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PM dispersion during stable winter episodes in tehran and effect of governmental emission regulations

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ABSTRACT

Tehran is one of the most polluted cities in Middle East which during winter extremely high levels of particulate matter (PM) occurs due to frequent stable weather episodes. This study aims to identify major sources of PM and quantify effectiveness of possible control measures and strategies during these episodes. The Brute Force Method (BFM) with Community Multiscale Air Quality model (CMAQ) was implemented to estimate the contributions from major local anthropogenic sources on PM levels. In this regard several scenarios including the effect of existing governmental policies and regulations to upgrade vehicles emission standards were investigated. Emission due to the existing condition and future scenarios were estimated and effect of them on concentrations were modeled. Major local contributors were found to be transportation, energy and residential sources with the contributions of 64%, 15%, and 11%, respectively. The major governmental regulation to upgrade vehicles standard could led up to average of 35% PM concentration reduction during these stable weather episode. It is estimated that a set of scenarios could result in a goal of about 10% reduction in overall pollutant emissions, including both primary PM and precursor pollutants such as sulfate, nitrate and ammonium species. Our results show primary pollutants reduction led to average 8.4% reduction in aerosol levels, whereas precursor gaseous reduction could led to less than 1% PM concentration reduction. The results emphasize the need for control strategies focusing on primary particulate emission and transportation source.

1. Introduction

Tehran frequently faces critically high pollutant levels episodes during the past years (Arhami et al., 2014; Ghotbi et al., 2016) with exceptionally high concentrations of particulate matter in winter due to stable weather condition and inversion (Ganguly et al., 2019; Givehchi et al., 2013). The annual average $PM_{2.5}$ concentration was about four times higher than the National Air Quality Standard (which is 12 μg/m^3) during recent years. Severe air pollution episodes in Tehran attributed to different factors including ineffective public transport system, vehicular traffic, low vehicle standards, low fuel standard, local Industrial activities, mountain chains surrounding the city and etc. (Arhami et al., 2014, 2013; Ganguly et al., 2019; Nayeb Yazdi et al., 2015; Shahbazi et al., 2016). To tackle this issue, the government usually attempts temporary urgent control strategies such as school and governmental sector closure, shutdowns of construction works, and traffic limitation. These are mainly temporary strategies which have high economic costs. Due to the air pollution crisis, laws and regulations were also adopted and gradually implemented that limit different sectors' emissions. Thus, to prioritize the emission control targets and determine the long-time sustainable strategies, it is essential to identify the relative contribution of local emissions.

Several computational models have been developed to simulate air pollution dispersion in urban areas. Gaussian dispersion models have been used in numerous local-scale studies (Afzali et al., 2017; Ganguly et al., 2009; Ganguly and Broderick, 2008; Kesarkar et al., 2007). Their simplicity and fast response time, make them a proper tool for long-term statistical simulations, health risk investigations, and immediate first-guess information in case of an accidental release (Ganguly et al., 2009; Ganguly and Broderick, 2008; Holmes and Morawska, 2006; Leelőssy et al., 2014). Gaussian models provide poor results in low wind speeds situations, which often occurred at a stable atmosphere or low-level inversions (Ganguly et al., 2009; Holmes and Morawska, 2006; Leelőssy et al., 2014). In general, these models apply to primarily emitted pollutants at simple terrain. Although US Environmental Protection Agency (EPA) Regulatory Model (AERMOD) includes modules to handle complex terrain and urban boundary layer, it still uses steady-state approximation and homogenous wind field. One way to overcome

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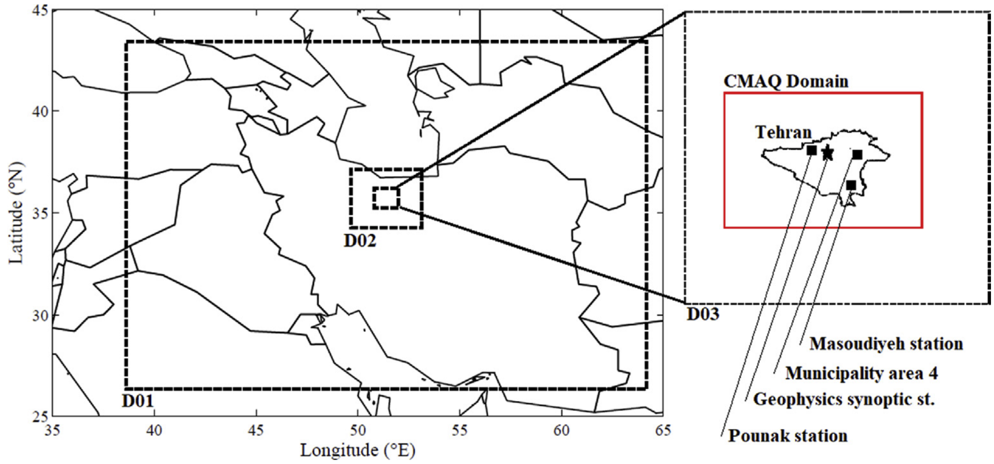


Fig. 1. Metrological modeling domains.

some of these limitations is to couple a Gaussian dispersion model with mesoscale models. Coupled models may consider larger-scale influences (i.e. local wind field, background concentrations, and urban photochemistry condition) in Gaussian model (Beevers et al., 2012; Lai et al., 2019; Pepe et al., 2016; Stein et al., 2007).

Eulerian grid-based models like CMAQ also were used to a wide range of studies from global to urban. They take into account transport, turbulence, and expanded chemical and physical processes of gaseous pollutants and particulate matter (PM). Due to their spatial resolution, they cannot correctly estimate concentrations very near the source (Stein et al., 2007). These models have widely been used as a source-oriented method for apportioning and identify the effect of sources of particulate pollutants (Burr and Zhang, 2011; Guo et al., 2017; Hu et al., 2015; Huang et al., 2018; Pun et al., 2008; Wei et al., 2014; Zhang et al., 2014). The simplest source apportionment method using air quality modeling is the brute force method (BFM). Depending on the objective of study, the BFM can be applied with varying degrees of emission perturbations, e.g., source eliminated (Burr and Zhang, 2011; Huang et al., 2018; Wang et al., 2015, 2012) or reduced (Im et al., 2010). The elimination of the source category can provide information on the effect of entire source on the air pollution. This method assumes that the contributions of emission categories are additive and ignores the highly non–linear relationships between precursor emission of other sources on secondary PM components (Burr and Zhang, 2011). Small perturbations are considered representative of potential emission changes based on public policy decisions. Due to complexity of atmospheric processes, the response of PM concentrations and its components to changes in precursor emission (e.g., PM_{10}, SO^2, NOx, and VOCs) is nonlinear and may also be antagonistic (Burr and Zhang, 2011; Pun et al., 2008). PM precursor's emission change also may affect the other components that result from interactions between secondary PM species and their gaseous precursors. The BFM capture these indirect effects for the perturbation at hand (Burr and Zhang, 2011). Despite the importance of this issue limited studies on identifying source and modeling disperse of PM during highly polluted episodes have been conducted.

The aim of this study is to examine the PM dispersion and investigate the characteristics and sources of PM pollution during severe air pollution conditions over Tehran. The Weather Research and Forecasting (WRF) and the Models-3/Community Multiscale Air Quality (CMAQ) modeling system was employed for a severely polluted winter period from Feb. 6 to Feb. 10, 2010. To do this, an anthropogenic emissions inventory was developed based on local activity and traffic data that included transportation, industry, residential, waste disposal, and energy emission categories. Finally, the study also assessed the effect of Clean Air Laws and governmental emission regulations for different emission sectors. The laws focus on emission from combination of different sources. These include incentives and binding regulations have also introduced that target the mobile as well as residential, commercial and industrial sectors. These regulations set emission limits for combination of different mobile and stationary emission sectors, such as advising industries to use gas and carry out annual technical audits. Some regulations have also set for refining fuel and improve gas station equipment's, which can be effective in individual reducing of precursor pollutants such as sulfur and VOC. These regulations are set to achieve a goal of around 10% reduction on total emissions during the first phase. So, in this analysis, the impact of individual and combined changes of PM, VOC_s, SO_2, NO_x, and NH_3 emissions on the concentration of particles PM_{10}, PSO_4, PNO_3, and PNH_4 were assessed. Due to emissions interaction of SO_2, NO_x, and NH_3; PSO4, PNO_3, and PNH_4 species also evaluated.

2. Material and methods

2.1. Model configurations

In this study, the WRF/SMOKE/CMAQ modeling system was applied to model PM in Tehran. CMAQ, version 5.0, was used for this modeling. Meteorology condition and emission values as CMAQ input were obtained using WRF-ARW, version 3.4, and SMOKE, version 3.1.

A severe air pollution episode in winter from Feb. 6 to Feb. 10, 2010, was investigated. In this period weather condition was calm and based on the Air Quality Index (AQI) was unhealthy for sensitive group. 3 one-way concentric nested domains were used, as presented in Fig. 1. Outer domain was developed over Iran with 144 by 108 grid cells on 18 Km resolution. The middle domain and inner domain respectively had grid resolution of 6 Km (grid size: 54 × 54) and 2 Km (grid size: 54 × 54). The inner domain covered Tehran and its adjusted area and had longitude range of 51–51.77 (E) and latitude of 35.5–35.95 (N). The vertical resolution was 27 layers from the surface up to 500 hPa whit lowest layer at approximately 50 m above ground level.

FNL data obtained from the National Center of Environmental Prediction (NCEP) provide initial and boundary conditions for WRF simulations. The accuracy of these data is 1° and collected every 6 h. WRF model is a fully compressible and nonhydrostatic model that using sigma coordinate and has various models to represent physical process of atmosphere (National Center for Atmospheric Research, 2014). In this study, shortwave and longwave radiative processes, respectively, were represented by Dudhia scheme (Dudhia, 1989) and Rapid Radiative Transfer Model (RRTM scheme) (Mlawer et al., 1997). Planetary boundary layer processes were represented with Yonsei University scheme (YSU scheme) (Hong et al., 2006). MM5 similarity surface layer scheme (Zhang and Anthes, 1982), and Noah Land Surface Model (Hong et al., 2006) were also used in WRF simulations.

Pre-gridded emission data were processed using SMOKE. It allocated the emissions from different sources to model grid and converted annual emissions to hourly emission data using the source-specific temporal profiles (The institute for the Environment - The University of North Carolina, 2013). Further, it transformed inventory emission species into model emission species based on air quality model chemical mechanism. In this research, anthropogenic resources were used. Emission data were divided into five resources, including transportation, industrial, residential, waste disposal and energy (power plants) that most of these groups were also used as major anthropogenic PM sources in other studies (Im et al., 2010; Li et al., 2015; Wang et al., 2014). Transportation emission is the dominant emission source that Other studies have also indicated it as largest emission source in Tehran (Arhami et al., 2017; Shahbazi et al., 2016; Torkian et al., 2012). Industrial sources is also one of the main stationary emission sources (Arhami et al., 2017). (Farahani and Arhami, 2020) used these five categories as local emission to study dust event at Tehran and their modeling result was fairly well. So, it seems these five emission resources contributing the most of anthropogenic emissions in Tehran. The process of computing annual emission and time allocation of emission sources are described in section 2.2.

Emission data and processed meteorology data were prepared as input for the CMAQ model. The Statewide Air Pollution Research Center-99 (SAPRC-99) gas-phase mechanisms were used to predict PM concentration. To diminish meteorological boundary condition effect, the air pollution modeling domain was designed to be at least 16 Km smaller than that of WRF on each boundary. Initial (IC) and boundary condition (BC) of chemical species were considered as default CMAQ profiles. The profile boundary concentration values are representative of relatively clean air and roughly affect concentration levels in the city. Several spin up periods up to 7 days were used to simulate air pollution levels in Tehran. The results of different spin up were rather similar, and the influence of IC was negligible after 24hr, which demonstrated that the local emissions dominate the effect of IC. The results of chemistry and pollutants transportation modeling were compared with observation Air Quality Control Company stations. The geographic location of these stations are shown in Fig. 1. It's worth mentioning, due to not registering $PM_{2.5}$ concentration, modeling results were just compared with observed PM_{10} values.

To assess modeling performance the statistical parameters including the mean, the normalized root mean square error (NRMSE), Pearson's correlation coefficient (R) and the index of agreement (IOA) were used. The R reflect linear association between predictions and observation and the NRMSE is a fundamental statistical parameter that reflects biases in model predicted values (Wilks, 1995). The IOA is a measure of how well the model predictions agree with the observation, with closer value to 1 implying better modeling performance (Ganguly et al., 2009). These statistical parameters have shown to be suitable metrics in assessing performance of air pollutant models (Pepe et al., 2016; Yao et al., 2016; Zhang et al., 2006).

2.2. Emission estimation

Emission data for VOCs, PM10, SO2, NOx, and NH3 were obtained using SMOKE. The transportation emission was calculated via GIS-based traffic data provided by Tehran Comprehensive Transportation and Traffic Studies Company (TCTTS). The TCTTS Company calculated the traffic volume and average speed in seven vehicle categories, including heavy truck, light duty truck (LDT), bus, minibus, taxi, light duty vehicle (LDV), and motorcycles in 9900 road links. To compute transportation emission from raw traffic data, air pollutant emission coefficient extracted from exhaust emission factors for road vehicles by Boulter in TRL group, report three; and links pollutant emissions were calculated using the following equation. Since the TCTTS data provides traffic activity data on the morning rush hour (7:30–8:30 AM), the emission inventory temporal resolution is 1hr; therefore, average daily transportation emission calculated by multiplying rush hour emissions by 10.

$$EF\,[g/km\,] = k * (a + b.\,x + c.\,x^2 + d.\,x^3 + e.\,x^4 + f.\,x^5 + g.\,x^6)/x \tag{1}$$

where EF is the emission rate in g km^{-1}, a to g and x are coefficients. These coefficients are different for various vehicles, emission standards, and pollutants. The emission standards define the acceptable limits for exhaust emissions of vehicle categories. In this study, European emission standard of year 2010 in Tehran was considered as Pre-Euro1 and coefficients for various vehicle types were adopted from Boulter study (Boulter et al., 2009).

For Other sources, due to lack of comprehensive data bank, the release of the GEIA (ECCAD) database was used. VOC_s, SO_2, NO_x, and NH_3 annual emissions are derived from emission estimates of MACCity, and PM_{10} is derived from (ECLIPSE_GAINS-4) database that operated by IIASA (International Institute for Applied Systems Analysis) in Austria. These data have a resolution of 0.5°.

2.3. Emission regulation scenarios

Due to the frequent occurrence of severe air pollution episodes in winter, it is essential to investigate the average contributions of emission source and their probable temporal variation. So Brute force sensitivity simulation was used to evaluate source contribution of each emission sector. In this method, by running multiple simulations and zeroing out the emissions from each source, emission sources contribution in PM_{10} concentration were calculated.

Effect of existing plausible policies to reduce pollutant emission were quantified. These policies focus on major urban pollutant sources such as vehicles, energy and residential emissions. Based on existing vehicle emission regulations and policies, by the year 2012, the minimum standard of EuroIV is set for LDV, and heavy trucks, LDT, and motorcycles should meet EuroIII emission standard. Current emission standards of vehicles of the year 2010 in Tehran considered as Pre-Euro. Considering the high share of transportation emission in the air pollution of Tehran, the hypothesis of laws and right decisions about this source can be one of the best solutions to reduce the concentration of pollutants. To determine the amount of emissions in this scenario, equation-1 was used for the new vehicle types (EuroIV and EuroIII). In this scenario, NOx emission of transportation resource was reduced by 58.5% and reaches 44,396 ton/year. PM_{10} and VOC emissions also, respectively, reduced 84.5% and 99.3% and reached 4152 ton/year and 6384 ton/year.

In this study, the impact of Clean Air Laws also was investigated. The laws focus on emission from combination of different sources. These include incentives and binding regulations have also introduced that target the mobile as well as residential, commercial and industrial sectors. These regulations set emission limits for combination of different mobile and stationary emission sectors, such as advising industries to use gas and carry out annual technical audits. Some regulations have also set for refining fuel and improve gas station equipment's, which can be effective in individual reducing of precursor pollutants such as sulfur and VOC. These regulations are set to achieve a goal of around 10% reduction on total emissions during the first phase. So, in this analysis, the impact of individual and combined changes of PM, VOC_s, SO_2, NO_x, and NH_3 emissions on the concentration of particles PM_{10}, PSO_4, PNO_3, and PNH_4 were assessed. Due to emissions interaction of SO_2, NO_x, and NH_3; PSO4, PNO_3, and PNH_4 species also evaluated.

2.4. Sources of uncertainty

Air quality modeling is influenced by the uncertainty of meteorological modeling and emissions inventories. The emission Inventory has a great impact on modeled air quality. Emissions estimates usually calculated based on annual activity rates. However, air quality models operate on hourly temporal scales to simulate complex chemical reaction. As mentioned earlier, Due to lack of a comprehensive emission inventory for Tehran, annual emission for energy, residential, industry and waste disposal are extracted from GEIA and MACCity databases. Due to the low efficiency of industries and different working pattern and meme in Iran, this estimation may not coincide with reality. More ever, these resources are distributed approximately, so the spatial distribution is not accurate and consistent with reality. Temporal allocation profiles that are used in current study are the best estimates, but improvements in temporal allocation may improve the air quality model results. All of these variabilities and uncertainty suggest that sensitivity analysis should be done to understand the effect of emissions input on predicted concentration.

Meteorological uncertainty also has a significant impact on estimated air quality. Differences in temperature, moisture and wind can have an effect on boundary layer stability, clouds fraction and radiation, that all would impact mixing and photochemistry in the air quality model. Underestimation of temperature indicates that boundary layer may also be underestimated. It would restrict the diffusion and mixing in boundary layer and cause more accumulation of particles near surface. The wind speed and direction also would affect and alter the transport of pollutants; for example, if the wind speed is higher than real, it would wash out pollutant from city. In third day of the modeling, wind speeds were lower than the observation. So the pollutants transfer were reduced, and more accumulation of pollutants occurred.

3. Results and discussion

3.1. Metrological modeling

The temperature and wind speed have a large influence on air quality. To evaluate the performance of meteorological modeling, the time series of observed and modeled near-surface temperature in Geophysics synoptic station are compared in Fig. 2. The modeled 2 m-temperature results for c had correlation coefficient 94% and index of accordance 86% with the observed values. Although the simulated temperature was lower than observed, the diurnal temperature cycle was simulated fairly well (high R-value). Similar cold bias (up to -3 °C) are reported by (Fathalli et al., 2016) that used WRF-ARW to downscale temperature over Tunisia. The errors could be related to physical processes modeling such as surface radiation, PBL physics, and short/longwave radiations that have a large impact on temperatures. Underestimation of the absorbed solar radiation or the upward surface sensible heat flux would also led to the underestimation of temperature. Further studies are required to evaluate the impact of physical options and study the origin of the WRF errors.

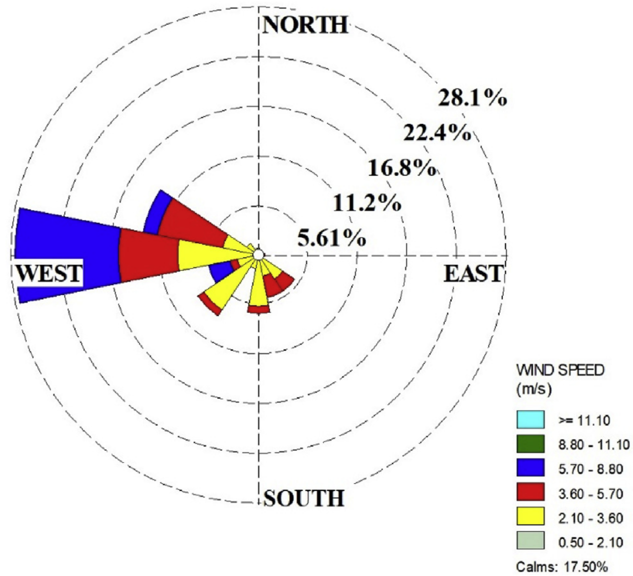


Fig. 3. Wind rose of observed wind at Mehrabad synoptic station.

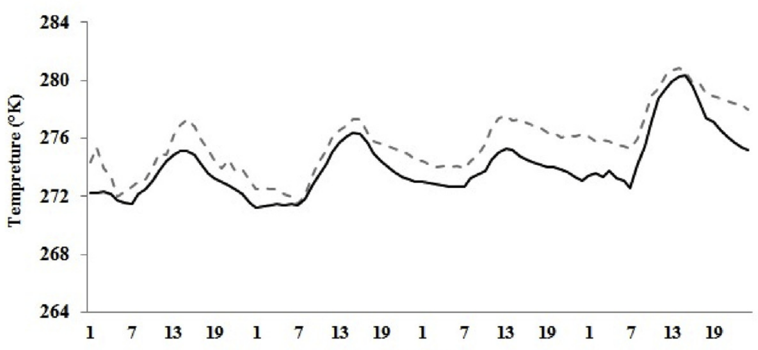
Other meteorological parameters like the modeled wind had lower correlation with observed values. This could be related to random characteristic of the wind that makes it considerably difficult to forecast. During the studied period, the observed wind speeds of Geophysics synoptic station were below 1 (m/s). Similar behavior of the WRF model during winter period and overestimation of low wind speeds was also recorded in other studies (Carvalho et al., 2014a, 2014b). Due to the colder surface temperatures and stable atmospheric conditions, non-local PBL scheme that used in this study can have bad performance.

The wind rose in Mehrabad station during the simulation period are presented in Fig. 3. The modeling results showed the West direction as the prevailing wind that is consistent with measurement and prevailing wind at Tehran.

3.2. Emission inventory

Emissions from residential gas consumption, waste disposal, and energy production were calculated and distributed in the city. Emissions from industrial resource were also calculated and distributed in southern, western and eastern suburbs of Tehran, where industrial areas are mainly located. Transportation resource was distributed via geographical locations of road's link. PM_{10} emission from transportation source is presented in Fig. 4. As shown in the figure, emissions in central part of the city were higher as more congested roadways are located.

Time allocation diagram of the residential resource is presented in



Observed avg.	275.7
Modeled avg.	274.1
Correlation coefficient	0.94
NRSME	0.18
Index of Accordance	0.86

Fig. 2. Time series of observed and WRF-Simulation 2 m temperature at Geophysics synoptic station.

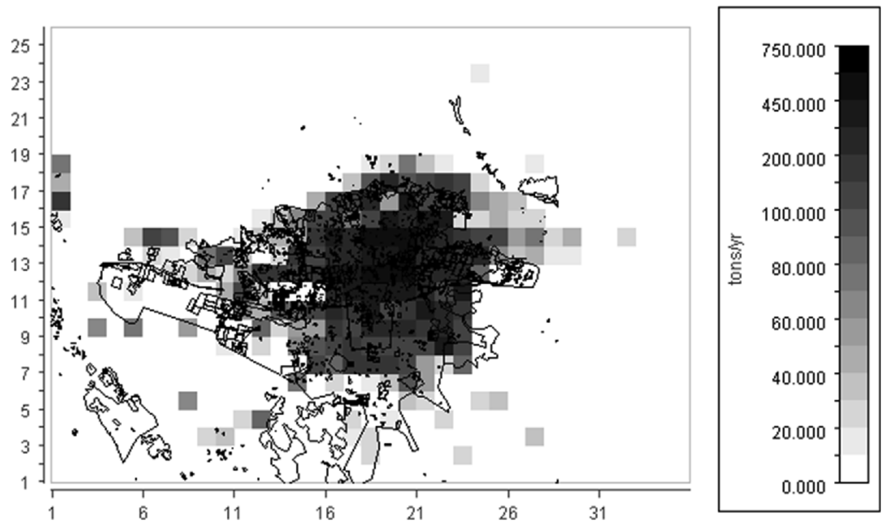


Fig. 4. Spatial distribution of PM10 emissions from transportation sources.

Fig. 5-b. Residential source classification codes were derived from natural gas consumption of households and small commercial sector provided by the National Gas Company. Residential emission increases from October, and it reaches to maximum in December. This increasement is due to cold weather and more gas consumption for heating houses. In April, as the weather gets warmer, residential emissions decreases. Due to closure of government offices, night emission is lower than daytime and lower emission, also, occurred on Thursday and Friday.

3.3. Chemistry and transport model results

3.3.1. Modeling performance evaluation

The modeled and observed PM_{10} levels at 3 stations, Masoudiyeh, Pounak, and Municipality area4 are presented in Fig. 6. The modeled results follows rather similar trend of recorded hourly PM_{10} concentration at all stations. The averaged modeled PM_{10} levels were in the range of the observations with slightly overestimate, Model Avg./obs. Avg. are 1.03, 1.25, and 1.19 for Masoudiyeh, Pounak, and Municipality area4, respectively. Also, in general, the peaks of modeled are higher than the measured values. This overestimation can be attributed to different uncertainty sources which will be later discussed.

The best modeling performance statistics were obtained for the Masoudiyeh station. The modeled results for Masoudiyeh station had a correlation coefficient of 79% and index of agreement 72% with the observed values, which indicates an acceptable accuracy in reconstruction of observed concentration. In Pounak station and Municipality area 4, the correlation coefficients were 56% and 57%, and index of agreement were about 52% and 57%. The results are generally consistent with results from previous studies such as (Im et al., 2010) that reported average IOA value of 0.42 for PM_{10} simulation during a winter episode (Yang et al., 2019). also reported R values of 0.50–0.70 and normalized mean square error of 0.47–1.03 for PM10 simulation for four winters in different years over the Xi'an in China.

The model performed rather well in the first 3 days of modeling span since the modeled results could follow the concentration trend. However, after the 3rd day, the modeled concentrations suddenly

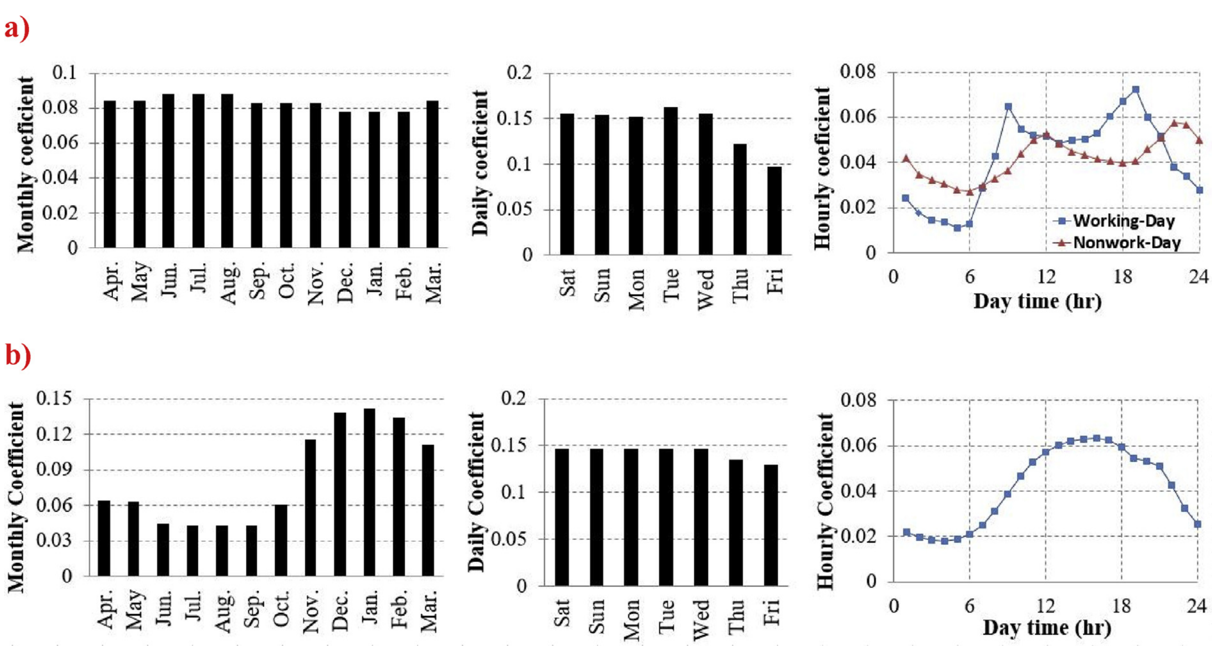
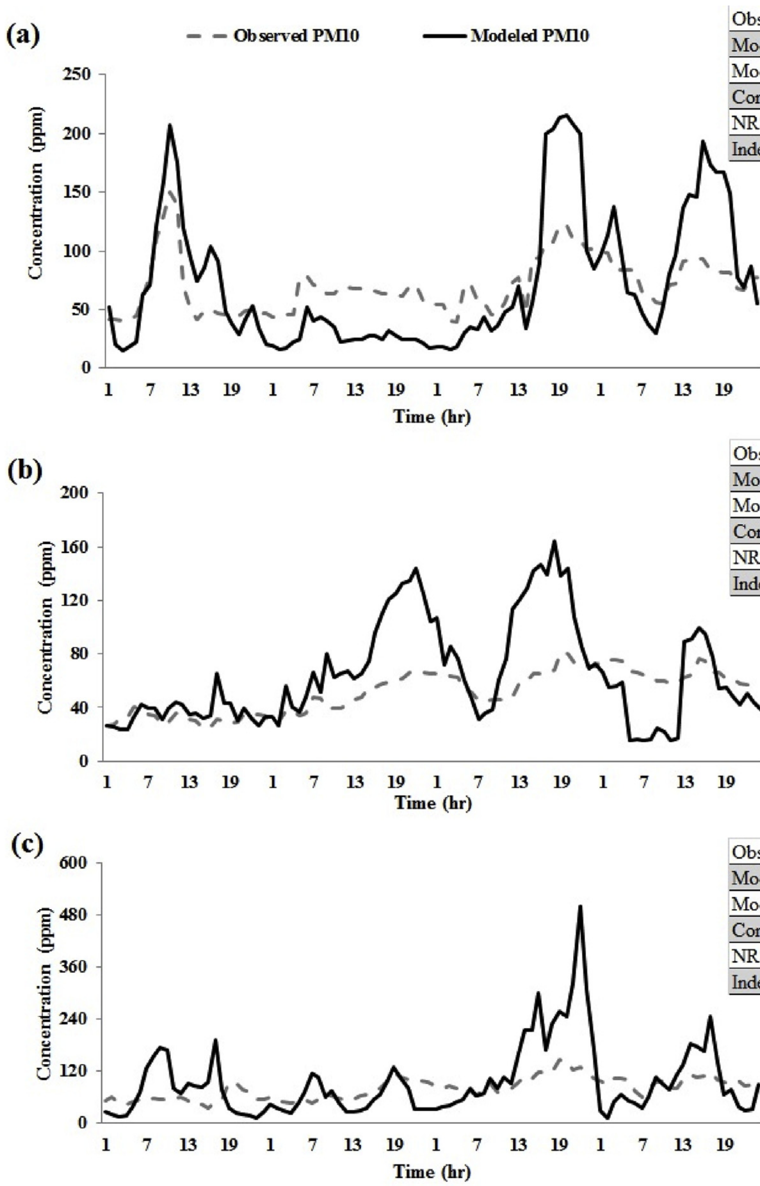


Fig. 5. Monthly, Daily and hourly time allocation of a) Transportation emission source and b) residential emission source.



(a)	
Observed avg.	70.79
Modeled avg.	72.5
Modeled avg./ Obs. avg.	1.03
Correlation Coefficient	0.79
NRSME	0.38
Index of accordance	0.72

(b)	
Observed avg.	51.71
Modeled avg.	64.85
Modeled avg./ Obs. avg.	1.25
Correlation Coefficient	0.56
NRSME	0.62
Index of accordance	0.57

(c)	
Observed avg.	80.46
Modeled avg.	95.42
Modeled avg./ Obs. avg.	1.19
Correlation Coefficient	0.57
NRSME	0.65
Index of accordance	0.52

Fig. 6. Comparison of CMAQ result and observation of PM10 Concentration for a) Masoudiyeh station, b) Pounak station, c) Municipality area4 stations.

increased. Tehran maximum concentration in third day of modeling period was obtained at 10:00PM in the downtown area. But maximum emission occurred during rush hour at about 7:00PM. For further investigating the lag time between emission and concentration peaks, the metrological condition of peak area was investigated. Wind speed, cloud fraction, planetary boundary layer and vertical profile of temperature for cell with maximum concentration are presented in Fig. 6. This cell is located in down town area of Tehran, which has heavy traffic. In third day the average wind speed was 0.4 m/s, so based on Beaufort scale, weather condition was calm. In such condition, wind could not disperse pollutants from city area effectively. Also night-time cloud fraction was 0.47, and maximum and minimum planetary boundary layer height during this day respectively were 213 m and 26 m. This indicated that based on Pasquill-Gifford stability classes, in 9th February, weather of Tehran was stable (in stability class of "F"). Considering changes of temperature in height (Fig. 7-d), in this day a temperature inversion also had occurred. During inversion air could not rise, so pollutants were trapped and accumulated near the surface.

3.3.2. Spatial and temporal distribution

Distribution of PM_{10} concentration at a normal hour and peak concentration hour of Feb. 7th are shown in Fig. 8. Maximum concentrations were, generally, located in the downtown area of Tehran with heavy traffic. This indicates that traffic condition and consequently, transportation resource has a great impact on particle's concentration. The western and southern part of city also had higher concentration level than other parts of city, which could be related to industrial emission source. It is worth noting that the wind also plays an effective role in pollutants dispersion and PM_{10} concentration. For example, in Feb 7th, 6:00PM, the wind blew from north, and it transferred pollutant to southern part of city. The wind washed out pollutant from city and led to reduction of concentration during the night. At 12:00AM the wind speed was rather low, and pollutant concentration had a pattern similar to emission distribution on city.

The maximum hourly concentration often occurred at about 6:00PM, corresponding to evening traffic jam; but the temporal pattern of PM_{10} concentration and emission were different in Feb. 9th. In Fig. 9, process of concentration and emission change in Feb. 9th for 5:00PM, 7:00PM, and 10:00PM is shown. The peak hour of emission occurred

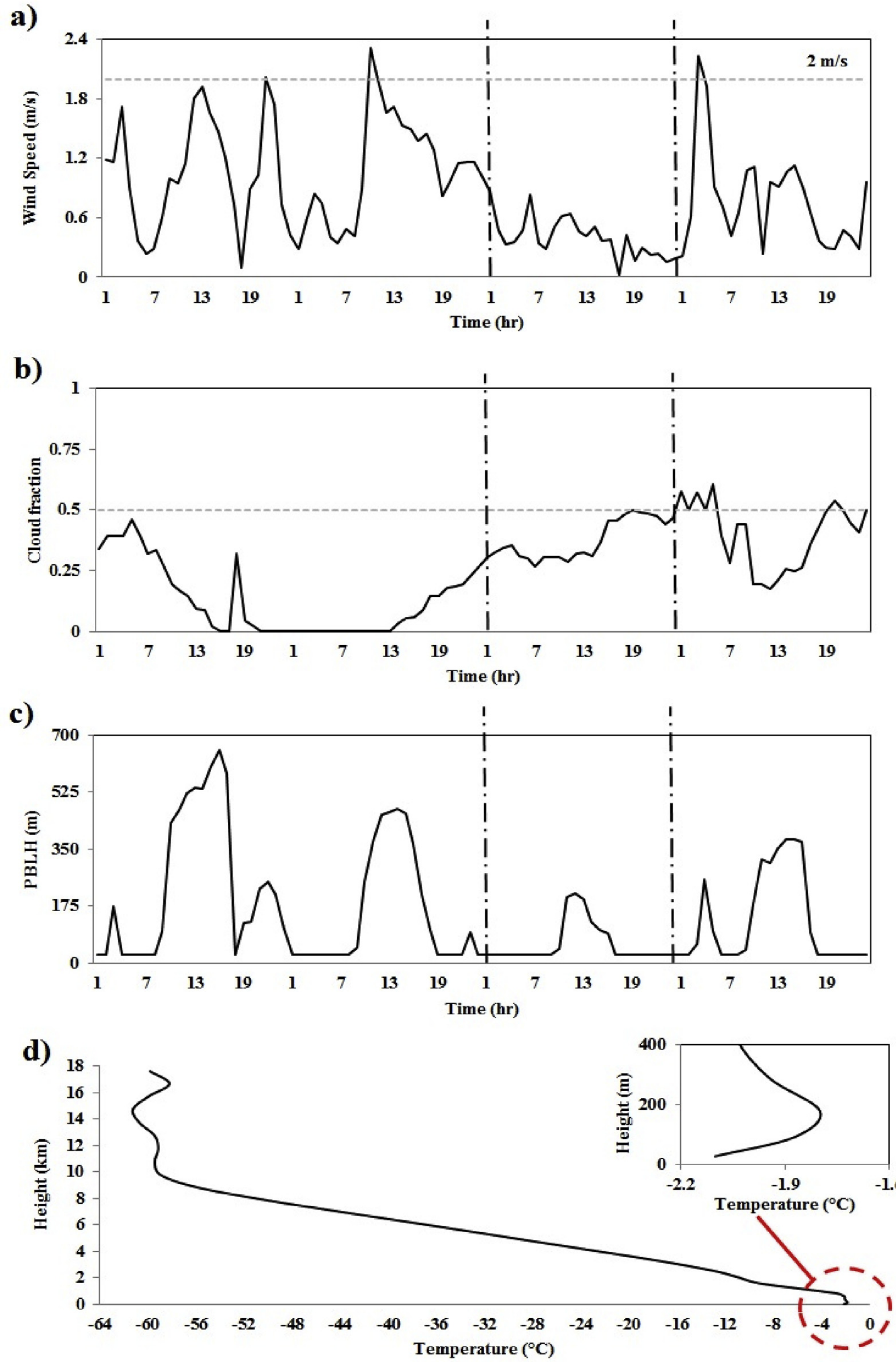
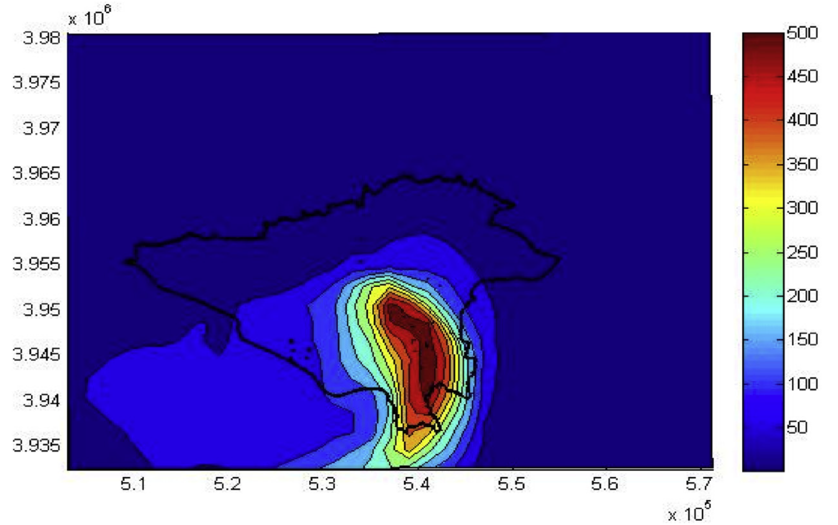


Fig. 7. Meteorological parameters modeling results in peak area: a) wind speed, b) cloud fraction, c) PBL Height, d) vertical changes of temperature at 10:00PM; for 9th Feb.

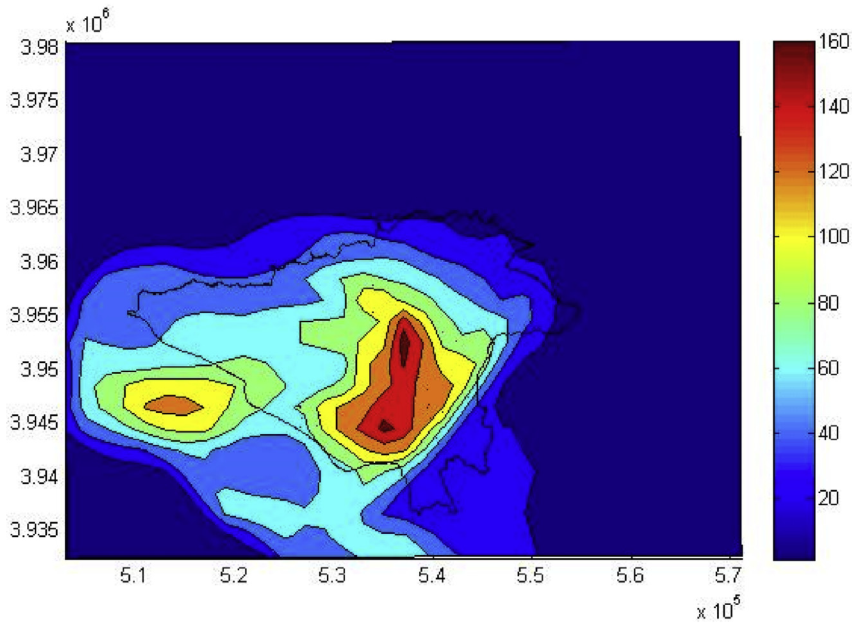
around 6:00PM. Despite gradually reduction of emission after 6:00PM, PM_{10} concentration continued to increase till 10:00 PM. Also, the location of concentration peak coincided with emission. It would be the result of stable weather condition on Feb. 9th. As mentioned earlier, at this night, a temperature inversion at about 180 m occurred, so all pollutant was accumulated at a thin layer and near-surface concentration increased. Besides, due to calm weather and low wind speed (averaged wind speed below 0.4 m/s), the wind could not transfer or diffuse pollution to reduce the concentration after peak hour of emission.

3.3.3. Sources of uncertainty

Air quality modeling is influenced by the uncertainty of meteorological modeling and emissions inventories. The emission Inventory



(a)



(b)

Fig. 8. PM_{10} concentration for the Tehran domain in Feb. 7th a) at 06:00PM, b) 12:00AM.

has a great impact on modeled air quality. Emissions estimates usually calculated based on annual activity rates. However, air quality models operate on hourly temporal scales to simulate complex chemical reaction. As mentioned earlier, Due to lack of a comprehensive emission inventory for Tehran, annual emission for energy, residential, industry and waste disposal are extracted from GEIA and MACCity databases. Due to the low efficiency of industries and different working pattern and meme in Iran, this estimation may not coincide with reality. More ever, these resources are distributed approximately, so the spatial distribution is not accurate and consistent with reality. Temporal allocation profiles that are used in current study are the best estimates, but improvements in temporal allocation may improve the air quality model results. All of these variabilities and uncertainty suggest that sensitivity analysis should be done to better understand the effect of emissions input on predicted concentration.

Meteorological uncertainty also has a significant impact on estimated air quality. Differences in temperature, moisture and wind can have an effect on boundary layer stability, clouds fraction and radiation, that all would impact mixing and photochemistry in the air quality model. In modeled episode, WRF modeled 2 m-temperature was lower than observation. Underestimation of temperature indicates that boundary layer may also be underestimated. It would restrict the diffusion and mixing in boundary layer and cause more accumulation of particles near surface. The wind speed and direction also would affect and alter the transport of pollutants; for example, if the wind speed is higher than real, it would wash out pollutant from city. In third day of the modeling, wind speeds were lower than the observation. So the pollutants transfer were reduced, and more accumulation of pollutants occurred.

3.3.4. Source apportionment

The percentage of each emission sources contribution and the temporal changes of their share at Pounak and Masoudiyeh Station are shown in Fig. 10. Tehran experienced rapid urban developments and has large population and extensive transportation network. In general, the major share of pollutants respectively were related to

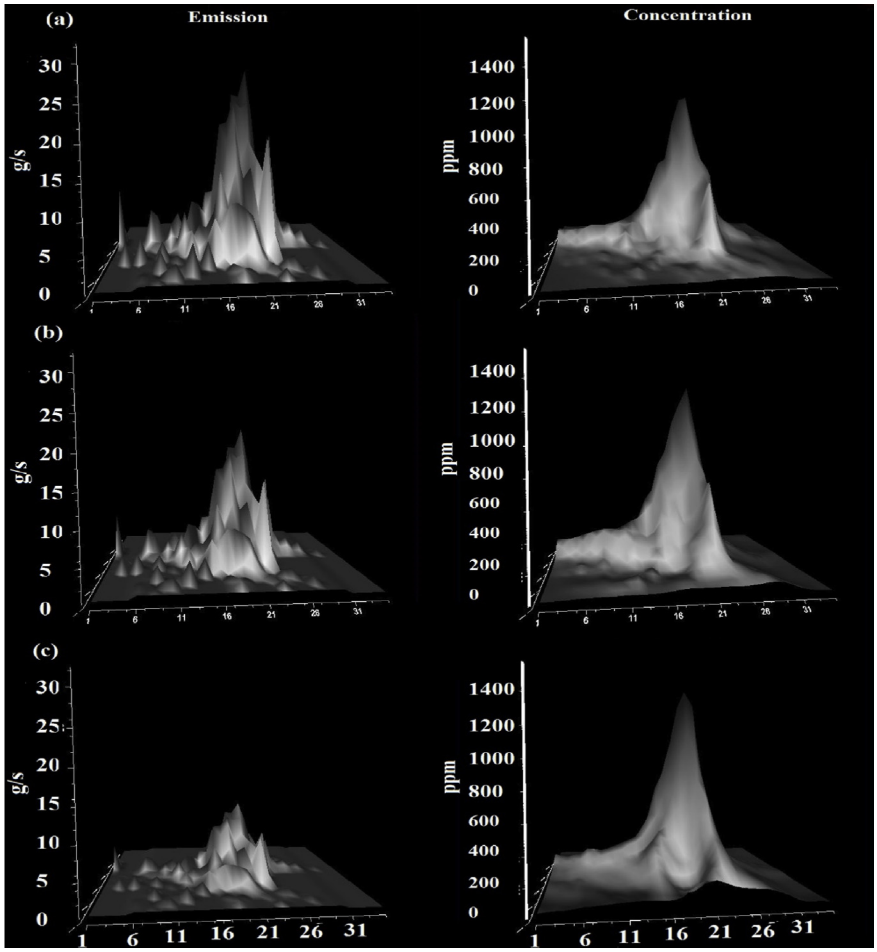


Fig. 9. Hourly PM_{10} emission (Left) versus Concentration (Right) in Feb. 9th a) 5:00PM, b) 7:00PM, c) 10:00PM.

transportation, energy, and residential sources. Transportation emission source had the highest contribution on particles concentration (59.9% for Pounak station and 67.5% for Masoudiyeh station). The contribution of emission sources indicated that, during winter polluted periods, the emission control of transportation are more effective. The residential and energy sources respectively contributed 11.8% and 17.4% for Pounak station and 9.7% and 14.0% percent for Masoudiyeh. These three sources also had the highest share of the total emission. The share of residential source decreased in summer, and the high share of this source in winter is related to house heating. Based on the monthly emission coefficient, transportation emission is almost the same throughout the year, and it's practically the most significant contributor from local sources. The general winter high pollutant levels are related to inversion and stagnant meteorological conditions. During summer, the higher temperature and deeper PBLH could increase pollutants dispersion in the atmosphere, but the average PM10 levels in summer were more elevated than winter. As the city is located in the arid area at the Middle East and experience frequent dust storm events. The studies indicated that the local urban source is still the primary source of PM during summer (Arhami et al., 2018, 2017; Farahani and Arhami, 2020).

In Pounak station, which is a residential area, transportation source is a dominant contributor, but during night (i.e., 20:00PM to 7:00AM) most of pollutant is related to other sources, and share of energy and residential sources in the PM concentration increased up to 30% and 25%. In Masoudiyeh station, transportation emission contributes less than 50% of total emission. So transportation source plays a lesser role, but still in rush hour, the share of this source is predominant. The different pattern of Masoudiyeh source contribution during 2nd and 3rd days may be related to wind field. Masoudiyeh station located in eastern suburb area of Tehran. In these days wind was blowing from NE/E, so the contribution pattern would be related to local emission sources and is not affected by the transportation emission of other parts of city. To evaluate this hypothesis further studies are required.

3.3.5. Emission regulation scenarios

As previously mentioned in this study, the impact of Clean Air Laws and governmental emission regulations for stationary and mobile emission sources examined.

Based on mobile source regulations, current vehicles standard (Pre-Euro1) was changing to European emission standard. Emission standards for LDV is changed to Euro4, heavy truck and LDT to Euro III and motorcycles standards also changed to Euro III. By this scenario, total PM_{10}, NOx and VOC emission were respectively reduced 53.7%, 32.6%, and 97.4%. PM_{10} daily concentration reduction in Masoudiyeh station are presented in Fig. 11. The average concentration of modeling episode (4-days) was reduced 35%; this indicated the importance of transportation source in PM_{10} concentration. The scenario had a relatively lower impact on 3rd day. As mentioned earlier, in this day the weather condition was calm, and wind speed was lower than other days. So, the 3rd day concentration is more affected by weather condition, and emission reduction had the least impact (15%).

The percentage of PM_{10} and $PM_{2.5}$ concentration reductions in peak hour of Feb. 9th, due to changing vehicles standard, are shown in Fig. 12. The most reduction of PM concentration occurred in the down town area of Tehran. The greatest reduction were 77% for both PM_{10} and $PM_{2.5}$. As we close to the city center by increasing the transportation network density, number of vehicles and the amount of

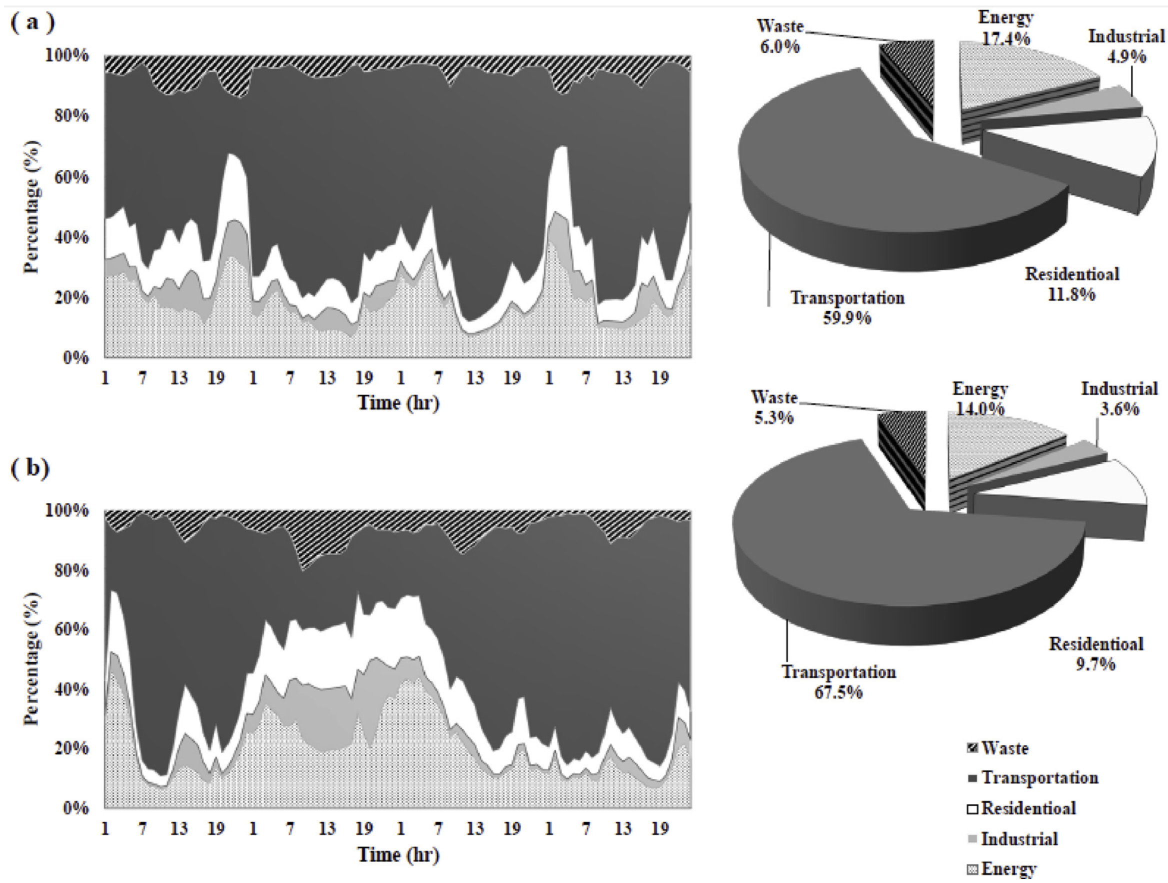


Fig. 10. Share of emission sources in PM_{10} concentration at the urban station: a) Pounak station, b) Masoudiyeh station.

transportation emission increases too. So the downtown emission is more affected by this scenario. Besides, due to calm weather and high share of primary particles in PM concentration, the PM reduction distribution would be nearly coincident with emission reduction pattern.

To evaluate the other emission controlling policies, the impact of decrease of PM_{10} and effective pollutants (including SO_2, NO_x, NH_3 and VOC_S) emissions on the PM_{10} concentration evaluated. The results are summarized in Table 1. Overall, the highest change of the PM_{10} concentration was due to the decrease in emissions of all pollutants (−8.8%). Although, the changes of effective pollutants had a little impact on particle concentrations, which represented the large share of primary particulate matters in PM_{10}. The impact of effective pollutants emission on PSO_4 concentration is much less than PNO_3 and PNH_4. It may represent the better meteorological conditions to the production of nitrate and ammonium particles in this period.

However the concentration changes resulted from decrease of all effective pollutants emissions is not proper to the some or single effect of policies that led to individual reduction of precursor's pollutants. Decrease the amount of SO_2 emissions reduced PSO_4 concentration slightly, but the concentration of PNH_4 and PNO_3 increased. These variations are related to Ammonium and sulfate reactions in the atmosphere. Ammonium neutralize sulfate and lead to production of ammonium sulfate ($(NH_4)_2SO_4$), then the remained ammonium reacts with nitrate and produces ammonium nitrate (NH_4NO_3); thus by

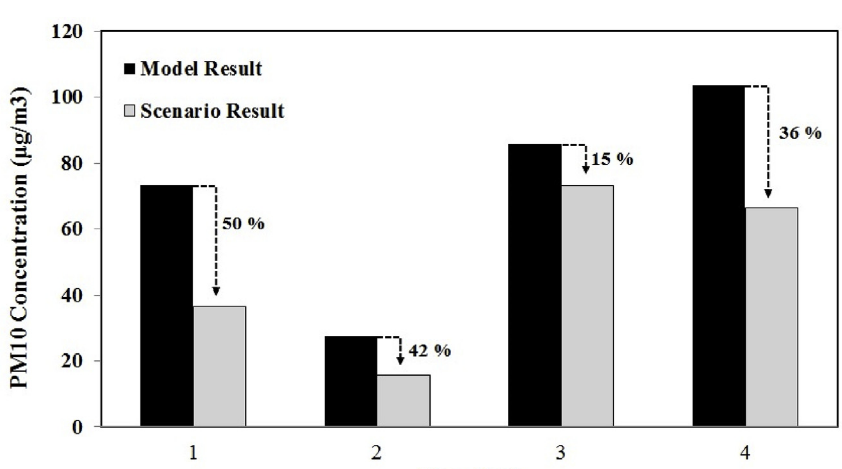


Fig. 11. Averaged PM_{10} concentration at Masoudiyeh station for base case and scenario.

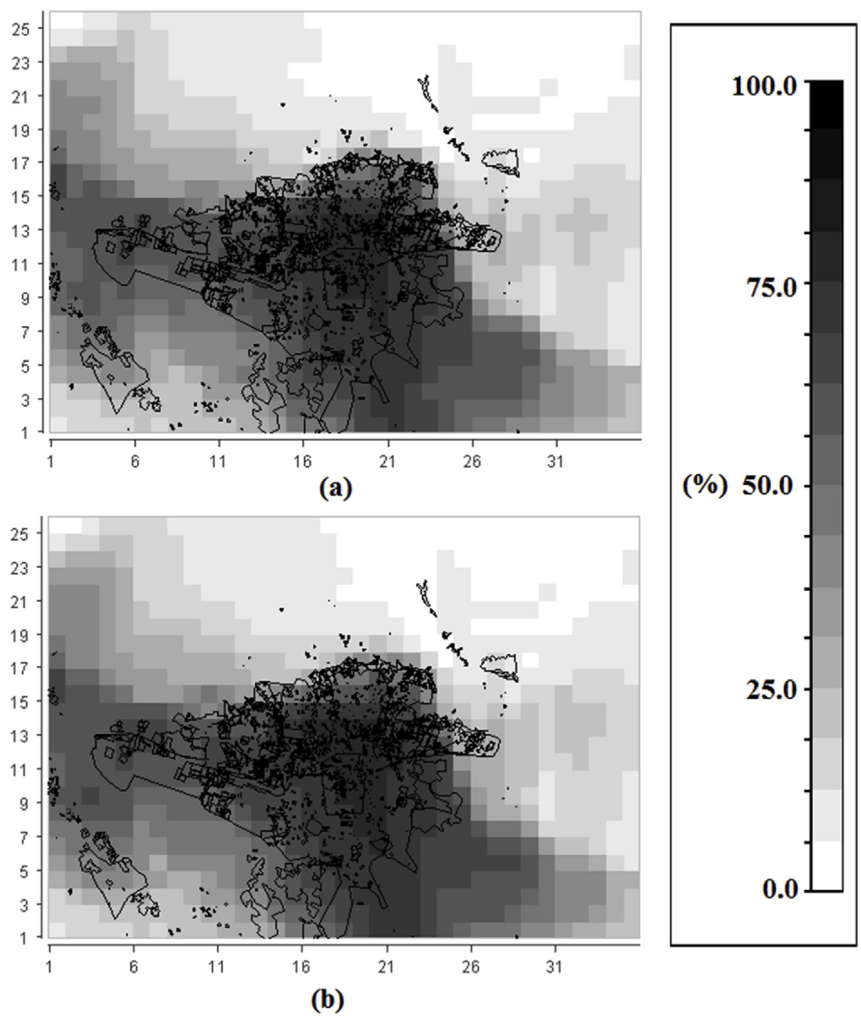


Fig. 12. The percentages of change in PM concentration at Tehran after governmental emission regulation in Feb. 9, 2010 at 10 PM a) PM_{10}, b) PM2.5.

Table 1
Response of aerosol concentrations at the Masoudiyeh station to 10 percent reduction of the emissions.

Sensitivity Analysis	Concentration changes (%)			
	PM_{10}	PSO_4	PNO_3	PNH_4
Decrease all	−8.8	−6.5	−6.4	−3.8
Decrease effective pollutants	−0.2	−0.3	−2.5	−2.7
Decrease PM_{10}	−8.4	−5.1	−5.0	−5.8
Decrease SO_2	−0.1	−0.8	0.1	2.1
Decrease NO_x	−0.1	0.4	−2.4	0.6
Decrease NH_3	−0.1	−0.0	−0.8	−0.8
Decrease VOC_S	−0.0	−0.0	−0.0	−0.0

decreasing SO_2, less ammonium sulfate produced that lead to increasing the amount of free ammonia to produce ammonium nitrate. Also, decreasing ammonia emissions cause a decrease in the concentration of ammonium and nitrate particles and have a minor impact on decreasing the sulfate particles concentration.

4. Conclusion

In this study, a WRF-CMAQ air quality modeling system is utilized in Tehran to simulate a severely polluted winter episode of February 6–10, 2010. The modeling results evaluated against synoptic meteorological observations and air quality monitoring database in Tehran. To investigate the contributions of local anthropogenic emission sources to the PM_{10} concentrations, the Brute-Force method was utilized. Besides, several emission reduction scenarios based on governmental policies and Clean Air Laws were also assessed to quantify the impact of them on the concentration of particles. These scenarios include the effect of emission controlling policies to upgrade vehicles emission standards and emission regulations for combination of different sources including mobile, residential, commercial and industrial sectors.

In general modeling results had good agreement with the observed values. The diurnal temperature cycle was simulated fairly well, and the simulated temperature was lower than observed. The modeled PM_{10} concentration also had an acceptable accuracy in compared to observed concentration. The averaged modeled PM_{10} levels were slightly overestimated that can be attributed to emission inventory estimation and meteorological modeling performance.

The determined source contributions to the PM_{10} concentration were transportation (60–67%), energy (14–17%), residential (10–12%), waste (5–6%), and industry (4–5%). The contributions of emission sources varied considerably throughout the day. In night hours which transportation reduced, the shares of residential and energy sources were increased respectively up to 30% and 40%.

As a conclusion, emission controls strategies that target transportation source and primary particulate emissions in Tehran are more effective than controlling policies that target gaseous precursor emissions reduction. Governmental emissions regulations of changing available vehicles to the vehicles with EuroIV and EuroIII emission standards were the most effective strategy. By this plan, total PM_{10}, NOx, and VOC emission were respectively reduced 53.7%, 32.6%, and

97.4% and led up to 77% reduction for both PM_{10} and $PM_{2.5}$ concentrations. The most considerable reduction in particulate concentrations occurred in the downtown area of Tehran where most of the population and dense road network located. The first phase of Clean Air Laws considered to have around a 10% emission reduction effect that reduced PM_{10} concentrations by about 8.8%. Controlling policies that led to reduction of precursor's pollutants (sulfate, nitrate, VOC and ammonium species) had a little impact on particles concentration (less than 1%), and there is no linearity or additivity in the effects. Generally, the concentration responses to reductions in precursor emissions are consistent with the chemistry mechanism.

Although the particulate matter is the major cause of frequent pollution episodes in Tehran, yet its composition and sources are poorly known. This study provides valuable information on source apportionment of PM_{10} in Tehran, which may be the first question that needs to be answered to conduct air pollution control strategies. More studies, observations and data sharing are needed to evaluate impact of regional emission and dust on air pollution in Tehran. Further research to assess different models' performance, including a combination of CTM and Gaussian models, also is needed to support the urban planning process.

CRediT authorship contribution statement

Nooshin Daneshpajooh: Writing - original draft, Writing - review & editing, Visualization, Investigation, Software. **Mohammad Arhami:** Conceptualization, Supervision, Writing - review & editing. **Hassan Azoji:** Software, Validation, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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