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Seasonal variability of atmospheric patterns leading to air pollution in the metropolis of Tehran

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ABSTRACT:

Introduction: Air pollution, due to its harmful effects especially on human health, is one of the major problems of industrial cities and metropolises, including Tehran. Therefore, recognizing the atmospheric conditions that lead to the accumulation of the pollutants can help decision-maker organizations.
Materials and methods: In this study, based on the intensity and persistency of the air pollution in the period of 1389-1397 and according to the season of its occurrence, 47 air pollution incidents in Tehran were identified and studied from synoptic perspective. Spatial (T-Mode) principal component analysis was applied to 500-hpa geopotential height data of these events to classify the synoptic patterns which make the city prone to intensification of pollution in different seasons.
Results: The results indicate three different synoptic patterns leading to an increase in the potential of pollution of Tehran. In these patterns, the main pollutant is the airborne particulate matter ($PM_{2.5}$ and PM_{10}). Accordingly, the first pattern with percentage frequency of 62% occurs in the fall and winter. In this pattern, the presence of Siberian high pressure, along with the mid-tropospheric ridge is obvious. Two other patterns are active in the late spring and summer (related to Indian monsoon in the southeast of Iran) and spring and autumn (related to dynamic low-pressure in Iraq and the west of Iran), respectively.
Conclusion: Classifying of the data of polluted days during recent eight years for Tehran results in three synoptic patterns related to different seasons. This information can help better managing of urban activities.

Introduction

Air pollution has always been considered as one of the most important issues of industrial and major cities in the world, including Tehran, the most populated city of Iran. The statistical survey shows that the number of polluted days and the amount of air pollution are increasing. This condition is due to the increase in the population of the major and industrialized cities and the increase of atmospheric pollutants sources, i.e., cars and industrial facilities. The World Health Organization (WHO) has identified air pollution as a cause of death for several million people per year [1]. Meteorological conditions and changes in the physi-

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cal and dynamic characteristics of the atmosphere play an important role in the variation of air pollution. Those meteorological parameters which affect atmospheric pollutants distribution include wind shear and its direction, the vertical structure of temperature in the atmosphere, humidity and solar radiation. For example, low wind speed and the temperature inversion preventing convective movements cause the accumulation of atmospheric pollutants in the lower layers of the atmosphere [2]. Considering the importance of this issue, numerous studies have been carried out on the relationship between weather conditions and atmospheric parameters with air pollution. For example, the effect of the synoptic patterns and boundary layer characteristic on the increase in pollutant emissions of suspended particulate matter with an aerodynamic diameter greater than 10 µm (PM_{10}) in the city of Changsha, China, has been investigated [3]. It has been shown that an increase in the pollutant level is associated with the increase of atmospheric stability and the establishment of an anticyclone pattern. Also, with rising wind speed, increasing the height of the mixing layer and reducing the depth of the temperature inversion layer, the PM_{10} level is reduced. In another study, the impact of local atmospheric patterns on the PM_{10} air pollution level in the city of Naples, Italy, has been examined and a basic model has been proposed for prediction of PM_{10} level [4]. The results show that the condition with the low wind speed, temperature inversion, and no significant precipitation lasted for at least one week, which leads to an increase in air pollution in this area. In addition, in a case study of Chengdu plain in China, which has several external pollution sources, the impact of meteorological parameters on the persistence of atmospheric pollution has been addressed [5]. The results of this study show that the low air temperature and wind speed, higher values of pressure and relative humidity, and temperature inversion occurrence, especially in layers near the ground, cause intensification of air pollution. In addition, it has been argued that not only surface factors, but also the structure of the boundary layer plays a role in the vertical propagation of pollutants.

Manual classification of atmospheric patterns is more common method than computer-based classification between meteorologists. The main disadvantage of the manual methods is the possible mistakes in classifying and being time and energy consuming. However, the main advantage of this method is using of skilled expert experience in the classification process [6]. Progressing of science and technology and emerging of powerful computers, manual methods (subjective) have been replaced with computer-assisted (objective) methods. Contemporary automated classification methods have been widely studied [7]. One of the most popular methods is correlation-based method because of its efficient classification with the pattern recognition algorithm. However, the results of this method depend on the researcher's decisions -- for example, in choosing the size and number of mesh points, in determining the number of map patterns and the correlation threshold that affects the intragroup and intergroup similarity. Thus, it has been proposed [8] to use the term "computer assisted" for all automated classifications rather than term "objective classification" [9]. It seems that there is no unique and recommended classification method, at this time [10]. Each classification method has its advantages and disadvantages and choosing appropriate method is matter of balancing the research needs, the researcher's skills, and the nature of the data [11].

Facilitating the influences of mesoscale processes directly or indirectly, the synoptic patterns play a very important role in environmental phenomena (e.g. flash floods, dust intrusions, high concentrations of air pollutants) [12]. In a study, 19 atmospheric patterns were determined using both manual and computer-assisted methods for the 10-years time period in the Eastern Mediterranean [9]. However, day-to-day comparisons of classifications for the three most common types of these patterns show a great difference between two methods. Then, they used "environment-to-circulation" approach [7] to test on three environmental processes of dust intrusions, air pollutants (ozone level), and flash flood. Their results show that for both methods the classification is more difficult when there are weak pressure gradients associated with high ozone levels. Also, for dust intrusion, the cold cyclone location is more important than the pressure gradient in classifications.

Due to the undesirable effects of the accumulation of pollutants in the atmosphere near the ground on humans and the infrastructures, the purpose of this study is to determine different atmospheric patterns in different seasons, which lead to the accumulation of pollutants and air pollution.

Materials and methods

To determine the atmospheric patterns that lead to air pollution and those which affect the persistency and increase of atmospheric pollutants in Tehran's metropolitan area, based on the amount of atmospheric pollutants of PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and O_3 and based on air quality classification using the pollutant standards index (PSI) (101-150, 151-200 and 201< for unhealthy for sensitive groups, unhealthy, and very unhealthy conditions, respectively; Table 1), polluted days in the 1389-1397 time period were identified. Considering that each pollutant can separately be effective in such conditions, the pollutant with highest index was considered as the main contributing factor of pollution. In the selected time period, based on the severity and persistence of the air pollution and according to the season, 47 air pollution periods in Tehran were identified and studied from thermodynamic and synoptic point of view.

If the purpose of the analysis is to find spatial synoptic patterns or circulation patterns, the use of T-mode principal component analysis (PCA) is appropriate; however, if the goal is to find out the teleconnection patterns, S-mode PCA is preferred [13]. To classify patterns, there should be subgroups whose members have the same spatial patterns. This is possible using T-mode PCA in which the columns is time and the rows correspond to the grid points of map [14]. So in this study, to find spatial synoptic patterns, selected days were clustered based on 500 hPa geopotential height maps using the T-mode PCA.

To obtain the synoptic pattern of each polluted day, 6 hourly Era-Interim reanalysis data sets include, the sea level pressure (SLP), 500 hPa geopotential height, 850 and 700 hPa relative humidity, and horizontal wind field from the European

Table 1. Pollutant standards index [16]

PSI	Pollutant standards index
0-50	Clear
51-100	Healthy
101-150	Unhealthy for sensitive groups
151-200	Unhealthy
>201	Very unhealthy

Centre for the Medium-Range Weather Forecasts (ECMWF) [15] were utilized. The ECMWF provides the data sets with a horizontal resolution of 0.75 degrees in latitude and longitude at 37 vertical levels starting from the earth surface up to 0.1 hPa level, which is about 64 km above the ground (reference). In addition, for recognizing the atmospheric patterns leading to air pollution, skew-T diagrams and dust RGB images from the second generation of meteorological satellites have been used.

Results and discussion

As mentioned, 47 cases of significant pollutant days were identified in Tehran. Applying T-mode PCA on the data resulted in three dominant synoptic patterns which are related to increase in the potential air pollution of Tehran in different seasons. To analyze the results, that member which is most closely resembles the average pattern of group selected as the group's representative. Major contributor of pollution in these groups is $PM_{2.5}$ or PM_{10}.

The study of the patterns shows that the first pattern includes the highest number of polluted periods and 29 of the 47 cases belong to this pattern. In this group, the duration of the polluted period is long and the pollutant index is high. This pattern mostly occurs in the fall and winter season and is usually accompanied by Siberian high pressure at the ground level. The presence of Siberian high pressure accompanied with the mid-tropospheric ridge results in increasing of the atmosphere stability, the descending motions, and the weakness of the horizontal wind field. Also, especially when the high-pressure at the ground level is strong, the temperature decreases near the surface of the earth, leading to a temperature inversion and increased stability, which in turn, will result in more pollutant accumulation produced by urban and industrial activities. By increasing the temperature, weakening the high-pressure surface, which is sometimes accompanied by the replacing high-pressure with low-pressure, and with strengthening of the horizontal wind field especially in low-troposphere, the temperature inversion is eliminated and the air pollution is reduced. Typically, these changes at the surface is accompanied with the penetration of the tough in the mid-troposphere, and if there is sufficient moisture and the precipitation occurrence, air pollution is totally eliminated. Sometimes, this change is so sensible and the air quality changes from the unhealthy condition to a healthy or clean one. The sample member of this group is the period from 1389/9/27 to 1389/10/12. During these 16 days, the air quality index was reported between 109 and 168. The governing pattern of this period reflects the impression of the Siberian high pressure on the north of Iran and the establishment of the ridge in the mid-troposphere. The study of the wind field in this period also shows a calm atmosphere (the wind field components are negligible) when the air quality index is inappropriate. The synoptic pattern for the fifth day (1389/10/1) of this period with PSI of 140 is shown in Fig. 1(a). From the ninth day (1389/10/5) to the 14^{th} (1389/10/10), by strengthening of the ridge (Fig. 1(b) and thus increasing the atmosphere stability, the amount of pollutants has reached the warning level. Passing mid-level trough over Tehran and northern areas of Iran and the impression of the low-pressure tongue over southern latitudes, the stability and the amount of pollutants has decreased. Based on synoptic reports from observation stations from 1389/10/11 to 1389/10/14, in some occasions there was a significant decrease in the amount of the pollutants (maximum of air quality index ≈ 70) due to an increase in the wind speed (about 10 m/s) and rainfall occurrence. As it is seen in Fig. 2, passing mid-tropospheric trough, the establishment of the low pressure, and decreasing of atmospheric stability, the horizontal component of the wind field had a significant increase in its magnitude while changing its direction to the east and this westerly wind field causes the pollutants leave the polluted areas. Fig. 3 shows the skew-T diagram at Tehran-Mehrabad station for 2010/12/31 (Fig. 3(a) & (b)) and 2011/1/1 (Fig. 3(c) & (d)). As is seen, for 2010/12/31 there is both the subsidence inversion and the radiation one. The maximum height of the mixed layer is up to 850 hPa and in the afternoon. For 2011/1/1, sinking air due to passage of warm front is obvious. The vertical structure of wind field also shows warm advection and significant wind shear with height. In addition, the height of the mixed layer has risen to 700 hPa. All of these atmospheric changes eventually led to a significant reduction in pollutants on the 2011/1/1.

The second pattern includes 13 out of 47 selected periods. This pattern, whose main activity is in the late spring and summer, shows the presence of Indian low pressure monsoon and significant pressure gradient in the southeastern parts of Iran. This situation causes severe dust storm in the arid and dry regions of the southeast and east of Iran. The penetration of this low-pressure center over the eastern and central parts of Iran results in advection of desert dust to the central regions including metropolitan areas of Tehran. Considering that at the same time there is mid-tropospheric ridge over the central regions, advected dust particles remain in the region. In this pattern, the air pollution is reduced by weakening the ridge and the impression of mid-tropospheric trough from western areas of Iran or by penetration of high pressure from the north and increasing the wind speed cause of changing in the pressure pattern. Also, the source of dust particles is weakened with decreasing of the low pressure monsoon activity. The period of 2015/6/22 to 2015/7/2 with maximum PSI of 127 is considered as a representative of this group. The synoptic pattern of this period (Fig. 4) shows the establishment of thermal low pressure over Iran. This type of air pollution occurs when the atmosphere is not stable at near-ground levels and consequently wind blowing leads to dust storm in the soil cover areas. But in the mid-troposphere,

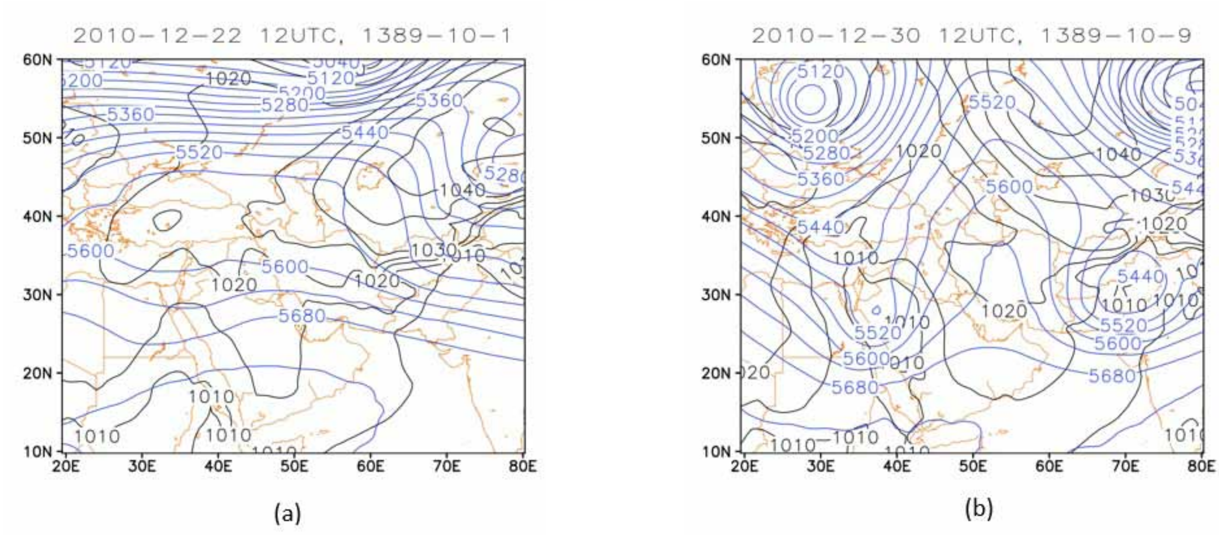

Fig. 1. Geopotential height at 500 hPa (blue lines, in geopotential meter), with sea level pressure (black lines, in hPa)

the atmosphere is stable and it is not possible for airborne particles to leave the lower levels of the atmosphere. Also, during the warm season, the establishment of low-pressure on the earth surface has led to convection and as a result, desert dust intrusions occur due to the wind blowing and wind shear at the lower levels of the atmosphere in the arid areas. As is shown in Fig. 5, due to the activity of Indian low pressure monsoon over the southeastern and eastern arid regions of Iran in the summer, suspended particulate matter advection may occur by southeasterly wind field specially between 850 and 700 hPa levels resulting in intensifying of air pollution of Tehran Such condition occurred for example on 1394/4/7 (see Fig. 6) and led to an increase in PSI, so that the highest index of this period is recorded on this day. As is seen in Fig. 7, the vertical structure of Tehran-Mehrabad station shows a neutral stable atmosphere at the lower levels of troposphere and absolute stable atmosphere due to establishment of anticyclone in mid-troposphere resulting in subsidence. On the day with highest PSI, Fig. 7(b), the height of the stable layer has decreased to a lower altitude and the wind speed has slowed in the lower levels of the atmosphere. Decreasing the atmospheric stability in the mid-troposphere and slowing of westerly wind, air pollution is reduced in this pattern.

The third pattern, which mostly occurs in the

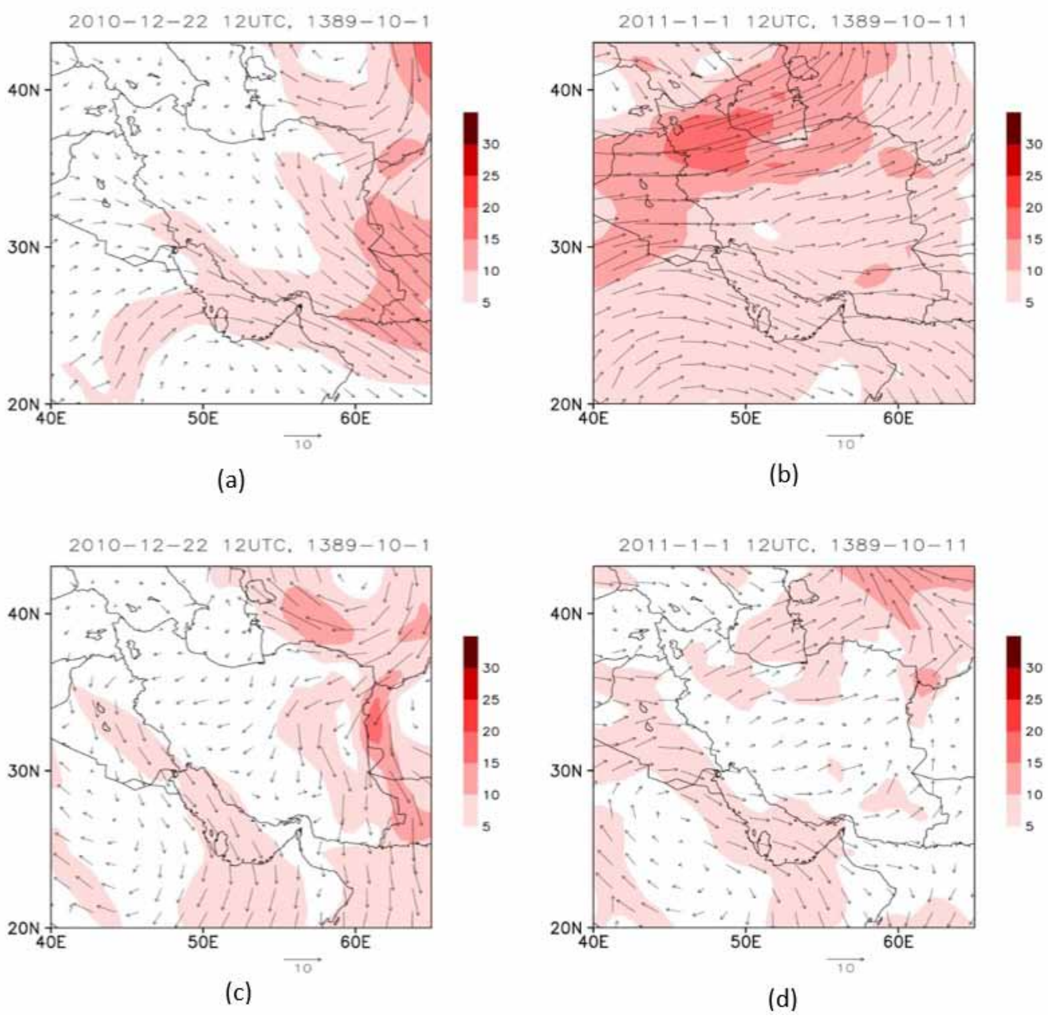

Fig. 2. Horizontal wind field (vector, in m/s); (a), (b) at 700 hPa and (c), (d) 850 hPa; The shaded areas are horizontal wind speed

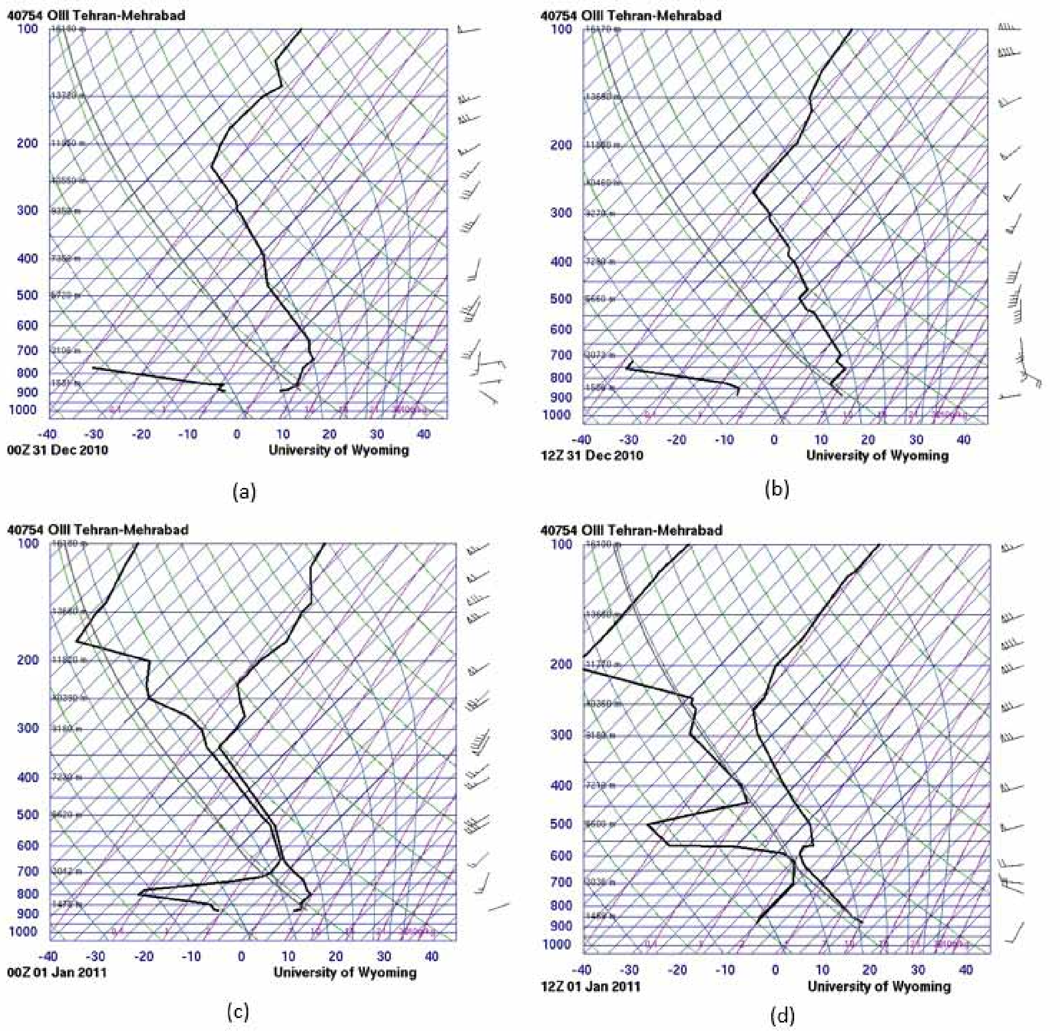

Fig. 3. The skew-T diagram at the Tehran-Mehrabad station; (a): 31 Dec 2010 at 00 UTC; (b): 31 Dec 2010 at 12 UTC; (c): 1 Jan 2010 at 00 UTC; (d): 1 Jan 2010 at 12 UTC

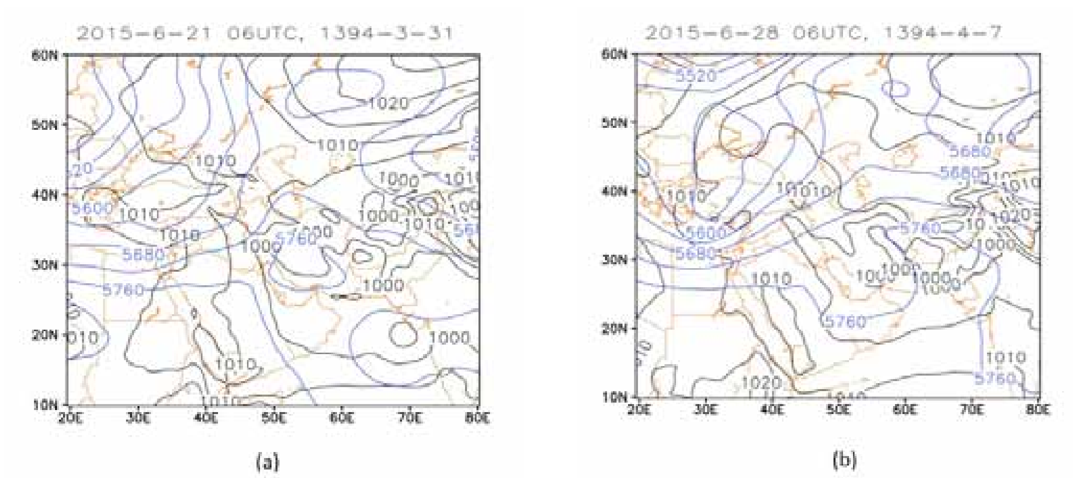

Fig. 4. Geopotential height at 500 hPa (blue lines, in geopotential meter), with sea level pressure (black lines, in hPa)

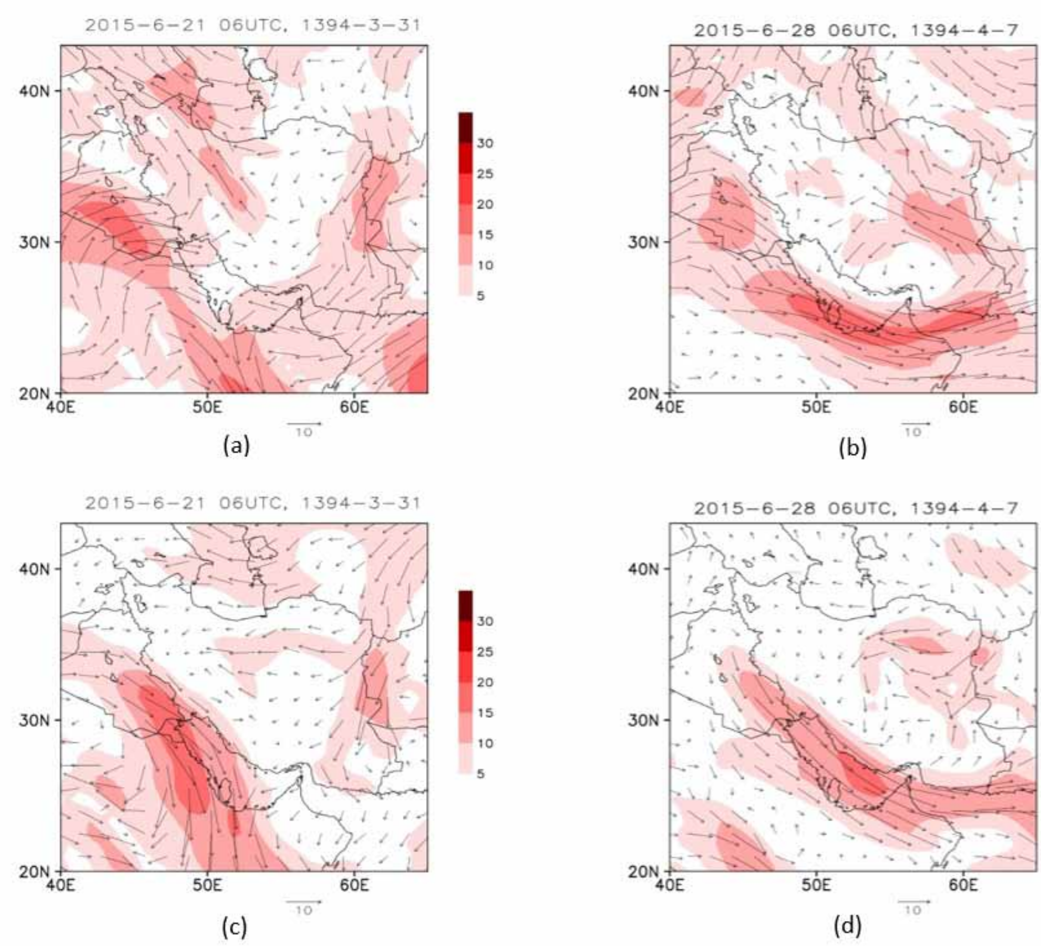

Fig. 5. Horizontal wind field (vector, in m/s); (a), (b) at 700 hPa and (c), (d) 850 hPa; The shaded areas are horizontal wind speed

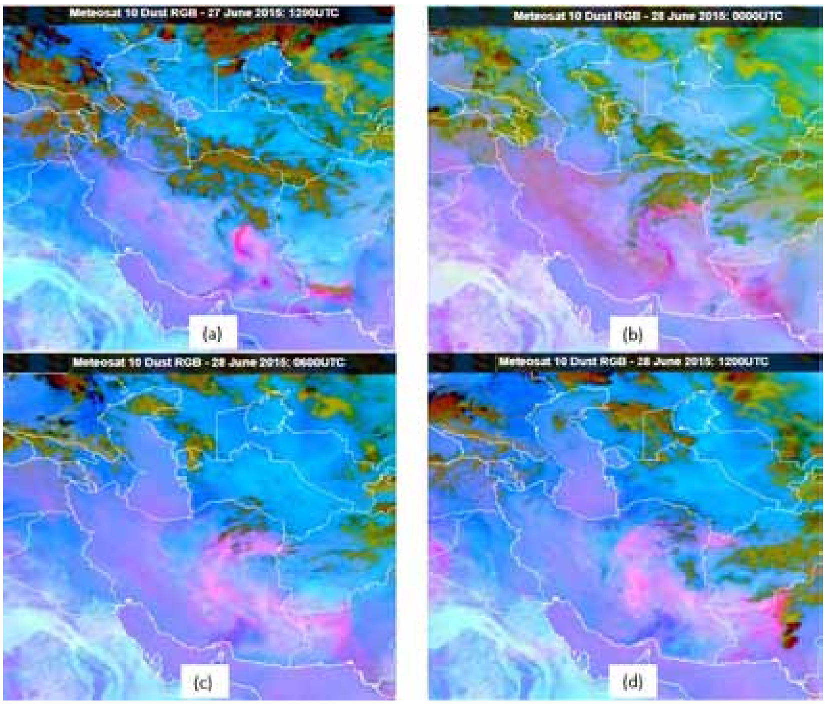

Fig. 6. Meteosat-10 dust RGB composite product for 2015/6/28

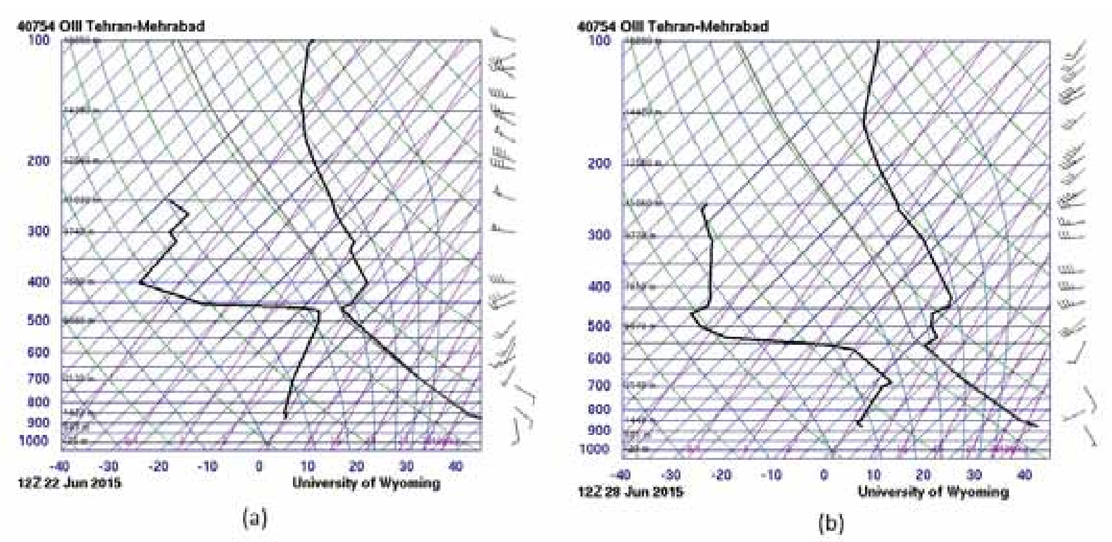

Fig. 7. The skew-T diagram at the Tehran-Mehrabad station; (a): 2015/06/22; (b) 2015/06/28

spring and autumn, represents the establishment of dynamic low pressure in the western regions of Iran and in Iraq, as well as the establishment of thermal low pressure over the central regions of the country. In this pattern, the upward movements and instability govern in the western regions have led to desert dust intrusion from dry and arid areas, especially in Iraq. If there is sufficient horizontal wind speed, suspended dust has been advected to other parts of Iran and also Tehran. As soon as the wind field shear in the regions of pollutants source is reduced and the mid-level trough-ridge is weakened, the air pollution is reduced. When the trough over western region moves to the east, the atmospheric stability decreases and, if there is sufficient humidity, with the occurrence of precipitation, the amount of pollutants will be rapidly and significantly reduced. The sample of this group for further analysis is the period of 2012/05/11 to 2012/05/18 with PSI of 109 to 192. Fig. 8 represents the first day of this period which reflects the establishment of dynamic low pressure over Iraq.

Governing unstable atmosphere in this region

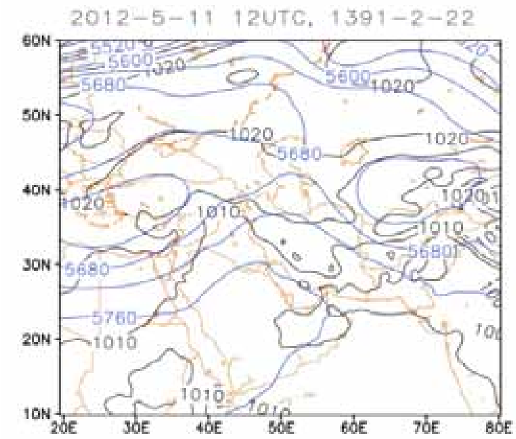

Fig. 8. Geopotential height at 500 hPa (blue lines, in geopotential meter), with sea level pressure (black lines, in hPa)

whose land surface cover is mainly soil, dust particles are raised from the surface. Regarding to the significant westerly wind field in the lower levels of the atmosphere, especially at 700 hPa (Fig. 9), these dust particles have been gradually advected to the eastern regions. Fig. 10 shows the path of the dust particles formed over Iraq from 2012/05/10 to 2012/05/15 at 6 UTC. As is seen, during the advection of dust particles, due to the establishment of the ridge in the mid troposphere and due to the atmospheric stability, these pollutants remain in the country.

At last, it should be noted that the second and third patterns, especially during the transition between spring and summer, are sometimes mixed, and the three sources including local dust storm, the atmospheric condition over Iraq and southwest of the Iran, and atmospheric condition over southeast and east of Iran combined and led to intense air pollution.

Conclusion

In this study, Tehran's air pollution in the last 8 years, which includes 47 occurrences of air pollution, has been studied in terms of synoptic and thermodynamic atmospheric patterns. The study of these days shows the activity of three atmospheric patterns, with percentage frequency of 62, 27 and 17%, respectively: in some days, two patterns existed at the same time. In the first pattern, which mostly governs in the autumn and winter, the period of pollution is more persistent and the PSI has higher values. In this group, the presence of Siberian high pressure, along with the mid-tropospheric ridge and also the decrease in temperature near the ground, increase the stability of the atmosphere, which leads to an increase in the accumulation of pollutants produced near the Earth's surface. In this pattern, the reduction of atmospheric pollutants occurs by increasing the temperature and weakening the surface high

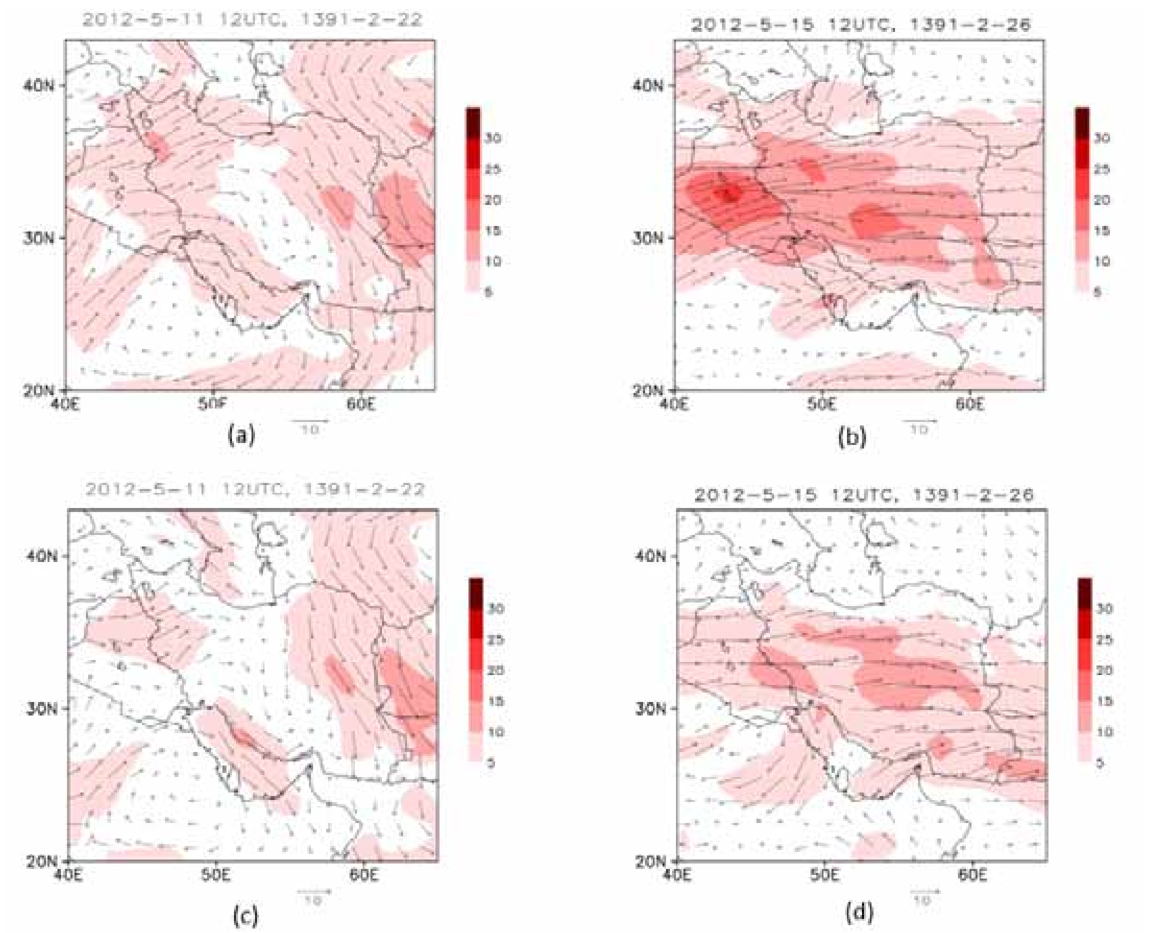

Fig. 9. Horizontal wind field (vector, in m/s); (a), (b) at 700 hPa and (c), (d) 850 hPa; The shaded areas are horizontal wind speed

pressure and the mid-tropospheric ridge or, in the better situation, by passing the trough, which is associated with intensifying of the wind field, especially at the lower levels. While impression of the trough in mid-troposphere, if there is sufficient humidity, the air pollution will completely eliminated due to the wind blowing and the occurrence of precipitation and the PSI will be in clean range.

The second pattern, whose main activity is in late spring and summer, occurs during the activity of the Indian monsoon in the southeastern part of Iran. This low pressure causes severe dust storm in the dry and arid areas of the southeast and east of the country. Strengthening the Indian monsoon, the dust storm is intensified and the advection of dust to the central areas of Iran and to Tehran is led to an increase in the PSI of these regions. At this time, in the central regions of the country, there is a mid-tropospheric ridge resulting in persistency of advected dust particles. Reducing the amount of suspended particles in this pattern is due to the weakening of the ridge and penetration of mid-tropospheric trough from west of the country or due to impression of northern high pressure and strengthening the wind field cause of changing of pressure pattern. In addition, the source of suspended particles is weakened due to lower activity Indian monsoon.

The third pattern, which dominates during spring

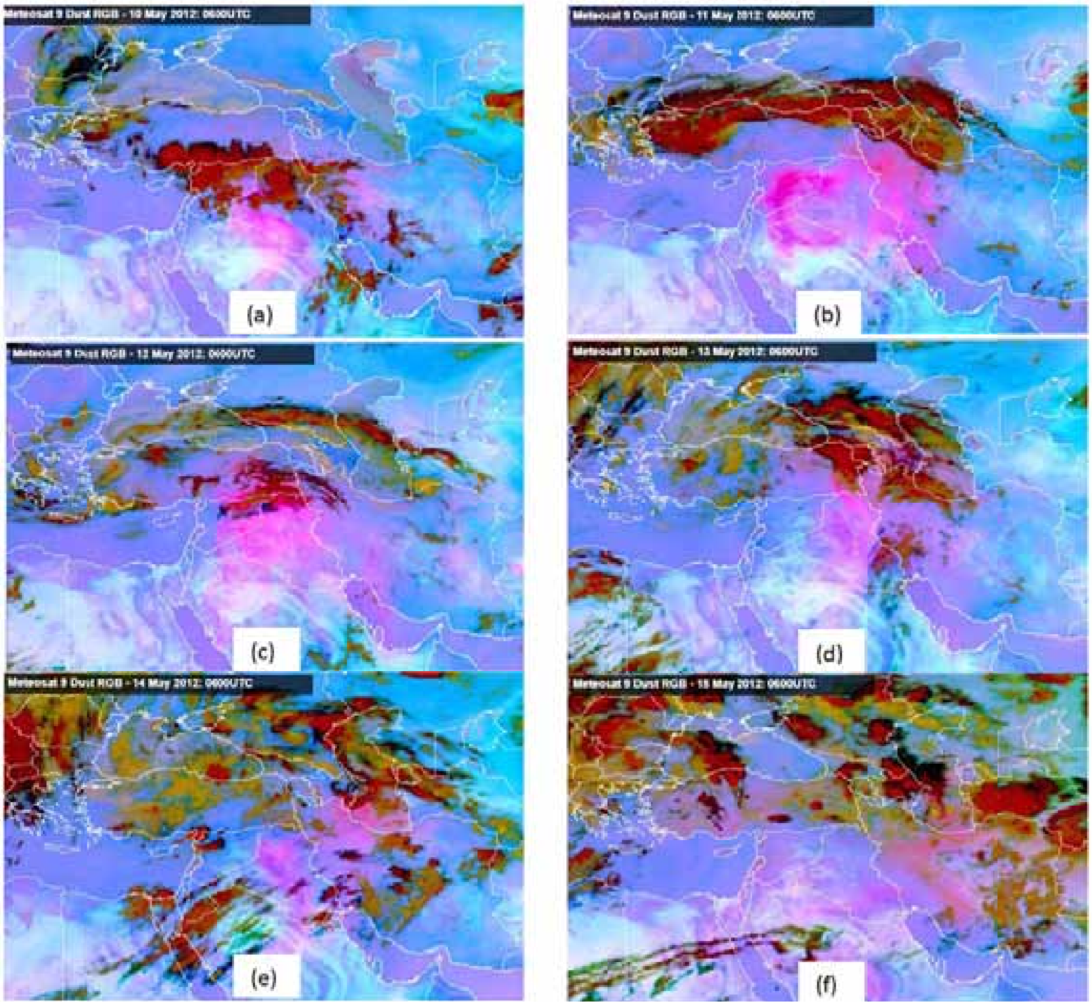

Fig. 10. Meteosat-10 dust RGB composite product from 2012/05/10 to 2012/05/15

and autumn, indicates the establishment of dynamic low-pressure in Iraq and the western regions of Iran, accompanied by establishment of thermal low-pressure over the central regions of the country. This pattern includes upward motion over the dust particles sources in the western regions and advection of suspended dust to other parts of the country, especially Tehran. As the wind shear over pollutants source areas decreases and mid-tropospheric ridge-trough is weakened, the air pollution is reduced.

Knowing the relation between synoptic patterns and the air quality in different seasons, decision-makers can adopt appropriate measures to control air pollution.

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Competing interests

The authors declare that there are no competing interests.

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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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