Temporal and spatial variations of particulate matter and gaseous pollutants in the urban area of Tehran

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HIGHLIGHTS

- High levels of particulate matter and gaseous air pollutants are found in Tehran.
- Significant spatio-temporal variations in concentrations of PM and gaseous pollutants are detected.
- Lower (higher) concentrations of PM are found in midday (midnight) in North (South) Tehran.

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ABSTRACT

Being hemmed in on two sides by high mountains, the urban area of Tehran is characterized by high levels of particulate matter and gaseous pollutants, which have adverse consequences on human health, ecosystems and environment. Using air quality measurements taken in different regions of Tehran, spatial and temporal variations of particulate matter and gaseous pollutants are analyzed to identify the typical climatological aspects of air pollutants. In terms of particulate matter concentrations, South Tehran is more polluted than Central to North Tehran, while West Tehran is more polluted than the East. Concentrations of particles in North Tehran are lower in the midday compared to the midnight, whereas the opposite is true in South Tehran. The observed annual mean concentrations of PM2.5 and PM10 in North Tehran were 37.5 and 76.3 μg m⁻³, respectively, which are substantially greater than the national annual mean safety limits of 10 μg m⁻³ for PM2.5 and 20 μg m⁻³ for PM10. The observed high levels of particulate matter underline the essential need for a coordinated action to reduce the rapidly increasing air pollution over the growing urban area of Tehran. Noticeable monthly (seasonal) variations are evident in the observed PM10 concentrations, with a minimum of 61.5 μg m⁻³ in March (spring) and a maximum of 82.9 μg m⁻³ in July (summer), reflecting contribution of weather conditions. Analyzing daily PM2.5 (PM10) concentrations indicate that mid-week Wednesdays (Mondays) are the most polluted days. The higher mid-week concentrations reflect contribution of heavy vehicular traffic, industrial operation and increased commercial activities. Strong diurnal variations in the concentrations of particulate matter in North Tehran are detected, varying from a peak in late night to a minimum in late afternoon, indicating contribution of deeper daytime convective boundary layer and stronger winds in dispersion of particles.

1. Introduction

As a major environmental problem, air pollution is responsible for a wide range of respiratory and cardiovascular diseases (Samet et al., 2000; Pope et al., 2004), and many premature deaths worldwide are related to long-term health impacts of fine particulate matter with a diameter smaller than 2.5 μm (PM2.5) (Lelieveld et al., 2015). It is estimated that annually 3.15 million premature deaths worldwide are caused by exposure to high levels of PM2.5, while the total annual mortality by outdoor air pollution is estimated to be 3.3 million (Lelieveld et al., 2015). This is in addition to 3.54 million deaths related to indoor air pollution (Lim, 2012). The health effects of increasing concentrations of particulate matter are remarkable, such that it is estimated that every 10 μg m⁻³ increase in PM2.5 and PM10 (particulate matter with a diameter...
smaller than 10 µm) levels is associated with up to 6–13% (Burnett et al., 2002; Beelen et al., 2008; Krewski et al., 2009) and 0.6% (Levy et al., 2000) increases in daily premature mortality, respectively. In addition to influencing the human health, air pollution damages agriculture (Shindell et al., 2011; Burney and Ramanathan, 2014), ecosystems and environment (Lovett et al., 2009), and through different processes (for example, interaction with clouds (Jin et al., 2005) or attenuation of solar radiation (Jauregui and Luyando, 1999)), air pollution contributes to climate change (Knippertz et al., 2015).

As evidenced by Greenland ice core data, air pollution has a long history which dates back to the ancient times when the first human communities were developed (Jacobson, 2012), but it was particularly worsened during the Industrial Revolution or ‘the age of smoke’ which began in Britain in the 1700s. Air pollution was a major problem in the first industrial cities of the world until the mid-20th century when nearly 12,000 people were killed by the Great Smog in London (Bell and Davis, 2001). Since then, stringent national laws for controlling air pollution have cleared the skies over the most cities of the developed world. Nevertheless, air pollution has remained a large health threat in many industrial and urban areas of the developing countries (Health Effects Institute, 2010), with less visible emissions from car exhausts are added to the problem. Prominent examples of currently most polluted areas in the developing world are some Chinese cities, including urban areas of Xian and Zhengzhou (Chai et al., 2014; Wang et al., 2015; Zhao et al., 2016).

Although most cities in the developing world share the air pollution problem, yet every city is different in terms of climate and geographical features, as well as the main sources of air pollution. As a large city in the developing world, Tehran has been subject to substantial land-use and land-cover changes, as well as residential area expansion caused by rapid urbanization and population growth (Zanganeh Shahraki, 2007; Saadatabadi and Bidokhti, 2011; Alizadeh-Chooobari et al., 2016b). This has been associated with a significant increase in the number of motor vehicles, up to 10 times during a 50-yr period from 1956 to 2006 (Roshan et al., 2010). As a result, concentrations of suspended particles and gaseous pollutants in its atmosphere have been rapidly increasing during the last few decades (Azizi, 2011). Following the discussed urban growth, air pollution has become a significant threat for human health and ecosystems in Tehran.

Nowadays, exposure to high levels of ambient air pollution is a ubiquitous feature of urban life in Tehran. In recent years, each year severe air pollution episodes force closures of schools, the last one was three days in mid-December 2015. A great number of air pollution-related premature deaths each year have been also reported in Tehran. According to the Health Ministry, in 2012, air pollution contributed to the premature deaths of 4500 people in Tehran. A numerical investigation by Lelieveld et al. (2015) also indicated that Tehran is among the cities of the world with high mortality due to long-term exposure to fine particular matter (see Fig. 1 in Lelieveld et al., 2015). This underlines the urgent need for effective plans to improve the air quality of Tehran. In spite of the importance of the topic, spatial and temporal variations of particulate matter and gaseous pollutants in the urban area of Tehran have not yet been adequately studied.

The main aim of the present study is to present the analyses of the temporal variations of particulate matter concentrations from diurnal to inter-annual scales based on measurements at a monitoring site in North Tehran. Using air quality measurements taken in different regions of Tehran, spatial distributions of particulate matter and gaseous pollutants in the urban area of Tehran are also examined in December 2012, during which prolonged temperature inversions led to high levels of particulate and gaseous air pollution. Knowledge on particle concentrations on the diurnal, weekly, monthly and seasonal basis, as well as understanding the spatial
distributions of particles are essential to better manage protection of the public health, while inter-annual variations give an insight into changes in levels of air pollutants over the past years.

2. Data description

Concentrations of particulate matter and gaseous pollutants at Aghdasieh monitoring station in North Tehran (35.8° N, 51.5° E, 1548.2 m above the mean sea level) were obtained from the Air Quality Control Company affiliated with Tehran Municipality. The obtained data are hourly averages of the air pollutants measured every 10 min for the period 2004–2015. Streets nearby the station are often characterized by low traffic; thus the obtained data represent typical ambient air quality and climatic conditions in highlands of North Tehran, away from major pollution sources. In addition, monthly mean concentrations of particulate matter and gaseous pollutants in 16 different regions of Tehran (their locations are shown in Fig. 1) in midnight (0000 local time) and midday (1100 local time) in December 2012 were obtained. Concentrations of suspended particles in the atmosphere were measured by the decrease in Beta’s radiation absorption, while gaseous pollutants were measured using different methods: CO concentration by standard method of nondispersive infrared spectroscopy, SO2 concentration by UV fluorescent, Nitrogen oxidents concentrations by chemiluminescence phenomenon, and ozone concentration based on Beer-Lambert’s law (Mazaheri Tehrani et al., 2009).

To examine the stability of the atmosphere, atmospheric radiosondes data at a synoptic station in Tehran (located at 35.7° N, 51.3° E and 1190.8 m above mean sea level) in December 2012 were obtained and analyzed. During this month, Tehran was often influenced by subsidence or surface temperature inversions. As examples, the observed strong temperature inversions and low wind speeds near the surface in two different days in December 2012 are shown in Fig. 2. This implies that our analyses of the spatial distributions of air pollutants (presented in Section 5) represent typical winter time high levels of pollutants in the urban area of Tehran. Monthly mean precipitation and temperature records measured at Aghdasieh station for the period 1988–2014 have been also used, and the long-term averages of these data are presented in Table 1. In addition, three hourly wind speed and direction in several synoptic stations located in the urban area of Tehran were obtained for December 2012. To identify variations of the prevailing wind on a diurnal basis, monthly averages of these data at 0000 and 1200 local times were calculated.

3. Characteristics of Tehran

3.1. Geography and climate

Tehran metropolitan area is geographically bounded by the high Alborz Mountains on the north, and desert lands of the Kavir Plain on the south, while the urban area of Tehran is also hemmed in by the Alborz Mountains on the east (Fig. 3). The topographical features of the city greatly influence the directions of the wind during the course of the day, such that during the night, north-westerly to westerly winds from the mountains toward the plains are dominated (particularly in western half of the city), while during the daytime the prevailing winds are south-westerly, from the plains toward the mountains (Fig. 4).

Depending on the topographical features of the landscape, the climate of Tehran varies from north to south, such that there is a wetter and cooler climate on the hilly north side compared to the flat south part. Overall, Tehran has a semi-arid climate, with an annual precipitation of 422.2 mm in its north highlands (Table 1).
and 233.4 mm in its west central lowlands (Alizadeh-Choobari et al., 2016b). The annual mean air temperature in the highlands of North Tehran is 15.5°C (Table 1), nearly 2°C less than its west central lowlands with the annual mean air temperature of 17.4°C (Alizadeh-Choobari et al., 2016b). The observed low annual precipitation in the urban area of Tehran (327.8 mm averaged over the data obtained from two stations in North and West Central Tehran) is partly caused by the fact that it is surrounded from two sides by high mountains. Surrounding mountains are also responsible for the observed frequent low winds (see Fig. 2a) and poor ventilation conditions.

On the seasonal basis, the climate of Tehran is generally characterized by hot-dry summers, and cool (occasionally cold) semi-dry winters, such that most precipitation falls between November and April, while little precipitation falls during the warm months from June to September (Table 1). Summer (June-July-August) and winter (December-January-February) daily mean air temperatures in the highlands of North Tehran are 27.4°C and 3.5°C, respectively (obtained from monthly values in Table 1), again nearly 2°C less than the observed mean air temperatures in the West Central lowlands, with the observed values of 29.1 and 5.1°C in summer and winter, respectively (Alizadeh-Choobari et al., 2016b).

3.2. Demographics

Size of the urban area of Tehran has been dramatically increasing during the last half century, reaching from 100 km² in 1956 to approximately 800 km² in 2006 (Ghadami et al., 2013). The sprawl of the city has caused extermination of agricultural lands and green spaces around the city, as previously discussed by
Zanganeh Shahraki (2007). It has also contributed to a significant increase in the length and distance of urban travels, and extended the use of private cars (Pourahmad et al., 2007; Zanganeh Shahraki, 2007). Accordingly, population of the urban area of Tehran has been also rapidly increasing, reaching from approximately 1.5 million in 1956 to 8.2 million in 2011 (Asgarpour, 2013; Ghadami et al., 2013). Likewise, the number of motor vehicles in Tehran increased 18 times between 1958 and 2006 (Roshan et al., 2010), and as one of the most polluting transportation systems, the number of motorcycles increased from 520,000 in 1996 to 2 million in 2006 (Pourahmad et al., 2007). All of these changes have significantly contributed to the deterioration of the air quality of Tehran.

4. Contribution of different sources of air pollutants

Air pollutants in the urban area of Tehran are emitted from various sources, but they mostly originate from the combustion of gasoline and other hydrocarbon fuels in motor vehicles, and to a lesser extent from industrial and residential sources (Bayat et al., 2012; Abbaspour and Soltaninejad, 2004). Indeed, a previous study by Bayat et al. (2012) indicated that fuel combustion by motor vehicles is the major source of suspended particulate emissions in Tehran, approximately accounting for 90% of the total air pollution, while the remaining 10% was attributed to domestic, power plants and industrial sources. An investigation by Abbaspour and Soltaninejad (2004) also highlighted the significant contribution of motor vehicles in polluting the atmosphere of Tehran, although they estimated that motor vehicles only account for approximately 70% of air pollution, 20% less than that estimated by Bayat et al. (2012). A report by Shahrabazi et al. (2015) indicated that, in 2013, as much as 85.1% of air pollution in Tehran was caused by mobile sources, while the remaining 14.9% was attributed to stationary sources. These studies are all in agreement on the fact that motor vehicles are the major sources of air pollutants in Tehran.

It should be noted that some recent studies suggest that transport of dust particles from remote sources (Alizadeh-Choobari et al., 2014; Crosbie et al., 2014) and from disturbed lands of the nearby areas (Alizadeh-Choobari et al., 2016a) have also partly contributed to the high levels of particulate matter in Tehran. Indeed, using multiple datasets, Crosbie et al. (2014) indicated that during the late spring and summer months (May–August) when precipitation is extremely low over the region, Tehran is significantly influenced by dust aerosols, which contribute to the observed peak particulate matter concentrations in summer, as further discussed in Section 6.

5. Spatial distribution of particulate matter and gaseous pollutants

Monthly mean mass concentrations of PM$_{2.5}$ and PM$_{10}$ at 0000 and 1100 local times in December 2012 (a typical winter time high levels of air pollutants) at different monitoring stations of Tehran are depicted in Fig. 5. Compared to the national safety limits, both PM$_{2.5}$ and PM$_{10}$ concentrations were extremely high in most areas of Tehran, raising serious concerns about the health impacts of such heavily-polluted air. Values of PM$_{2.5}$ range from the lowest monthly mean concentration of 29.1 $\mu$g m$^{-3}$ at Masoudieh to 68.4 $\mu$g m$^{-3}$ at Shadabad at 0000 local time, and 26.4 $\mu$g m$^{-3}$ at Geophysics to 71.8 $\mu$g m$^{-3}$ at Shadabad at 1100 local time. The observed PM$_{10}$ values range from the lowest concentration of 63.4 $\mu$g m$^{-3}$ at Region 10 to 192.1 $\mu$g m$^{-3}$ at Shadabad at 0000 local time, and

Fig. 5. Mass concentrations of PM$_{2.5}$ ($\mu$g m$^{-3}$) and PM$_{10}$ ($\mu$g m$^{-3}$) over the urban area of Tehran averaged in December 2012 at 0000 and 1100 local times.
53.2 µg m⁻³ at Geophysics to 200.5 µg m⁻³ at Shadabad at 1100 local time. The values demonstrate rather large spatial variations of 45.4 µg m⁻³ (39.3 µg m⁻³) for PM₂.₅ and 147.3 µg m⁻³ (128.7 µg m⁻³) for PM₁₀ at 1100 (0000) local time, reflecting the strong connection of particulate matter concentrations to hot emission spots and vehicular traffics. Daily mean averages (at 0000 and 1100 local times) at all monitoring sites indicate high concentrations of 46.8 µg m⁻³ for PM₂.₅ and 96.1 µg m⁻³ for PM₁₀ in the urban area of Tehran in December 2012.

Examination of Fig. 5 indicates that concentrations of both PM₂.₅ and PM₁₀ were the highest in Southwest Tehran (at Shadabad). On the other hand, the lowest concentrations of PM₂.₅ were generally measured in Southeast Tehran (Masoudieh) at 0000 local time and Central North Tehran (Geophysics) at 1100 local time. The lowest PM₁₀ concentrations at both local times were recorded in Central North Tehran (Geophysics). Generally, in terms of mass concentration, South Tehran is more polluted than Central to North, while West Tehran is more polluted than the East. Southwest Tehran is the most polluted region, while Central North Tehran is the least polluted region. The highest observed concentration of particulate matter in Southwest Tehran is due to the fact that several sand and gravel mines are in operation in the nearby of this region. In addition, compared to the North Tehran, this region is more influenced by mineral dust emitted from the nearby disturbed lands.

Further analysis of Fig. 5 indicates that both PM₂.₅ and PM₁₀ concentrations in North Tehran were generally lower in the midday compared to the midnight, whereas the opposite was true in South Tehran. Higher particulate concentrations in the midnight than midday in North Tehran is due to the fact that at night stable shallow boundary layer and residual layer above that are decoupled from each other. As motor vehicle emissions continue until midnight in the urban area of Tehran, the existence of a stable shallow boundary layer at night implies that particles are trapped close to the surface, within comparatively smaller volume of air. Thus, concentrations of particulate matter increase from midday to midnight in North Tehran. The same argument can be applied in South Tehran, but the difference is that many agricultural/non-agricultural disturbed lands and desert lands of the Kavir Plain, as well as several sand and gravel mines are located near South Tehran. Sand and gravel mining is in operation during the day; accordingly in South Tehran higher levels of particulate matter are observed in the midday compared to the midnight. In addition, as during the daytime, lower layers of the atmosphere are generally more unstable and winds are stronger (see Fig. 4), entrainment of dust particles originated from the susceptible lands near South Tehran partly contributes to the higher levels of particulate matter during the daytime compared to the nighttime.

Monthly mean spatial distributions of some gaseous pollutants at 1100 local time in December 2012 are also shown in Fig. 6. Concentrations of carbon monoxide (CO) were the least in south and west corners of Tehran (1.1 ppm in Tehransar), but reached to higher values, particularly in Central Tehran (4.5 ppm in Poonak). Concentrations of sulfur dioxide (SO₂) reached to the highest value in South (57.1 ppm in Region 16) and the lowest value in Central (15.7 ppm in Sharif) Tehran. Concentrations of nitrogen dioxide (NO₂) were the highest in Central North Tehran, with the value of 111.4 ppm in Region 4, while its concentrations were lower in western and southern margins of the city. Two regions with high concentrations of nitrogen oxides (NOₓ) are clear in the figure, the primary peak was observed in Region 4 (316.8 ppm), and the

Fig. 6. Mass concentrations of gaseous pollutants of (a) carbon monoxide (ppm), (b) sulfur dioxide (ppb), (c) nitrogen dioxide (ppb) and (d) nitrogen oxides (ppb) over the urban area of Tehran averaged in December 2012 at 1100 local time.
secondary peak in Region 10 (305.9 ppm). In general, except for sulfur dioxide which shows higher concentrations in South Tehran (note that the most important sources of sulfur dioxide emissions are electric power generating plants), other gaseous pollutants, which are mostly emitted from vehicular traffics, were generally more concentrated in Central to North Tehran. This is in opposite to particulate matter pollutants (PM$_{2.5}$ and PM$_{10}$) which were more concentrated in Southwest Tehran, mainly because, as mentioned earlier, several sand and gravel mines nearby the Southwest Tehran contribute to the high levels of particulate matter concentrations.

6. Time series of particulate matter and gaseous pollutants

Inter-annual variations in PM$_{10}$ concentrations at Aghdasieh monitoring station in North Tehran for the period 2004–2015 are shown in Fig. 7a. During this period, the annual mean values range from approximately the minimum concentration of 64.5 $\mu$g m$^{-3}$ in 2004 to the maximum of 100.3 $\mu$g m$^{-3}$ in 2008. The observed minimum and maximum PM$_{10}$ concentrations are 3–5 times greater than the national annual mean safety limit of 20 $\mu$g m$^{-3}$. In spite of the fact that throughout this period, concentrations of particulate matter were much higher than the national safety limit, the trend indicates an improvement of the air quality over the last 4 years since 2012.

Annual mean mass concentration of PM$_{10}$ in North Tehran, averaged for the period 2004–2015, is 76.3 $\mu$g m$^{-3}$, nearly 4 times (281.5%) greater than the national annual mean safety limit of 20 $\mu$g m$^{-3}$. The observed annual mean concentration of PM$_{10}$ in North Tehran is also much higher than the concentrations recorded in cities of the developed world. For example, annual mean mass concentrations of PM$_{10}$ were found approximately 26.0 $\mu$g m$^{-3}$ in London (Harrison et al., 2001), 26.5 $\mu$g m$^{-3}$ in Vienna (Gomisicke et al., 2004) and 26.0 $\mu$g m$^{-3}$ averaged over 585 monitoring sites across the United States (Darlington et al., 1997). However, the observed annual mean concentration in Tehran is much less than that measured in most polluted urban areas of Xian and Zhengzhou in China (the fastest developing country), with annual mean PM$_{10}$ concentrations of 135.4 and 131.7 $\mu$g m$^{-3}$, respectively (Wang et al., 2015). Extremely high levels of particle pollution in some Chinese cities due to rapid urban growth and economic expansion were also recently highlighted by Chai et al. (2014) and Zhao et al. (2016).

Annual mean mass concentration of PM$_{2.5}$ in North Tehran averaged for the year 2011 also shows the high value of 37.5 $\mu$g m$^{-3}$, nearly 4 times greater than the national annual mean safety limit of 10 $\mu$g m$^{-3}$. The observed concentration is also nearly as much as twice the annual mean PM$_{2.5}$ concentrations of 17.7 and 18.6 $\mu$g m$^{-3}$ recorded in London (Harrison et al., 2001) and Vienna (Gomisicke et al., 2004), respectively. It is, however, much less than the annual mean values of 93.6 and 84.8 $\mu$g m$^{-3}$ recorded in urban areas of Xian and Zhengzhou of China, respectively (Wang et al., 2015).

Monthly variations and seasonality are evident in the mass concentrations of PM$_{10}$ (Table 1 and Fig. 7b). On the monthly basis, strong fluctuations of the concentrations of PM$_{10}$ can be observed, vary from the minimum value of 61.5 $\mu$g m$^{-3}$ in March to the maximum value of 86.4 $\mu$g m$^{-3}$ in July, i.e. 40.5% difference. On the seasonal basis, mean PM$_{10}$ concentrations are 77.6, 68.4, 83.9 and 75.4 $\mu$g m$^{-3}$ in winter (December–January–February), spring (March–April–May), summer (June–July–August) and autumn (September–October–November), respectively. The most and least polluted seasons in terms of mass concentrations of PM$_{10}$ are summer and spring, respectively. It is interesting to note that in spite of generally deeper boundary-layer heights and the lack or few occurrences of temperature inversions in summer which are not favor the accumulation of pollutants near the ground, the peak PM$_{10}$ concentration in this season is related to transports of dust particles from remote sources (Alizadeh-Choobari et al., 2014; Crosbie et al., 2014) and from disturbed lands of the nearby areas (Alizadeh-Choobari et al., 2016a). On the other hand, the minimum PM$_{10}$ concentration in spring is caused by the fact that warmer temperatures in spring create deeper boundary-layer heights compared to winter and autumn; thus some particles can be lifted to higher levels. In addition, unstable weather conditions, wet deposition of particles by relatively higher amounts of rain and reduced vehicular traffics due to nearly two weeks of the Persian New Year public holiday all contribute to the least concentrations of particulate matter in spring. Note that although precipitation in Tehran is the highest in winter (187.9 mm compared to 146.2 mm in
spring), winter-mean PM$_{10}$ concentration ranks the second highest value after summer. This is caused by more stable weather conditions in cold winter days during which the concentration levels could rise due to accumulation of particles in a relatively shallow boundary layer, as previously discussed by Sorooshian et al. (2011) over southern Arizona and Hersey et al. (2015) over the South African region. Domestic burning could also partly contribute to relatively high levels of PM$_{10}$ concentrations in winter.

Variations of PM$_{10}$ concentrations in different days of the week averaged for the year 2010 are shown in Table 2 and Fig. 7c. It should be clarified that Friday is the weekend in Tehran, while government organizations and some industries are also closed in Thursday. A weekly cycle in PM$_{10}$ concentrations is evident, with the peak concentration of 37.3 μg m$^{-3}$ on Thursday. A weekly cycle in PM$_{10}$ concentrations is evident, with the peak concentration of 37.3 μg m$^{-3}$ on Thursday. Higher levels of particulate matter concentrations in mid-week clearly demonstrate contribution of human activities, manifested in heavy vehicular traffic, industrial operation and increased commercial activities. This is in agreement with the results of Crosbie et al. (2014) who showed an improvement in the visibility of Tehran on weekends. There are some evidence that Friday is the weekend in Tehran, while government organizations and some industries are also closed in Thursday. A weekly cycle in PM$_{10}$ concentrations is evident, with the peak concentration of 37.3 μg m$^{-3}$ on Thursday.

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Table 2
The day of week PM$_{2.5}$ (μg m$^{-3}$, averaged for the period 2011–2015) and PM$_{10}$ (μg m$^{-3}$, averaged for the period 2004–2015) concentrations, and corresponding standard deviations (in parenthesis) at Aghdasieh air quality monitoring station in North Tehran.

<table>
<thead>
<tr>
<th>Particulate matter</th>
<th>Saturday</th>
<th>Sunday</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM$_{2.5}$ (μg m$^{-3}$)</td>
<td>32.9 (15.1)</td>
<td>34.6 (17.2)</td>
<td>35.6 (17.2)</td>
<td>36.3 (17.9)</td>
<td>37.3 (17.7)</td>
<td>36.8 (20.4)</td>
<td>34.0 (17.2)</td>
</tr>
<tr>
<td>PM$_{10}$ (μg m$^{-3}$)</td>
<td>72.5 (32.8)</td>
<td>78.6 (37.0)</td>
<td>79.8 (30.1)</td>
<td>79.5 (39.5)</td>
<td>77.3 (35.4)</td>
<td>76.4 (38.7)</td>
<td>71.9 (39.3)</td>
</tr>
</tbody>
</table>

Fig. 8. Temporal variations of PM$_{2.5}$ concentrations (μg m$^{-3}$) at Aghdasieh air quality monitoring station in North Tehran on (a) monthly (averaged for the period 2011–2015) and (b) diurnal basis (averaged for the year 2011).
time, then starts to increase and reaches to the highest value at 1300 local time when electricity demand is high especially in warm seasons due to air conditioner usage. Since then, the trend is decreasing, such that the concentration reaches to the second minimum at 1900 local time, after which an increasing trend is dominated due to electricity consumption for lighting, reaching to the second maximum at 0000 local time. Since then, a decreasing trend is observed until the minimum at 0600 local time (Fig. 9b).

As low-level ozone is formed as a result of the photodissociation of nitrogen oxide in the presence of ultraviolet light of the sun, its concentration follows a unimodal distribution, starts to rapidly increase after sunrise, reaches to the peak in the afternoon at 1600 local time, and then starts to rapidly decrease as a result of the deposition to the earth surface and chemical destruction by nitrogen monoxide (Fig. 9d). It should be noted that previous studies indicate that part of the increase in the low-level ozone following the sunrise is attributed to the entrainment of the residual layer ozone into the daytime convective boundary layer (Millán et al., 2000; Salmond and McKendry, 2005).

7. Conclusions

Being hemmed in on two sides by high mountains which contributes to low near-surface winds, combined by traffic-related and industrialized air pollutants all year long, as well as frequent temperature inversions in winter, and high entrainment and subsequent transport of dust particles from remote areas and nearby disturbed lands in summer, all make the urban area of Tehran a perfect place for pollution and particles to linger and accumulate. Some actions have been taken over the past years for controlling the air pollution of Tehran, including some improvements in public transportation, increasing green spaces of the city, converting many diesel buses to compressed natural gas buses, implementation of vehicle inspection rules, and expansion of the subway and bus fleet. Nevertheless, as evidenced by the results of the present study, these actions have not been sufficient to meet (or even reach close to) the national ambient air quality standards, such that current concentrations of both coarse and fine particulate matter are much higher than the national safety standards. The results of the current study are summarized in the following.

Spatial distribution of particulate matter and gaseous pollutants in the urban area of Tehran is analyzed using air quality measurements taken at different air quality monitoring sites in December 2012, representing a typical winter time high levels of air pollutants. In general, our results indicate that in terms of mass concentration of air pollutants, South Tehran is more polluted than Central to North Tehran, while West Tehran is more polluted than the East; while in terms of gaseous air pollutants mostly emitted from motor vehicles, Central to North Tehran is generally more polluted.

In addition, temporal variations in the concentrations of particulate matter from diurnal to inter-annual scales and diurnal variations of some gaseous pollutants have been analyzed using measurements taken at an air quality monitoring station in North Tehran. Our results highlight high annual mean concentrations of PM_{2.5} and PM_{10}, nearly 4 times greater than the annual mean safety limits established by the World Health Organization (WHO). In addition, strong temporal variations in concentrations of particulate matter from diurnal to seasonal scales have been identified, reflecting contribution of weather conditions for monthly and seasonal variations, and contribution of human activities for the day of week variations. Both human activities and atmospheric conditions, however, have contributed to the diurnal variations in the concentrations of particulate matter.

In winter, air pollution of Tehran is almost exclusively anthropogenic, mostly from traffic emissions, and to a lesser extent from industrial and residential sources (Abbaspour and Soltaninejad, 2004; Bayat et al., 2012; Shahbazi et al., 2015). During winter, meteorological conditions favor the accumulation of air pollutants near the ground because frequent influence of subsidence or strong temperature inversions near the surface, combined by light winds limit vertical and horizontal dispersion of air pollutants. In addition, as Tehran is situated in a mountain valley, its geographical features further restrict ventilation and dispersion of air pollutants. In summer, on the other hand, the atmospheric conditions are not favor for accumulation of particles near the ground surface.

![Fig. 9. Diurnal variations of gaseous pollutants of (a) carbon monoxide (ppm), (b) sulfur dioxide (ppb), (c) nitrogen dioxide (ppb) and (d) low-level ozone (ppm) at Aghdasieh air quality monitoring station in North Tehran averaged for the year 2010.](image-url)
However, due to the extreme dryness of the region, Tehran is often influenced by both transported dust from remote sources and nearby disturbed lands, causing concentration of particulate matter to reach to the highest level in summer compared to other seasons. Therefore, the first and secondary peaks of particulate matter concentrations in summer and winter, which have been identified in the present study, are related to high frequent number of dust events in summer and frequent temperature inversions in winter. On the other hand, unstable weather conditions, relatively high amount of precipitation and reduced vehicular traffics due to the Persian New Year holiday (which lasts nearly 2 weeks) make spring (March) the cleanest season (month) of the year.

On the daily basis, higher levels of particulate matter concentrations in the mid-week compared to the weekend have been observed, reflecting contribution of heavy vehicular traffics, industrial operation and increased commercial activities. On the diurnal basis, particulate matter concentration in North Tehran is higher at night compared to the day, while the opposite is true in South Tehran. The difference has been attributed to the accumulation of particles in a stable shallow boundary layer in North Tehran at night, and the fact that several sand and gravel mines near South Tehran are in operation mostly during daytime.

Overall, the results of the present study suggest that with rapid urban sprawl, population growth, the increase of motor vehicles and subsequent intensification of traffic, and the development of industry including sand and gravel mines, as well as due to limited access to clean fuels and lack of effective control programs, Tehran, which is located in a mountain valley, has now become one of the largest and polluted cities in the world.

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