10 micrometers, and $PM_{2.5}$ are those with an aerodynamic diameter of less than 2.5 micrometers. It should be noted that generally, PM_{10} particles include dust and $PM_{2.5}$ particles (EPA 2012). Particulate matter is a significant threat to sustainable development (Choubin et al., 2020) due to its disturbing effects on the balance of radiation in the atmosphere (Prospero et al., 2002), increasing air pollution (Munir et al., 2017), reducing visibility, leading to climate change, and damaging vegetation (Onuorah et al., 2019). The most important threat of particulate matter is that it can easily penetrate the lungs (De Rooij et al., 2017) and is one of the most dangerous air pollutants in urban areas (Cujia et al., 2019; Ganguly et al., 2019; Han et al., 2020). Particulate matter can also affect climate indirectly by altering

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the optical and chemical properties of clouds (Prospero et al., 2002). On the other hand, climate change can significantly affect the amount of particulate matter (Csavina et al., 2014; Kim et al., 2014). Particulate matter is divided into two categories, including that of natural origin and anthropogenic origin, which can be caused by dust, rising sea salt, the spread of carbon from fires (Czernecki et al., 2017), the emission of pollutants by vehicles, and power plants (Azarmi et al., 2016; Taheri Shahraiyni and Sodoudi, 2016). Dispersion and accumulation of particulate matter are mainly influenced by emission sources, meteorological parameters, and local topography (Anake et al., 2016).

Numerous studies have explained the relationship between PM_{10} concentration and climate conditions. Sharma and Sharma (2016) investigated PM_{10} correlation with the mean temperature, relative humidity, and rainfall in Gurgaon, India. Their results showed a significant relationship between PM_{10}, the mean temperature, relative humidity, and rainfall in spring and pre-monsoon. Alifa et al. (2020) studied the effects of meteorological variables on PM_{10} concentration in two monsoon climatic patterns. In wet monsoon, the relative humidity and precipitation had negative influences and in dry monsoon, temperature had a positive influence on PM_{10} concentration in Malaysia. Kliengchuay et al. (2021) estimated Pearson correlation between PM_{10} concentration and temperature, rainfall, relative humidity, pressure, and wind speed in Lamphun, Thailand. Their results indicated that the correlation between PM_{10} concentration and climate variables was not strong. One of the main reasons behind the dispersion of PM_{10} in arid and desert areas of Iran is dust storms whose number has increased over recent years (Mehrabi et al., 2015; Ebrahimikhusfi and Dargahian, 2018; Modarres and Sadeghi, 2018). The number of dust storms in Birjand has not been constant. Another point to mention is that Birjand has no problems in terms of gas pollutants, and it is mainly dust that affects the air quality of this city (Moosavi and Pourkhabaz, 2017).

Climatic characteristics have a significant impact on dust hotspots, which is why many hotspots are located in arid and semi-arid regions of the world (Kalderon-Asael et al., 2009). Iran's geographical location has also exposed the country to numerous dust occurrences (Rashki et al., 2013; Goudie, 2014). Every year, South Khorasan suffers a great deal of damage caused by dust events (Department of Natural Resources of South Khorasan Province, 2007). Based on the government reports, the effects of dust and wind erosion have a significantly negative effect on the quality of life of South Khorasan residents. According to the government reports, particulate matter in Birjand has caused damage to public health. Birjand has a temperate climate in which many dusty days have been reported; thus, this city can be a comprehensive case for studying particulate matter variability. Moreover, no specific studies have been conducted on PM_{10} changes in Birjand as the capital city of South Khorasan province (Sayadi, 2014; Sayadi *et al.*, 2015).

Birjand is located in arid and semi-arid areas, and the elevation of this city is higher than most of the nearby cities. Furthermore, no research has been conducted on the spatial origin of particulate matter on account of the city's location in arid and semi-arid regions. In this study, considering the location of two important dust sources in Turkmenistan and southeast Iran (Ekhtesasi and Gohari, 2012; Baghi et al., 2020), and Birjand being affected by various dust events, and also given the fact that this city has been less studied in dust research, PM_{10} concentration and its relationship with climate variables was investigated. In addition, according to backward trajectories and dust amount on unhealthy days, the particles were tracked in order to identify local sources of dust.

Materials and Methods

Study area and dataset

Birjand is located in South Khorasan, Iran. It is located in South Khorasan with a longitude of 59°13’ E, a latitude of 32°53’ N, and an altitude of 1470 above the sea level. (Fig. 1). Previous studies in Birjand have been conducted in a short period of time. Among all these papers, the most important one, with a one-year study period, investigated PM_{10} values and wind speed in 2012; a positive relationship was found between PM_{10} and wind speed (Rezaei et al., 2017).

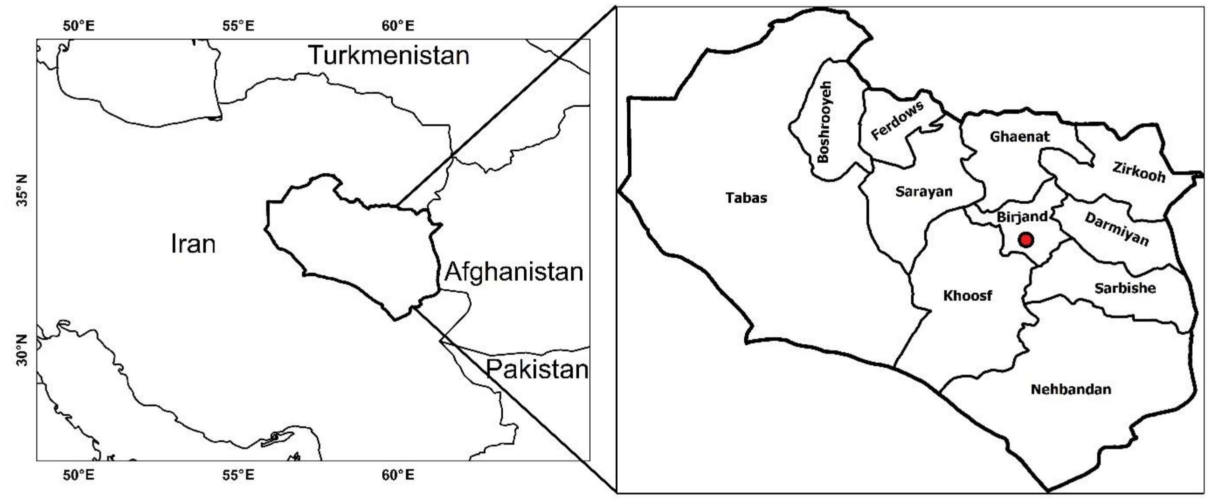

Figure 1. Location of Birjand synoptic station

In this study, we utilized particulate matter, air pressure, frequency of dusty days, the mean temperature, total precipitation, visibility, wind direction, and wind speed observational data. PM_{10} data were obtained from The Environmental Protection Department of South Khorasan (instrument: verewa – F701). In addition, other factors were obtained from the South Khorasan Meteorological Organization. It should be noted that PM_{10} data were prepared on an hourly basis and climate-related data on a three-hour basis in the period of 2014-2018.

Variation of PM_{10} concentration

Understanding PM_{10} concentration and its trend has an important role in the analysis of PM_{10} variations in annual (Krasnov et al., 2014; Shaziayani et al., 2020), seasonal (Arslan and Akyürek, 2018; Sánchez-Soberón et al., 2019), monthly (Hassan et al., 2020), weekly (Bodor et al., 2021), and hourly (Qiao et al., 2021) time scales. To estimate PM_{10} concentration trend, scatter plots of PM_{10} were drawn in different time scales. Slope changes also determined upward or downward trends of PM_{10} concentration.

PM_{10} relationship with climate variables

To estimate the effect of climate on PM_{10} variation, Pearson Correlation was calculated. In this research, we studied the relationships between PM_{10} and air pressure, dusty days, the mean temperature, total precipitation, visibility, and wind speed on seasonal and monthly time scales. Among the climate variables, the only dependent variable was visibility.

Particles trajectories

According to the standards of the United States Environmental Protection Agency (USEPA) and AQI†, days with a PM_{10} concentration of higher than 150µg/m^3 are unhealthy (EPA, 2012). One of the methods for identifying dust origins, in addition to satellite images, is the HYSPLIT model, which can detect the movement path and sources of dust with a suitable approximation. The HYSPLIT model is a dual model for calculating the trajectory of dust movement and emission (Draxler et al., 2009). In this research, the possible trajectory of dust particles was investigated with the backward approach on dusty days (according to the EPA standard). It should also be noted that particles were detected 24 hours prior to the unhealthy day record and at altitudes of 500, 1000, and 1500 meters above the ground (Sharif et al., 2015). The wind roses of Birjand were drawn to be compared with the direction of suspended particles entering Birjand.

Dust origin

One of the basic atmosphere-associated parameters for evaluating regional aerosol optical properties is the Aerosol Optical Depth (Filonchyk et al., 2019). Aerosol Optical Depth is the most comprehensive variable for remote assessment of aerosol load in the atmosphere and is used to reflect aerosol column loading (Che et al., 2015; Sarkar and Mishra, 2018). The high values of AOD can display natural sources of dust (Maghrabi and Alotaibi, 2018). Moreover, the advantage of using AOD and other satellite products over observation data is that they can better monitor the vertical loading of aerosols (Drury et al., 2008; Wang et al., 2010). Over the land, the dynamic aerosol models are derived from ground-based sky measurements and employed in the net retrieval process (Levy and Hsu, 2015). The main steps in calculating AOD are as follows: applying the rayleigh correction for terrain elevation to measure reflectance, defining the surface reflectance of a given pixel from clear-scene data based upon its geolocation, and comparing that with the values of solar zenith, single scattering albedo, and aerosol optical thickness (Safarpour et al., 2014). In this study, the data of dusty days were collected with satellite images. For this purpose, Terra-MODIS images (MOD04_L2) with Deep Blue AOD at 550 nm were used (Sayer et al., 2014; Kaskaoutis et al., 2019). Combination of the HYSPLIT and AOD provides the possibility to track the path of the air masses that brought the particles to Birjand and find out whether the particles have passed through the dust sources or not (Namdari et al., 2016; Ali et al., 2019; Li et al., 2021). After overlapping backward trajectories of HYSPLIT, the regions with higher AOD were detected. These regions were probably the dust sources, which increased PM_{10} in Birjand.

Results and Discussion

Annual, seasonal, monthly, weekly, and hourly variability in PM_{10} concentration

According to the results, between 2014 and 2017, the average annual concentration of PM_{10} had a decreasing trend. In 2014, the average annual concentration of PM_{10} was approximately 46 µg/m3, which reached 32 µg/m3 in 2017. However, the average annual concentration of PM_{10} increased significantly in 2018 and was reported to be close to 51 µg/m3. There was also a similarity between the pattern of concentration changes and frequency of dusty days (Fig. 2.a). The highest average PM_{10} concentration was observed in summer. In spring, the average PM_{10} concentration was close to that in summer. Meanwhile, the average PM_{10} concentration

† Air Quality Index

in autumn and winter were much lower than that in spring and summer. There was a similarity between the pattern of changes in particle concentration and frequency dusty days (Fig. 2.b). According to the monthly examination of the changes in the average PM_{10} concentration, in July, May, and April, the average PM_{10} concentration was higher than that in the other months. The relationship between PM_{10} concentration and the number of dusty days was significant (Fig. 2.c). In most of studies, July, May, and April had the highest number of dusty days in the east and southeast of Iran (Ahmadi et al., 2015; Rashki et al., 2017). Regarding the number of dusty days in Birjand, some other studies have been conducted, implying the importance of these months (Yarmoradi et al., 2020). Furthermore, in different days of the week, the concentration of particles on Friday was lower than that on other days (Fig. 2.d). Among different hours of the day, the highest concentration of PM_{10} belonged to the late hours of the night and the early hours of the morning. PM_{10} concentration increased after 8 AM, which was the start of working hours (Fig. 2.e).

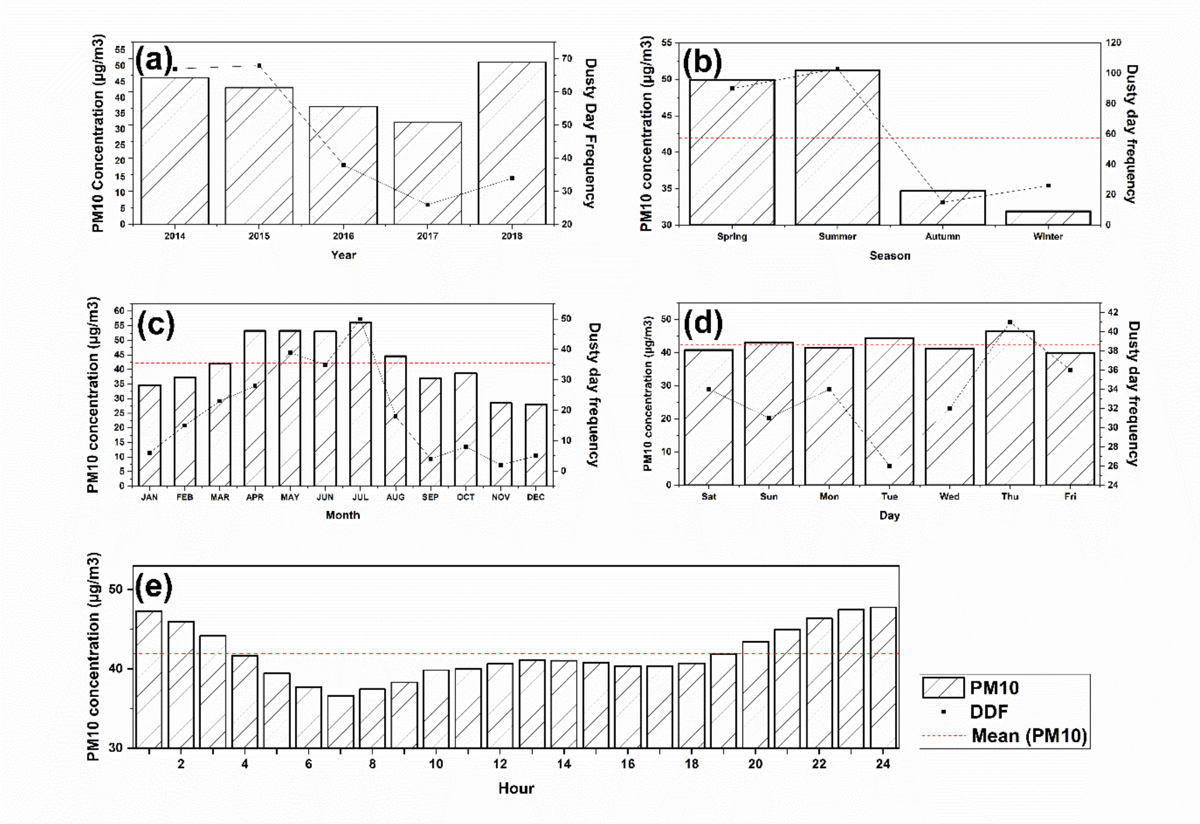

Figure 2. Annual, seasonal, monthly, weekly, and hourly variation of PM_{10} in Birjand from 2014 to 2018

A number of papers have been conducted on the relationship between particulate matter concentration and climatic variables. A study in Kuwait found that the highest concentrations of particulate matter were observed in July, May, and June; this finding is in line with our results. In this study, the peak concentration of suspended particles was reported at 8 AM and 7 PM (Al-Hemoud et al., 2018). Additionally, in another work conducted in Sanandaj, Iran, between 2008 and 2012, the highest concentrations of suspended particles were reported in spring and summer and in May, June, and July. The trend of changes in the concentration of suspended particles had a significant correlation with the number of dusty days and temperature (Rahimi et al., 2015). However, in a study conducted in Mecca from January 2014 to September 2015, the concentration of particulate matter in October and September was slightly higher than that in the other months (Munir et al., 2017). A study conducted in Zahedan in 2013 showed that wind speed, compared to precipitation, relative humidity, and temperature, was more closely correlated with the concentration of suspended particles in autumn and winter (Atabaki et al., 2017). In another study, the relationship between PM_{10} concentration changes and climatic variables in Iași city between 2013 and 2015 was examined. It was found that the highest particle concentrations belonged to May and March (Sfîcă et al., 2018). Another work published in 2019 indicated that $PM_{2.5}$ and PM_{10} in Pourt Harcourt, Nigeria, are affected by temperature, wind speed, and rainfall, and the highest concentrations of particulate matter were reported in December and July (Onuorah et al., 2019). The comparison of the results of this study to ours suggest that the concentration of suspended particles in semi-arid and arid regions was generally high in summer.

PM_{10} and climate in the seasonal time scale

During the study period, the concentration of PM_{10} in spring, summer, and autumn had a downward trend. Meanwhile, in winter, PM_{10} concentration was rising (Fig. 3). Nonetheless, none of these trends were significant based on R^2 values and no reliable conclusion can be reached concerning the trend of change in different seasons.

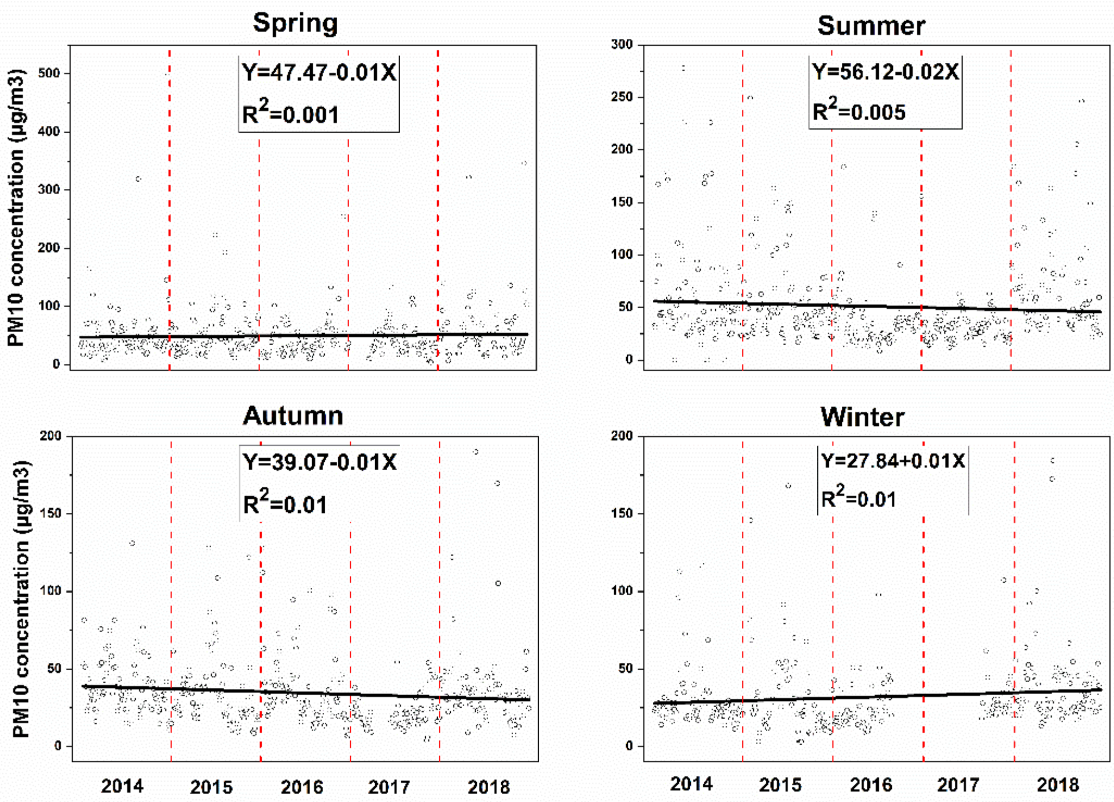

Figure 3. Seasonal trends of PM_{10} in Birjand from 2014 to 2018

To analyze climate variables, the changes in the variables in different seasons were drawn via box charts. Air pressure reached the lowest in summer, yet increased in autumn and winter. The trend of air pressure was contradictory with that of PM_{10}. Temperature and wind speed had positive effects on PM_{10} concentration and the pattern of the mean temperature and wind speed were similar to the PM_{10} pattern. The precipitation trend was irregular and did not have a significant relationship with PM_{10} concentration. Only in summer, the effect of precipitation on PM_{10} concentration was noticeable, and there was a significant relationship between them (Fig. 4).

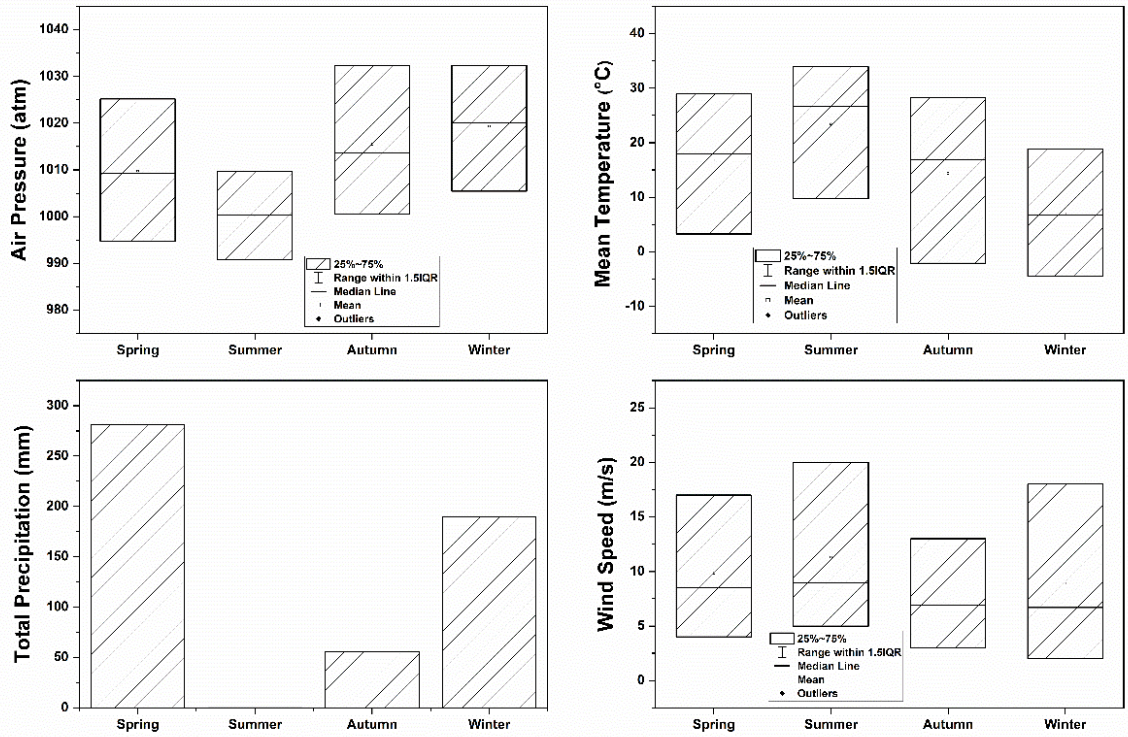

Figure 4. Seasonal variation of climate variables from 2014 to 2018

Furthermore, the results revealed that the concentration of PM_{10} in all the seasons (except for autumn) had a significant correlation with all the variables, except for the total precipitation. In autumn, the concentration of PM_{10} and the total precipitation were significant. The highest correlation was calculated to be between the concentration of PM_{10} and visibility in summer. However, in general, in addition to visibility, PM_{10} concentration had a significant correlation with the number of dusty days in different seasons. It could be also noted that the correlation between PM_{10} concentration and climate variables had the highest value in summer and the lowest value in winter (Table1).

Table1. Seasonal Pearson correlation between PM_{10} and climate variables

Season		Air pressure	Dusty days	Mean temperature	Total precipitation	Visibility	Wind speed
Spring	Pearson Cor.	-0.202	0.314	0.238	-0.048	-0.446	0.229
	Sig.	0.000	0.000	0.000	0.342	0.000	0.000
Summer	Pearson Cor.	-0.122	0.494	0.278	-0.022	-0.649	0.367
	Sig.	0.011	0.000	0.000	0.645	0.000	00.000
Autumn	Pearson Cor.	-0.202	0.335	0.268	0.210	-0.372	0.18
	Sig.	0.000	0.000	0.000	0.000	0.000	0.000
Winter	Pearson Cor.	-0.345	0.249	0.285	0.02	-0.183	0.201
	Sig.	0.000	0.000	0.000	0.725	0.001	0.000

PM_{10} and climate in the monthly time scale

Based on the results, the monthly changes in PM_{10} concentration were very irregular and no significant trend could be achieved based on it. PM_{10} concentration trend was increasing in

January, February, and December from 2014 to 2018. The slope change and R^2 in December were higher than those in January and February. PM_{10} concentration in March and May had an increasing trend whereas in April, the trend was decreasing. Moreover, the slope change was negative in spring. In June and July, PM_{10} trend was decreasing while in August, it was increasing. In September, October, and November, PM_{10} concentration trend from 2014 to 2018 was descending (Fig. 5).

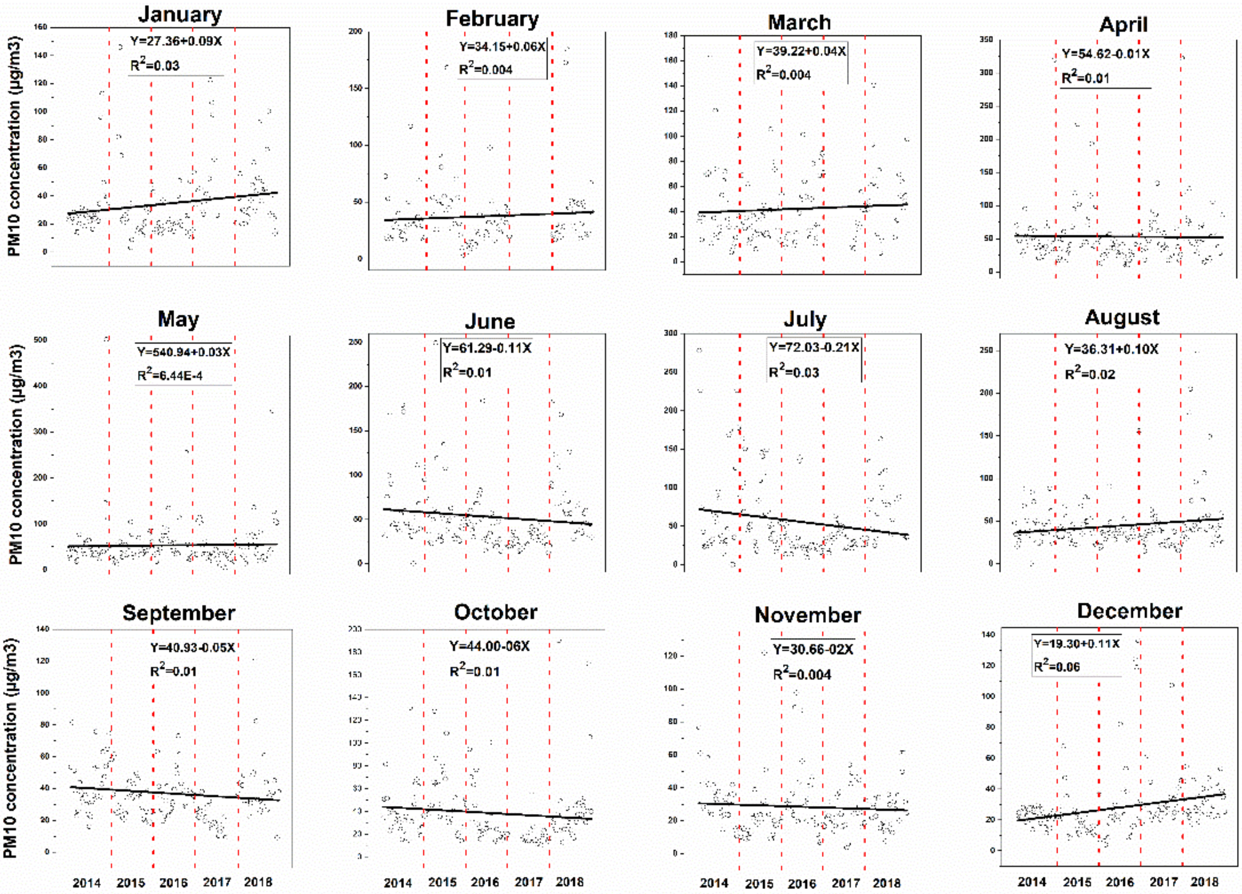

Figure 5. Monthly trends of PM_{10} in Birjand from 2014 to 2018

Air pressure pattern changes was different with PM_{10} pattern changes. In July, the lowest air pressure and the highest PM_{10} concentration were recorded. The pattern of the changes in air pressure and mean temperature variables were similar to that of the changes in PM_{10} concentration (Fig. 6).

The correlation between PM_{10} concentration and climatic variables in January showed that the changes in PM_{10} concentration were significant with air pressure, the mean temperature, and the number of dusty days. In January, PM_{10} concentration was the most closely correlated with air pressure. In February, March, April, May, June, July, and August, there was a significant relationship between the changes in PM_{10} concentration with air pressure, average temperature, wind speed, visibility, and dusty days. The closest correlations of PM_{10} were with air pressure in February, with average temperature in March, and with visibility in April, May, July, June, and August. In September, PM_{10} concentration had a significant relationship with air pressure, the mean temperature, and visibility. October was the only month in which PM_{10} concentration had a significant relationship with total precipitation; in this month, PM_{10} relationship with all climatic variables was significant, except for that with wind speed. In November, PM_{10} concentration was significantly associated with the number of dusty days and wind speed, and in December PM_{10} concentration was significantly correlated with air pressure, the mean temperature, and wind speed (Table 2).

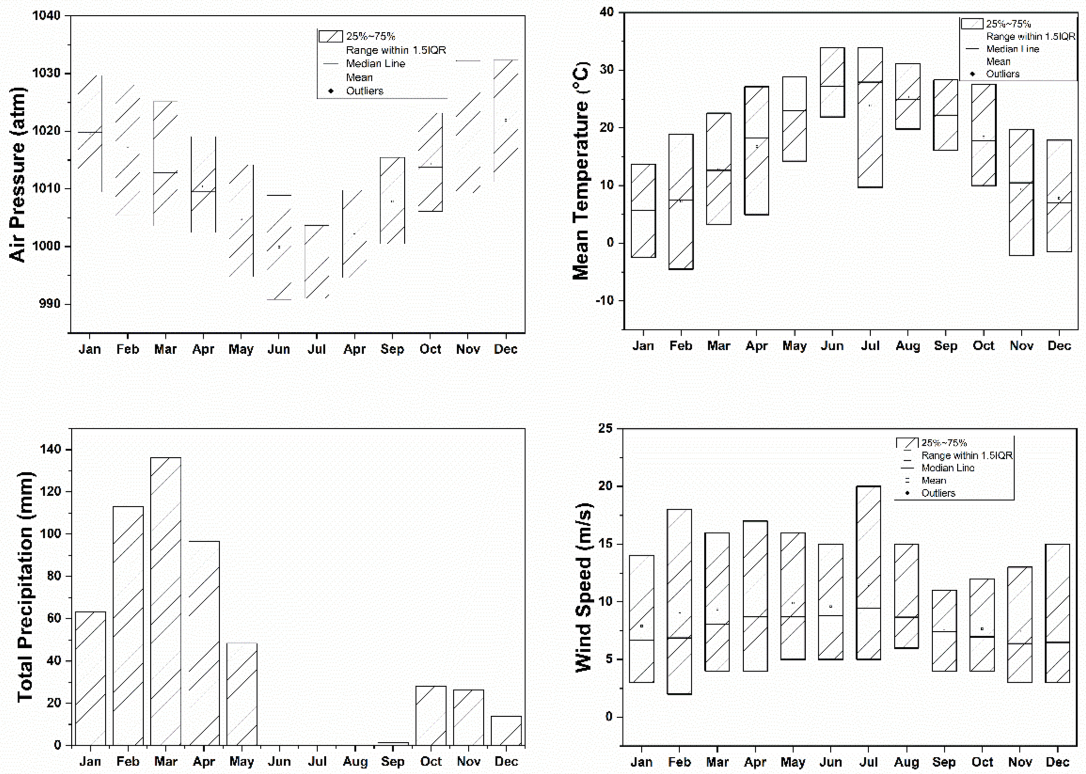

Fig. 6. Monthly variation of climate variables from 2014 to 2018.

Table 2. Monthly Pearson correlation between PM_{10} and climate variables

		Air pressure	Dusty days	Mean temperature	Total precipitation	Visibility	Wind speed
Jan	Pearson Cor.	-0.375	0.274	0.233	0.010	-0.143	0.096
	Sig.	0.000	0.002	0.008	0.912	0.108	0.281
Feb	Pearson Cor.	-0.301	0.201	0.237	0.023	-0.215	0.229
	Sig.	0.002	0.037	0.014	0.820	0.025	0.018
Mar	Pearson Cor.	-0.353	0.280	0.375	-0.086	-0.211	0.201
	Sig.	0.000	0.002	0.000	0.347	0.020	0.027
Apr	Pearson Cor.	-0.178	0.214	0.283	-0.040	-0.534	0.267
	Sig.	0.033	0.010	0.001	0.643	0.000	0.001
May	Pearson Cor.	-0.130	0.398	0.176	-0.018	-0.498	0.197
	Sig.	0.116	0.000	0.033	0.830	0.000	0.017
Jun	Pearson Cor.	0.011	0.363	0.153	-0.045	-0.500	0.227
	Sig.	0.897	0.000	0.069	0.593	0.000	0.006
Jul	Pearson Cor.	-0.50	0.619	0.267	-	-0.755	0.448
	Sig.	0.553	0.000	0.001	-	0.000	0.000
Aug	Pearson Cor.	-0.237	0.388	0.354	-	-0.634	0.349
	Sig.	0.003	0.000	0.000	-	0.000	0.000
Sep	Pearson Cor.	-0.228	0.100	0.362	-0.009	-0.214	0.105
	Sig.	0.007	0.244	0.000	0.916	0.012	0.218
Oct	Pearson Cor.	-0.178	0.450	0.290	0.324	-0.524	0.112
	Sig.	0.035	0.000	0.001	0.000	0.000	0.188
Nov	Pearson Cor.	-0.084	0.325	0.096	0.072	-0.154	0.246
	Sig.	0.319	0.000	0.254	0.400	0.065	0.003
Dec	Pearson Cor.	-0.200	0.046	0.249	-0.142	-0.067	0.144
	Sig.	0.016	0.586	0.003	0.094	0.424	0.087

PM_{10} and particle trajectories

According to the wind roses, the wind direction in Birjand varied in different seasons. In spring, the wind direction was mainly towards the west, when the wind speed in the west direction was higher than other directions. In spring, the wind mostly blew towards northwest and north compared to other seasons (Fig. 7.a). Nevertheless, in the summer, the wind direction to the west was so low that it is pretty negligible although the winds that blew slightly to the west was considerable. In autumn and winter, the wind speed was lower than that in spring and summer (Fig. 7.b). In autumn, the wind direction was mainly towards the north and west. The winds blowing to the west was faster than that to the north (Fig. 7.c). In winter, the wind directions were mainly towards the west and east, and the frequency and speed of the wind that blew to the northwest and north were lower than the wind that blew to the west and east (Fig. 7.d). The important point in all the wind roses is that the direction of the wind in Birjand was mainly towards the north, east, and west.

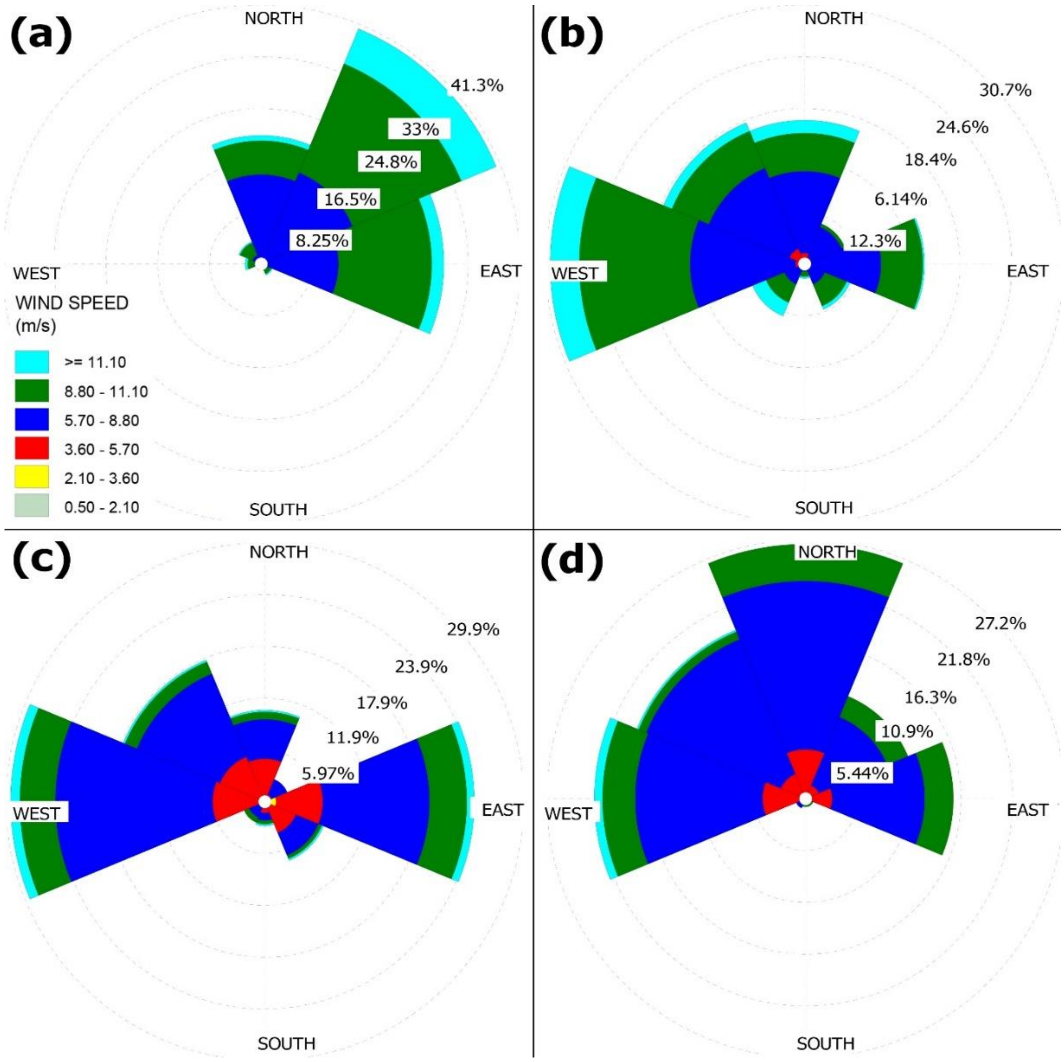

Figure 7. Wind roses in spring (a), summer (b), autumn (c), and winter (d) from 2014 to 2018

In Birjand, from 2014 to 2018, the concentrations of suspended particles in 34 days were higher than those in the EPA standard. In 70% of these days, dusty days (suspended dust or rising dust) were reported in Birjand synoptic station. In other stations close to Birjand, dusty days occurred in most of these 34 days (Online Resource 1), and it was likely that the high concentration of PM_{10} in Birjand be due to the high concentration of dust.

Based on the recorded data, 12 unhealthy days – with a PM_{10} higher than EPA standard - in 2014 (in March, April, May, June, July), seven unhealthy days in 2015 (in February, March, April, June, July), three in 2016 (in May, June, August), and 12 in 2018 (in February, April, May, June, July, August, October) were reported. Thus, the highest number of unhealthy days were recorded in 2014 and 2018 (3.28%), 2015 (1.91%), and 2014 (less than 1%), respectively. Seasonal detection of dust particles using HYSPLIT on the days when the PM_{10} concentration was higher than EPA standard indicated that dust particles in spring mainly entered Birjand from the west. In this season, most of the particles probably entered Birjand from the south and west (Fig. 8.a). On the other hand, in summer, dust particles moved mainly from the northeast and north to Birjand. Trajectories indicated that a large volume of dust entering Birjand in summer was likely to be from the Iran-Turkmenistan border (Fig. 8.b). In autumn and winter, when the number of unhealthy days were fewer than that in warm seasons, the particles entered Birjand mainly from the west and southwest. It is also possible that in autumn, a part of dust entering Birjand was from the east and in winter, it could be from southwest of Birjand (Fig. 8.c and Fig. 8.d).

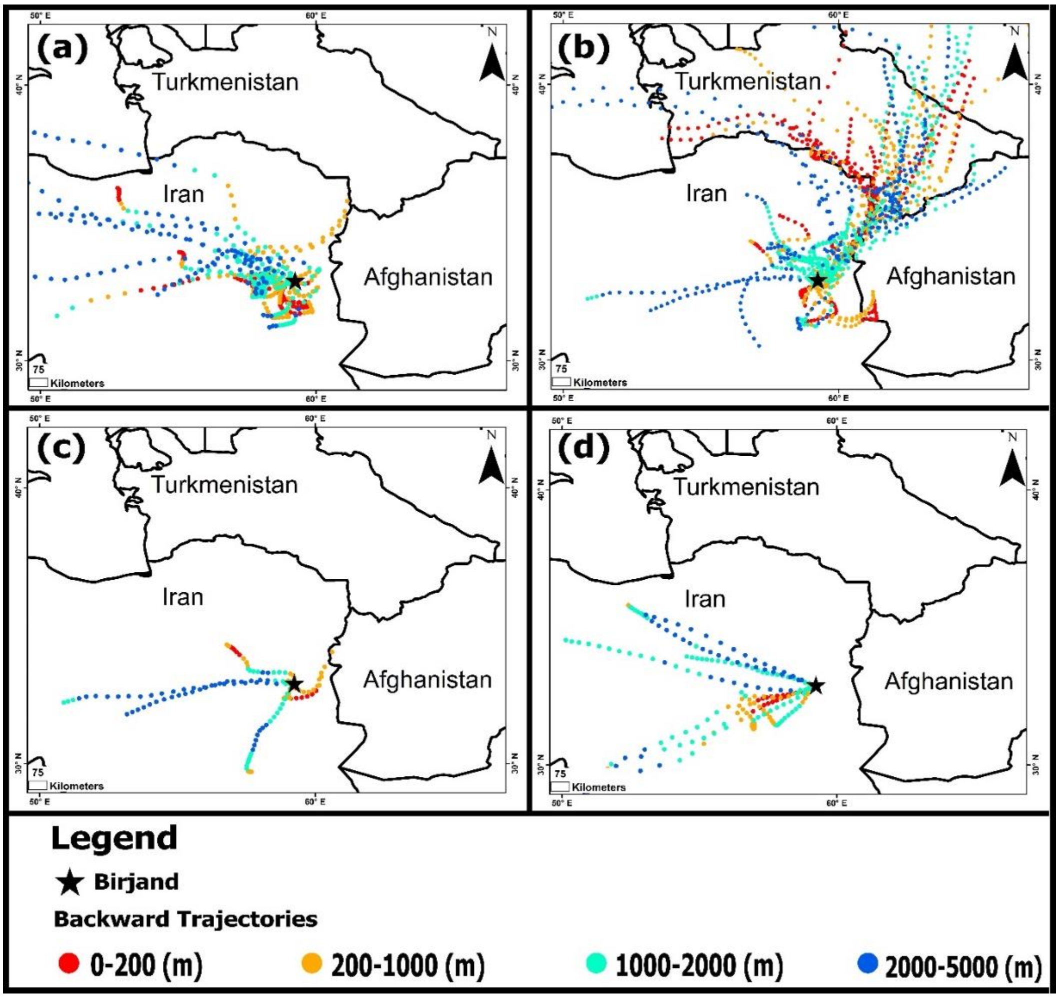

Figure 8. Backward trajectories in spring (a), summer (b), autumn (c), and winter (d) in unhealthy days

PM_{10} concentration in unhealthy days

One of the most important issues to consider is the changes in the concentration of PM_{10} with dust events. On dusty days, three-hour visibility data were used and hourly data on the concentration of PM_{10} were converted into three-hour data (the maximum concentration during three hours). The results demonstrated a significant relationship between the concentration of PM_{10} and visibility (Sig =0.002, Pearson Correlation=-0.163).

Examination of satellite imagery of the AOD in unhealthy days and the overlap of tracking suspended particles with the HYSPLIT model indicated that dust is in areas where the particles have passed. In the next step, the AOD amount for 24 hours before the dusty days, along with particle tracking that started 24 hours beforehand, were examined. PM_{10} concentration was higher than standard in the next day of a few days out of a total of 34 unhealthy days.

On May 28, 2014, in most parts of South Khorasan, the density of dust particles was high, and in the next day, the concentration of PM_{10} was over three times higher than usual. The 24-hour particle tracking indicated that particles entered Birjand from the west of Birjand, and due to the high density of dust on that side, it was likely that the source of the high concentration of PM_{10} on May 29, 2014, was probably from dust particles. On July 1, 2014, suspended particles in Birjand were reported to be above the standard level. Examination of the density of dust particles in the previous day and tracking them showed that on that day, in the northeast of Birjand, a dust source was formed, and the particles moved from that area (Iran-Afghanistan border) to Birjand. Additionally, on this day, on top of Birjand, dusty days were reported in Ferdows, Ghaenat, Nehbandan, and Tabas. On April 26, 2015, the concentration of PM_{10} was reported to be higher than the standard level. Observing the dust density in the day before and tracking the particles indicated that the particles probably entered Birjand from the northwest of Birjand, where the dust density was higher. Furthermore, on this day, dusty days were observed in Ghaenat, Tabas, and Nehbandan. On June 8, 2015, PM_{10} concentrations were reported to be above the standard level. 24-hour tracking of dust particles and observation of AOD images showed that the dust density was critically high in the northwest of Birjand. Since the path of dust particles was from Turkmenistan to Birjand, the source of the high concentration of PM_{10} on June 7, 2015, was probably the high density of dust in the northwest of Birjand. It should be noted that in addition to Birjand, dusty days were reported in Nehbandan, Ghaenat, and Tabas. On May 28, 2018, dust density was high in the east and northeast of Iran and Turkmenistan, and dusty days were reported in all the stations of South Khorasan. Based on the backward trajectories, particles entered Birjand from the northeastern and western parts of the city. According to the synoptic stations, dusty days were reported in Birjand, Nehbandan, Ferdows, Ghaenat, and Tabas. On August 12, 2018, the PM_{10} concentration in Birjand was higher than the EPA standard. The synoptic stations also reported dusty days. Dust storms were also observed in Nehbandan, Tabas, and Ghaenat. However, the detection of dust particles and AOD on August 11, 2018, implied that in the northeast of Birjand and Turkmenistan, the density of dust particles was very high, and it was predicted that these particles move to Birjand from the south of the city. As a result, it could be assumed that the high concentration of PM_{10} originates from the northeast of Birjand (Fig. 9).

Subsequently, particles movement was examined 24 hours prior to the unhealthy day. To this end, three days of unhealthy days were selected.

On July 28, 2014, dust density in the northeast of Birjand reached a critical level, and 24-hour tracking of dust particles showed that the particles entering Birjand had passed through the northeast of the city (in Afghanistan). On July 29, 2014, the concentration of PM_{10} was also higher than the EPA standard. It could be seen that during these two days, the dust moved from the Iran-Turkmenistan border to the center of Iran, during which the concentration of particles in Birjand increased. On April 15, 2015, in the south of Birjand, the dust density reached a critical level. Tracking the dust path indicated that dust particles had entered Birjand from the south. Moreover, on April 16, 2015, the PM_{10} concentration reached a high level. During these two days, the dust moved from the south of Birjand to its north. On the other hand, a mass of particles was transferred from the center of Iran to the east of Iran and caused an increase in dust concentration in Birjand and other cities in its vicinity. On this day, dust storm occurred in

Birjand, Ghaenat, Nehbandan, Ferdows, and Tabas. On May 25, 2016, dust density increased in northeastern Birjand and trajectories passed through that area. On May 26, 2016, PM_{10} concentration was reported to be higher than usual. Additionally, on this day, a dusty day was observed in Birjand. Dusty day was also reported in Nehbandan, Tabas, Ferdows, and Ghaenat, and high levels of PM_{10} were likely to occur due to dust. As it is known, the movement of particles originating from the west and center of Iran towards the east of Iran and Afghanistan leads to the creation of dust events, and sometimes the height of the movement of particles decreases in these areas. This problem increases the concentration of particles and reduces visibility in eastern Iran and South Khorasan province (Fig. 10).

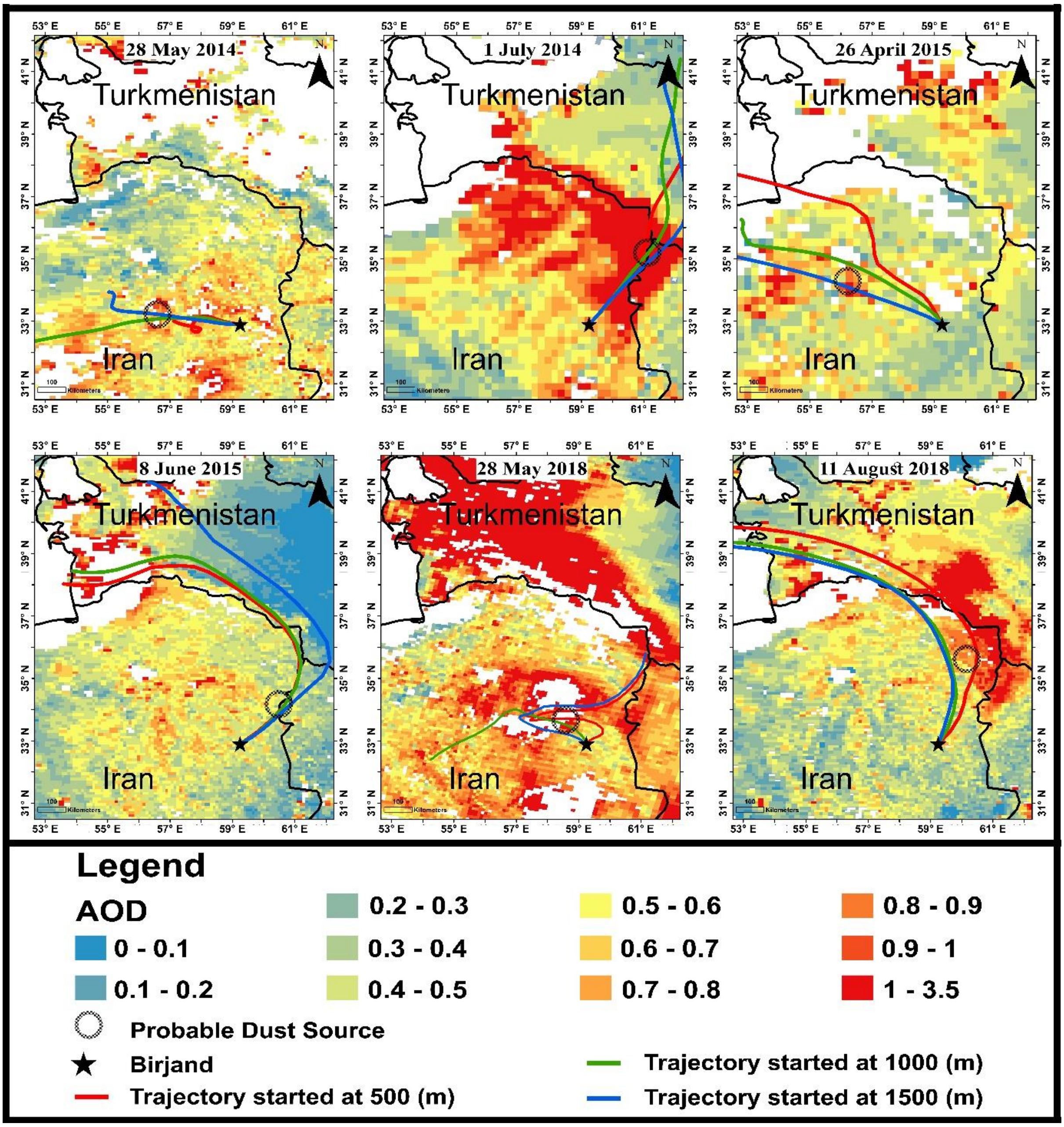

Figure 9. The spatial distribution of AOD and probable dust sources

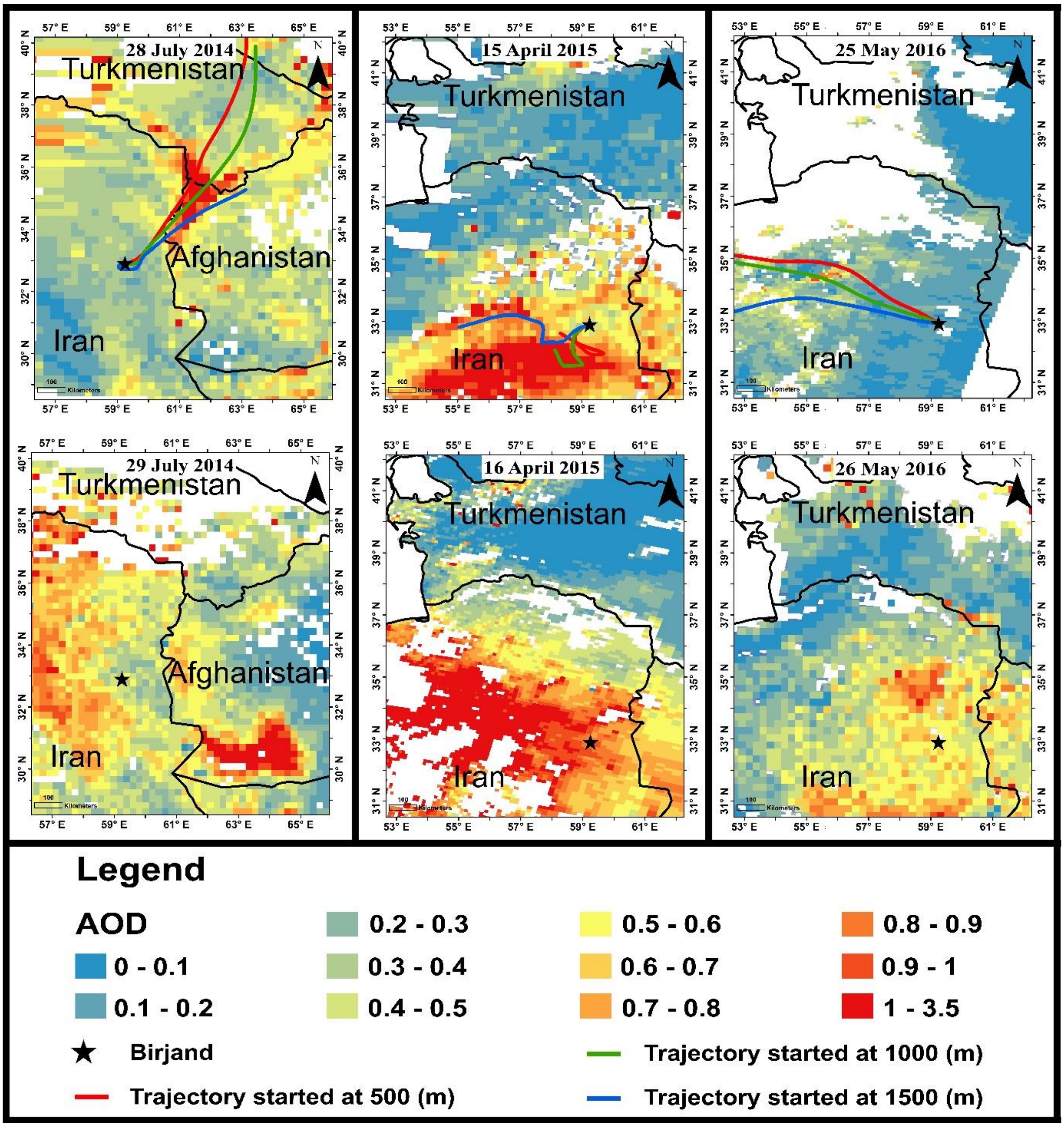

Figure 10. The movement of AOD in unhealthy days

Conclusion

In this study, hourly, weekly, monthly, seasonal, and yearly variations of PM_{10} concentration were calculated. The results revealed that the average PM_{10} concentration decreased until 2018 whereas in 2018, it saw a significant increase. In spring and summer, PM_{10} concentration was higher than that in autumn and winter. In July, the average PM_{10} concentration was the highest, and in April, May, and June, it was higher than that in other months. On Thursdays, the average PM_{10} concentration was considerable. Pattern changes of PM_{10} concentration were almost similar to dusty day frequency. Furthermore, PM_{10} concentration had a significant relationship with air pressure, the mean temperature, wind speed, visibility, and dusty days on the seasonal and monthly time scales. As mentioned previously, the geographical location of eastern Iran and its location in arid and semi-arid regions increases the potential of local and regional dust storms (Goudie, 2009). Birjand is also located in this area, and over the recent years, the average concentration of PM_{10} has been affected by dust events. Moreover, dust tracking and dust amount analysis showed that several unhealthy days were attributed to the increase in AOD in local sources around Birjand. Backward trajectories indicated that most of the particles originated from the northeastern of Birjand, and in summer, autumn, and winter, the main wind direction was toward the west. However, it was found that on a number of unhealthy days, the particles parted from the west to the east. As stated in all cases, the concentration of PM_{10} in Birjand had a strong correlation with dust occurrences and it could be said that PM_{10} was probably affected more by natural occurrences than human activities. It seems as if the rising of dust particles in the regions in vicinity was a threat, increasing PM_{10} concentration. In addition, PM_{10} was affected by climate variables (expect for total precipitation). Hence, it could be said that dust events in the surrounding regions and climate changes more significantly affect PM_{10} concentration, and managers must consider these events and variables in the urban planning of Birjand. With further information on PM_{10} concentration in the coming years, it could suggested that employing different models, particle concentration changes be predicted; thus, better management decisions can be made.

Acknowledgement

The authors would like to thank The Environmental Protection Department of South Khorasan, especially Dr. Akbari and Mr. Hashem Abadi, who let us access PM_{10} data. Furthermore, we must thank the South Khorasan Province Meteorological Organization, particularly Mr. Khandanroo and Ms. Sepehri, who shared climatic data with us.

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