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Spatial and Temporal Trends of Short-Term Health Impacts of $PM_{2.5}$ in Iranian Cities; a Modelling Approach (2013–2016)

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ABSTRACT

Estimation of the spatial and temporal trends of health impacts attributable to air pollution is an effective measure for evaluating implemented interventions. The aim of this study was to estimate the short-term mortality attributable to exposure to $PM_{2.5}$ among individuals older than 30 years old in ten Iranian cities from March 2013 to March 2016 using the World Health Organization's (WHO) AirQ+ software. Hourly concentrations of $PM_{2.5}$ were acquired from the Department of Environment and Tehran Air Quality Control Company. Only stations with 75% and 50% of valid data were qualified for Tehran and other cities, respectively. The annual average $PM_{2.5}$ concentrations in all ten of the cities were higher than the WHO guideline value of 10 µg m^{-3}. The total number of attributable short-term deaths during the three-year period in these 10 cities was 3284 (95% CI: 1207–5244). The average daily premature deaths were calculated to be 3. The highest number of premature deaths within the three-year period was estimated to be 548 in Tehran, largely reflecting its population of nearly 9 million. The western and southern cities of Iran experience severe dust storms and showed a high estimated rate of death attributed to air pollution. The health impacts in all cities decreased in the third year compared to the first year except for Ahvaz, Khoram Abad, and Ilam. Governmental interventions need to be enforced more effectively to reduce the high level of adverse health impacts in Iran. Special considerations should be given to the air quality of cities affected by dust storms.

Keywords: Particulate matter; AirQ+; Middle Eastern dust storm; Health impact assessment; Air pollution.

INTRODUCTION

Over the past several decades, many studies have reported adverse human health effects from exposure to air pollution in areas around the world (Rahlenbeck and Kahl, 1996; Sunyer *et al.*, 1996; Michelozzi *et al.*, 1998; Saez *et al.*, 2002; Shin *et al.*, 2008; Burnett *et al.*, 2014; Global Burden of Disease (GBD), 2015). One of the most important criteria air pollutants is particulate matter (PM), for which previous investigations have presented clear evidence of relationships to acute and chronic effects on health, including cardiovascular and respiratory mortality and hospitalizations (Chen *et al.*, 2008; Wang *et al.*, 2013; MohseniBandpi *et al.*, 2017). PM with an aerodynamic diameter of 2.5 µm or

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less ($PM_{2.5}$) is a more robust mortality-related exposure metric than PM with an aerodynamic diameter of 10 µm or less (PM_{10}) (USEPA, 2012).

Estimation of attributable health impacts of air pollution can clarify the economic and health burden of air pollutants for a given country (World Bank, 2016). The Iranian government's air quality management (AQM) activities have expanded from understanding the scope of the problem to targeting interventions. Thus, identification of spatial and temporal trends of health impacts attributable to air pollution is becoming more critical as an approach to assess the effectiveness of the control strategies (Liu *et al.*, 2017).

AirQ+ is a software tool for quantifying the health impacts of air pollution developed by the WHO Regional Office for Europe. The software can handle different air pollutants, such as $PM_{2.5}$, PM_{10}, NO_2, O_3, and black carbon (BC). This software has been developed to assess the effects of long-term and short-term exposure to ambient air pollution. In addition, AirQ+ can estimate the effects of household air pollution related to Solid Fuel Use (SFU). Acute and chronic mortality and morbidity of several health outcomes can be considered to enter the model. The underlying scientific evidence on health effects from ambient air pollution used in the software is derived mainly from epidemiological studies conducted in Western Europe and North America (Mudu *et al.*, 2016).

Many health impact assessments of air pollution have been conducted around the world, including Iran. A study in Greece estimated the adverse health effects of PM_{10} concentrations recorded at six monitoring stations in the GAA (Greater Athens Area) in the 13-year period from 2001 till 2013 using the AirQ 2.2.3 software developed by WHO (Ntourou *et al.*, 2017). In the European Apheis study, PM_{10} concentrations of 19 cities were used in a health impact assessment. The results showed that the reduction in long-term exposure to PM_{10} concentrations by 5 µg m^{-3} would have prevented between 3300 and 7700 premature deaths annually, 500 to 1000 of which were associated with short-term exposure (Medina *et al.*, 2004). Health impacts of air pollution in several cities of Iran have been estimated in several studies using AirQ software (Goudarzi, 2014; Asl *et al.*, 2015; Nourmoradi *et al.*, 2015; Ghozikali *et al.*, 2016; Miri *et al.*, 2016; Mohammadi *et al.*, 2016; Nourmoradi *et al.*, 2016; Khaniabadi *et al.*, 2017). However, only a few of them have considered the health effects of $PM_{2.5}$ as a pollutant.

In a study on spatial and temporal trends in the mortality burden of air pollution in China during 2004–2012, the health burden showed strong spatial variations, with high attributable deaths concentrated in areas with high air pollution, high population, or both. Temporal trends were observed in most provinces but with varied growth rates (Liu *et al.*, 2017). In Tehran, Kermani *et al.* (2016) estimated the short-term health impacts attributable to $PM_{2.5}$ over the period 2005–2015. The total number of short-term premature deaths during this decade was estimated to be 20,015 (Kermani *et al.*, 2016).

Many cities of Iran are ranked as highly polluted areas of the world according to the WHO report (WHO, 2016). Iran is faced with rapid industrial growth, a large number of old vehicles, and environmental crises such as Middle Eastern dust storms (MED) (Shahsavani *et al.*, 2012a, b; Sowlat *et al.*, 2012, 2013; Shahbazi *et al.*, 2015). The Department of Environment (DOE) has designed and initiated plans and actions to control air pollution, including fuel substitution in mobile sources and power plants (Department of Environment (DOE), 2017). Monitoring and identification of the trend of reduction in air pollution and its health impacts can be an effective measure to evaluate implemented interventions (Liu *et al.*, 2017).

The aim of this study was to estimate the short-term mortality attributable to exposure to $PM_{2.5}$ among individuals older than 30 years old in 10 cities of Iran during March 2013–March 2016 using AirQ+ modelling software.

METHODS

Location and Time

Ten cities of Iran were selected for a health impact assessment of the exposure to $PM_{2.5}$. These cities were Tehran, Mashhad, Isfahan, Shiraz, Tabriz, Ahvaz, Arak, Sanandaj, Khoram Abad, and Ilam. These cities were selected because of the availability of ambient air monitoring data during the 21 March 2013 to 19 March 2016 period, which are three sequential years of the Iranian calendar: 21 March 2013–20 March 2014, 21 March 2014–20 March 2015, and 21 March 2015–19 March 2016.

Air Quality Data

Hourly concentrations of $PM_{2.5}$ were acquired from the Department of Environment and Tehran Air Quality Control Company. Only monitoring stations in residential areas were selected, and industrial and suburban (where there is no population exposure) areas were excluded. Negative and zero values were removed from the dataset. In Tehran, only stations with more than 75% data in each of the three years were considered as valid stations (EC Directive, 2008). In other cities, due to less completeness of datasets, stations with more than 50% data were considered valid (WHO, 1999). The monitoring stations with seasonal ratios of valid data greater than 2 were omitted from the dataset (WHO, 1999). Then, 24-hour averages were calculated and entered in AirQ+. WHO's air quality guideline for 24-h concentrations of $PM_{2.5}$ (25 µg m^{-3}) was used as the cut-off value. AirQ+ estimates only the health effects attributable to concentrations over this cut-off value.

Demographical Data

This study investigates the mortality among people who have attained the age of 30 years or more. Thus, the total population and at-risk population (> 30 years old) of all cities were acquired from the Statistical Centre of Iran. The total population and at-risk population of all cities were approximately 20 and 10 million, respectively. Detailed city-specific demographical information is presented in Table S1 of Supplementary Material.

Baseline Incidence

Baseline incidence (BI) values for all cause, non-accidental deaths per 100,000 population were calculated by using the information obtained from the Ministry of Health and Medical Education, and Statistical Centre of Iran. The applied baseline incidence rates for Tehran and other cities were 943 and 807 per 100,000 population, respectively. The BI for all cities other than Tehran was estimated from total non-accidental deaths in Iran outside of Tehran in 2011 for persons older than 30. Due to the lack of valid precise city-by-city information, the baseline incidence for the 9 cities other than Tehran was assumed to be the same.

AirQ+ Software

For quantifying the short-term effects of particulate matter, the following input data are required: detailed concentration distributions (frequency of days with specified pollutant concentration values), the at-risk population, health data such as baseline rates of given health outcomes, a cut-off value of concentration for consideration, and Relative Risk (RRs) values if different from the default ones provided by WHO (Mudu *et al.*, 2016). However, it only provides morbidity and mortality risk estimates for ozone, sulfur dioxide, nitrogen dioxide, black carbon, PM_{10}, and $PM_{2.5}$. It does not provide estimates for PM chemical components except for black carbon or more specific particle sizes such as ultrafine particles.

AirQ+ calculates different health-related estimates, including the attributable proportion of cases, number of attributable cases, number of attributable cases per 100,000 at-risk population, proportion of cases in a pollutant concentration range, and cumulative distribution by air pollutant concentration. These different estimates can be used in various ways depending on the assessment's objectives (Mudu *et al.*, 2016).

RESULTS

$PM_{2.5}$ Concentration

Table 1 presents the average concentrations of $PM_{2.5}$ in ten cities of Iran during the periods of March 2013 to March 2014, March 2014 to March 2015, and March 2015 to March 2016. It should be noted that the annual concentrations of $PM_{2.5}$ have been reported previously (Hadei *et al.*, 2017a, b). The annual average $PM_{2.5}$ concentrations in all ten cities were higher than 10 µg m^{-3}, which has been proposed by WHO as a health protective guideline for annual mean $PM_{2.5}$. The most polluted cities in all three years were Ahvaz and Isfahan.

In all the cities except Ahvaz and Khoram Abad, concentrations of $PM_{2.5}$ in the third year were significantly lower than those in the first year. In the cases of Ahvaz and Khoram Abad, concentrations of $PM_{2.5}$ in the third year had decreased significantly in comparison to the second year. $PM_{2.5}$ concentrations were compared between these ten cities. The details of the statistical results are provided as supplementary material.

Short-Term Mortality

Table 2 presents the attributable proportion of mortality due to short-term exposure to $PM_{2.5}$ in the selected 10 cities. Attributable proportion is the percentage of disease in the exposed group that can be attributed to the exposure.

In Table 3, the total attributable short-term deaths during the three-year period in the ten Iranian cities is estimated to be 3284 (95% CI: 1207–5244). The average daily number of deaths due to $PM_{2.5}$ short-term exposure was calculated to be 3. The most premature deaths, with a three-year average of 548, were estimated to be in Tehran, reflecting its nearly 9 million population. After Tehran, Isfahan and Mashhad have the most estimated premature deaths over the three-year period. The fewest cases have been estimated for Ilam and Sanandaj.

Table 4 gives the estimated rates of attributable premature deaths per 100,000 in the 10 cities. The western and southern cities of Iran, with occurrences of severe dust storms, showed a high rate of premature death. Among these cities, Ahvaz showed a higher value, with a three-year average of 19.24 premature deaths per 100,000 population. However, the premature death rate in Isfahan, an industrialized megacity, was calculated to be 17.72 per 100,000 population—higher than other cities except for Ahvaz.

Figs. 1 and 2 illustrate the spatial distribution of three-year averages of $PM_{2.5}$ concentrations and estimated mortality, respectively. The western and southern cities of Iran have higher concentrations of $PM_{2.5}$ than other areas. However, the estimated mortality in these cities is lower than in central areas.

Table 1. Annual average concentrations (± SD) of $PM_{2.5}$ in 10 selected cities (2013–2016)[a].

City	Average (± standard deviation), µg m^{-3}			Monitors: total (valid)
	2013–2014	2014–2015	2015–2016	
Tehran	41.89 (± 15.45)	39.17 (± 17.81)	36.42 (± 17.98)	37 (7)
Mashhad	36.05 (± 26.96)	27.29 (± 13.24)	30.59 (± 13.8)	12 (8)
Isfahan	56.15 (± 28.73)	54.99 (± 25.58)	37.29 (± 13.72)	7 (4)
Shiraz	32.22 (± 14.92)	25 (± 10.41)	26.8 (± 15.5)	3 (2)
Tabriz	30.68 (± 22.67)	17.22 (± 8.36)	22.72 (± 12.63)	6 (2)
Ahvaz	62.6 (± 71.68)	53.08 (± 52.58)	60.88 (± 61.67)	3 (2)
Arak	43.13 (± 34.25)	32.53 (± 17.71)	23.63 (± 14.5)	2 (1)
Sanandaj	29.77 (± 18.43)	29.73 (± 20.12)	25.02 (± 15.97)	2 (2)
Khoram Abad	32.57 (± 28.07)	41.01 (± 33.41)	33.94 (± 38.42)	1 (1)
Ilam	28.77 (± 23.68)	26.04 (± 27.37)	28.15 (± 31.93)	1 (1)

[a] These concentrations are reported previously (Hadei *et al.*, 2017a, b).

Table 2. Attributable proportion (AP) of mortality due to short-term exposure to $PM_{2.5}$ among individuals older than 30 years in March 2013–March 2016.

City	Attributable proportion % (95% CI)		
	2013–2014	2014–2015	2015–2016
Tehran	1.8 (0.66–2.92)	1.38 (0.51–2.25)	1.04 (0.38–1.7)
Mashhad	1.6 (0.58–2.65)	0.68 (0.25–1.11)	0.96 (0.35–1.57)
Isfahan	4.13 (1.52–6.71)	3.68 (1.36–5.97)	1.56 (0.57–2.54)
Shiraz	1.14 (0.42–1.86)	0.4 (0.15–0.66)	0.69 (0.25–1.14)
Tabriz	1.23 (0.45–2.02)	0.16 (0.06–0.27)	0.44 (0.16–0.73)
Ahvaz	5.02 (1.75–8.78)	3.6 (1.28–6.06)	4.59 (1.63–7.71)
Arak	2.58 (0.94–4.25)	1.17 (0.43–1.91)	0.51 (0.18–0.84)
Sanandaj	1.12 (0.41–1.84)	0.96 (0.35–1.59)	0.67 (0.24–1.09)
Khoram Abad	1.52 (0.55–2.52)	2.4 (0.87–3.96)	1.83 (0.65–3.1)
Ilam	0.96 (0.34–1.59)	0.85 (0.3–1.43)	1.18 (0.42–2)
Total/Average	-	-	**-**

Table 3. Number of attributable premature deaths due to short-term exposure to $PM_{2.5}$ among individuals older than 30 years in March 2013–March 2016.

City	Total attributable mortality (95% CI)		
	2013–2014	2014–2015	2015–2016
Tehran	676 (249–1097)	561 (206–912)	408 (150–666)
Mashhad	118 (43–193)	64 (23–105)	94 (35–154)
Isfahan	228 (84–369)	226 (84–366)	125 (46–203)
Shiraz	120 (44–195)	24 (9–39)	40 (15–65)
Tabriz	56 (21–92)	11 (4–17)	27 (10–44)
Ahvaz	117 (43–190)	96 (35–156)	125 (46–204)
Arak	36 (13–59)	23 (8–37)	11 (4–18)
Sanandaj	13 (5–21)	11 (4–19)	8 (3–14)
Khoram Abad	14 (5–23)	23 (8–38)	16 (6–27)
Ilam	4 (1–7)	4 (1–6)	5 (2–8)
Total/Average	**1382 (508–2146)**	**1043 (382–1695)**	**859 (317–1403)**

Table 4. Number of attributable premature deaths per 100,000 population due to short-term exposure to $PM_{2.5}$ among individuals older than 30 years in March 2013–March 2016.

City	attributable mortality per 100,000 population		
	2013–2014	2014–2015	2015–2016
Tehran	14.57 (5.36–23.64)	11.65 (4.27–18.94)	8.17 (3–13.35)
Mashhad	9.1 (3.31–14.89)	4.58 (1.64–7.52)	6.44 (2.4–10.56)
Isfahan	21.83 (8.04–35.34)	20.87 (7.76–33.81)	10.47 (3.85–17.01)
Shiraz	15.67 (5.74–25.47)	2.89 (1.08–4.7)	4.45 (1.67–7.24)
Tabriz	6.94 (2.6–11.41)	1.27 (0.46–1.97)	2.99 (1.11–4.88)
Ahvaz	21.3 (7.8–34.58)	16.69 (6.08–27.12)	19.74 (7.2–32.21)
Arak	13.1 (4.75–21.58)	7.46 (2.59–12.01)	3.36 (1.22–5.55)
Sanandaj	7.29 (2.8–11.78)	5.77 (2.1–9.98)	3.96 (1.48–6.93)
Khoram Abad	8.5 (3.05–14.03)	12.81 (4.45–21.16)	8.32 (3.1–14.05)
Ilam	4.99 (1.24–8.7)	4.59 (1.14–6.89)	5.28 (2.11–8.45)
Total/Average	**14.2 (5.18–21.9)**	**10.1 (3.7–16.42)**	**7.89 (2.91–12.88)**

DISCUSSION

The attributable proportion and number of short-term deaths caused by $PM_{2.5}$ exposure among people older than 30 years in ten cities of Iran during March 2013 to March 2016 were estimated using the AirQ+ modelling approach. Prior works (Hoek *et al.*, 2013; WHO-Europe, 2013; Burnett *et al.*, 2014) have suggested that the risk estimates for people older than 30 years are more robust than those including younger individuals. The results showed some spatial and temporal variations.

Source identification and apportionment studies have only been conducted in Ahvaz. To better understand the causes of spatial variations in PM concentrations, the sources of $PM_{2.5}$ in each city or region will need to be investigated. Traffic will be important in all cities, but there are likely to

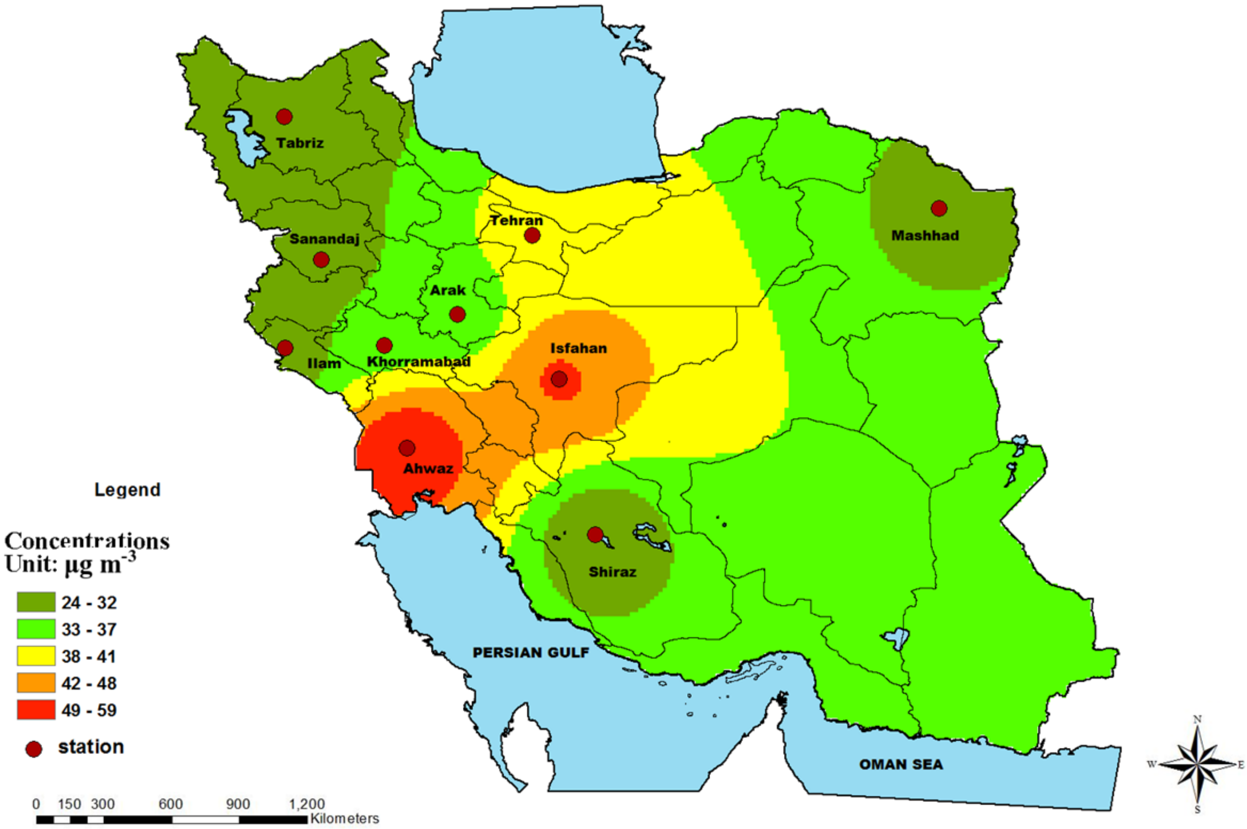

Fig. 1. Spatial distribution of three-year average of $PM_{2.5}$ concentrations in ten Iranian cities (March 2013–March 2016).

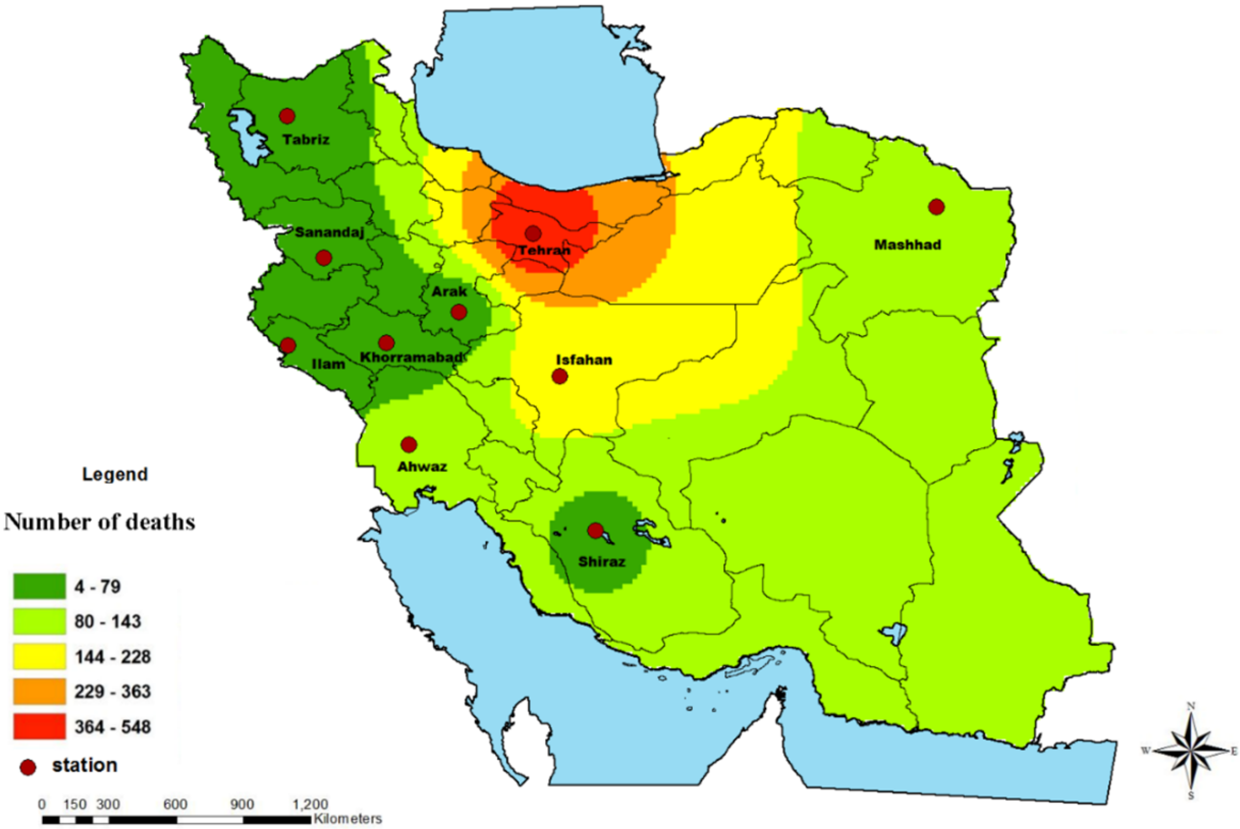

Fig. 2. Spatial distribution of three-year average of mortality attributed to $PM_{2.5}$ concentrations in ten Iranian cities (March 2013–March 2016).

be different local fine-PM sources in each city, including industrial activities and dust storms. The western and southern cities of Iran, such as Ahvaz, Khoram Abad, Sanandaj, and Ilam, have been subjected to Middle Eastern dust storms (MED) in recent years. The MED events are probably responsible for the high rate of death attributable to air pollution in these cities. However, their relatively low population moderates the effect of high $PM_{2.5}$ concentrations. In a study during a Middle Eastern dust storm period (April–September 2010) in Ahvaz, overall mean values of 319.6 ± 407.1, 69.5 ± 83.2, and 37.0 ± 34.9 µg m^{-3} were monitored for PM_{10}, $PM_{2.5}$, and PM_1, respectively, with corresponding maximum values of 5338, 911, and 495 µg m^{-3}, respectively (Shahsavani *et al.*, 2012a, 2017). Two studies have been conducted to apportion the sources of PM_{10} and TSP in Ahvaz (Sowlat *et al.*, 2012, 2013). The possible sources of PM_{10} were crustal dust (41.5%), road dust (5.5%), motor vehicles (11.5%), marine aerosol (8.0%), secondary aerosol (9.5%), metallurgical plants (6.0%), petrochemical industries and fossil fuel combustion (13.0%), and vegetative burning (5.0%). In addition, seven sources were identified for TSP, namely, crustal dust (56%), road dust (7%), motor vehicles (8%), marine aerosol (9%), secondary aerosol (7%), metallurgical plants (4.5%), and finally petrochemical plants and fossil fuel combustion (8.5%). For Tehran, Isfahan, Mashhad, Tabriz, and Shiraz, mobile sources are likely to make significant PM contributions, given the number of registered vehicles. However, there have not been comparable studies in any other city.

The average PM_{10} concentrations during dust episodes in Sanandaj (187 µg m^{-3}) were significantly higher than on other days (48.7 µg m^{-3}) (Ebrahimi *et al.*, 2014). According to WHO's database, the annual average $PM_{2.5}$ concentrations in Ahvaz and Sanandaj during 2010 were 95 and 41 µg m^{-3}, respectively (WHO, 2016). The annual, winter, and summer averages of PM_{10} in Khoram Abad were reported to be 80.59, 58.28, and 80.59 µg m^{-3}, respectively (Nourmoradi *et al.*, 2015). Mirhosseini *et al.* (2013) have reported that the daily average concentrations of particulate matter in Khoram Abad during the warm seasons (spring and summer) were higher than the average concentrations in cold seasons (autumn and winter) (Mirhosseini *et al.*, 2013). Middle Eastern dust storms are likely to be the main cause of this seasonal difference, even given the extensive anthropogenic activities as major PM sources.

The most premature deaths were estimated to be in Tehran. The high mortality in Tehran is driven by both its high population and high concentrations of $PM_{2.5}$. It is reported that about 70% of particulate air pollutants in Tehran were emitted from mobile sources during 2015 (Ahadi *et al.*, 2016). There are more than three million personal vehicles in Tehran, 75% of which have emissions meeting the Euro-2 standards or lower. In addition, there are about 750,000 motorcycles, 40% of which are older than 10 years, and more than 95% of their emissions meet the Euro-2 standard or lower (Shahbazi *et al.*, 2015). About 76% of the air pollution in Isfahan was reported to be produced by mobile sources in 2010 (Zarabi *et al.*, 2010). The major source of particulate matter in Arak is probably different. Industries have been suggested as the main sources of air pollution in this city (Hosseini and Shahbazi, 2016).

Studies about the use of AirQ+ are very rare (Hadei *et al.*, 2017a, 2017c); however, many studies can be found about the quantification of health effects attributable to air pollution using the AirQ 2.2.3 model. Hadei *et al.* (2013) estimated short-term mortality attributable to various air pollutants. The total number of mortality cases attributable to $PM_{2.5}$ over the three-year period 2013–2016 was 4336 (Hadei *et al.*, 2017b). In a study in Mashhad, the number of premature deaths due to short-term exposure to $PM_{2.5}$ was estimated to be 600 during the 2014–2015 period (Miri *et al.*, 2016). Another study in Ahvaz showed that the number of mortality cases attributed to short-term exposure to PM_{10} was 278 in 2014 (Nourmoradi *et al.*, 2015). These values seem to be higher than those obtained in this study. The difference is due to different relative risk values, functions, and interest populations. In addition, a different procedure was used in this study to obtain $PM_{2.5}$ concentrations that were used as the population exposure.

The temporal trends showed a decline in health impacts observed in Tehran, Isfahan, Arak, and Sanandaj. Some interventions performed by the government, such as fuel substitution in mobile sources and the industrial sector, and the replacement of older vehicles with new ones, may be the reason for this reduction, especially in Tehran (Department of Environment (DOE), 2017). Other cities have shown variations within the three-year period. However, one-year variations cannot be the basis for determining long- and medium-term trends. The third year's results can be compared with the first year's values to identify a short-term difference. This comparison showed that health impacts in all cities decreased in the third year compared to the first year, except for Ahvaz, Khoram Abad, and Ilam. This lack of change may be due to the occurrence of severe dust storms in these cities.

This approach has limitations that must be recognized. The model considers the air pollutant's concentration as the measure of population exposure. In addition, due to the limitations in epidemiological studies, the model calculations do not account for multiple exposure cases or multipollutant scenarios. Finally, the exposure–outcome data that are the basis of the health outcome estimates were developed by epidemiological assessments conducted outside of this region. Thus, they represent the relationships in different populations, exposure to different particle mixtures, and othser socio-economic conditions Therefore, the results that have been obtained have additional uncertainties and should be considered with caution and expert judgment (WHO Regional Office for Europe, 2016).

CONCLUSIONS

Based on these results, it can be concluded that interventions initiated by the government may have provided some improvement in air quality and lowered estimated mortality. However, given the high remaining concentrations, they need to be more aggressive to reduce the high health impacts of $PM_{2.5}$ in Iran. Special considerations should be given to the air quality of cities that are affected by Middle Eastern dust storms, such as Ahvaz, Khoram Abad, and Ilam. For future studies, satellite-based $PM_{2.5}$ concentrations may provide better estimates of spatially-specific population exposure and more reliable health-impact assessments.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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