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Clustering of different atmospheric patterns leading to an increase in different types of atmospheric pollutants in the greater Tehran area during the last 17 years (2004-2020)

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ABSTRACT

Introduction: Air pollution is one of the main problems of industrial and large cities like Tehran, due to its harmful effects, especially on human health.
Materials and methods: Based on the intensity and continuity of the standard air pollution index during 2004-2020 for 112 cases in Tehran, the principal component analysis method was applied in T-mode and clustering of days for similar 500hPa geopotential height changes were provided. The synoptic patterns leading to these different pollution cases were obtained.
Results: The study of the mentioned days shows the activity of five atmospheric patterns with the frequency of 47, 28, 12, 13, and 4%, respectively.
Conclusion: The first pattern happens during the cold season, associated with the simultaneous placement of the atmospheric ridge along with Siberian high-pressure system. The second group, which occurs mostly in summer and during late spring, is controlled with the predominant ozone pollutant. The main activity of the third pattern occurrences in summer and late spring, which is associated with the presence of monsoon Indian low-pressure on the southeastern regions in Iran. The fourth pattern, which occurs mostly in spring and autumn, associates with the establishment of dynamic low pressure in the western regions of Iran and Iraq, as well as the establishment of the thermal low-pressure system in the central part of the country. The last group is a local pattern that occurs due to the passage of the gust front and the shear of the wind field dust rise in the Tehran.

Introduction

Air pollution has always been one of the most important issues in industrial and large cities of the world, including Tehran. Statistical analysis shows that the number of polluted days and the amount of air pollution is increasing across the world, and this is due to the increase in population in large and industrial cities and the increase in air pollution sources, such as cars and industrial places [1, 2]. The World Health Organization identifies air pollution as the cause of several million deaths each year [3]. It is projected that ~87% of the worldwide people live in areas surpassing the World Health Organisation's

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(WHO) air quality standards for yearly mean ambient $PM_{2.5}$ (10 mg/m^3) [1]. Recent studies of the Global Burden of Disease (GBD) assess that ambient PM2.5 exposure is a main factor risk factor to local and worldwide burden of illness [4-7].

Meteorological conditions and changes in the physical and dynamic properties of the atmosphere play an important role in changes in air pollution [8-11]. Meteorological parameters which can affect the way atmospheric pollutants change are including wind shear and direction, atmospheric vertical temperature structure, humidity, and solar radiation [12-14]. For example, the absence of wind with appropriate intensity and temperature inversion that prevents convective movements can cause the accumulation of atmospheric pollutants in the lower layers [15]. Due to the importance of this issue, many studies have been conducted on the relationship between meteorological conditions and atmospheric parameters with air pollution. For example, investigated the effect of synoptic patterns and boundary layer characteristics on the increase of particulate pollutants with an aerodynamic diameter greater than 10 micrometers (Particulate Matter: PM_{10}) in Changsha, China [16]. In this study, it has been shown that increasing the intensity of this pollutant is associated with increasing the stability of the atmosphere and the establishment of an anti-cyclonic pattern. Also, with increasing wind speed, increasing the height of the mixed layer, and decreasing the depth of the temperature inversion layer, the amount of this pollutant decreases. Using a model, investigated the effect of local and synoptic atmospheric patterns on PM_{10} atmospheric pollutants in Naples, Italy [17]. The results show that low wind speed, temperature inversion as well as the absence of significant rainfall for at least a week led to increased air pollution in this area. Also investigated the effect of meteorological parameters on the persistence of severe atmospheric pollution in Chengdu Plain, which has several sources of off-site pollutants, in a case study [18]. The results of this study show that low air temperature and wind speed, higher surface pressure, and relative humidity, the occurrence of temperature inversion, especially in the layers close to the surface, aggravate air pollution. In addition, it has been stated that not only surface factors but also the structure of the boundary layer plays a role in the vertical release of pollutants.

Among air pollutants, in addition to PM_{10} and $PM_{2.5}$, the harmful effects of ozone should not be ignored. Ozone is one of the most important air pollutants near the earth's surface. The transparent layer of ozone, or in other words, the thin blue band that surrounds the Earth's atmosphere, has an important role in life over the Earth's atmosphere. So that only with this protective coating, human life on Earth can continue. But the presence of ozone near the Earth's surface has a severely destructive effect on the mucous tissues and respiratory organs of living organisms. Usually, in warm weather and without clouds, the conditions for photochemical production of ozone are more favorable. Also, low wind speed and downward motions cause this pollutant to be trapped in the surface layer [19]. The relationship between the thickness of the boundary layer and the amount of ozone in it has been investigated by [20]. In this study, it is stated that the amount of this pollutant changes with the variation of the thickness of the boundary layer at different hours of the day and corresponding to the number of sunny hours. As the height of the boundary layer increases, so does the amount of ozone, and vice versa. This is because, in the thicker boundary layer, the air near the surface mixes with the air richer with the ozone of the higher layers, and the amount of ozone near the surface increases. There have also been many studies on the relationship between ozone formation and atmospheric temperature [21-23]. In general, ozone concentrations do not appear to be dependent on temperatures below 27°C but are strongly dependent on temperatures above 32°C [24].

Also, some Iranian studies have been conducted on air pollution in greater Tehran, which are divided into two main groups. In the first group, the increase in air pollution index is due to the stability of the atmosphere and the consequent confinement of pollutants due to incomplete combustion of fuel and other pollutants [10]. The second group is related to the increase of the pollution index due to the rise of dust in the region or the advection of dust from the ground outside the region of Tehran to this region [25]. Many case studies have been conducted in connection with these two different mechanisms of increasing the pollution index in Tehran, but the long-term and simultaneous study of these patterns have not been investigated. For example, studied the spatial distribution of atmospheric pollutants in Tehran in 2005 [10]. In this study, using the principal component analysis method, five synoptic meteorological models based on the amount of air pollution in Tehran have been introduced. The results of correlation of pollutants with each pattern show that in the conditions of heat low pressure develops over the central part of Iran and high-pressure penetration from the northeast accompanying with middle tropospheric zonal pattern with dry southerly winds, the concentration of pollutants increases. While the occurrence of precipitation and westerly high-speed winds reduce air pollution in Tehran. Also, have studied the changes in the concentration of atmospheric pollutants for several specific periods in the duration of 2004-2007 [26]. The results of this study indicate that carbon monoxide shows two maximum values, one in the morning and one at night in Tehran. These polluted days are associated with severe temperature inversion and increased surface pressure. Other studies from the first group include the study of investigated the average of synoptic patterns based on the occurrence of different concentrations of carbon monoxide in summer and autumn in Tehran during 2001-2006 [27]. The results of this study showed that the development of high pressure on the Caspian Sea, the passage of the trough line, or zonal currents of the middle level of the troposphere reduce atmospheric pollution in Tehran. While the formation of thermal low pressure in the southeastern parts of the Caspian Sea and the high-pressure tongue in the south of the Alborz mountain range along with strengthening the ridge cause an increase in the potential of air pollution in Tehran. Also, have studied the synoptic characteristics of atmospheric systems that have led to the occurrence of severe pollution during the period (1999-2008) in Tehran using the manual method [28]. The results of this study showed that pressure patterns for days with severe pollution in Tehran, although occurring in different seasons, but there are similar in terms of the type of weather system and location. In all cases studied, the formation of the high-pressure system cited on the Zagros and southern Alborz and thermal low pressure in the northern Alborz with mid-atmosphere ridging along with calm wind conditions and a very sharp reduction in the boundary layer depth in Tehran are specific synoptic features of all these polluted days.

In the field of studying the occurrence of dust in the region of Tehran area or the southeast and southwest of Iran as well as Iraq, many studies of synoptic perspectives and simulations have been done using numerical models. In some cases, the dust is advected from the south, east, and southwest of Iran, as well as Iraq to the Tehran region. For example, studied the identification of the best algorithm for dust occurrence in the southwest of the country by using Miller method and the Modis data [29]. Also, the dust storm of June 12, 2014, was simulated in Tehran using the WRF-Chem model and it was stated that the MADE-SORGAM scheme had a good performance in simulating the dust concentration [30]. In this study, a dust storm event on the first to third of April 2015, which affected the Persian Gulf and the southeast of the country, was simulated by using the WRF-Chem model. The model is examined using three-station information. The results of this study showed that the performance of the AFWA schema in simulating the behavior of dust particles is appropriate in terms of the particle distribution.

Atmospheric patterns are classified manually before automated methods with the help of computers, and this method is more familiar to meteorologists. Its main problem is the possibility of personal mistakes in classification and heavy and intensive work. However, its main advantage is the application of the experience of skilled experts in the classification process [31]. With the advancement of science and the emergence of powerful computers in the world of science, manual (intrinsic) methods have given way to automatic (objective) computer methods. Contemporary automatic classification methods have been extensively studied by [32]. One of the correlation-based methods is the most popular method due to its efficient classification with a computer pattern recognition algorithm. However, this method requires the researcher to make mental decisions such as the size and number of network points, determining the number of map patterns, and correlation thresholds that affect intragroup similarity and intergroup differentiation. Hence, suggested abandoning the term "objective classification" and replacing it with automated methods called computer-assisted classification [33, 34]. However, it looks that there is no single classification method being the best and proposed one [35]. Also, it was concluded that each classification method has advantages and disadvantages, and the choice of the appropriate method depends on balancing the research needs, the researcher's skills, and the nature of the data [36].

Atmospheric synoptic patterns directly or indirectly play a very important role in environmental phenomena by allowing the impact of mesoscale processes [37]. These phenomena include, for example, flash floods, dust emissions, and an increase in atmospheric pollutants such as ozone depletion [34]. It was obtained 19 atmospheric patterns for a ten-year period in the eastern mediterranean using both manual and computer-assisted methods [34]. However, a day-to-day comparison of classifications for the three common types of these patterns shows a large difference between the two clustering methods. The "environment- to- circulation" approach has been tested on three environmental processes: air pollutants, dust emissions, and floods [32]. The results show that the weak pressure gradient associated with increasing ozone content makes classification difficult for both methods. Patterns related to dust emission show the importance of studying the formation of the cold cyclonic system rather than pressure gradient analysis. Also, in the case of floods, it is important to study the patterns of upper atmosphere levels due to study severe convective processes than to study the patterns of the lower atmosphere. Also, used the analysis method of the main components of atmospheric patterns and studied the case of the period of 2000 to 2018 which led to an increase in atmospheric pollutants in Tehran [9]. In this study, the severity and persistence of severity in terms of pollution were chosen. However, the selected days did not include ozone pollutants as well as any presence of the gust front system with a short lifetime of about one day. Due to global warming and the dependence of increasing atmospheric pollution by ozone pollutants with rising temperature, it is necessary to consider these specific atmospheric patterns associated with ozone pollutants. Therefore, ozone pollutants have also been studied in this study.

Materials and methods

To determine the weather patterns leading to air pollution or the cause of persistence and increase

Table 1. Air Quality Index (AQI) Values based on PSI

0 to 50	51-100	101-150	151-200	201-300	300-500
Clean or good	Moderate or healthy	Unhealthy for sensitive groups	Unhealthy	Very unhealthy	Hazardous

of air pollutants in Tehran, it is first necessary to use the information of the amount of these pollutants for example the PSI (Pollutant Standard Index) to identify days with polluted air. The PSI index is a measure of air pollution, which is between zero and five hundred. Based on the value of this index, air quality is classified into five groups: clean, healthy, unhealthy, very unhealthy, and hazardous (Table 1). Therefore, in the study period (2004-2020), based on the number of air pollutants in the Greater Tehran area, including PM_{10}, CO, NO_2, SO_2, and O_3 pollutants were identified using the PSI index and according to Table 1, the polluted days were identified. It should be noted that since 2010 when the number of hazardous pollutants of suspended particles with an aerodynamic diameter of smaller than 2.5 micrometers ($PM_{2.5}$) was also measured and it was added to the information used due to identify contaminated days.

Therefore, based on the air quality index, unhealthy days were identified as warnings and emergencies. The air quality index data has been obtained from [38]. Because each factor alone can be effective in creating unhealthy conditions, warnings, and emergencies, the factor that has the highest amount of pollution index was determined as the main polluting factor. The study of the PSI index shows that in the period of March 20, 2004, to Nov. 20, 2010, pollutants of CO, PM_{10}, and O_3 had the highest role in air pollution with 66, 24, and 9%, respectively. It should be noted that the contaminant $PM_{2.5}$ was not measured during this period. Also, in the period of Nov. 22, 2010, to March 21, 2021, it is observed that the main air pollution in Tehran is caused by $PM_{2.5}$ suspended particles. Then, based on the studies, with two criteria of severity and persistence of air pollution according to the season of its occurrence, 112 periods of air pollution cases in Tehran in the last 17 years were selected. Table 2 lists the characteristics of these 112 selected cases. The group number indicates the number of synoptic patterns leading to air pollution in the study period, which is obtained in the continuation of the research. Each group is analyzed on a selected day marked in blue in the table.

Table 2. 112 Selected air pollution periods in Tehran with two criteria of severity and continuity of air pollution during the years 2004-2020.

Experiment number	Group	Starting date	Days number	Max PSI	Main pollutant	Experiment number	Group	Starting date	Days number	Max PSI	Main pollutant
1	1	2004-09-23	14	167	CO	57	2	2017-07-28	2	128	O_3
2	1	2004-12-30	4	168	CO	58	1&4	2017-10-25	16	151	$PM_{2.5}$
3	1	2005-12-30	14	190	CO	59	1&4	2017-11-15	7	123	$PM_{2.5}$
4	1	2006-09-04	8	137	CO	60	1	2017-11-30	8	144	$PM_{2.5}$
5	1	2006-09-21	6	145	CO	61	1	2017-12-10	16	172	$PM_{2.5}$
6	1	2008-02-07	4	113	PM_{10}	62	1	2017-12-29	5	152	$PM_{2.5}$
7	5	2008-04-06	1	217	PM_{10}	63	1	2018-01-05	9	132	$PM_{2.5}$
8	3	2009-07-06	8	381	PM_{10}	64	1	2018-01-22	5	138	$PM_{2.5}$
9	2	2008-07-29	4	111	O_3	65	1	2018-01-30	15	177	$PM_{2.5}$
10	2	2009-08-14	3	130	O_3	66	2	2018-07-02	2	150	O_3
11	2	2009-08-16	3	166	O_3	67	2	2018-07-05	2	129	O_3

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Experiment number	Group	Starting date	Days number	Max PSI	Main pollutant	Experiment number	Group	Starting date	Days number	Max PSI	Main pollutant
12	2	2009-08-27	2	118	O_3	68	2	2018-07-13	2	117	O_3
13	2	2010-07-03	3	113	O_3	69	1	2018-11-18	4	120	$PM_{2.5}$
14	5	2010-07-16	1	220	PM_{10}	70	4	2018-11-28	3	134	$PM_{2.5}$
15	1	2010-11-22	22	157	$PM_{2.5}$	71	4	2018-12-03	3	140	$PM_{2.5}$
16	1	2010-12-18	16	168	$PM_{2.5}$	72	1	2019-01-20	5	128	$PM_{2.5}$
17	4	2011-04-12	15	278	PM_{10}	73	2	2019-06-03	3	111	O_3
18	3&4	2011-05-29	21	214	PM_{10}	74	2	2019-06-11	2	114	O_3
19	3	2011-06-26	21	129	PM_{10}	75	2	2019-06-19	1	120	O_3
20	3	2011—8-14	14	109	PM_{10}	76	2	2019-06-23	2	119	O_3
21	1	2011-11-30	27	140	PM_{10}	77	2	2019-06-30	3	160	O_3
22	4	2012-05-11	8	192	$PM_{2.5}$	78	2	2019-07-04	3	134	O_3
23	4	2012-05-23	4	201	PM_{10}	79	2	2019-07-09	2	126	O_3
24	1	2012-11-21	15	122	PM_{10}	80	2	2019-07-14	2	122	O_3
25	4	2013-09-29	11	170	$PM_{2.5}$	81	2	2019-08-01	2	149	O_3
26	1	2013-12-21	25	165	PM_{10}	82	2	2019-08-05	3	139	O_3
27	3	2014-06-08	6	125	$PM_{2.5}$	83	1&4	2019-11-06	10	144	$PM_{2.5}$
28	3	2014-06-24	10	190	$PM_{2.5}$	84	1	2019-11-23	8	156	$PM_{2.5}$
29	3	2014-07-21	6	129	$PM_{2.5}$	85	1	2019-12-13	5	157	$PM_{2.5}$
30	3	2014-08-05	4	129	$PM_{2.5}$	86	1&4	2019-12-20	9	156	$PM_{2.5}$
31	3	2014-08-12	5	133	$PM_{2.5}$	87	1	2020-01-15	3	119	$PM_{2.5}$
32	3	2014-09-18	6	133	$PM_{2.5}$	88	1	2020-01-27	4	147	$PM_{2.5}$
33	4	2014-09-28	7	146	$PM_{2.5}$	89	1	2020-02-28	3	136	$PM_{2.5}$
34	1	2014-11-13	9	142	$PM_{2.5}$	90	1	2020-06-15	2	113	O_3
35	1	2014-12-14	7	134	$PM_{2.5}$	91	2	2020-06-24	5	141	O_3
36	1	2014-12-26	9	152	$PM_{2.5}$	92	2	2020-07-01	1	149	O_3
37	1	2015-01-13	4	145	$PM_{2.5}$	93	2	2020-07-03	3	139	O_3
38	1	2015-01-26	5	137	$PM_{2.5}$	94	2	2020-07-08	4	133	O_3
39	1	2015-03-08	8	157	PM_{10}	95	2	2020-07-15	10	161	O_3
40	3	2015-06-08	4	162	$PM_{2.5}$	96	2	2020-07-26	2	110	O_3
41	3	2015-06-14	5	146	$PM_{2.5}$	97	2	2020-07-31	1	129	O_3

Table 2. 112 Selected air pollution periods in Tehran with two criteria of severity and continuity of air pollution during the years 2004-2020.

Experiment number	Group	Starting date	Days number	Max PSI	Main pollutant	Experiment number	Group	Starting date	Days number	Max PSI	Main pollutant
42	3	2015-06-22	11	127	$PM_{2.5}$	98	2	2020-08-04	1	121	O_3
43	3	2015-07-17	4	127	$PM_{2.5}$	99	2	2020-08-08	2	113	O_3
44	5	2015-08-11	1	154	PM_{10}	100	2	2020-08-11	2	108	O_3
45	5	2015-09-01	1	252	$PM_{2.5}$	101	2	2020-08-14	3	128	O_3
46	1	2015-11-05	5	146	$PM_{2.5}$	102	1	2020-10-12	8	123	$PM_{2.5}$
47	1	2015-11-23	8	134	$PM_{2.5}$	103	4	2020-10-26	3	113	$PM_{2.5}$
48	1	2015-12-09	23	162	$PM_{2.5}$	104	1	2020-11-01	4	135	$PM_{2.5}$
49	1	2016-01-12	10	149	$PM_{2.5}$	105	1	2020-11-24	4	131	$PM_{2.5}$
50	1	2016-02-13	4	135	$PM_{2.5}$	106	1	2020-12-01	5	146	$PM_{2.5}$
51	2	2016-06-15	1	128	O_3	107	1	2020-12-09	3	133	$PM_{2.5}$
52	1	2016-11-09	11	156	$PM_{2.5}$	108	1&4	2020-12-13	12	146	$PM_{2.5}$
53	1	2016-11-27	6	152	$PM_{2.5}$	109	1	2020-12-27	9	168	$PM_{2.5}$
54	1	2016-12-22	6	154	$PM_{2.5}$	110	1&4	2021-01-06	11	174	$PM_{2.5}$
55	1	2016-12-30	4	151	$PM_{2.5}$	111	1	2021-01-25	6	150	$PM_{2.5}$
56	1	2017-01-07	15	159	$PM_{2.5}$	112	1	2021-02-03	3	136	$PM_{2.5}$

Results and discussion

Study of atmospheric patterns affecting air pollution in the greater Tehran

In this section, air pollution in Tehran is examined from the perspective of synoptic meteorological patterns. Atmospheric synoptic patterns play a controlling role in local and regional conditions, including air pollution. To identify the environmental characteristics of the events with increasing air pollutants in the Tehran region, the climatological approach of reaching the Environment- to- circulation pattern from method has been used [32]. For this purpose, as mentioned before, by using the PSI index, 112 periods of obvious pollution occurrence in Tehran in the period 2004-2021 were identified. If the purpose of the analysis is to find spatial synoptic patterns or flow patterns, it is appropriate to use principal component analysis in the T mode. However, if the goal is to find interpolation patterns, the use of principal component analysis in the S mode is recommended [39]. To clustering the patterns, it must have subgroups that have the same spatial patterns. This is possible by performing principal component analysis in T mode. That is when the columns of the time input matrix and the rows correspond to the grid points [40]. Considering that the aim of the present analysis is to find spatial synoptic patterns, this study, uses the T-mode analysis of principal components. Then the clustering of days that are similar in terms of 500 hPa geopotential height changes was provided. This clustering was performed using data from the European Center for Medium-Range Weather

Forecast (ECMWF) [41].

Based on the number of variables for the studied days, five different synoptic patterns were obtained which led to the increase of pollution potential in Tehran. It should be noted that in these groups, except for the second group, the main pollutant of suspended particles with aerodynamic diameter is less than 2.5 and larger than 10 µm and the main pollutant in the second group is ozone. The five mentioned patterns have a frequency of 47, 28, 12, 13, and 4%, respectively, for the 112 periods studied. In some periods, sometimes two synoptic patterns have been involved in the increase of pollutants. These patterns are ranked and named based on the frequency percentage. The results of clustering of synoptic patterns leading to an increase in the PSI index have identified three important sources of air pollution for Tehran. In the first model, which is usually the duration of long-term pollution, and the atmosphere is very stable and occurs more in the cold season, the pollutants include cars, vehicles, and industrial factories. So, the cause of air pollution comes from combustion and incomplete fuel is formed. The second group, which is usually a very short period of one to two days, occurs more in the warm season and is due to an ozone pollutant. The third and fourth groups are related to the advection of dust from foreign sources (southeast of the country and Iraq), respectively. Finally, in the fifth model, which, like the second group, has a short duration of pollution, the polluting factor is related to severe soil erosion from local areas due to strong wind shear. In order to better identify these synoptic patterns leading to increased air pollution in Tehran, the average pattern of these groups is studied.

The first pattern (Figs. 1a, b) contains the highest number of contaminated periods studied, and 53 out of 112 cases belong to this synoptic pattern. In this group, usually, the duration of the pollution period is high, and the pollution index has high values. This pattern is more prevalent in autumn and winter, which is usually accompanied by the Siberian high-pressure system. The presence of high Siberian pressure along with the tropospheric mid-level ridge increases the stability of the atmosphere, downward motions, and the weakness of the horizontal wind field. Also, due to the presence of Siberian high on the surface, which is also very strong in some periods, the temperature near the surface decreases. This causes temperature inversion and increases stability, which leads to increased accumulation of pollutants. The pollutants are produced especially by cars and industrial generators. With increasing temperature and weakening of the surface pressure, which is sometimes accompanied by the replacement of low pressure with high pressure, and with increasing the intensity of the horizontal wind field, especially in the lower levels of the troposphere, a temperature inversion is eliminated, and air pollution is reduced. Usually, this change in the pattern on the surface is accompanied by the penetration of the trough in the middle levels of the troposphere, which generally vanishes inversion and air pollution. This change sometimes is so obvious that the emergency determination reaches a healthy or clean state.

The second pattern (Fig. 1 c, d) covers 32 of the 112 study cases and is related to the major ozone pollutant case that usually occurs at high summer temperatures. It should be noted that this group has a continuous period of short-term pollution, but the type and mechanism of pollutant formation is different from other groups. So, here this specific case has been studied and analyzed in more detail. In summer, the air quality index is usually in a good status; therefore, changing the air quality to unhealthy conditions or warnings in this season should be assessed and considered. The structure of this synoptic pattern of this group shows dominant low-pressure surface and subtropical high. Due to the extreme heat, especially in the afternoon, convective motion is formed, and the height of the boundary layer is well mixed, even reaching the middle levels of the troposphere. This mixing of the atmosphere near the surface with higher levels with more ozone is caused to increase the amount of this pollutant and in some periods can even has caused the "warning" issues. This pollutant mostly causes air pollution in the hot season, and since the heat of the air causes the formation of ozone, its amount increases with increasing temperature. In this synoptic pattern, air pollution is reduced by weakening ridge and low pressure which is accompanied by a decrease in temperature and an increase in wind speed.

The third model (Fig. 1 e, f) includes 14 of the 112 study cases. This pattern, which is mainly dominant during summer and late spring, indicates the presence of Indian monsoon low pressure pattern on the southeastern regions of Iran. This causes severe dust activities in the desert and arid regions of the southeast and east of the country. The extension of this low pressure to the eastern and central regions of Iran causes dust to move from these arid and desert areas to the central and Greater Tehran area and leads to an increase in the pollution index in these areas. Since at this time in the central regions of the country including Tehran, is affected by the prevailing ridge, the suspended transported particles of dust remain in the region. In this model, by weakening the ridge and penetrating the trough from the western borders, air pollution is reduced. So, because of decreasing stability or by influencing high pressure from the north of the country and increasing wind because of changing the pressure gradient pattern air pollution is decreased. It is also necessary to weaken the source of pollution in the desert areas of the east of the country, which will be improved by reducing the activity of Indian monsoon low pressure system.

The fourth pattern (Fig. 1 g, h), which occurs mostly in spring and autumn, shows the deployment of dynamic low pressure in the western regions of Iran and Iraq, as well as the deployment of thermal low pressure on the central regions of the country. In this model, upward motions and instability in Iraq and the western regions of the country cause dust to rise from arid and desert areas, especially from Iraq. Suspended dust is transported to other areas and the city of Tehran if there is a suitable horizontal wind field. In this model, as soon as the wind field shear is reduced, the source of pollution is weakened, and the amount of air pollution is reduced by weakening the ridge. With the eastward movement of the trough located in Iraq and the west of Iran, the atmospheric stability decreases, and if there is enough moisture, the number of pollutants decreases quickly and considerably with the occurrence of precipitation.

The last pattern (Fig. 1 i, j), which includes only 4 of the contamination periods studied. It is a local pattern that occurs due to the passage of the gust front and the existence of wind field shear causing dust rise in the Tehran region. In this model, the lifetime of this pattern is usually one to two days. With the sudden wind shear in the lower levels of the troposphere due to the passage of the gust front, the status of the air pollution index from clean or healthy changes to unhealthy at once. In this model, as soon as the gust front passes and the wind shear decreases, the dust rising from the region decreases, and with the westerly wind, the suspended dust particles depart the Tehran region. Here are the general characteristics of each of the five resulting synoptic patterns. To express in more detail each of the patterns, a sample of each pattern has been analyzed and examined. These selected days have been marked in blue in the table. The selected days related to the first, third, and fourth groups in the study of have been brought [9]. Therefore, only the selected day of the second and fifth groups have been analyzed.

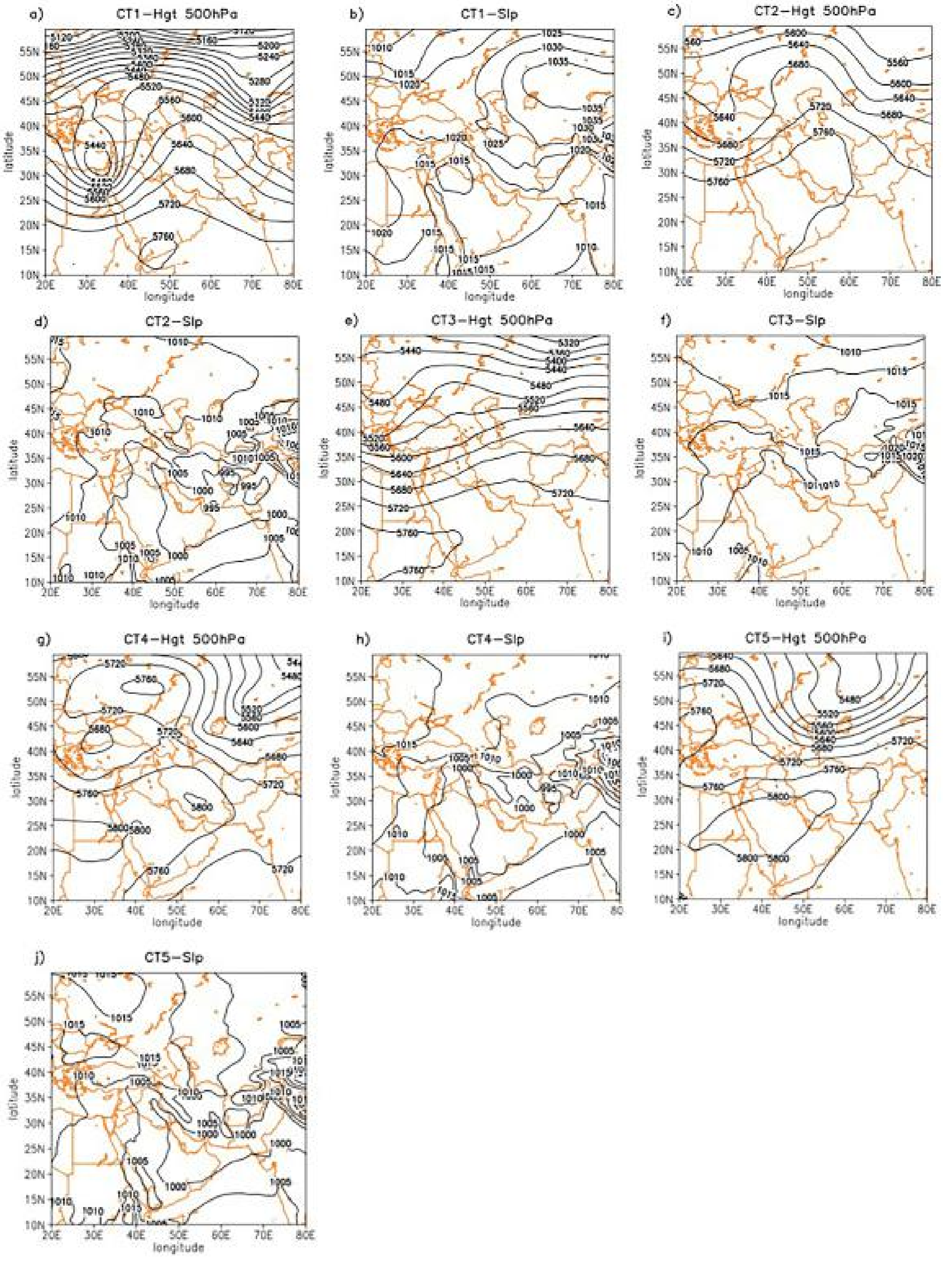

Fig. 1. The Pattern of mean geopotential height field at 500 hPa in geopotential meters (left), along with sea level pressure in hectopascals (right) for members of each group.

Synoptic analysis of air pollution from the second group: period 2018-07-02 to 2018-07-03

The polluting factor in this period of pollution, which occurred in the hot summer season with a maximum air quality index of 150 and on the alert border, was ozone. As the synoptic pattern of the surface and the mid-level of the troposphere shows, with the formation of surface heat low pressure, and upper tropospheric subtropical high, a hot and stable atmosphere dominates the region (Figs. 2a and 2b). Also, due to the extreme heat during these days, convective motions are formed in the afternoon and the height of the well-mixed layer has even reached the level of 550 hPa (Fig. 3). This mixing of the atmosphere near the surface with higher layers that contain more ozone, as well as the heat of the air that causes the formation of ozone, has increased the amount of this pollutant even to the warning level. This pollutant causes more air pollution in the hot season and its amount increases with increasing temperature. In this period, as shown in Fig. 4, with increasing temperature from 2018-07-01, an increase in the amount of ozone occurs in the atmosphere near the surface; so that on 2018-07-02, PSI value reached a maximum of 150. As shown in Figs 5a, 5b, and 5c, with the decreasing trend of temperature from 2018-07-02 to 2018-07-04, the amount of ozone (Fig. 5d) also decreases to the amount of 52. Therefore, on days when ozone is the main pollutant, air pollution decreases with decreasing temperature and increasing wind speed.

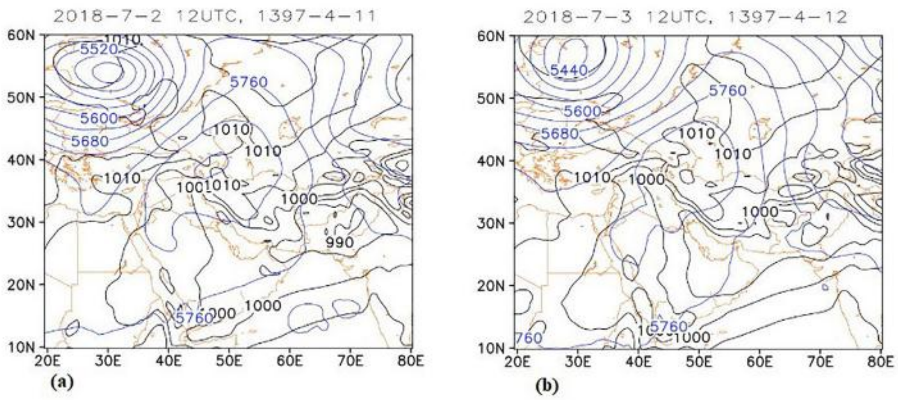

Fig. 2. Geopotential height field at the level of 500 hPa (blue lines, in terms of geopotential meters), along with sea level pressure (black lines, in terms of hectopascals). a: the first day of the period, b: the second day of the period.

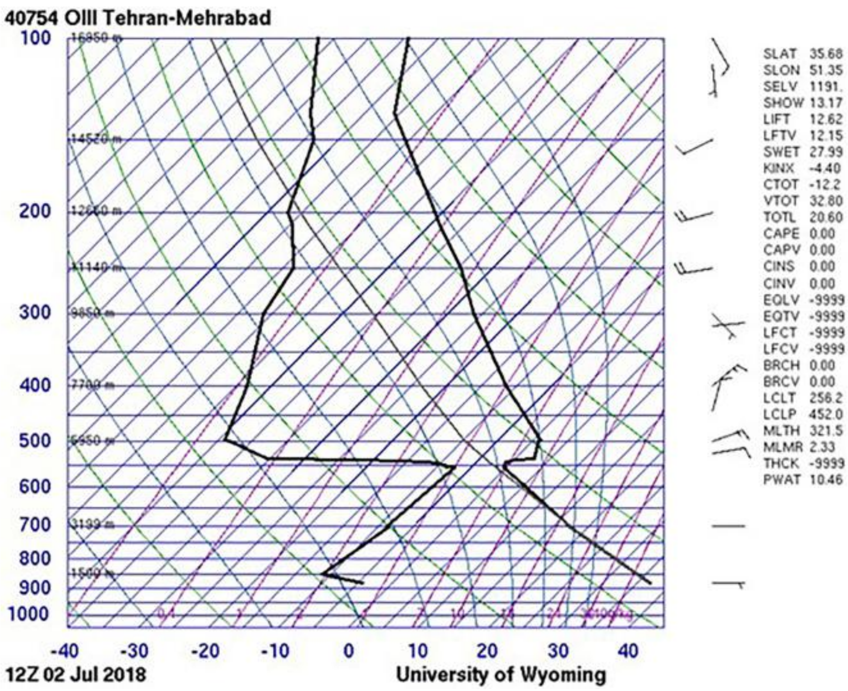

Fig. 3. The skew-T chart at Mehrabad station at 1200 UTC on the second day of July 2018. The Skew-T chart for Mehrabad station has been performed from [42].

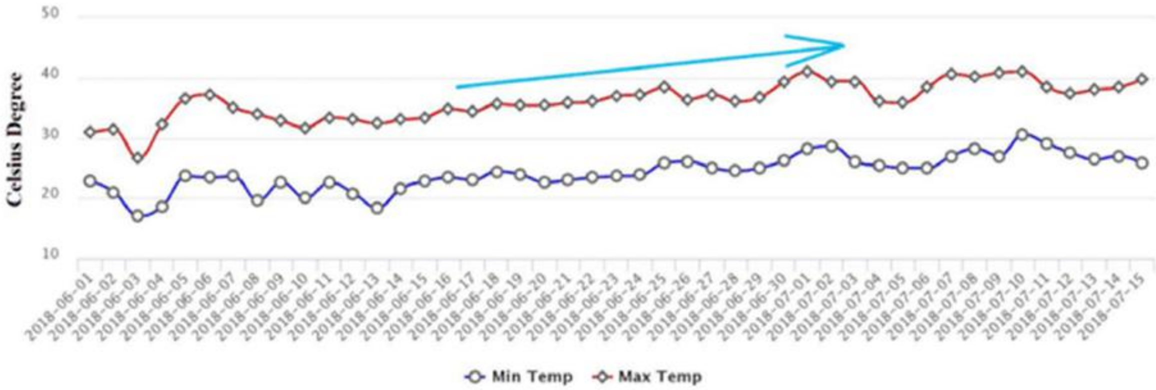

Fig. 4. Diagram of maximum and minimum temperature changes in the period of 2018-06-01 to 2018-07-15 in Mehrabad station.

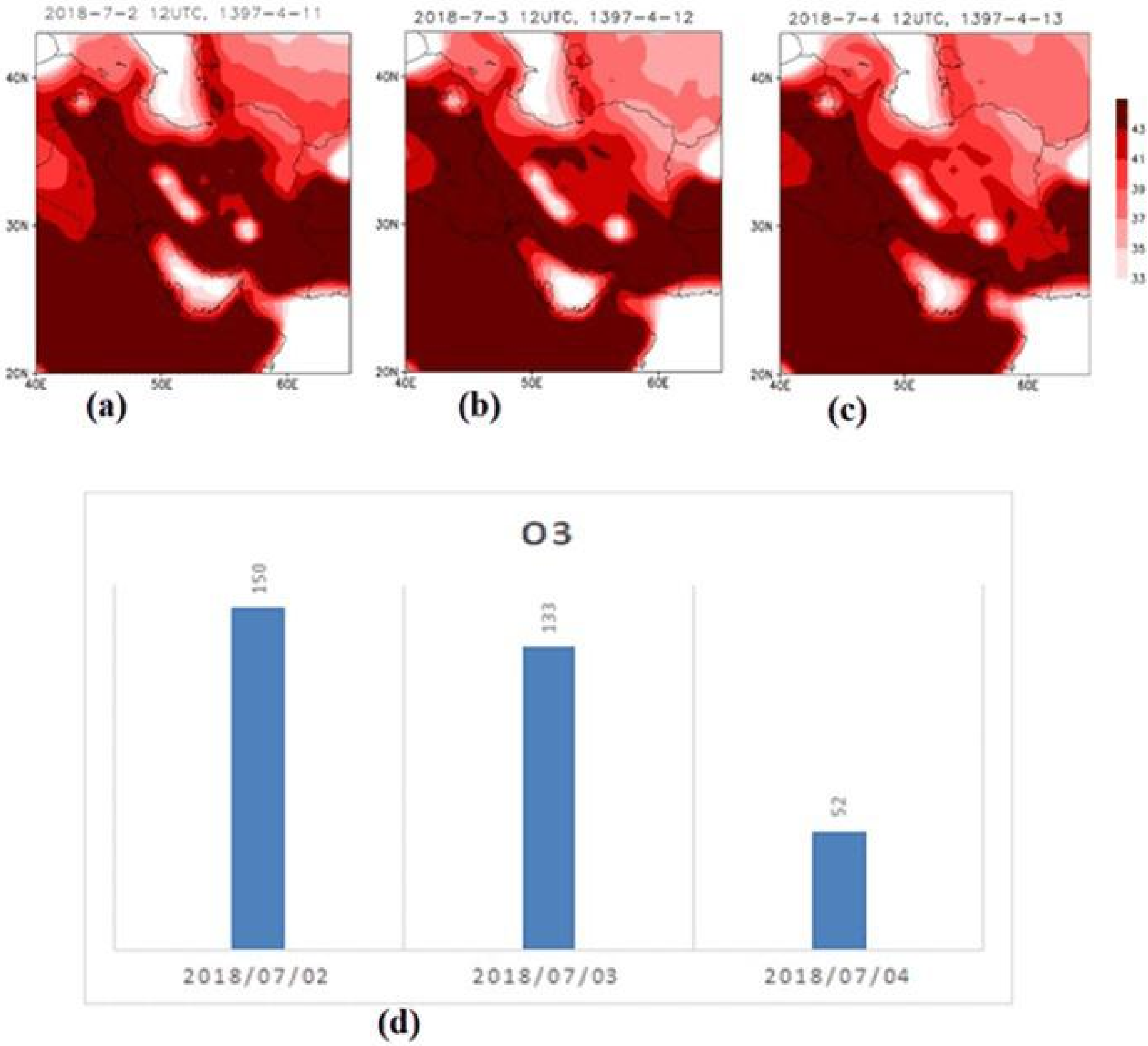

Fig. 5. a, b, c: Surface air temperature field (in terms of degrees Celsius) from 2018-07-02 to 2018-07-04 respectively, d: The average daily value of air quality index.

Synoptic analysis of air pollution from the fifth group: period 2015-08-31 to 2015-09-01

This period of pollution with a lifetime of one day has occurred from the late of 2015-08-31 to the mid-day of 2015-09-01 due to the passage of the gust front. During this time, there was an unstable atmospheric condition due to the passage of the mid-tropospheric trough. Also, with the existent of dominant surface low pressure in the central part encountering the high-pressure tongue penetration from the northern band of the country, a considerable pressure gradient has been occurred (Figs. 6a and 6b). The wind shear in the lower levels of the atmosphere (Figs. 7a to 7d) has occurred suddenly causing a dust storm in the region. As the wind field pattern shows, from the 850 hPa level (Figs. 7c and 7d) to the 700 hPa level (Figs. 7a and 7b) wind direction from east to the southwest has changed. In addition, its amount has also increased significantly, and considerable wind shear has occurred in the dust storm area. In this situation, the air quality status has reached from the healthy index to the emergency index with an average daily value of 252, which was the main pollutant of PM_{10}. However, at the time of the dust storm, the average hourly rate of some pollution measuring stations has shown the value of the air quality index up to about 2500. Figs. 8a to 8d show the potential vorticity penetration (PV streamer) or in other words, the intrusion of stratospheric air into the higher layers of the troposphere (300 hPa level). PV streamer is associated with the dynamical forcing for upward motions, reducing the static stability of the troposphere and strengthening the low-level wind field. This increases the potential for storm occurrence. Areas with more decreasing changes in static stability are located below the southern side to the east of the PV streamer, and smaller changes in static stability are observed in other regions [43]. Periods of air pollution associated with this synoptic structure usually have a short lifetime of about one day, with dust particles being removed from the area by decreasing wind shear and formation of the westerly winds. Storms of June 02 and June 6, 2014 in Tehran, which caused many fatalities and financial losses, also had such a same identical structure. However, because the pollutants quickly left the region with the strong westerly winds, this type of storm has a short lifetime on average. Also, the air quality index for these days has been reported as 80 and 81, respectively.

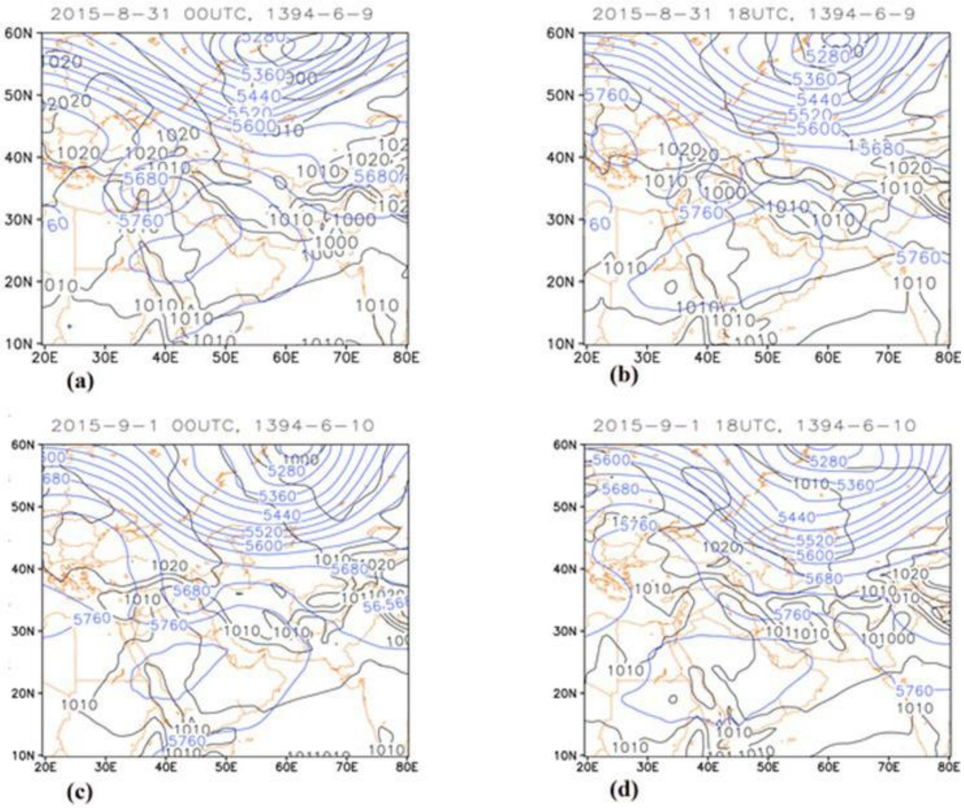

Fig. 6. Geopotential height field at the level of 500 hPa (blue lines, in terms of geopotential meters), along with sea level pressure (black lines, in terms of hectopascals), a: 00UTC on 2015-08-31, b: 18UTC on 2015-09-01 (during the peak period of pollution), c: 00 UTC on 2015-09-01 (during the peak period of pollution) and d: 18UTC on 2015-09-01.

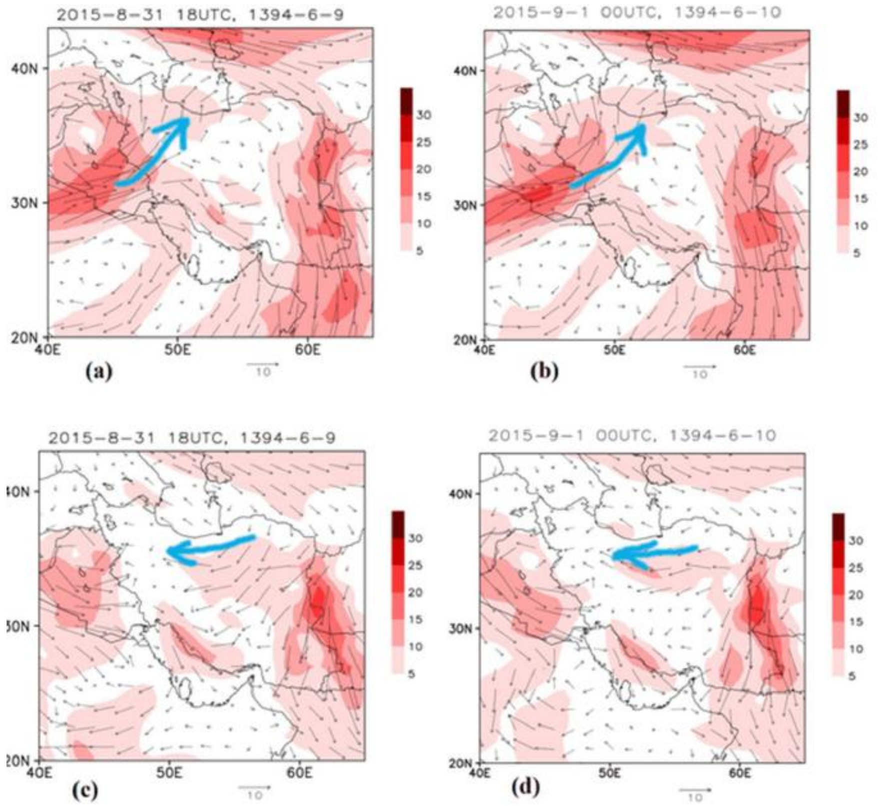

Fig. 7. Horizontal wind field (vector, in meters per second) at the level of 700 (a, b) and 850 hPa (c, d) along with the amount of horizontal wind (shaded areas), the blue-colored vector used for better detection of wind shear field.

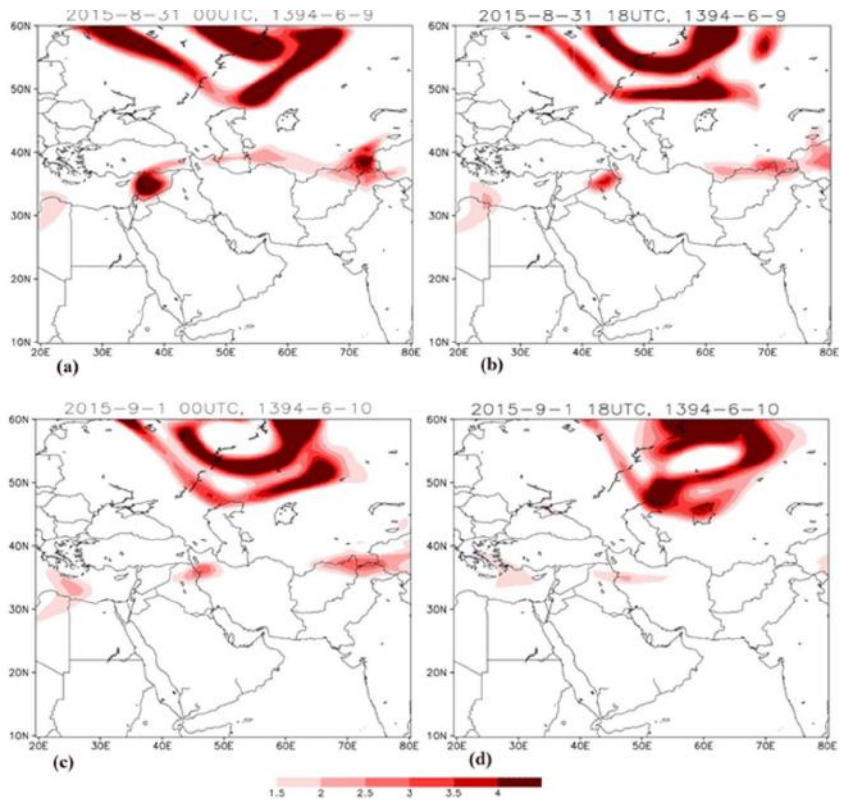

Fig. 8. Potential vorticity at 300 hPa (in terms of PVU), a: 00UTC on 9/6/1394, b: UTC 18 on 2015-08-31 (during the peak period of pollution), c: 00UTC on 2015-09-01 (during the peak period of pollution), and d: 18UTC on 2015-09-01.

Conclusion

In this study, air pollution in Tehran in the last 17 years, which includes 112 periods of obvious occurrence of air pollution, was studied from the perspective of synoptic and thermodynamic meteorological patterns. The study of the mentioned days shows the activity of five atmospheric patterns with a frequency of 47, 28, 12, 13, and 4%, respectively. The first model, with a number of 53 out of 112, has the highest number in the study period. In this pattern, which is more common in autumn and winter, the duration of the pollution period and the pollution index have high values. In this group, the presence of Siberian high pressure along with ridge and decreasing temperature near the surface increases the stability of the atmosphere, which leads to an increase in the accumulation of pollutants produced near the surface. In this model, the reduction of atmospheric pollutants will occur by increasing the temperature and weakening the high pressure and the mid-level ridge. However, in better case of passing the mid-tropospheric trough, which is accompanied by increasing the intensity of wind field, especially in the lower levels can reduce the pollution. If the trough penetration in the middle levels of the troposphere is accompanied by sufficient humidity, the pattern will be eliminated due to wind increase and rain. Sometimes this change is so significant that the atmosphere is in a state of alert can change to a healthy or clean state. The second pattern, with the main ozone pollutant, occurs at high summer temperatures with a heat low-pressure at the surface accompanied by a subtropical high ridge in the mid-troposphere. Because, the high air temperature causes ozone to form, its value increases with increasing temperature. Because of the extreme heat, especially in the afternoon, also due to the formation of convective motions, the mixing of the near-surface atmosphere with higher levels that have a higher amount of ozone, increases the amount of this pollutant, which sometimes even reaches the warning level. In this group, air pollution is reduced by decreasing the temperature and increasing the wind speed, which occurs when ridge and surface low pressure are diminished. The third pattern, which is mainly active in summer and late spring, occurs during the presence of the Indian monsoon low-pressure system in the southeastern regions of the country. The presence of this low pressure causes severe dust in the desert and arid regions of the southeast and east of the country. With the strengthening of India's monsoon low pressure, the dust of these areas has increased and its transportation from these arid and desert areas to the central and Greater Tehran area leads to an increase in the pollution index in these areas. During this time, in the central regions of the country, in the middle level of the troposphere, there is a pattern of the ridge, which causes the persistence of suspended particles of transported dust. Reduction of suspended particles in this group occurs by weakening the ridge and penetration of the mid-tropospheric trough from the western borders of the country and because of decreasing stability. Also, by high-pressure penetration from the northern of the country and increasing wind due to changing the pressure pattern, the pollution could be reduced. In addition, it is necessary to weaken the source of suspended particles, which occurs with a decrease in the activity of the Indian monsoon low pressure. The fourth model shows the development of the dynamical low pressure in the western regions of Iran and Iraq, as well as the formation of the thermal low pressure on the central regions of the country. In this pattern, which occurs mostly in spring and autumn, upward movements near the surface in Iraq and the western regions of the country cause dust to rise from arid and desert areas, especially Iraq. Suspended dust is transported to other areas and the city of Tehran when there is a suitable horizontal wind field. In this model, as soon as the wind field shear decreases in the soil uplift zone, which is accompanied by the weakening of the mid-level ridge, the amount of air pollution decreases and with the eastward movement of the mid-tropospheric trough, the atmospheric stability decreases. Sufficient humidity reduces the number of pollutants rapidly with the occurrence of precipitation. The last group is a local pattern that occurs due to the passage of the gust front and the shear of the wind field dust rise in the Tehran region and has the lowest number in occurrence frequency. In this model, the lifetime is usually one to two days. With the sudden wind shear occurrence in the lower levels of the troposphere to the passage of the gust front, the status of the air pollution index from clean or healthy changes to unhealthy or alarm and emergency at once. In this model, as soon as the gust front passes and the wind shear decreases, the dust rising from the region decreases, and with the westerly wind, the suspended dust particles leave the Tehran region.

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Competing interests

The authors declare that there are no competing interests.

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Ethical considerations

Ethical issues have been completely observed by the authors.

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