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Statistical classification of synoptic weather patterns associated with Tehran air pollution

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ABSTRACT:

Introduction: Poor air quality in the heavily polluted cities like Tehran is often the main city problem that influences people health and comfort. The main goals of this study are summarized as: 1) Seasonal pollutants mean variations during 2005, meteorological conditions effects on pollutant concentration; 2) Meteorological conditions case study and pollution spatial distribution for three determining synoptic patterns (MET1, MET4, MET5); 3) Further analysis of the episode from 30th November to 13th December 2005 (MET4); 4) Episode analysis from 30th November to 13th December 2005 (MET4) and 5) Episode analysis from 12th-22th of September 2005 (MET5). These are systematic weather patterns that usually affect the air pollution levels in Tehran.

Materials and methods: Concentration changes of CO, PM_{10}, SO_2 and O_3, as the relationship between the air pollution extreme events and atmospheric conditions in Tehran have been investigated. The hourly air pollution data from 11 representative monitoring sites were used. To understand the relationship between local meteorological synoptic patterns and air pollution, the principal component analysis (PCA) method has been applied to meteorological data. Then for minimizing the data complication the varimax rotations (VR) was used and five synoptic perspectives weather patterns have resulted for highly polluted periods.

Results: Pollutants correlation investigation of the five patterns showed that air quality was highly dependent on middle tropospheric high geopotential ridge development, local southerly wind with strong static stability.

Conclusion: The most polluted periods were associated with a weak pressure gradient, a weak wind, severe air descent, and radiation inversion.

Introduction

With recent increases in industrial activities and population and consequently more fossil fuels burning have impacted the atmospheric pollution significantly, especially near the large cities. Air pollutants that are transported in the atmosphere by local and global circulations, can increase with weaknesses of these circulations. These pollutants can cause harm to human health and the environment [1, 2]. In addition, the scientific studies related to the weather, air quality and health have shown the existence of the relations between

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weather and climate conditions and human health such as heart problem and mental diseases and the respiratory problems [25]. Therefore, understanding the kinds of air pollutants and their transportation by atmospheric motions and their impacts on the environment are very important. Weather conditions can affect the atmospheric pollution in several ways. For example, visibility is a significant factor that indicates the severity of air pollution in large cities. In addition, the wind speed less than 2 m/s and 1 m/s has shown that in some areas it can cause haze pollution for example in China [6]. The important roles of the meteorological conditions are to diffuse, to transport, and to purify air pollutants in the atmosphere. Also, the emission rates of the pollutants, for example the evaporative emission, is directly related to meteorological conditions. The severe air pollution in urban environments is not usually due to a sudden increase in pollutant emissions but can be due to specific meteorological conditions that reduce the atmospheric ability to disperse pollutants. In addition, local weather systems have a strong impact on local air quality, which can lead to accumulation or dispersal of pollutants [7].

Many studies have been conducted to investigate air pollution and its relation to various meteorological conditions in the polluted cities around the world. For example, the statistical analysis of meteorological and air pollution data for their relationships which showed that the regional air quality was highly dependent on the meteorological conditions, such as atmospheric stability, wind speed and direction, airborne capacity, and moisture content [8, 9]. Also, it was investigated the effect of the weather parameters such as temperature and the wind on the concentrations of pollutants in Alpine valley during winter and concluded that under normal conditions, the correlation of these parameters with low contaminations was low, but this correlation is significant during the passage of the cold front and foehn wind [10]. In addition, it was examined the relationship between the number of sick people in hospitals due to respiratory diseases and contaminated atmospheric conditions during the period 2000-2006 with the highest number during spring and winter [11]. This study was conducted in these two seasons based on age and gender and the effects of atmospheric patterns on the number of respiratory illnesses were studied using the main components of meteorological parameters such as temperature, pressure, relative humidity and radiation as well as atmospheric pollutants, and with the high impact of the anticyclonic weather patterns on air pollution severity.

The impact of the winter low-level tropospheric waves disturbances on ozone (O_3) was examined over Iran from 2005 to 2013 by [12]. They concluded that the presence of troughs (ridges) could increase (decrease) the amount of daily total ozone in the area significantly.

One of the important toxic pollutants is carbon monoxide (CO) which is produced by the incomplete burning of fossil fuels such as natural gas and gasoline with the most sources are being vehicles emissions. This is a toxic gas leads to health problem of the people. From 1980 to 1999 the CO concentration has decreased due to the control of the CO emission in many countries such U.S. cities for example by 21%, but during summers, due to dispersion limitation, these areas face high ozone (O_3) concentration and high constant particle matter, PM in the atmosphere.

Also, the high concentration of CO is also related to local topography for example for the areas close to the highly sloped hills or mountains which slow air flow and reduce dispersion of pollution and the meteorological conditions such as strong temperature inversion and low temperatures may cause accumulation the pollutants [13, 14].

In this paper some air pollution and meteorological data are used to find atmospheric circulation patterns associated with acute air pollution episodes in Tehran that suffers from air pollution due to often weak airflow condition and hence, not much efficient air ventilation.

Materials and methods

There are various meteorological variables such as temperature, wind, humidity which can affect air pollution in large cites [15-17]. However, the study of the relationship between air pollution (AP) and each of the meteorological variables needs the consideration of the all relationships among the variables. Therefore, a combination of the meteorological variables in a group is needed to show all meteorological conditions in every AP episode. The analysis of the effect of meteorological conditions on air pollution consists of two stages, firstly, diagnosis of large-scale synoptic patterns using various meteorological variables and analysis of the main components and secondly, analysis of the air pollution characteristics along with each of these patterns. After the second stage with the characteristics of air pollution analysis along with each of these synoptic patterns, in each, a coherent pattern was resulted for each atmospheric pollution episode, as a period that is selected for each investigated pattern. This study is performed for 2005 (as Tehran suffered quite a number of severe air pollutions in this year, leading to more traffic restriction in this city) and then the synoptic patterns causing severe atmospheric pollution in this year are analyzed to show the main Tehran air pollution contributor of the atmospheric pollutant, especially CO, during past years. Firstly, the average diurnal changes in atmospheric pollutants in different seasons during 2005 are investigated and then the synoptic conditions found for these cases are classified.

In the next step of this work for the classification of the synoptic conditions, five synoptic patterns and 16 meteorological parameters are considered. These parameters include the relative humidity (RHM), rainfall (PRC), radiation (RAD), temperature (TMP), dew point temperature (DEW), cloudiness (CLD), sea level pressure at Mehrabad airport station (SLP), the geopotential height of 500hPa (H500), the zonal and meridional components of wind at 850 hPa (u,v) and the horizontal pressure gradient between Mehrabad airport station and Bojnourd station (TBG), Maku (TMG) Noshahr (TNG), Sanandaj (TSG) and Shiraz (TZG). The locations of these Metrological stations are shown in Fig. 1. Then, the association of co-patterns with the concentrations of CO, PM_{10}, SO_2 and O_3 in each station with more available data are then investigated. This study is conducted for CO, PM_{10}, SO_2 and O_3 at 11, 10, 7 and 5 stations in Tehran (Fig. 2) respectively (depending on availability od data). For the set of 16 meteorological variables, the first five components represent a total of 73.9% of the data variation (Table 1). In addition, the first to fifth components separately represent 24.9, 15.5, 14.5, 11.6 and 7.4% of the data variations. Each component is defined by variables with a correlation coefficient greater than 0.4.

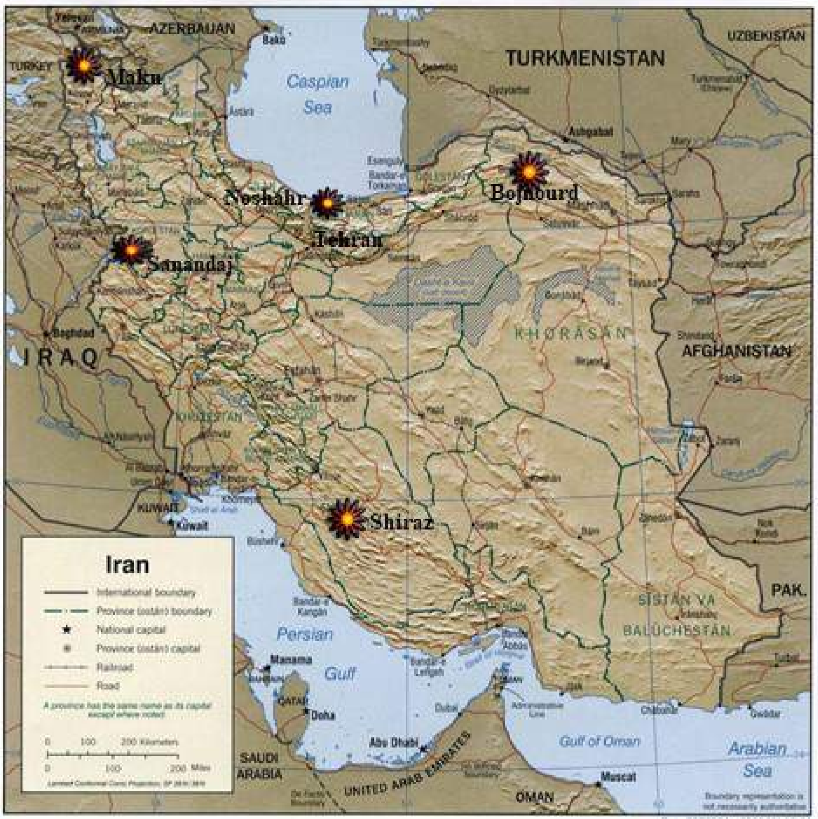

Fig. 1. The geographical locations of the five meteorological stations (shown with the flower sign) with respect to Mehrabad airport station in Tehran.

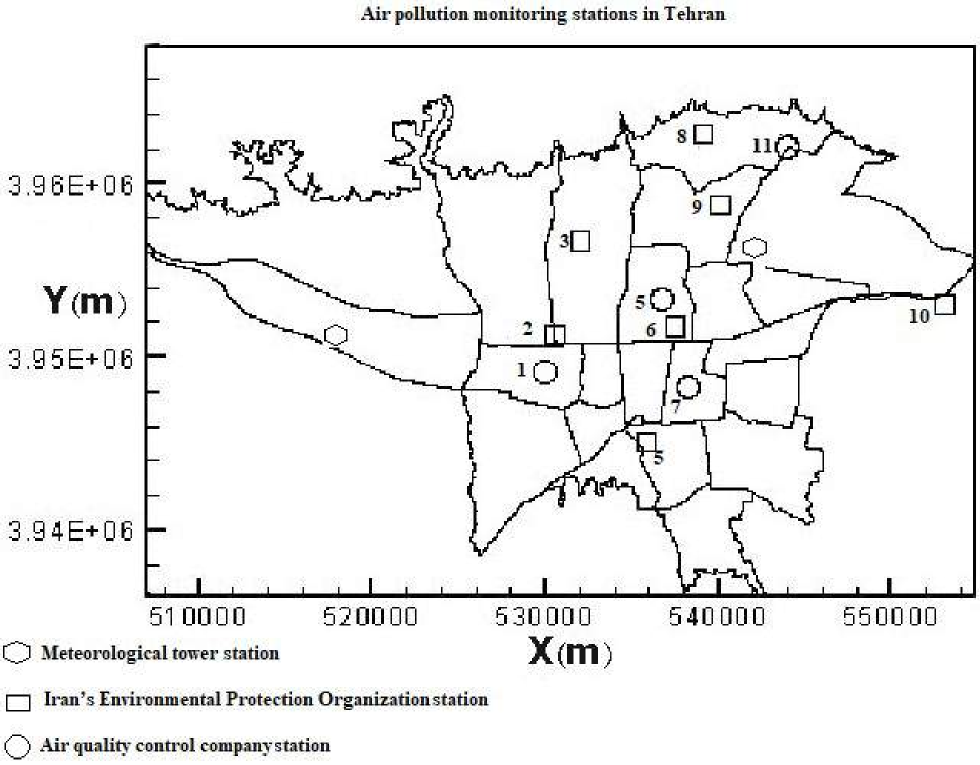

Fig. 2. The distribution of Tehran air pollution monitoring stations.

Table 1. The variables coefficients obtained for each principal component by the PCA

Variables	Principal Components				
	MET1	MET2	MET3	MET4	MET5
RHM	-0.7521	0.531943	0.005542	0.115842	-0.00544
PRC	-0.0972	0.793407	0.104505	0.010448	0.013505
RAD	0.288904	-0.81218	0.144148	0.13019	0.074112
TMP	0.952109	-0.21279	-0.07604	-0.00054	0.068735
DEW	0.13719	0.045644	-0.118	-0.09026	0.780157
H500	0.826172	-0.25516	-0.2901	0.069937	0.082554
CLD	-0.14343	0.735413	-0.11198	-0.21319	-0.18902
WSP	0.225961	0.077857	0.818285	0.037241	-0.1239
u850	-0.11578	-0.04452	0.769702	-0.09511	0.14551
v850	-0.06924	0.161285	-0.00854	-0.12151	-0.45393
SLP	-0.88509	-0.04399	-0.15795	0.107436	-0.10336
TBG	0.601318	-0.24457	0.04401	0.577699	0.192771
TMG	-0.11802	-0.0826	0.580759	0.553674	0.316326
TNG	0.663268	-0.05719	0.348451	0.528511	0.184995
TSG	-0.15088	-0.35154	0.605558	-0.36645	0.300133
TZG	0.112266	0.138623	0.240366	-0.82977	0.07052
Var%	24.94054	15.46301	14.50186	11.64582	7.353621
Cumulative%	24.94054	40.40355	54.90541	66.55122	73.93484

Statistical analysis

The categorization of synoptic meteorological conditions was conducted using principal component analysis (PCA) and Varimax rotation (VR) using SPSS 14 software. Before applying the PCA, the data were firstly standardized and then the PCA statistical method was applied to the meteorological data correlation matrix. The number of main components is extracted after varimax rotation and the specific values larger than one are selected.

The PCA sometimes cannot be understood and it should be rotated using another method such as varimax rotation for better data presentation. This method can minimize the data complication and then the eigenvalues larger than 1 are considered [18]. Choosing a cluster analysis of the meteorological parameters is essential for the proper categorization of the coherent patterns.

Results and discussion

Diurnal mean variation of pollutants in different seasons during the year 2005

The diurnal variations of CO concentrations are nearly consistent with the traffic pattern in the city (Fig. 3a). In different seasons, the variations of the pollutant's concentrations are nearly the same and there are not much differences. From early morning, the levels of pollutants increase and then fall in the mid-day due to lower traffic and more importantly increase in atmospheric boundary layer, and again an increase start in the late afternoon and evening and continues until the middle of the night, with maximum pollution levels at rush hours times. Comparison of the seasonal trend shows that CO concentration is higher in autumn. In the mid-summer, due to an increased in the atmospheric mixed layer depth during the day, the concentrations decrease, but it is higher at rush hours in both morning and afternoon. In the winter, the average value of CO is less than that of summer due to more active weather system activity (low-pressure systems) and the increase in the average wind speed. Fig.3b shows the mean diurnal PM_{10} changes in different seasons of the year 2005. Based on the PM_{10} borderline for health defined by WHO report, the PM_{10} concentration in Tehran is higher than the allowed amount, especially in the summer and autumn seasons [19]. The average diurnal variation of this pollutant shows two maximum peaks during rush hours, early in the morning and late evening. Since, the traffic is the main source of PM_{10} [20], the total concentration of PM_{10} is higher at peak traffic hours and at nights. This is due to more heavy vehicles in nighttime traffic of the city, nighttime construction works and burning of garbage in different parts of the city. The graphs are more consistent during spring and winter and show more variations in autumn and summer seasons. Generally, in a season where the average rainfall is higher, the particles are washed out by precipitation, so the average concentration of PM_{10} is lower.

The average trends of SO_2 variations are shown in the four seasons of 2005 in Fig. 3c. This figure shows SO_2 concentration increases during the early daytime and then decreases due to the increase of atmospheric mixed layer depth in the midday time. In early nighttime, there is another peak but smaller than that of the morning time. Also, this figure shows apparently that the concentration of SO_2 in the autumn has a higher value than those of other seasons. This due to the fact that the synoptic condition during this

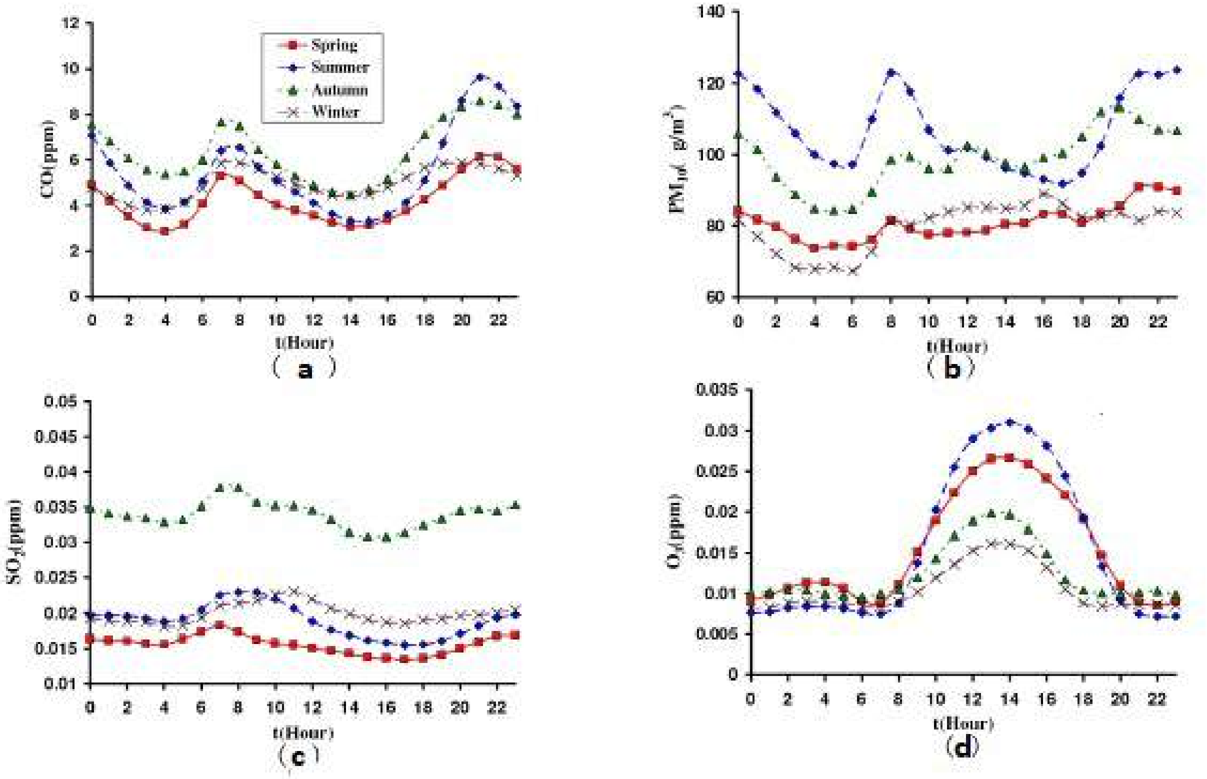

Fig. 3. Mean diurnal changes in CO, PM_{10}, SO_2 and O_3 pollutants in different seasons of 2005.

month usually has a high pressure area over most of Iran with the mean air flow changing from the easterly to westerly (with SO_2 emission sources as factories upstream, in western part of the city) and the sudden temperature reduction which encourages the near surface inversion. Fig. 3 (d) shows the mean O_3 concentration as a secondary pollutant for four seasons of the year. The accumulation of O_3 strongly depends on the physical parameters of the boundary layer properties such as the temperature profiles, wind, and the mixing height and solar radiation. As usual, the higher temperature, sunny and calm conditions lead to higher concentrations of ozone. As a result, the maximum O_3 occurs in the early hours of the afternoon, especially in summer time. This condition not only increases the production of photochemical O_3 but also increases the emission and concentration of ozone-producing chemicals as NOx, and VOCs which lead to an increase in ozone concentrations [21]. The maximum ozone-induced concentration is related to summer and spring. In addition, lightning can also increase the concentration of O_3 in the spring season [22].

Recent diurnal mean variation of pollutants in different seasons

Fig. 4 shows recently mean diurnal changes in CO, PM_{10}, SO_2 and O_3 pollutants in different seasons in 2016. A comparison of this figure with Fig. 3 shows nearly same seasonal patterns for CO, PM_{10}, SO_2 and O_3 pollutants during 2016, although the mean concentrations of CO and SO_2 have decreased nearly to half values of 2005 and PM_{10} has been nearly the same pattern, but O_3 pollutant has increased for 2016.

Table 1 shows the coefficients of the variables, contributing to air pollution, that are obtained for each principal component of the PCA [23]. The last two rows in the table present the percentage of changes and cumulative percentages. The red figures are significant.

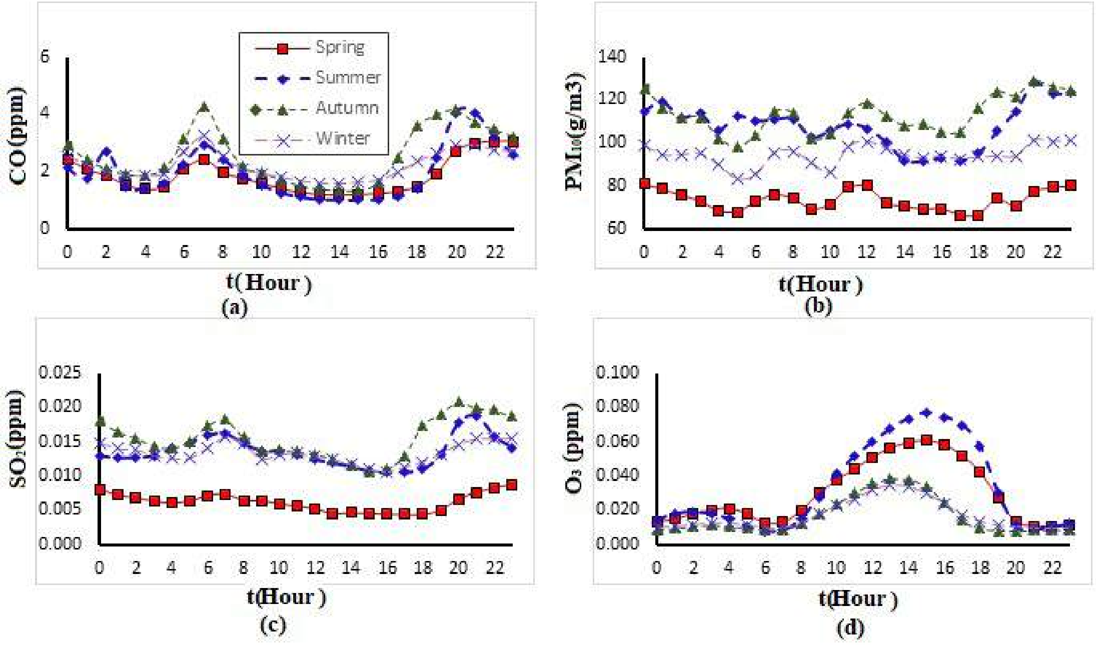

Fig. 4. Recent mean diurnal changes in CO, PM_{10}, SO_2 and O_3 pollutants in different seasons in 2016.

Description of the resulting PCA components

As shown in Table 1, the first component has positive mean coefficients for TBG and TNG variables which indicates the horizontal pressure gradient of Tehran surface pressure in the north and northeast directions. An examination of the synoptic patterns for days correspond to specific weather conditions reveals the expansion of a low-pressure system from the east towards the southeast of Iran, which decreases the Tehran surface air pressure. A high-pressure system is also extended from the north towards the southern part of the Caspian Sea coast, along with the extension of the southwesterly winds towards the country central part at 500hPa geopotential height. This pattern corresponds to a large positive factor for H500 and a large negative for SLP. Considering these coefficients and the moderately high relative humidity coefficient (RHM) and the high coefficient for temperature (TMP), this pattern shows the formation of a thermal low-pressure system over the country. This pattern is more common during warm seasons (late spring and summer). This weak southwesterly wind is consistent with the thermal low-pressure pattern over the surface.

The second component contains relatively large positive coefficients for RHM, PRC and CLD but a strong negative component of RAD. This component shows unstable conditions with rainfall over the region. The synoptic maps of the days associated with this component indicate the development of the strong low-pressure weather system over Europe, extending towards Turkey. In addition, there is a trough line in geopotential contours at 500hPa over the north-west of the country. This pattern is more general during late autumn, winter and early spring, with more westerly wind over the city.

The third component with moderate and positive coefficients for TMG and especially TSG displays a horizontal pressure gradient between Tehran area and west and north-western parts of the country. The corresponding synoptic patterns related to the days associated with this component indicate the existence of the high-pressure system over the west and the development of low-pressure over the eastern part of the country. At the level of the 500 hPa, there is a westerly trough over Turkey and a 500 hPa geopotential height ridge centered over Pakistan. This pattern leads to westerly winds over Tehran, which is consistent with the large positive coefficients for the u850 hPa and WSP.

The fourth component with moderate and positive coefficients is for TBG, TMG and TNG, with a greater value for TBG. This pattern shows the influence of a high-pressure area in the northeast. A large negative factor for TZG indicates a higher value of the Tehran pressure rather than that of the southern part of the country. The investigation of these synoptic patterns indicates the influence of Siberian high-pressure towards to the central part of Iran. At the level of 500hPa, there is a low geopotential height over Europe and Siberia, and a high geopotential ridge over Iran (blocking pattern). This condition is very stable and there is no significant variation in low winds that contributes significantly to air pollution in the city.

The fifth component is associated with a relatively large positive coefficient for DEW and a negative average coefficient for the v850. Synoptic pattern along with the fifth component shows the extension of the low-pressure system from the southern part of the country associated with a ridge at 500hPa geopotential height. This pattern indicates a dry condition with weakly southerly winds. This pattern is more likely to be seen in the transition period from summer to autumn.

At the next stage of this work, after finding the synoptic perspective patterns during 2005, the study of the characteristics of air pollution with each of these patterns is discussed in the next section.

The effect of meteorological conditions on pollutant concentrations

The correlation analysis between the average diurnal concentrations of CO, PM_{10}, SO_2 and O_3 pollutants and the meteorological (MET) components is to determine the effect of different meteorological conditions on air pollution in Tehran during 2005. Here, correlations with a statistical significance greater than or equal to 90% are considered, and smaller correlations are neglected. The results of this study indicate that the CO concentration increases under heat low-pressure conditions with the weak zonal to southeasterly wind (MET1 and MET5), under the existence of instability with precipitation (MET2) and under the conditions associated with the strong westerly winds (MET3), the concentration of this pollutant is decreased.

In addition, the concentrations of PM_{10} increase under the conditions of the heat low-pressure system (MET1) along with the high-pressure system from the north towards the east with descending air (MET4). Also, under unstable conditions with strong wind speeds, the PM_{10} concentration decreases.

The SO_2 pollutant decreases under precipitation and heat low-pressure conditions and there is no clear positive correlation with any of the components. In addition, under the conditions of heat low pressure, O_3 increases, and in unstable conditions along with precipitation and winds, the concentration of this pollutant decreases.

In general, the absolute values of positive and negative correlation coefficients seem to increase with the air pollution associated with MET1, MET4 and MET5, whereas the pollution decreases with the patterns of MET2 and MET3. So, after this stage of work and associating the correlation analysis between the average diurnal different pollutants concentrations with each weather pattern, in form of the coherent pattern, in the next step of this work, the time of each polluted episode is selected. Then the meteorological patterns of the acute air pollution episodes in 2005, with CO as the main contributor, is studied and is presented in the next section (The effect of meteorological conditions on pollutant concentrations).

Case study of the meteorological conditions and spatial distribution of pollution for three synoptic patterns (MET1, MET4, MET5)

Three atmospheric air pollution patterns (MET1, MET4, and MET5) are selected and are presented in Table 2 with their time interval for each episode.

Table 2. The time intervals for selected air pollution episodes.

Date	Synoptic pattern
From 5th-9th of August 2005	MET1
From 30th November to 13th December 2005	MET4
From 12th-22th of September 2005	MET5

a) Analysis of the episode from 5th-9th of August 2005 (MET1)

During these five days air pollution episode from August 5th-9th 2005, the concentration of the main pollutant CO, with the pollution index ranging from 111 to 124, has a peak on 8 of August, that is rather high. The study of the spatial and temporal variations of the CO pollutant indicates that the CO increases during night hours in the centre of Tehran in this day. Then it gradually decreases in the central part of Tehran and with another increase in the southern part of Tehran. During the daytime, due to effect of the rather warmer air and hence, thicker mixed layer and anabatic winds, CO concentration decreases in the south and its maximum shifts to the northern part of the city. In the early afternoon, with the increasing of the mixed layer depth, CO concentration begins to decrease. In addition, in the early morning with the increase of traffic, the CO concentrations increase everywhere, especially in the centre and southern parts of the city. As the night starts due to katabatic winds (due to mountain range in the north of the city), the maximum of CO concentration area begins to move from the northern part of Tehran towards the southern parts. In this period, local weak winds transport pollution over the city. Fig. 5 shows the sample (12 Dec. 2012) for daily trends of PM_{10} (a) and CO (b) for this episode for different stations (north, south, center) indicating these spatial variations.

Fig. 6 shows the surface sea level pressure map and the 500hPa geopotential map at 00UTC and 12UTC on August 8 with the pollution index of 124. At the same time, the southern low-pressure system extends from the south towards the east and the southeast area of the country, causing a decrease in Tehran near-surface pressure. In other words, this time is accompanied by a summer heat low system. In addition, atmospheric flows are often southeasterly and weak, which are consistent with the pattern of surface pressure over this area. Whereas the surface high-pressure tongue is dominated over the north to the southern part of the Caspian Sea coastline and the 500hPa subtropical ridge extends from the south towards the west, and so the general weather condition is quite stable. Present study outcomes can be used in management plans for the control of air pollution in this and other large cities.

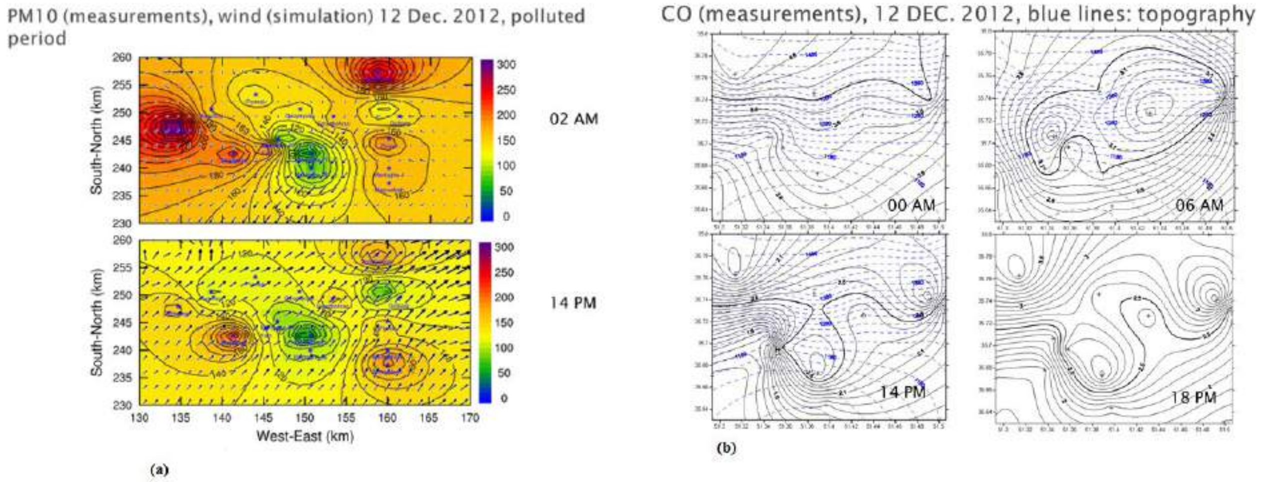

Fig. 5. The sample distributions of PM_{10} (a) and CO (b) for daily trends for Tehran different stations in the north, south and center indicating the spatial variations.

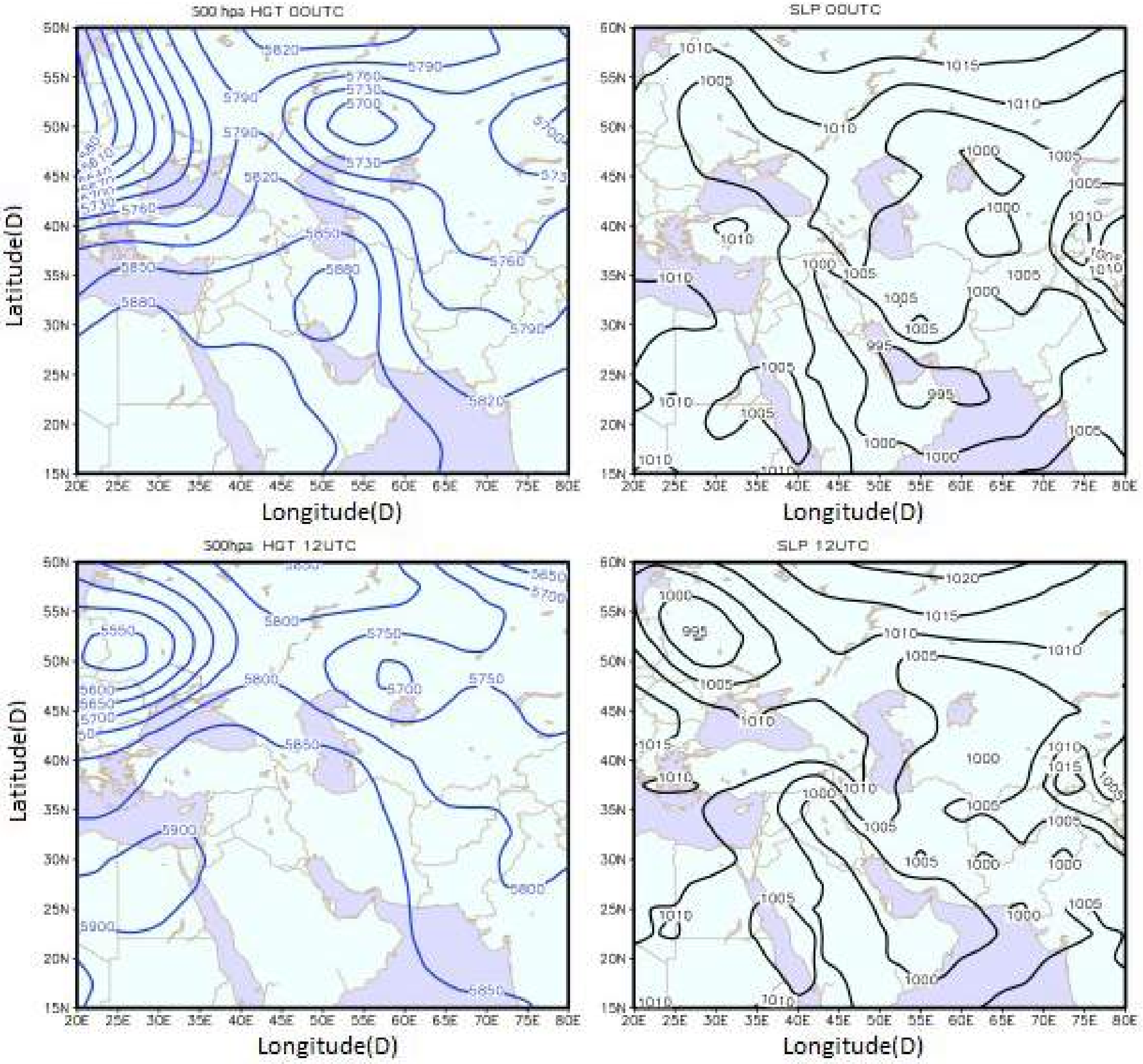

Fig. 6. 500hPa geopotential height (left column) and surface pressure maps (right column) for August 8, 2005 (from cluster 5th-9th of August 2005). The upper and lower figures represent the maps at 00UTC and 12UTC respectively.

The Skew-T charts for August 8, 2005 (Fig. 7a at 00UTC and Fig. 7b at 12UTC) show quite small air relative humidity. As Fig. 7a shows, there is an inversion that extends to the level of 850 hPa and also in the following condition of the 12UTC (Fig. 7b), the temperature line has a negative but steep slope, and the air parcel line is to the right of the ambient temperature line, indicating the stability of the air parcel in the air column. Also, at 00UTC, the convective inhibition energy (CIN) shows the amount of energy that stops the air parcel to rise from the surface to the level of the free convective energy level, and is 557 J/kg which is much higher than the convective available potential energy. This indicates the existence of a very stable atmospheric condition. The horizontal visibility at Mehrabad airport station was reported about 5 km for 00UT. At 12UTC, the stable condition was weakened slightly, and then horizontal visibility was increased. In the rest of the days of this time, the same characteristics were observed. Fig. 8 shows the vertical profile of the buoyancy parameter ($N^2=((g/\theta_o)[\partial\theta/\partial z])^{1/2}$, where θ is the air potential temperature. The values of N^2 vary from a positive mean value at midnight (Fig. 8a) to a very small negative number in the afternoon (Fig. 8b). Therefore, this parameter shows the air stability at different altitudes, especially during the night of the studied episode. As stated earlier, in this period, the MET1 condition existed and this pattern mainly caused air pollution in this summer episode. Analysis of wind speed and direction indicates that under these conditions, winds are very low, and the pollutants have much higher concentrations than their mean values.

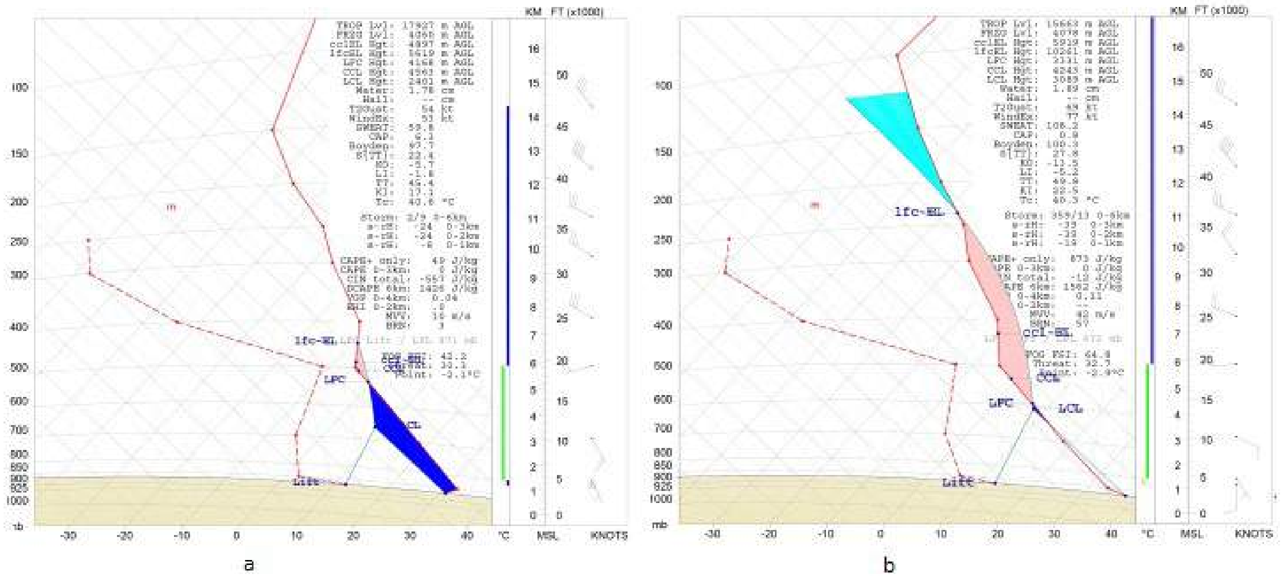

Fig.7. Skew-T chart for 2005/08/08 (from cluster 5th-9th of August 2005). (a) at 00UTC and (b) at 12UTC, the convective inhibition energy is presented in blue color and the available potential energy is shown in pink.

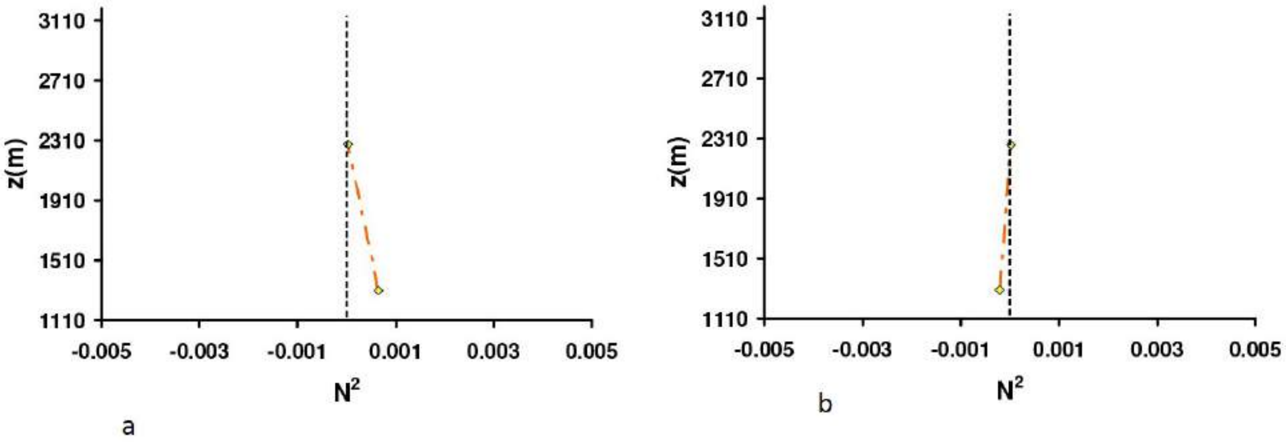

Fig. 8. The buoyancy parameter profiles for August 8, 2005 (from cluster 5th-9th of August 2005).
(a) at 00UTC and (b) at 12UTC

b) Analysis of the episode from 30th November to 13th December 2005 (MET4)

During these 14 days of Tehran air pollution episode with the main contaminant as CO, the pollution index varies between 102 and 190, with sever conditions as a warning issued for the fourth, sixth and seventh of December. The contributed synoptic pattern shows the existence of the Siberian high-pressure along with a ridge of the geopotential height at 500 hPa on Dec. 4, 2005 in the winter (Fig. 9). This case is associated with the subsidence of a cold air mass in the middle atmospheric level, and the coherent pattern is attributed to the anti-cyclonic ridge with no upward motion, causing very stable, cold weather and therefore the possibility of the pollutant accumulation near the surface, with little ventilation. The wind was weak or very calm during this period. This period was one of the worst polluted episodes studied, especially for CO and PM_{10} pollutants in Tehran. During this period, CO has accumulated in the western part of Tehran, and it was gradually enhanced in the southwest part of the city and then declined slowly. At dusk, with the increase of traffic, the pollution in the western part of the city increased again and high concentration area extended towards the southern part of the city. In the early hours of the night in the northern and western parts, the concentration of PM_{10} was reported high and was gradually increased throughout the city. This increase continued in the northern part of the city during this day. From 9:00am at local Tehran time, the pollution was reduced in the southern part of Tehran and later in the afternoon in the north of city. Then at 10:00 pm, it turned into its peak value.

The skew-T graphs show a temperature inversion due to cold and stable air at around the level between 750-650hPa at 00UTC (Fig 10a). As Fig. 10b shows, this inversion is intensified at 12UTC. On this day, the horizontal visibility was gradually changed from 5000 to 3000, 1500 and then to 350 m in Mehrabad airport station, with the minimum around 250 m, leading to the cancellation of scheduled flights. The vertical profiles of the buoyancy parameter for this episode are shown in Fig. 11a and Fig. 11b. In both cases, the buoyancy parameters were more positive than the values of the case of MET1, which indicates larger atmospheric stability. This parameter also increased with elevation in the afternoon, showing the temperature inversion in the middle level with rather more stability than that of the surface.

Generally, in this period, with the existence of the cold high-pressure system along with very weak winds, the concentration of air pollution is extremely high, and the local northern-southern circulation forcing due to mountain winds can only influence the displacement of the polluted area in the city.

c) Analysis of the episode from 12th-22th of September 2005 (MET5)

This episode occurred during the transition from summer to autumn season, and the pollution index was reported between 103 and 133. This cluster is the fifth group (MET5) of the meteorological patterns. The first day of this period was the most sever polluted case with the highest amount of 133 during September 12, 2005. During this time, there was a strong increase in the concentrations of pollutants, especially CO. The sky was clear with dry air and with weak southerly winds which corresponded to the MET5 component coefficients. In this episode, the CO was mainly concentrated in the city center during the night and slowly decreased overnight and increased in the early morning by the increase in city traffic, mostly in the central area. By rather less traffic around the noon, the concentration of this pollutant decreased and again increased during the hours before sunset near the rush hours from the southern part towards the northern part of the city. At night, in the western part of Tehran, the concentration of PM_{10} was reported with a higher value, which was decreased slowly during the night. In the early morning, the pollution increased and reached a maximum level at nine o'clock local time, mostly in the northeastern areas. Then the concentration of this pollutant decreased from the east, and again at sunset in the south, it reached another peak at 10 pm and finally its peak was moved towards the norther area of the city.

The surface pressure map for September 12, 2005, shows the warm low-pressure penetration from the south of the country along with the middle-level anti-cyclonic ridge development at 500hPa at 00UTC and 12UTC (Fig. 12).

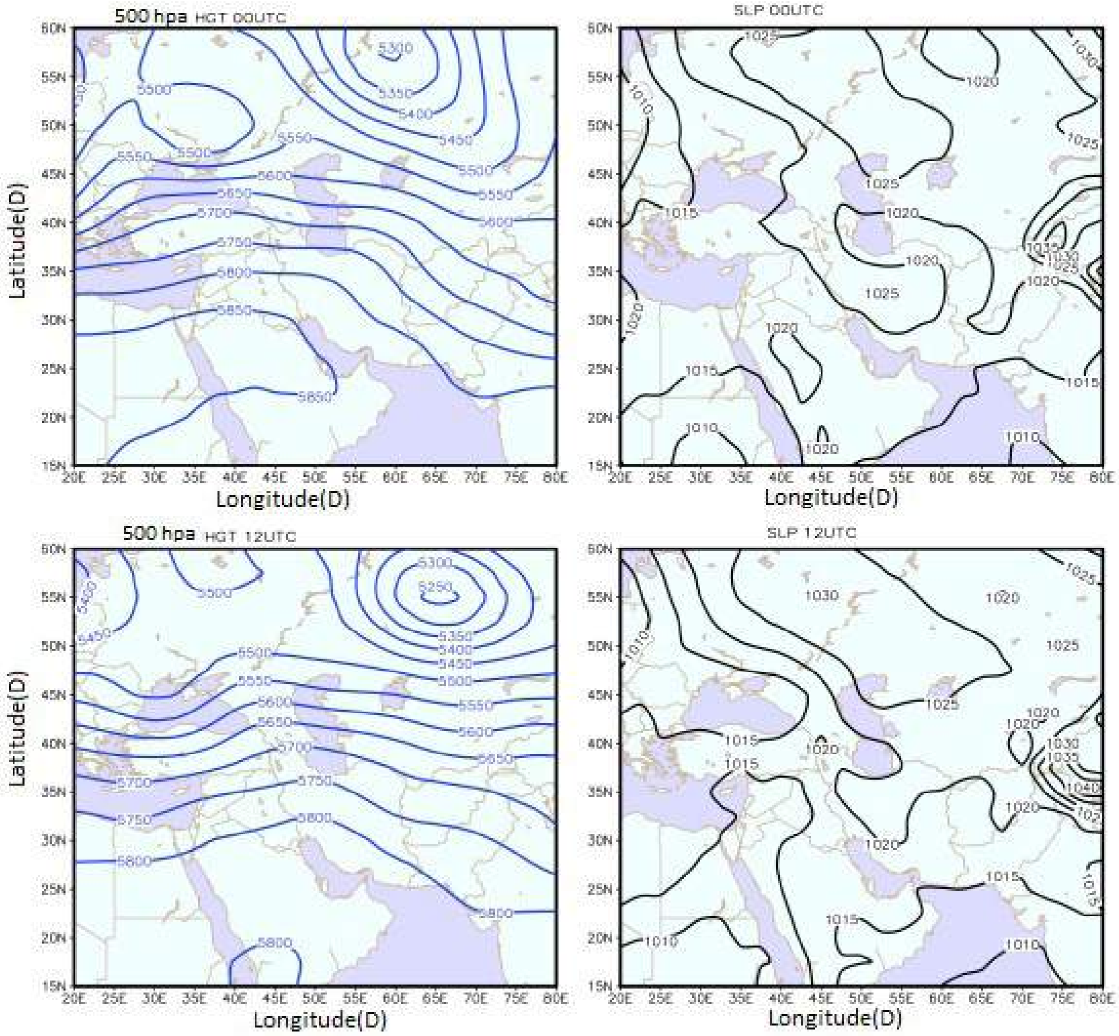

Fig. 9. 500hPa geopotential height (left column) and surface pressure maps (right column) for 2005-12-04 (from cluster 30th November to 13th December 2005). The upper and lower figures represent the maps at 00UTC and 12UTC respectively.

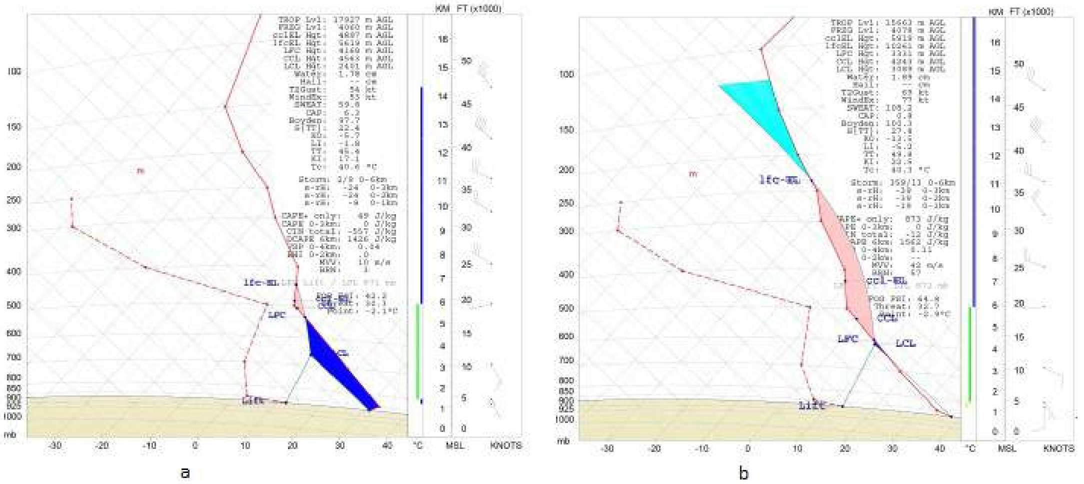

Fig. 10. Skew-T chart for December 4, 2005 (from cluster 30th November to 13th December 2005). (a) at 00UTC and (b) at 12UTC, the convective inhibition energy is presented in blue color and the available potential energy is shown in pink

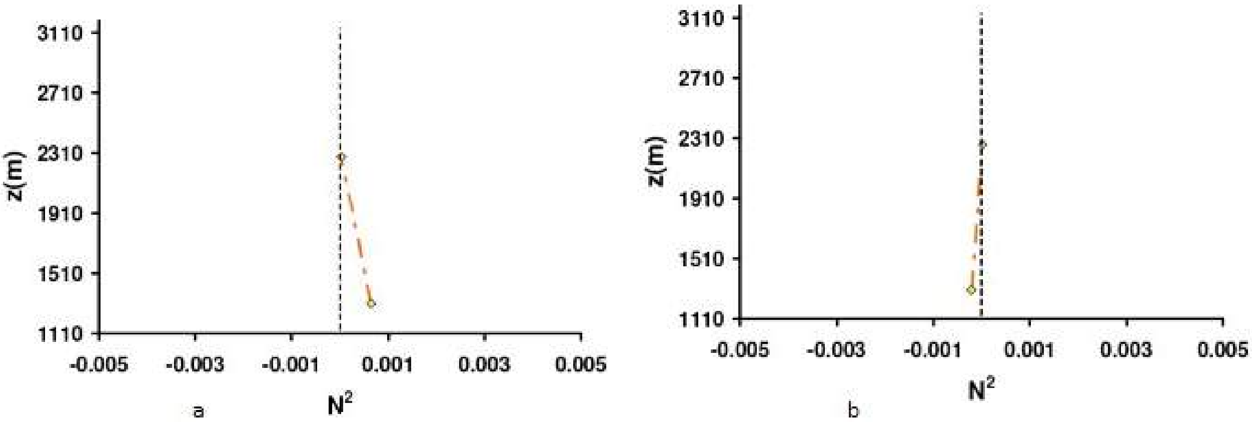

Fig. 11. The buoyancy parameter profiles for December 4, 2005
(from cluster 30th November to 13th December 2005). (a) at 00UTC and (b) at 12UTC

Fig. 13a and Fig. 13b show the skew-T charts at hours 00UTC and 12UTC. There is a surface inversion of the temperature at 00UTC (Fig. 11a), which continues to the level of 820hPa. In addition, the rising air parcel is located to the left of the ambient temperature lapse rate line, which shows atmospheric stability. At 12UTC (Fig. 13b), the stability at the lower levels of the atmosphere was reduced. The buoyancy parameter profiles are shown in Fig. 14a and Fig. 14b, indicating the strong stability at 00UTC, whereas at 12UTC except for the near surface, the atmosphere is almost neutral or slightly stable.

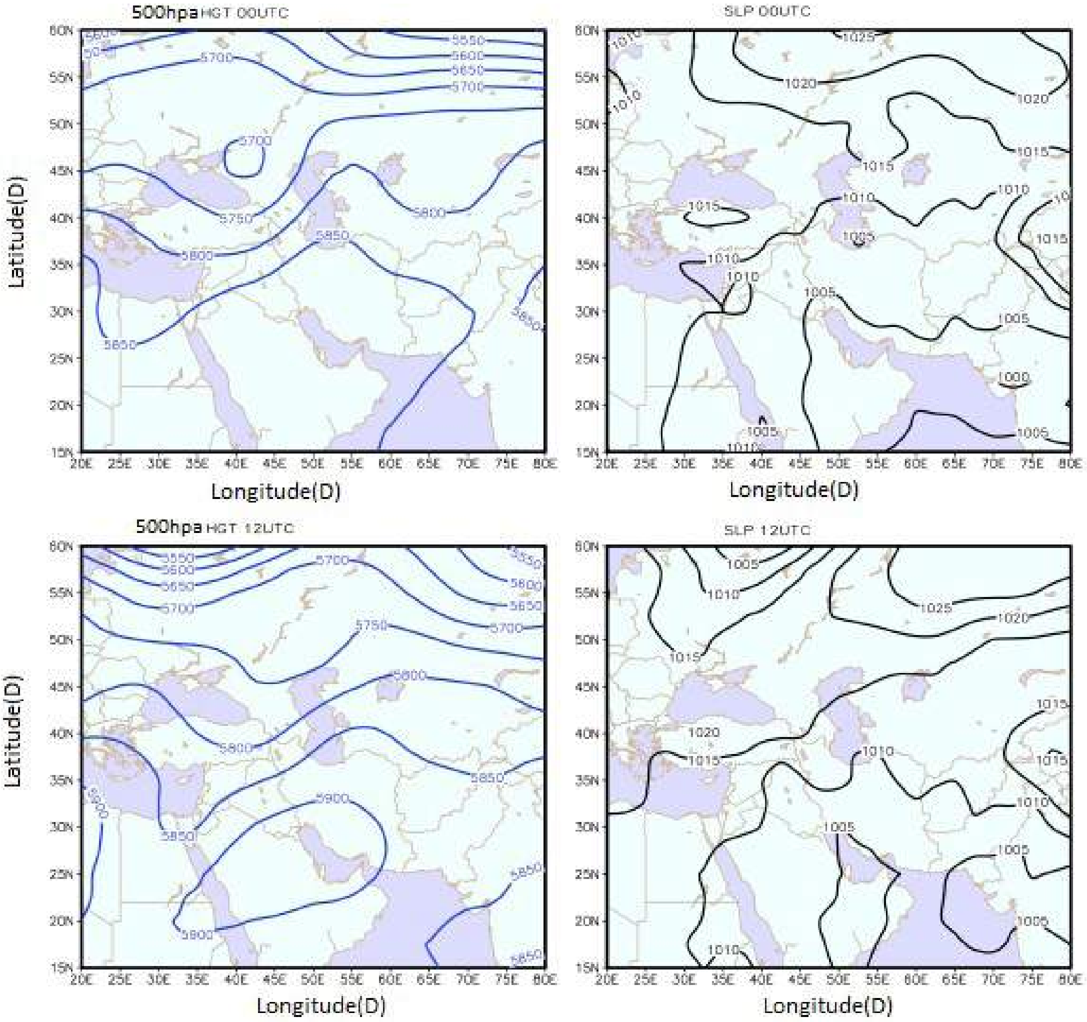

Fig. 12. 500 hPa geopotential height (left figures) and surface pressure maps (right figures) for September 12, 2005 (from cluster 12th-22th of September 2005). The upper and lower figures represent the maps at 00UTC and 12UTC respectively.

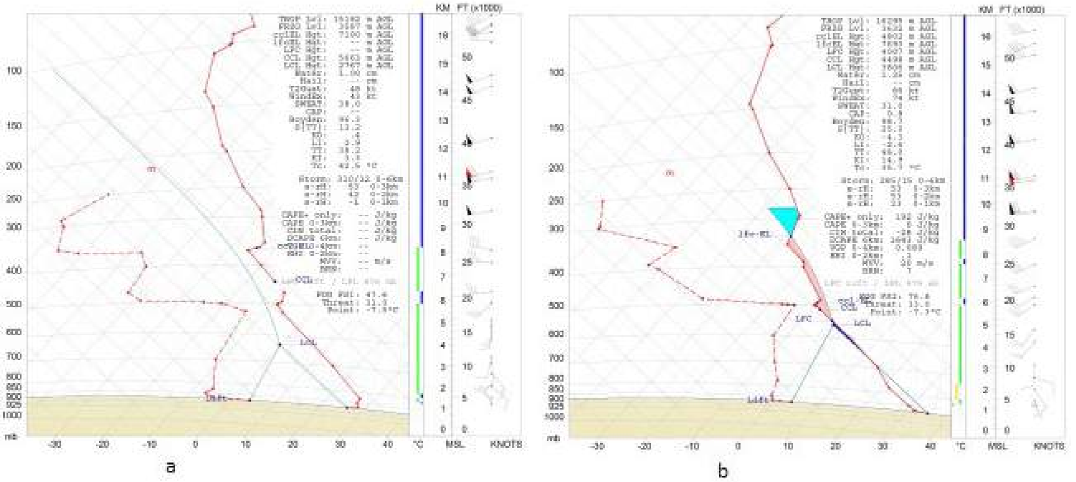

Fig. 13. Skew-T charts for September 12, 2005 (from cluster 12th-22th of September 2005). (a) at 00UTC and (b) at 12UTC, the convective inhibition energy is presented in blue color and the available potential energy is shown in pink.

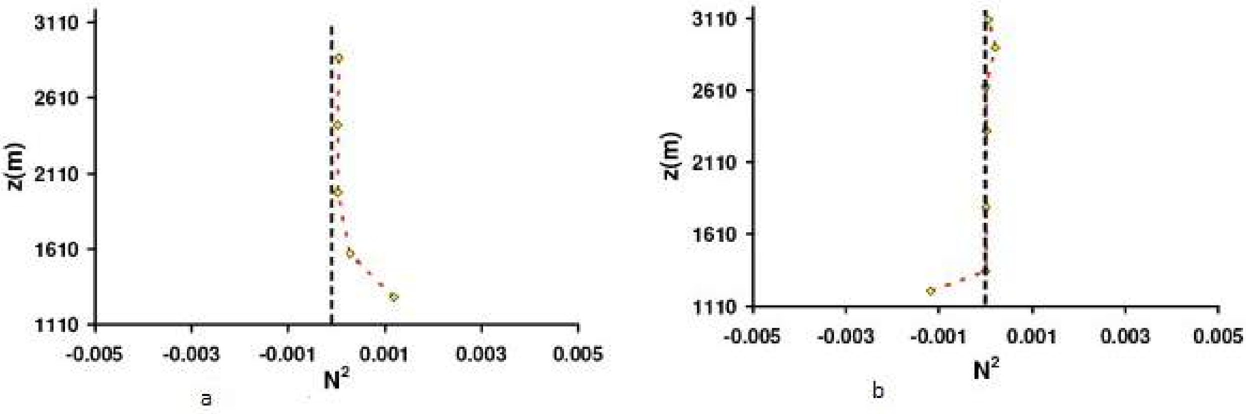

Fig. 14. The buoyancy parameter profiles for September 12, 2005 (from cluster 12th-22th of September 2005). (a) at 00UTC and (b) at 12UTC.

Conclusion

The variations of CO, PM_{10}, SO_2 and O_3 concentrations and the relation between the extreme events of air pollution and the relevant meteorological conditions and patterns in the city of Tehran have been investigated. The hourly CO, PM_{10}, SO_2 and O_3 concentrations from 11 representative monitoring sites located in the city of Tehran were used, covering a 1-year period (2005). The results of our analysis showed that the concentrations of air pollutants differed mainly from one monitoring site to another, due to the location and proximity of each station to the emission sources. Although, the hurly mean daily trends for the season is the same for all stations. For each site, there were also significant differences in concentrations from day to day, and from month to month. Daily and seasonal changes in air pollutants showed that the concentrations of CO at the end of the summer and early fall had the highest amount. In addition, the daily maxima of CO matched with the peak hours of traffic flow (usually two). In addition, the PM_{10} concentrations during summer and autumn were higher. Also, the concentration of this pollutant in spring and winter, due to the increase in average rainfall, was decreased. The maximum PM_{10} was observed during traffic peak hours and at nighttime. The SO_2 was higher in autumn during the day as the near-surface daily heating has lessened after summer and had a smaller peak with the increasing traffic during the evening. In the early autumn wind direction is usually reversed from the easterly summer regime to the westerly, autumn and winter regime. This westerly wind can advect air pollutant as SO_2 from western part of the city, that accommodates many industrial sources. The O_3 concentration in spring and summer due to the rather warmer condition is higher. Also, in the early hours of the afternoon with a rather higher temperature, the accumulated air pollutants were increased (except O_3). Also, a smaller peak was observed during the early morning with the increase in traffic and NO_2

emission. In general, the frequency of the highest amounts in SO_2 and O_3 were smaller than those of CO and PM_{10}.

The spatial distribution of the CO and PM_{10} showed that the pollution accumulation was mostly around the northern and southwestern parts of the city of Tehran. These differences are significantly attributed to the dominant synoptic and meteorological conditions. The statistical techniques of Principal Component Analysis (PCA) were applied to the data for understanding such dependences. The classification of the synoptic conditions for polluted episodes was done using the PCA method and varimax rotation using SPSS14. Then 16 meteorological parameters from surface and high altitude levels including the relative humidity (RHM), precipitation (PRC), radiation (RAD), temperature (TMP), dew point (DEW), cloudiness (CLD), sea level pressure over the Mehrabad station (SLP) and 500 hPa geopotential height (H500) and zonal and meridional components of wind at 850 hPa level (u, v) and horizontal gradient pressure between Mehrabad station and Bojnoord (TBG), Maku (TMG), Noshahr (TNG), Sanandaj (TSG) and Shiraz (TZG) stations were considered to find appropriate synoptic patterns.

Five synoptic patterns associated with air pollution episodes in the city were found. The correlation between air pollutant patterns and each of the five found synoptic patterns were investigated. Five synoptic weather patterns including a summer thermal low-pressure (MET1), the unstable conditions associated with precipitation (MET2), the conditions of mechanical and thermal turbulence and prevailing westerly winds (MET3), the high-pressure influence from northeast of the country with the ridge pattern in mid atmospheric level (MET4) and lastly the dry southerly winds associated with low-pressure pattern centered in Tehran (MET5), were found. The examination of the relationship between resulted synoptic weather patterns and pollutants such as CO, PM_{10}, SO_2 and O_3 showed that the lowest of pollutants were associated with the weather systems with precipitation and westerly winds, namely MET2 and MET3. The polluted periods were associated with the low-pressure gradient, weak wind, strong descent of air mass (surface high-pressure condition) with inversion radiation (clear sky and the weak wind), namely MET1, 4 and 5.

These results also showed that the air quality in the city of Tehran was highly dependent on meteorological conditions such as wind speed and wind direction, humidity contents, net radiation, temperature, and pressure, of which the wind speed was the most important. It should be indicated that the mean wind speed in this city is usually low, emphasizing that lower pollution emissions strategies should be considered in managing the air quality in this city. This analysis of different episodes showed that the worst cases were associated with the existence of the mid-level tropospheric ridge, weak wind or near-surface calm condition with the surface temperature inversion. The spatial and temporal distributions of pollutants revealed that the effects of local conditions (such as anabatic and katabatic winds) and the distribution of emission sources in this urban area were also important. Therefore, the most polluted periods were associated with a weak pressure gradient, a weak wind, the existence of the severe air descent and radiation inversion.

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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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