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Temporal profile of PM_{10} and associated health effects in one of the most polluted cities of the world (Ahvaz, Iran) between 2009 and 2014

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Abstract

Ahvaz, Iran ranks as the most polluted city of the world in terms of PM_{10} concentrations that lead to deleterious effects on its inhabitants. This study examines diurnal, weekly, monthly and annual fluctuations of PM_{10} between 2009 and 2014 in Ahvaz. Health effects of PM_{10} levels are also assessed using the World Health Organization AirQ software. Over the study period, the mean PM_{10} level in Ahvaz was 249.5 μg m^{-3}, with maximum and minimum values in July (420.5 μg m^{-3}) and January (154.6 μg m^{-3}), respectively. The cumulative diurnal PM_{10} profile exhibits a dominant peak between 08:00–11:00 (local time) with the lowest levels in the afternoon hours. While weekend PM_{10} levels are not significantly reduced as compared to weekdays, an anthropogenic signature is instead observed diurnally on weekdays, which exhibit higher PM_{10} levels between 07:00–17:00 by an average amount of 14.2 μg m^{-3} as compared to weekend days. PM_{10} has shown a steady mean-annual decline between 2009 (315.2 μg m^{-3}) and 2014 (143.5 μg m^{-3}). The AirQ model predicts that mortality was a health outcome for a total of 3777 individuals between 2009 and 2014 (i.e., 630 per year). The results of this study motivate more aggressive strategies in Ahvaz and similarly polluted desert cities to reduce the health effects of the enormous ambient aerosol concentrations.

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Keywords

PM_{10}; Dust storm; Aerosol; Health effects; AirQ; Ahvaz

1. Introduction

The World Health Organization (WHO) recently reported that the most polluted city based on mean-annual PM_{10} concentration is Ahvaz, Iran (372 μg m^{-3}) (Goudie, 2014). Three other cities in Iran ranked in the top ten including Sanandaj as third (254 μg m^{-3}), Kermanshah as sixth (229 μg m^{-3}), and Yasouj as ninth (215 μg m^{-3}). Among these cities, all of which are in western Iran, Ahvaz is the most populated with approximately 1.11 million people (UN Data, 2013; http://data.un.org/). As a result, dust is a major issue in Ahvaz owing to effects on public health, visibility, radiative transfer, agriculture, air traffic, industrial activity, and tourism (e.g., Soleimani et al., 2013, 2016; Derakhshandeh et al., 2014; Goudarzi et al., 2014). Major sources of dust observed in Ahvaz include the Sahara Desert and deserts in Iraq, Saudi Arabia and Kuwait (Soleimani et al., 2013; Naimabadi et al., 2016). Many investigations have been conducted to determine the physical, chemical and biological characteristics of Middle East Dust (MED) and its impact on both human and animal (Dianat et al., 2016a,b; Heidari-Farsani et al., 2014; Naimabadi et al., 2016; Radmanesh et al., 2016; Rezaei et al., 2014; Shahsavani et al., 2012a,b). However, there is a scarcity of information about the diurnal, weekly, monthly and inter-annual variability in PM_{10} in Ahvaz. This is especially important for this city, which is an area of global focus owing to its ranking as one of the most polluted cities in terms of particulate matter.

PM_{10} has been extensively examined in many global regions with a wide range of concentrations and documented sources. PM_{10} concentrations range widely globally with mean-annual concentrations as low as 30 μg m^{-3} and 40 μg m^{-3} across the United States (Malm and Sisler, 2000) and Madrid, Spain (Salvador et al., 2011), respectively, and up to 95 μg m^{-3} in western Saudi Arabia between 2012 and 2015, 138.5 μg m^{-3} in Beijing between 2004 and 2012 (Liu et al., 2015), and 140.1 μg m^{-3} and 196.6 μg m^{-3} in residential and industrial sites, respectively, in Kolkata, India (Gupta et al., 2008). Major PM_{10} sources include crustal matter (dust, sea salt), biomaterials, combustion, biomass burning, shipping, industrial activity, construction, and vehicular emissions (e.g., Im et al., 2010; Unal et al., 2011; Hersey et al., 2015; Lopez et al., 2016). PM_{10} is influenced by seasonally-dependent source emissions and meteorological factors such as wind and precipitation. Thermodynamic factors are also important including boundary layer height, which strongly influences ambient aerosol concentrations. It is currently uncertain as to how such environmental factors affect PM_{10} in Ahvaz on a temporal basis.

The first objective of this work is to evaluate the temporal nature of PM_{10} in Ahvaz between 2009 and 2014 using surface measurements at four locations. The second objective is to assess the health effects of PM_{10} concentration on citizens of Ahvaz. The subsequent results discussed have major implications for inhabitants of this and other nearby regions of the Middle East that consistently rank as the most polluted cities of the world owing to the overwhelming influence of dust on a mass basis.

2. Materials and methods

2.1. Field measurements

Ahvaz (31° 32′ N and 48° 68′ E) is in the Khuzestan province and is the most populated city in southwest Iran, with an area of ~530 km^2. Measurements of PM_{10} were conducted at four locations (Fig. 1) to achieve improved spatial coverage as compared to one site. The environmental protection agency of the Khuzestan province is responsible for the operation of these four stations. PM_{10} concentration was measured each month from 2009 through 2014 using the Beta Attenuation method. This sampling method relies on absorption of beta radiation by sampled aerosol to quantify PM_{10} and is often used in routine monitoring networks (e.g., Watson et al., 2000; Salminen and Karlsson, 2003; Hauck et al., 2004). Data collected from the four stations are averaged for the results discussed subsequently.

Based on the classification method of Hoffmann et al. (2008) involving PM_{10}, wind speed, and visibility, our PM_{10} are placed into different categories based on the severity of dust storms experienced (Table 1). The categories are referred to here as the following: Dusty Air (DA), Light Dust Storm (DS_1), Dust Storm (DS_2), Strong Dust Storm (DS_3) and Serious Dust Storm (DS_4).

2.2. Health effect calculations

Health assessment calculations attributed to PM_{10} are computed using the Air Quality Health Impact Assessment software (AirQ2.2.3) developed by the WHO. This software has been employed in a variety of past studies (Fattore et al., 2011; Naddafi et al., 2012; Gharehchahi et al., 2013; Gholampour et al., 2014; Ghozikali et al., 2015; Goudarzi et al., 2015; Marzouni et al., 2016) and allows for calculations of the potential impact of exposure to air pollutants in specific urban areas during a specific time period. The method is based on quantification of ‘attributable proportion (AP)’, which is the fraction of a given health outcome in a population due to exposure to a specific pollutant with the assumption of a proven causal relationship between exposure and the health outcome. The formula for AP is as follows:

$$AP=\frac{\sum[(RR(c)-1)\times p(c)]}{\sum[RR(c)\times p(c)]} \quad (1)$$

where RR(c) is the relative risk for a health outcome in category “c” of exposure, and p(c) is the proportion of population in category “c” of exposure. In this study we compute the number of cases associated with total mortality (TM), cardiovascular mortality (CM), respiratory mortality (RM), hospital admission respiratory disease (HARD), hospital admission for chronic obstructive pulmonary disease (HA COPD), and hospital admission cardiovascular disease (HACD) attributed to PM_{10} in Ahvaz between 2009 through 2014.

3. Results

3.1. Temporal profile of PM_{10}

The cumulative diurnal PM_{10} profile exhibits a dominant concentration peak between 08:00–11:00 (local time) with values ranging between 259 and 261 μg m^{-3} (Fig. 2). The next largest PM_{10} concentration (253 μg m^{-3}) was observed at 01:00. The lowest PM_{10} was measured at 17:00 reaching 212 μg m^{-3}. The lowest levels were observed in the afternoon hours at least partly due to the deeper mixing layer that dilutes the concentrations of pollutants as compared to the early morning hours (e.g., Crosbie et al., 2014). Diurnal wind speed data were obtained from the Iran Meteorological Organization (www.irimo.ir) and they exhibit a trend similar to PM_{10} with a dominant peak in the late morning (Fig. 2). Thus, the PM_{10} mode in the morning after 08:00 is due to a likely combination of wind-driven emissions and activities associated with the work day such as vehicular emissions, road dust, construction and emissions from steel, oil, gas and petroleum industries.

It is of interest to contrast the results of Fig. 2 with the diurnal profile observed in the nearby metropolitan city Tehran (Hassanvand et al., 2014). The latter study showed that minimum and maximum concentrations of PM_{10} between May 2012 and January 2013 occurred at 06:00 and 09:00, respectively, and that concentrations were much less than at Ahvaz. Ahvaz exhibits a more long-lived peak in the mid-to-late morning and a more defined long-lived minimum in the afternoon as compared to Tehran. It is unclear as to what explains the varying diurnal behavior but possibilities include a larger population in Tehran (>12 million; United Nations Population Fund, http://iran.unfpa.org/), the closer proximity of Ahvaz to natural dust sources to the west, and varying wind patterns owing partly to different surrounding terrain.

As Ahvaz is a city with over 1 million people, the diurnal PM_{10} profile is also divided between weekday and weekend days to determine if there is an anthropogenic signature manifested in the form of enhanced levels during weekdays. Note that the weekend in Iran is typically on Friday but that Thursday is also a reduced work day for some industries. Fig. 2 shows that weekday PM_{10} levels indeed are enhanced between the hours of work (07:00–17:00) by an average amount of 14.2 μg m^{-3}, which is suggestive of anthropogenic effects leading to the difference in the diurnal profiles. In nearby western Saudi Arabia, PM_{10} exhibited a minimum in the early afternoon and peaks around 09:00 and 19:00; when diurnal data at that location was examined separately for weekends and weekdays, PM_{10} was higher between 11:00–20:00 on weekdays. In Beijing, PM_{10} exhibited a bimodal diurnal behavior with peaks at 07:00–08:00 and 19:00–23:00, owing presumably to rush hour traffic, and a minimum at noon (Liu et al., 2015). In western India, PM_{10} peaked during the morning and evening rush hours with minimum values in the afternoon when there is less vehicular traffic.

To further isolate an anthropogenic pollution signature, the day-of-week profile of PM_{10} is shown in Fig. 3. There is a minimum value on Monday (226.9 μg m^{-3}) and a maximum value at the end of the work week on Wednesday (269.2 μg m^{-3}). The weekly average of PM_{10} level in Ahvaz (250 μg m^{-3}) is 1.7 and 5 times higher than daily average guideline values of the National Ambient Air Quality Standard (NAAQS) (US EPA, 2008) (150 μg

m^{-3}) and WHO (WHO, 2006) (50 μg m^{-3}), respectively. It is interesting that there is no evident 'weekend effect' observed (i.e., lower PM_{10} levels on the weekend owing to less anthropogenic activity) but that higher PM_{10} is observed during work hours on weekdays (Fig. 2). This is likely due to the large influence from natural dust emissions that are insensitive to the day of the week.

The weekend effect is more evident in other desert regions such as in the Sonoran Desert where dust tracers such as Si exhibit a peak near the end of the work week (Thursday) and a minimum on the weekend (Sunday) (e.g., Prabhakar et al., 2014). Weekend PM_{10} levels are lower in other regions such as western Saudi Arabia, western India, and eastern India (Gupta et al., 2008). Even in less arid regions such as Istanbul, Turkey, PM_{10} exhibits a weekend effect with lower levels on weekends, especially Sunday (Unal et al., 2011).

The monthly profile of PM_{10} level in Fig. 4 exhibits a clear mode in June and July with average values of 376.8 and 420.5 μg m^{-3}, respectively. The lowest values were in the winter, with a minimum in January (154.6 μg m^{-3}). These results indicate that Ahvaz is much more influenced by dust sources as compared to anthropogenic sources and seasonally-related burning, the latter two of which translate to higher aerosol levels in winter months typically. In addition, the overwhelming abundance of airborne dust in the summer in Ahvaz easily trumps the dilution effect due to higher boundary layer heights at that time of the year as compared to the winter.

There are varied monthly profiles of PM_{10} in different global regions. In the Sonoran Desert of North America, PM_{10} was shown to be highest in the winter in the highly urbanized city of Phoenix, Arizona while less populated areas in the same region exhibited peak levels in the spring and summer owing to the more dominant relative influence of dust versus anthropogenic sources at those times of the year (Sorooshian et al., 2011). Other sites with maximum PM_{10} levels in the winter include the Gobi Desert of Mongolia (Jugder et al., 2011), an urban area of Italy (Malandrino et al., 2013), northern China (Zhou et al., 2016), and Kolkata, Indian (Gupta et al., 2008). In contrast, peak PM_{10} was observed in the spring in Beijing (Liu et al., 2015), western Saudi Arabia, and western India. PM_{10} was a maximum between June and September in the Madrid, Spain air basin (Salvador et al., 2011). The varying results between these sites are attributed to the relative importance of dust and anthropogenic emissions, in addition to seasonally dependent wind directions and emissions.

The interannual profile of PM_{10} interestingly shows a clear and steady decline in levels during the study period between 2009 (315.2 μg m^{-3}) and 2014 (143.5 μg m^{-3}), with a slope of −30.31 μg m^{-3} yr^{-1}. Even the lowest annual-mean concentration in 2014 still exceeded both the annual-mean limits of NAAQS (US EPA, 2008) and WHO (WHO, 2006) by factors of 2.9 and 7.2, respectively. It is unclear exactly with the dataset as to what factor(s) govern this reduction of PM_{10} to result in a mean level in 2014 that is 46% of that in 2009. Possibilities include changes in meteorology, land use change, and variations in human activity. In contrast, PM_{10} levels increased significantly between 1997 and 2012 to the west in Mecca, Saudi Arabia (Munir et al., 2013) with stated reasons including construction, increasing number of people who visit for Hajj and Umrah, and meteorological factors.

Thus, it may be possible that an examination of PM_{10} over a longer time scale would yield different results for Ahvaz, but such data are not available for this study.

3.2. Temporal profile of number of dust storm days

Tables 2 and 3 summarize the distribution of dust storm days as a function of month and year, respectively. The total number of dust storm days (i.e., $DS_1 + DS_2 + DS_3 + DS_4$) reached 780, which equates to a cumulative 2.14 years of time within the six-year study period (2009–2014). As expected based on results of Fig. 4, the most and least amount of dust storm days occurred in June–July (105–110) and January (23), respectively, during the entire six-year period. A previous study in Ahvaz spanning from 2001 to 2009 reported that the monthly concentration maximum of total suspended particles (TSP) was observed in July and September during dusty days (Shahsavani et al., 2012a). A remarkable result of the current study is that 58.3% and 59.1% of days in June and July, respectively, qualified as dust storm days.

In terms of interannual variability, the number of dust storm days ranged from 186 (in 2009) to 42 (in 2014). There was a decreasing trend of dust storm days with time, similar to interannual variability in PM_{10} concentration (Fig. 5). Although not shown, a linear best fit line between number of dust storm days versus year exhibits a slope of -23.2 days yr^{-1} and a r^2 value of 0.75.

3.3. Categorization of PM_{10} data

Table 4 shows how the PM_{10} data are distributed among the categories defined in Table 1. Of the 2191 days between 2009 and 2014, 39 of them (1.8% of all days) exhibited PM_{10} levels below 50 μg m^{-3} and 1372 days (62.6% of all days) were Dusty Air (DA) days with PM_{10} between 50 and 200 μg m^{-3}. After DA days, the next most common category of events was for Light Dust Storm Days (DS_1) with 618 days (28.2% of all days). DS_2, DS_3, and DS_4 comprised the remaining 6.6%, 0.7%, and 0.1% of days in the dataset. Table 4 shows that as the average PM_{10} concentration increased from DA to DS4, the standard deviation also increased from 36.6–1838.5 μg m^{-3}.

3.4. Health risk assessment of PM_{10}

Results of health effects of PM_{10} in Ahvaz, as simulated by the AirQ2.2.3 model, are summarized in Table 5. A total of 3777 individuals were calculated as having Total Mortality (TM) as a health outcome due to PM_{10} exposure between 2009 and 2014, which equates to an average of 630 per year during the study period. The interannual profile of TM closely mimics that of the number of dust storm days in Table 3 rather than PM_{10} levels. The interannual profile of Cardiovascular Mortality (CM) and Respiratory Mortality (RM) correlate strongly with TM, where a mean-annual amount of 381 and 108 people are computed as having CM and RM, respectively, as health outcomes. The interannual profile of hospital admissions due to respiratory disease (HARD), chronic obstructive pulmonary disease (HACOPD), and cardiovascular disease (HACD) matched those of mortality. The highest mean-annual amounts of admissions was for HARD (2411), followed by HACD (505) and then HACOPD (99).

While the calculations with the AirQ2.2.3 model are specific to PM_{10} data, it is well documented that particulates associated with $PM_{2.5}$ are better related to health effects as compared to coarser particles ($D_p > 2.5$ μm) as the latter deposit more effectively in the upper respiratory tract via impaction (e.g., Dockery et al., 1993). Future work is warranted in the study region to examine aerosol concentrations for smaller sizes than this study, and to relate those concentrations to PM_{10} as the latter is routinely monitored in the study region. It is highly plausible that smaller particles are enhanced in concentration during dust storms in Ahvaz. Aside from health effects associated with inhaling dust, another important issue with regard to PM_{10} is that of decreased visibility leading to traffic accidents.

4. Conclusions

This study examines six years of PM_{10} data in Ahvaz, Iran to characterize the temporal profile of airborne particulate matter, and to also calculate the health impacts of PM_{10} exposure in this area with the AirQ model. The mean PM_{10} level in Ahvaz was 249.5 μg m^{-3}, with maximum and minimum values in July (420.5 μg m^{-3}) and January (154.6 μg m^{-3}), respectively. The cumulative diurnal PM_{10} profile exhibits a dominant peak between 08:00–11:00 (local time) with the lowest levels in the afternoon hours. An anthropogenic signature is observed diurnally on weekdays, which exhibit higher PM_{10} levels between 07:00–17:00 as compared to weekend days. Interannually, PM_{10} has shown a steady mean-annual decline between 2009 (315.2 μg m^{-3}) and 2014 (143.5 μg m^{-3}). The AirQ model predicts that mortality was a health outcome for a total of 3777 individuals between 2009 and 2014 (i.e., 630 per year).

The results of this study motivate more aggressive strategies in Ahvaz and similarly polluted desert cities to reduce the health effects of the enormous aerosol levels confronting the public. The integration between temporally-resolved measurements of PM_{10} and health model calculations provides a suitable tool for the general public, urban air pollution managers and decision makers to mitigate effects associated with the time of PM_{10} peaks. The results of this work motivate immediate the use of personal protection devices and use of air conditioning systems equipped with effective particle filtration to improve indoor air quality.

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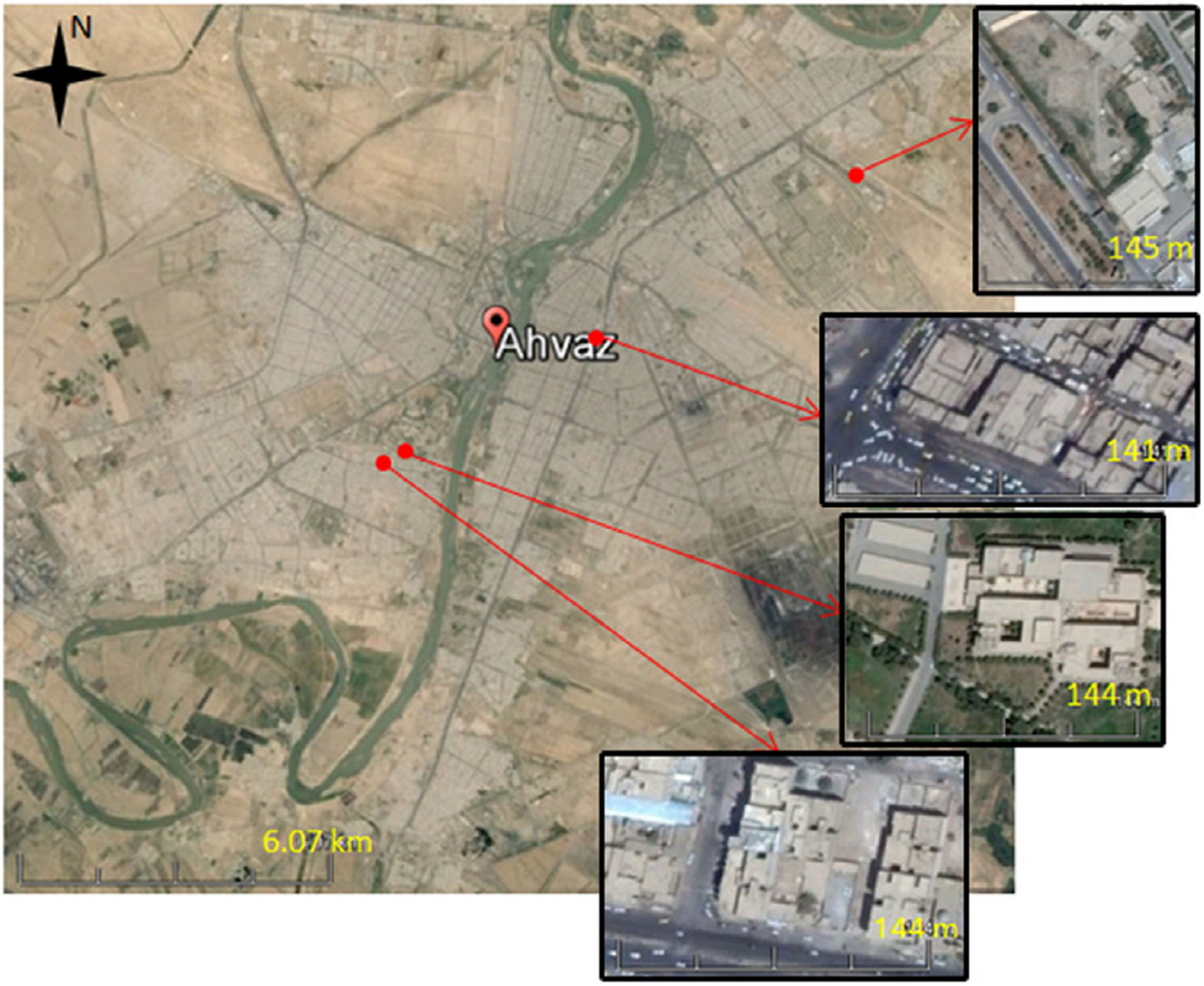

Fig. 1.

Location of the four air quality monitoring stations in the city of Ahvaz, Iran. Names of stations (from top to bottom) are Havashenasi, Naderi, Behdasht ghadim, and Mohit Zist.

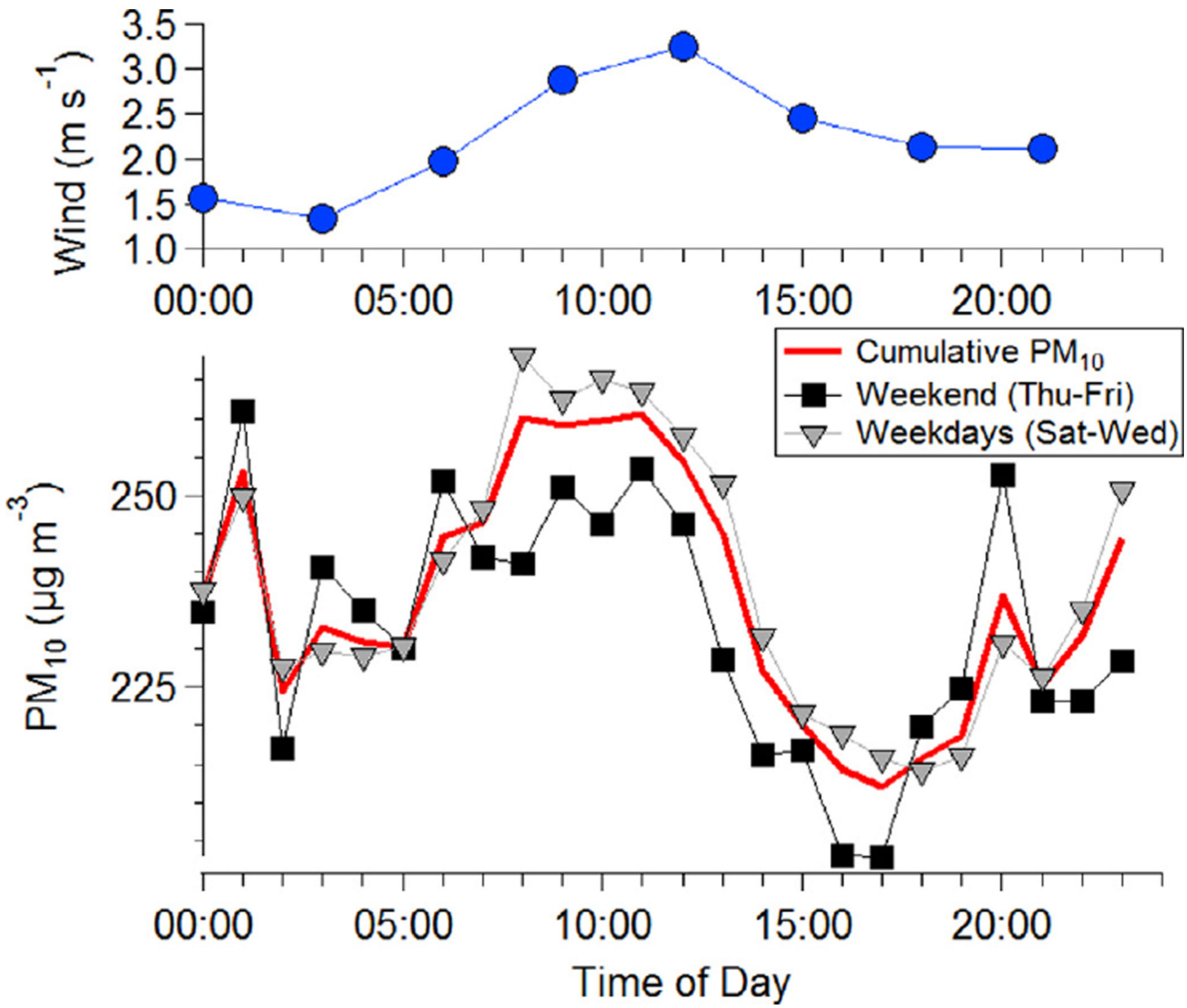

Fig. 2.

Diurnal profile of (top) wind speed and (bottom) PM_{10} concentration in Ahvaz based on average data from the four stations in Fig. 1. Data are shown for the cumulative dataset and when divided between weekdays and weekends.

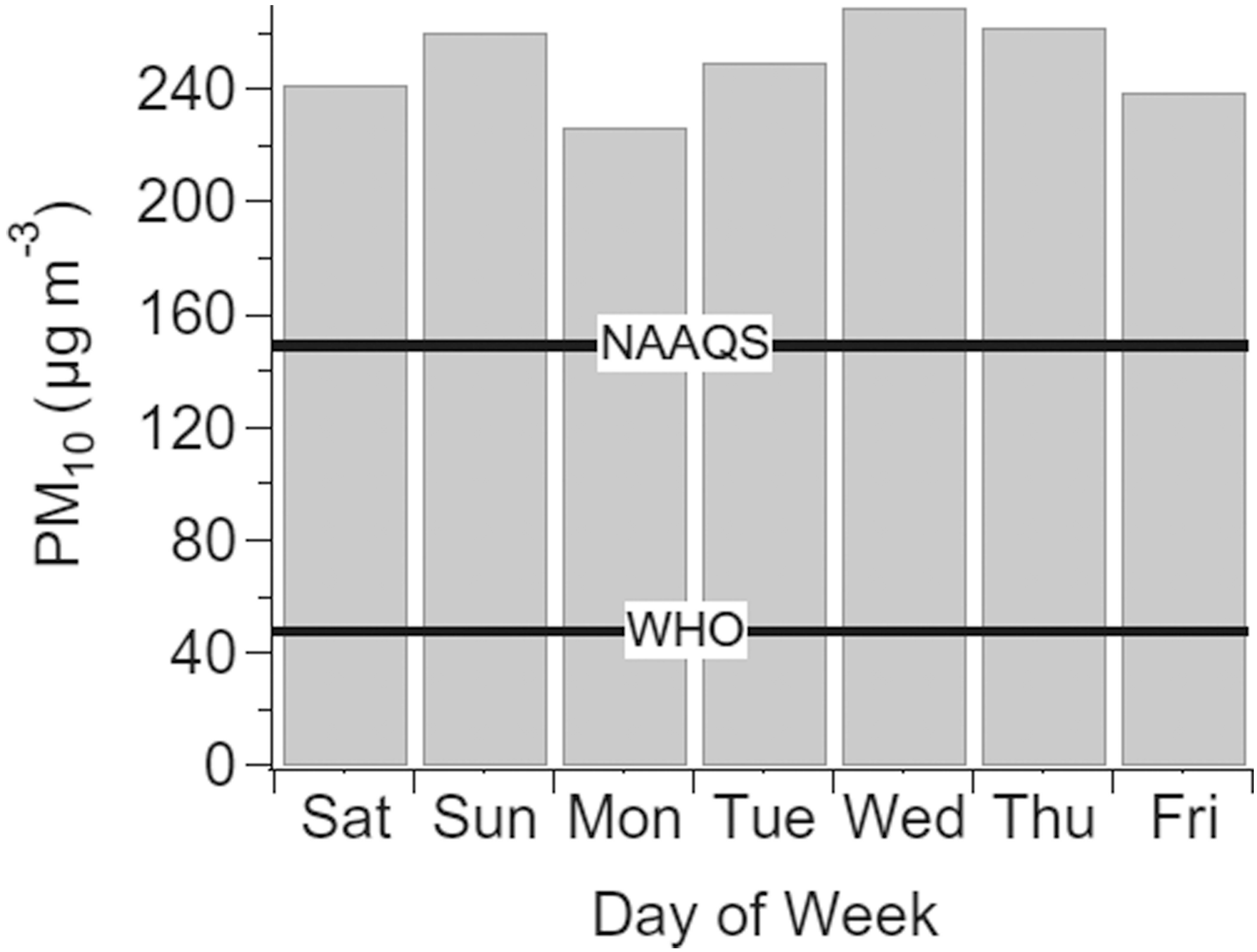

Fig. 3.

Weekly average variation of PM$_{10}$ concentration in Ahvaz relative to the 24-h guidelines of WHO (50 µg m^{-3}) and NAAQS (150 µg m^{-3}).

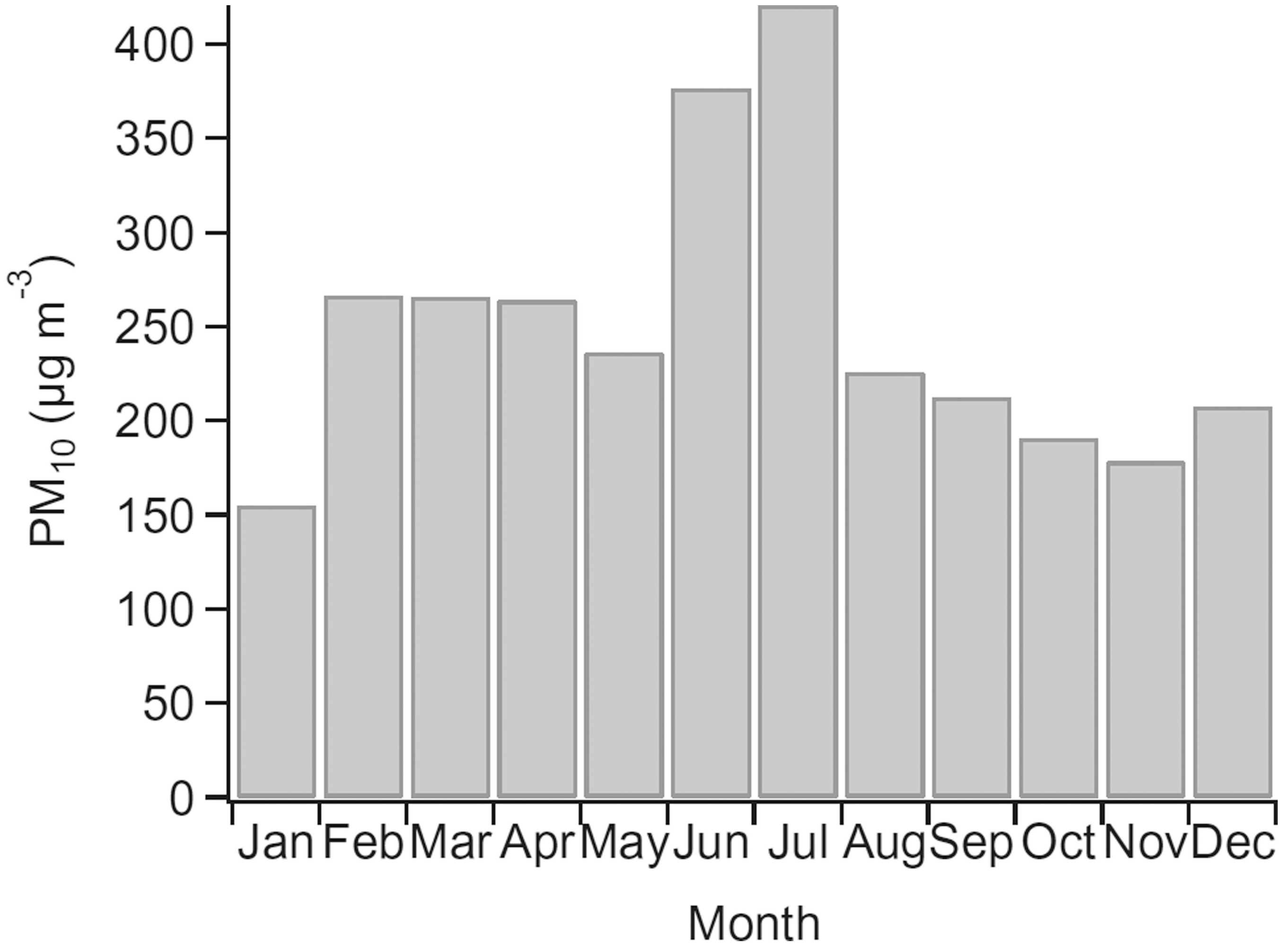

Fig. 4.

Monthly average variations of PM_{10} concentration in Ahvaz based on average data from the four stations in Fig. 1.

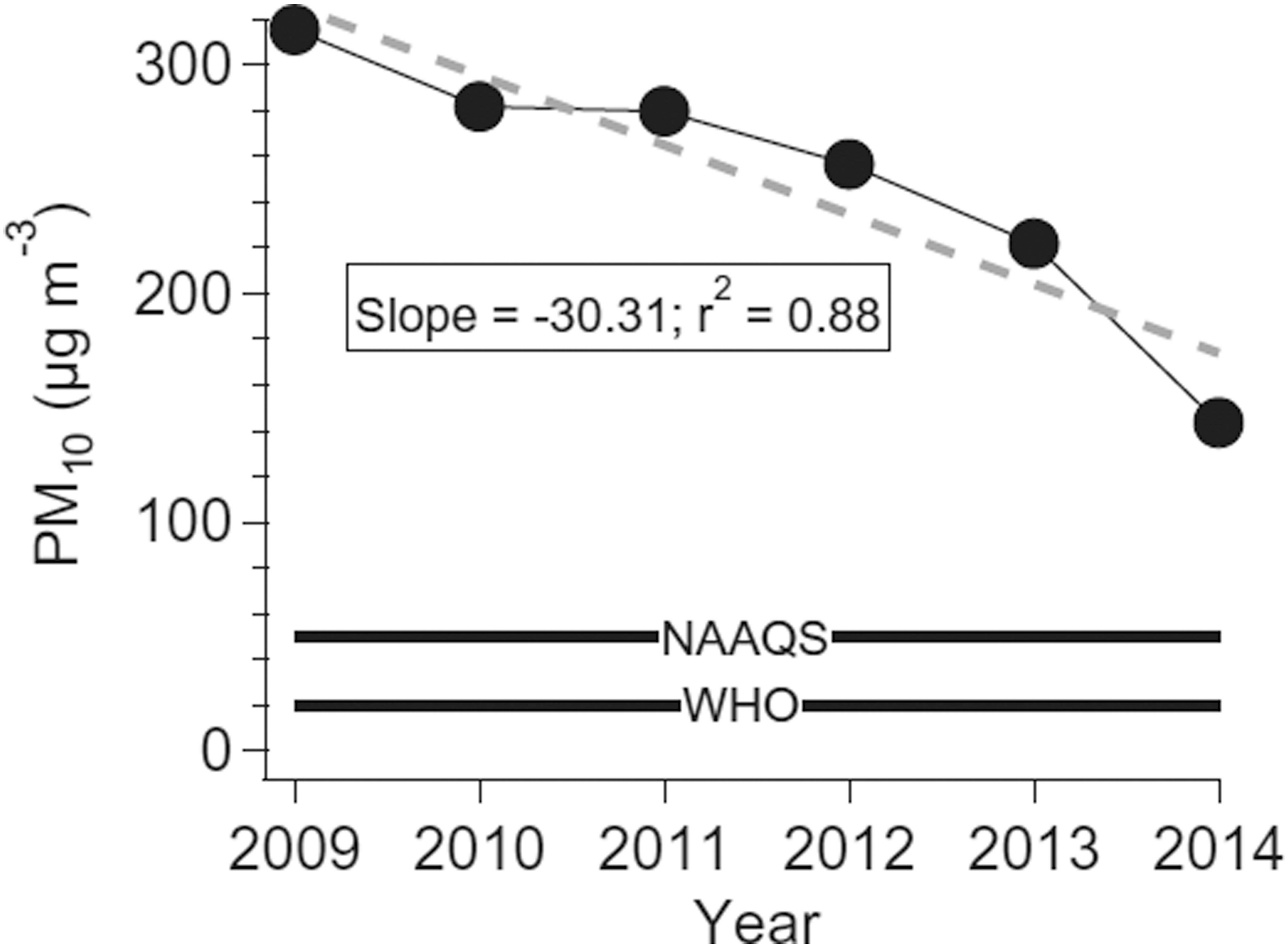

Fig. 5.

Interannual profile of Ahvaz PM$_{10}$ concentration relative to the annual-mean guidelines of WHO (20 µg $^{m-3}$) and NAAQS (50 µg m^{-3}).

Table 1

Dust storm classification method as described by Hoffmann et al. (2008).

Category	Visibility (m)	Wind speed (m s^{-1})	Hourly PM$_{10}$ (μg m^{-3})
Dusty air (DA)	Haze	–	50–200
Light dust storm (DS$_1$)	<2000	–	200–500
Dust storm (DS$_2$)	<1000	>17	500–2000
Strong dust storm (DS$_3$)	<200	>20	2000–5000
Serious strong DS (DS$_4$)	<50	>25	>5000

Table 2

Monthly profile of number of dust storm days, in addition to the average and standard deviation of PM_{10} measurements in Ahvaz between 2009 and 2014.

Month	**# dust storm days**	**% of dust storm days in month**	**PM_{10} average ($\mu g\ m^{-3}$)**	**PM_{10} Std. Deviation**
January	23	12.4	439.9	237.7
February	51	30.2	586.2	518.5
March	77	41.4	466.2	477.8
April	63	35.0	507.5	1233.9
May	75	40.3	392.6	279.3
June	105	58.3	546.2	800.0
July	110	59.1	610	722.8
August	71	38.2	376.3	207.1
September	56	31.1	370.7	482.2
October	66	35.5	295.7	107.4
November	39	21.7	411.2	261.8
December	44	23.7	483.1	536.9

Table 3

Interannual profile of number of dust storm days, in addition to the average and standard deviation of all PM_{10} measurements in Ahvaz between 2009 and 2014.

Year	# dust storm days	% of dust storm days in year	PM_{10} average ($\mu g\ m^{-3}$)	PM_{10} Std. Deviation
2009	186	51.0	480.1	445.0
2010	165	45.2	453.9	458.0
2011	117	32.1	602.1	1233.2
2012	145	39.6	445.3	405.3
2013	125	34.2	396.7	334.6
2014	42	11.5	411.2	401.1

Table 4

Categorization of Ahvaz PM_{10} data into groups defined in Table 1.

Category	**Wind speed ($m\ s^{-1}$)**	**# days**	**% of total days**	**PM_{10} average ($\mu g\ m^{-3}$)**	**PM_{10} Std. Deviation**
Other	2.64	39	1.8	40.2	7.3
DA	2.00	1372	62.6	130.8	36.6
DS_1	2.49	618	28.2	296.9	75.7
DS_2	2.89	145	6.6	834.7	316.7
DS_3	2.62	15	0.7	2945.4	758.1
DS_4	3.94	2	0.1	8700	1838.5

Table 5

Health impact assessment of PM_{10} on Ahvaz inhabitants.

Year	TM	CM	RM	HARD	HACOPD	HACD
2009	771	463	130	3047	121	619
2010	707	426	120	2117	111	567
2011	605	368	105	2445	94	486
2012	653	395	112	2619	102	524
2013	625	379	108	2517	98	501
2014	416	256	75	1723	65	334
Average	630	381	108	2411	99	505
Sum	3777	2287	650	14468	591	3031

TM = Total Mortality; CM = Cardiovascular Mortality; RM = Respiratory Mortality; HARD = Hospital Admission Respiratory Disease; HACOPD = Hospital Admission For Chronic Obstructive Pulmonary Disease; HACD = Hospital Admission Cardiovascular Disease.