Temporal changes of particulate concentration in the ambient air over the city of Zahedan, Iran

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Abstract

Air pollution in developing countries has recently become a serious environmental problem which needs more active air quality monitoring and analyses. To assess air quality characteristics over the city of Zahedan, southeast Iran, airborne Particulate Matter (PM) concentrations with aerodynamic diameters of < 10 µm, < 2.5 µm and < 1.0 µm were measured during the period July 2008 to March 2010 using an Environmental Dust Monitor (EDM-180). The data were analyzed on daily, monthly and seasonal basis. The highest monthly mean PM_{10} levels (172 μgm^{-3}) were recorded during the summer period (June - August), presumably due to frequent dust storms from the nearby Sistan desert located to the north, while less PM_{10} concentrations are recorded in winter (December-February) (101 μgm^{-3}). Linear regression analysis between the $PM_{2.5}$ and PM_{10} time series reveals high correlation coefficients (r>0.82) for all seasons, implying that PM_{10} and $PM_{2.5}$ may have the same source regions, or that they are influenced by the same local conditions. In contrast, neutral correlation is found between PM_{10} and $PM_{1.0}$ in autumn and winter. Taking into account that the annual variation of $PM_{1.0}$ exhibits a clear pattern of peaking in winter and dropping in summer (in contrast to PM_{10}), it is suspected that $PM_{1.0}$ is of different origin than PM_{10} and mainly influenced by local anthropogenic emissions. The daily PM_{10} variation is strongly seasonally defined. The maximum PM_{10} concentrations occur in the morning hours during winter, autumn (September-November) and early spring (March), while in summer PM_{10} concentrations increase significantly in the afternoon closely associated with the intense northerly winds blowing from the desert. As far as the Air Quality Index (AQI) is concerned, its highest monthly values occur in summer, while they are reduced in winter. Desert dust aerosols are found to be the major component in determining the AQI in Zahedan. The analysis shows that 15.3 % of the days are unhealthy for sensitive people, while 2 % are considered as hazardous.

Keywords*:* Particulate matter, dust, mass concentration, Air Quality Index, Zahedan, Iran

1. Introduction

Increased air pollution has recently become a major health concern in the developing countries of south Asia (e.g. Singh *et al*., 2004; Ramachandran and Rajesh, 2007). Several studies demonstrated that airborne Particulate Matter (PM) has an impact on climate (Broecker, 2000), biogeochemical cycling in ecosystems (Nriagu and Pacyna, 1988), visibility (Husar *et al*., 1997) and human health (Nriagu, 1988; Dockery *et al*., 1993; Dockery and Pope, 1996;). More specifically, air pollution appears to have an adverse effect on respiratory and cardiovascular systems (Nastos *et al*., 2010), which might result in an acute reduction of lung function, aggravation of asthma, increased risk of pneumonia in the elderly, low birth weight and high death rates in newborns (Wilson *et al*., 2004). Over recent years in the public health domain the PM concentration has become a topic of considerable importance, since epidemiological studies have shown that exposure to particulates with aerodynamic diameters of < 10 µm (PM_{10}) and especially < 2.5 µm ($PM_{2.5}$) induces an increase of lung cancer, morbidity and cardiopulmonary mortality (e.g. Pope, 2000; Schwartz, 2004; Pozzi *et al*., 2005; Chakra *et al*., 2007; Brook *et al*., 2009; Sivagangabalan *et al*., 2010; Bhaskaran *et al*., 2011). Although there is still a fundamental lack of understanding of the underlying mechanisms of their toxicity to humans, one of the widely accepted hypotheses is that toxicity of PM depends not only on their size, but also on their composition, both of which depend on emissions, location, time of year, meteorological conditions and mixing processes (Akyuz and Cabuk, 2009). The national air quality standards in many countries are currently under review with the aim to include the monitoring of aerosol load in order to maintain a healthy atmospheric environment. For example, the United States Environmental Protection Agency (USEPA) replaced the monitoring of total suspended particulate matter with PM_{10} measurements and, has recommended the monitoring of the $PM_{2.5}$ fraction of aerosols (USEPA, 2006). Based on Environmental Protection Agency (EPA) standards, the concentration of PM_{10} is regarded as an important criterion for determining the Air Quality Index (AQI), which is a measure of quality of the ambient air at a specific location.

In addition to increased anthropogenic emissions as a result of population growth, air quality in south Asia is also affected by natural phenomena such as dust storms (Badarinath *et al.*, 2007; Alam et al., 2011a, b). Dust is considered to be one of the major components of tropospheric aerosols over the globe (Mishchenko and Geogdzhayev, 2007) with global flux estimations of 1500-2600 Tg yr^{-1} (IPCC, 2007) and constitutes a key parameter in climate aerosol-forcing studies (Pandithurai *et al.*, 2007; Prasad *et al.*, 2007; Gautam *et al.*, 2009). The impact of dust on solar radiation depends mainly on its physical properties such as size, shape and mineralogy (e.g. Washington *et al.*, 2003; Kalashnikova and Kahn, 2008). These are initially determined by the terrestrial sources from which the soil sediments are entrained, although these parameters are subjected to change during dust transport (Mahowald *et al.*, 2005). Dust aerosols strongly affect visibility, atmospheric dynamics and weather, perturb the radiation balance of the earth-atmosphere system and might have a noticeable effect on ecosystems and even human health (Goudie and Middleton, 2001; Engelstaedter *et al.*, 2006; Kaskaoutis *et al.*, 2010).

Provisional studies focusing on air quality and dust over Iran have already been carried out. Amongst others, Mousavi and Nadafy (2000) performed a comparative study of air quality in Tehran during the period 1997-1998. The results revealed that in 1997 the air quality on 32% of the days was unhealthy, and on 5% of the days was regarded as very unhealthy, whereas in 1998 the unhealthy and very unhealthy days increased to 34% and 6%, respectively. Cheraghi (2001) studied the air quality in Tehran and Isfahan and offered solutions for its improvement using the AQI. It was found that on 329 days of the year in Tehran, and on 34 of the days in Isfahan, the AQI departed beyond 100. Ardakani (2006) also studied AQI in Tehran reporting that on 273 days in 2001 the values were higher than those set for the air quality standards; 47 of the days were considered as very unhealthy and 1 was classified as dangerous.

The present work analyzes the temporal variation of PM_{10} and $PM_{2.5}$ concentrations in the atmosphere above the city of Zahedan in southeastern Iran focusing mainly on the following four objectives: (i) establishing baseline PM_{10} and $PM_{2.5}$ concentration levels, which could be used in the future to assess the effectiveness of any implemented emission control strategies; (ii) comparing the observed PM_{10} and $PM_{2.5}$ concentration levels to the corresponding EU and USA ambient particle standards; (iii) determining the relative contribution of $PM_{2.5}$ and examining the relationship between PM_{10} and $PM_{2.5}$ levels, which may be used to estimate retrospectively particle concentration trends, (iv) revealing the role of wind speed, especially in summer, to the PM levels and, (v) revealing the fraction of days that are unhealthy for the population based on AQI values. The AQI might be used to provide information regarding the status of Zahedan's air quality and the associated health concerns for the public, especially during summer when severe air pollution episodes and dust outbreaks occur as a result of favourable meteorological conditions. It should be noted that such studies are lacking from this region and this is the first that examines the seasonal evolution of PM concentrations and AQI over Zahedan, aiming also to relate the peak values in PM with dust exposures from the nearby Sistan desert.

2. Study area and data collection

2.1. Study area and the Levar

All measurements have been carried out in the city of Zahedan located in the southeastern part of Iran (60.52^o East, 29.32^o North, 1384 m a.m.s.l) close to the Iranian borders with Pakistan and Afghanistan (Fig 1). Located just south of the Sistan desert, Zahedan is affected by frequent dust and sand storms, especially during the summer season (June to August) due to the prevailing northerly winds, commonly known as the "120 day wind" or "Levar" (Middleton, 1986; Goudie and Middleton, 2001). The city has a population of more than 800,000 and is regarded as a moderately urbanized area with several small industries and a large number of automobiles, which contribute to the production of local aerosols. The climate is semi-arid to arid, with a low annual average precipitation of 84 mm occurring mainly in winter (Dec to Feb). Monthly mean values of temperature, Relative Humidity (RH), atmospheric pressure and accumulated precipitation in Zahedan during the study period (July 2008 – March 2010) are plotted in Fig. 2. The monthly mean temperature exhibits a clear annual pattern with low values in winter (10-13 ^{o}C) and high values (~33 ^{o}C) in summer following the common pattern found in the northern mid-latitudes. RH illustrates an inverse annual variation with larger values in winter (50-65%) and very low values in summer (below 20%), which are indicative for an arid environment. The atmospheric pressure is generaly steady (~869 hPa) from January to April, and then decreases significantly during summer, and increases again in autumn. The summer low pressure (862 hPa in July) is attributed to the

Indian thermal low that extends further to the west over the arid environments of Iran and Middle East as a consequence of the south Asian monsoon system. These low pressure conditions are the trigger for the development of the Levar wind. During the study period the rainfall was restricted to winter and spring, while the maximum acccumulated rainfall in February (20 mm) is indicative of the typical arid environment.

The Levar wind circulation is not only an atmospheric system that has a significant environmental impact in the Sistan basin, but is also one of the least studied meteorological phenomena in Iran and its surroundings. The Levar wind is modulated by the intense solar heating of the south Asian landmass in summer months. It develops as a result of the formation of an intense near-surface low-pressure system over south Asia associated with strong positive turbulent sensible heat flux (Hossenzadeh, 1997; De Wekker *et al.*, 1998, and references therein). Other studies suggest that the Levar might be a limb of the return flow of the Indian monsoon circulation (Hahn and Manabe, 1975). However, the physical mechanism involved has not yet been satisfactorily explained. Despite the above, the Levar wind contributes significantly to dust storms and degradation of air quality over the study region.

2.2. PM measurements

PM concentrations at near-surface level in the city of Zahedan have been systematically measured using Environmental Dust Monitor model 180 (EDM-180). The present measurements were carried out during the period July 2008 to March 2010 (total of 399 days) at the Environmental institute in Zahedan, Iran. The EDM-180 measures PM concentration (in μgm^{-3}) for 3 particle sizes, namely PM_{10}, $PM_{2.5}$ and $PM_{1.0}$, with a relatively high temporal resolution (5-min) of recordings. The recording station is located at the outskirts of the city, in a sparsely-populated area without any industries and direct influence by anthropogenic emissions. The 5-min measured PM data were converted to 24-hour averages (daily averages) from which the monthly and seasonal values and variations were obtained. For assessment of air quality in Zahedan, the desired data were sorted according to AQI standards and were analyzed to determine the fraction of days per month and season where air pollution was above AQI standards, or levels regarded as dangerous for public health.

3. Results and discussion

3.1. Seasonal and monthly variability in PM concentrations

Figure 3 illustrates the annual variation of PM concentrations as obtained from the monthly mean EDM recordings during the period July 2008 to March 2010. The vertical bars depict one standard deviation from the monthly mean and are indicative of the day-to-day variation. On this basis, it is observed that the months with the highest PM levels also depict the largest standard deviations. This occurs mainly in summer, which is the period with the most frequent dust-storm events. One can, therefore, conclude that the intense dust storms taking place on specific days during summer are predominantly responsible for the large day-to-day variations at all PM concentrations.

The annual pattern of PM_{10} shows a significant increase in summer where monthly mean concentrations of up to ~170-180 μgm^{-3} were recorded in June and July (Table 1). PM_{10} concentrations during winter months are significantly lower with 64 μgm^{-3} measured in December. January and February exhibit PM_{10} concentrations of above 100 μgm^{-3}, which persist until April when PM_{10} levels increase as a result of the Levar wind. The highest PM_{10} concentration (970 μgm^{-3}) is recorded during June (Table 1) closely associated with a severe dust event. The annual variation of monthly mean $PM_{2.5}$ is somewhat similar (July maximum), but with a more complex pattern. In contrast, the annual variation of monthly mean $PM_{1.0}$ is reversed since maximum values (14-20 μgm^{-3}) are observed in winter months. A small peak is also observed in July associated with a large standard deviation. The difference in the annual variation between PM_{10} and $PM_{1.0}$ suggests differences in source regions for these aerosol sizes. The main anthropogenic source of PM in the Zahedan urban environment can be confined to vehicular traffic, fossil-fuel combustions, central heating and industrial activities that release a large amount of near-surface anthropogenic aerosols. Similar annual variations of the anthropogenic aerosols have been observed within urban environments in India (Badarinath *et al.*, 2009; Ramachandran and Kedia, 2010; Pathak *et al.*, 2010). In addition, the boundary layer mixing height is lower in winter and traps the pollutants near the ground as a result of temperature inversions. All the above explain the higher concentration of small-sized particles ($PM_{1.0}$) in winter. In contrast, during summer months thermal heating at the surface and the increase of the mixing layer height favors buoyancy and the dilution of anthropogenic aerosols ($PM_{1.0}$). Apart from desert dust, a natural contribution to the total PM (mainly to $PM_{2.5}$ and PM_{10}) concentrations is also expected to originate from aeolian and traffic-driven re-suspension, since the scarce rainfall favors the accumulation of road dust in summer.

Some studies conducted in other urban environments, e.g. Akyuz and Cabuk (2009) in Turkey and Chaloulakou *et al.*, (2003) in Athens, Greece found, contrary to our results, that in winter both PM concentrations were higher, which was attributed to larger use of fossil fuels in winter. Chaloulakou *et al.*, (2003) reported monthly mean PM_{10} concentrations in Athens ranging from 60.3 μgm^{-3} (January) to 88.9 μgm^{-3} (December), with an annual mean value of 75.5 μgm^{-3}. In Barcelona, Spain, the ambient PM_{10} and $PM_{2.5}$ were in the range of 39 to 42 μgm^{-3} and 25 to 29 μgm^{-3}, respectively over the period 2003-2006 with 97 daily values exceeding 50 μgm^{-3} (Perez *et al.*, 2008), while the mean annual PM_{10} concentration ranges from 20 to 37 μgm^{-3} in Rio de Janeiro, Brazil (Godoy *et al.*, 2009). Comparing the present results with those of the above-mentioned studies, it is concluded that the city of Zahedan experiences much higher PM concentration levels. This is not only the case for summer, when the area is affected by natural phenomena, but also for winter. This emphasizes the fact that PM concentrations over Zahedan can be regarded as a real environmental problem that poses a serious risk to quality of life and endangering human health.

The frequency of occurrence for PM_{10} and $PM_{2.5}$ concentrations for each season is depicted in Fig. 4a, b, respectively. In spring and summer ~33% of the PM_{10} values were between 100 to 150 μgm^{-3}, with higher frequency for lower values in spring. In summer, the frequency distribution shifts towards larger values, with values even above 500 μgm^{-3} and negligible PM_{10} values below 50 μgm^{-3}. On the other hand, considerable fraction (24%) of PM_{10} values < 50 μgm^{-3} is observed in winter. Regarding the frequency distributions of $PM_{2.5}$ in all seasons except summer, the largest frequency is observed for values between 20 and 30 μgm^{-3}, while in summer the largest frequency shifts towards lower values (10-20 μgm^{-3}), which is opposite to that observed for PM_{10}. However, similarly to PM_{10}, summer presents a broader distribution for $PM_{2.5}$, with values > 100 μgm^{-3} range. Apart from these similarities in the PM_{10} and $PM_{2.5}$ frequency distributions, some differences in winter and summer reveal a possible different source of aerosols in these seasons (natural or anthropogenic). For example, the intense dust storms during summer do not have such a pronounced signal in $PM_{2.5}$ concentrations as in PM_{10} ones, while the larger contribution of anthropogenic aerosols in winter increases more the $PM_{2.5}$ levels. Also note that the mean $PM_{2.5}$ in winter (32 μgm^{-3}) is similar to that of spring and larger than that of autumn, despite the fact that winter PM_{10} is the lowest (Table 1). However, it should be noted that dust events may also affect significantly the $PM_{2.5}$ levels, as observed during a severe dusty day in June ($PM_{2.5}$ daily value of 182 μgm^{-3}) (Table 1). An important finding revealed from Fig. 4b is the absence of $PM_{2.5}$ <10 μgm^{-3}, while mean monthly $PM_{2.5}$ values (Table 1) are similar or even lower, than those reported for urban Athens (Chaloulakou *et al.*, 2003).

Relationships between daily-mean $PM_{2.5}$ and PM_{10} concentrations were calculated using linear regression analysis for each season (Fig. 5) and with the Pearson's coefficient of correlation (Table 2). Such correlations may reveal the consistency of the sources for PM_{10} and $PM_{2.5}$ emissions. Results indicate maximum and minimum correlations in summer (r=0.95) and autumn (r=0.82), respectively implying that the sources of $PM_{2.5}$ and PM_{10} are somewhat similar. The correlation between PM_{10} and $PM_{2.5}$ regarding the whole dataset is associated with the 81% of the variance (R^2=0.81), while poor correlation was found for PM_{10} vs $PM_{1.0}$ (R^2=0.11). It should be noted that the correlation between PM_{10} and $PM_{1.0}$ exhibited (not presented) strong seasonality with very low r values in winter and autumn and large r values in spring (0.66) and summer (0.86) (Table 2). This indicates that sub-micron aerosols during winter are of local anthropogenic origin, whilee larger aerosols have a strong natural component. In contrast, during summer, increase of PM_{10} from natural sources may also have an impact on fine aerosol concentrations ($PM_{1.0}$), since transported dust can be also of fine mode (Hess et al., 1998). The relationship between $PM_{2.5}$ and $PM_{1.0}$ reveals similar results and discussions, with high correlations in summer and spring and lower in winter and autumn (Fig. 6).

3.2. Diurnal variability of PM concentrations

Daily mean variations in PM concentrations at all levels during the period 2 July 2008 to 16 March 2010 are shown in Fig. 7. A threshold value of 400 μgm^{-3} was chosen for the city of Zahedan in order to identify days with severe PM_{10} levels. Such extremely high PM concentrations were observed in Athens during an intense dust storm (Kaskaoutis *et al.*, 2008) and are also considered as very unhealthy and hazardous for the human life. Days with severe PM_{10} concentrations are observed mainly in summer (4 days), but also in winter (3 days) and spring (1 day). The maximum of daily PM_{10} and $PM_{2.5}$ concentrations was up to 970 μgm^{-3} and 182 μgm^{-3}, respectively on 29 June 2009. These values are comparable in magnitude to those observed during an intense dust storm in Beijing (Sun *et al.*, 2004; Zhao *et al.*, 2007). Despite that long-range advection of dust usually takes place above the boundary layer, subsidence, fumigation and sedimentation allow for a large proportion of dust to diffuse into it (e.g. Gobbi *et al.*, 2007; Kaskaoutis *et al.*, 2008), thus strongly influencing the PM concentrations in the ground.

Significant daily variability is observed especially for PM_{10} with several peaks and gaps attributed to the intensity of local emissions, regional meteorology, boundary layer dynamics and long-range transported aerosols. The current European Union (EU) legislation employs PM_{10} concentrations as one of the reference parameters in assessing urban air quality (Chaloulakou *et al.*, 2003; Gobbi *et al.*, 2007). According to EU standards from 1st January 2005 it is allowed that the daily-average threshold of 50 μgm^{-3} at any station is exceeded for a maximum of 35 times per year, while the annual average PM_{10} should not exceed 40 μgm^{-3}. These are ambitious goals considering the current levels of PM_{10} observed in Zahedan (Fig. 7, Table 1), since in 361 out of 399 days (90.5%) the PM_{10} levels were found to be above the daily EU threshold value of 50 μgm^{-3}.

In order to examine the influence of dust outbreaks on the coarse-mode aerosols in Zahedan, the daily variation in $PM_{10-2.5}$ (coarse particles) and $PM_{2.5}/PM_{10}$ was analyzed (Fig. 8). Comparing Figs. 7 and 8 it is observed that in 5 out of the 8 days with extreme PM_{10} values coarse-mode concentrations of above 400 μgm^{-3} were reached, while all these events occurred in spring and summer. In Zahedan $PM_{2.5}$ values ranged from 10 to 182 μgm^{-3}, while coarse particles ranged from 4 to 788 μgm^{-3} with a mean value of 94±76 μgm^{-3}. Although the range and mean of $PM_{2.5}$ is similar to that observed in Athens (Chaloulakou *et al.*, 2003), the coarse-mode particles and the $PM_{2.5}/PM_{10}$ ratio (29±11) in Zahedan are much higher and lower, respectively, indicating the influence of the arid environment. Fig. 8 shows that the $PM_{2.5}/PM_{10}$ ratio is larger on days with low PM_{10} concentration, mainly in winter and autumn, suggesting a dominance of local anthropogenic aerosols. Daily PM_{10} concentrations during four Saharan dust outbreaks in Madrid ranged from ~80 μgm^{-3} to ~200 μgm^{-3} depending on the emission rates, the altitude of the dust plume and the measuring location, while dust is the second biggest contributor to PM_{10} in Madrid making up 40%, on average, of total emissions (Coz *et al.*, 2009). Our results reveal that the PM_{10} concentrations are much higher, while the fraction of coarse-mode particles ($PM_{10-2.5}$) ranges from 72% to 85% during dust events.

Fig. 9 depicts mean diurnal variation of PM_{10} concentrations (upper panel) for each season in Zahedan. Significant seasonal differences in the maximum of the diurnal variation are observed while in all seasons PM_{10} values reach a minimum in the early morning hours (~04:00 LST) before human activities start. In winter and autumn, maximum PM_{10} levels occur in the morning hours close to rush hour and the associated increase of anthropogenic pollution in the city. Solar heating and vertical mixing of pollutants may be the main reasons for the reduction of PM_{10} levels at local noon and early afternoon hours, while fossil-fuel combustion and the use of thermal heating in the evening result in an increase in PM_{10} levels in these seasons. Similar diurnal variation was found (not presented) for $PM_{2.5}$ levels, but with more pronounced morning and evening increases in winter. The similarity between diurnal PM_{10} variations recorded in this study during autumn and winter and those recorded over several Indian cities (e.g. Madhavan *et al.*, 2008; Pathak *et al.*, 2010) suggests that local anthropogenic emissions and vertical mixing in the boundary layer play a major role in controlling diurnal PM concentrations. During spring no clear pattern in PM_{10} diurnal variation is observed since several peaks and gaps occur. However, there is a slightly steady increasing trend from morning till late afternoon. In further contrast, the maximum PM_{10} concentrations normally occur between 12:00 and 20:00 (LST) in summer, indicating that Sistan dust storms (generally originating in Sistan between 8:00 to 11:00 LST) reach the study region after 6 to 9 hours. The diurnal PM_{10} variability in summer is closely associated with the intensity of the wind speed measured at the Zahedan meteorological station (see Fig. 9 bottom panel). This wind, being northerly in direction, carries large quantities of dust from the Sistan desert. It should be noted that the mean diurnal wind speed variation is similar for all seasons; however, the wind favors the increase of aerosol load in summer (maximum PM_{10} for higher wind speeds) and acts as a ventilation tool for the atmosphere in autumn and winter (minimum PM_{10} levels at noon and early afternoon). Studying the weekly variability of PM_{10} and $PM_{2.5}$, it was found that both PM levels were lower on Friday (mean value of 108 against 127 μgm^{-3} for the other days for PM_{10} and 29 against 33 μgm^{-3} for $PM_{2.5}$), which is the day of rest in Muslim culture; lower PM levels were also found on weekend against weekdays.

Days with extremely high PM_{10} concentrations (>400 μgm^{-3}), as illustrated in Fig. 7, are further examined regarding diurnal variability of PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ (Fig. 10a, b, c). More specifically, during severe pollution events in winter PM_{10} values are much higher during the night and early morning hours. The shallow boundary layer and the strong thermal inversion that occur during cold winter nights in the arid environment of Zahedan reduce buoyancy and, therefore, “trap” pollutants near the surface; thus, the extremely large PM_{10} concentrations (up to 1000 μgm^{-3}) sometimes found during winter nights and early morning hours. Because of the stable nocturnal boundary layer conditions it is concluded that the larger nighttime PM_{10} concentrations in winter are attributed to local emissions (e.g. thermal heating and fossil-fuel combustion).

During severe polluted days in spring, and mainly in summer, the diurnal variability in PM_{10} concentrations follows an opposite pattern with low values in nighttime and early morning and extremely high values at noon and afternoon hours. The diurnal variation on four summer days that were influenced by intense dust storms (Fig. 10a) controls the summer seasonal diurnal variability (Fig. 9), although it was found that during most summer days PM_{10} values were high in the afternoon. This can be explained by the frequent arrival of dust storms from the Sistan desert during noon and afternoon, and the associated stronger northerly winds (18 to 20 $km.hr^{-1}$).

The diurnal variability in $PM_{2.5}$ and $PM_{1.0}$ on the 8 selected most polluted days is similar to that of PM_{10}. Higher $PM_{2.5}$ and $PM_{1.0}$ concentrations were also measured from noon to afternoon hours in summer, indicating that dust storms can also carry significant quantities of sub-micron particles over distances of greater than ~300 km from the source region. On the 8 polluted days the correlation between hourly PM_{10} and $PM_{2.5}$ and between hourly PM_{10} and $PM_{1.0}$ was found to be high, with R^2 =0.82 and 0.63, respectively. This clearly indicates that during severe atmospheric conditions in Zahedan, the main source region for all particle sizes is the dust transported from Sistan desert. It should be noted that the influence of long-range transported aerosols, such as dust particles, on surface aerosol concentrations is more profound in rural or suburban areas with local background pollution levels than in downtown urban environments, as has been found in Rome (Gobbi *et al.*, 2007). Thus, apart from local emissions, dust deposition during dusty days significantly affects PM concentrations in Zahedan, thereby causing dramatic increases in all PM levels, even much higher than prescribed by EU standards.

3.3. Air Quality Index (AQI)

Air pollution indices are commonly used in order to define the level of impact of air pollution on human health (Cogliani, 2001; Nikolaou *et al.*, 2004). As a consequence, the AQI is a powerful precautionary tool to ensure public health protection (EPA, 1999).

The AQI varies from 0 to 500 divided into six categories and its health indicators are mentioned in Table 3, each of which corresponds to a different level of health concern (EPA, 1999). All AQI categories have less or more impact on human health, and specifically the last AQI category (hazardous, >425 PM_{10} μgm^{-3}), is associated with a serious risk of respiratory symptoms and aggravation of lung disease, such as asthma, for sensitive groups and with respiratory effects likely in the general population (Ozer *et al*, 2006; Mohan and Kandya, 2007).

Based on the technological rules related to AQI, the following formula was used to derive the PM_{10} concentration from AQI (Triantafyllou *et al.*, 2006; Larissi *et al.*, 2010):

$$I = \frac{I_{high} - I_{low}}{C_{high} - C_{low}}(C - C_{low}) + I_{low} \qquad (1)$$

Where I is the (Air Quality) sub-index, C is the pollutant concentration, I_{low} and I_{high} are the index breakpoints corresponding to C_{low} and C_{high}, respectively and, C_{low} and C_{high} are the concentration breakpoints that are $\leq C$ or $\geq C$.

Considering air pollution standards as defined by the USEPA which specifies that AQI values can be higher than 100 on only one day of the year, the city of Zahedan did not perform well at all. It was found that AQI values exceeded 100 on 86 days out of 399 (21.5%) in Zahedan. Such severe atmospheric conditions occur mainly in summer and, as indicated before, transported or re-suspended dust plays a major role in the air pollution. An assessment of air quality during the period of investigation showed that 86 days (21.5%) had air pollution levels of above the air quality standard (> 155μgm^{-3}). 61 days were regarded as unhealthy for sensitive people, 17 days were unhealthy or very unhealthy and 8 days were hazardous (Table 3). The accumulation of ambient air pollutants associated with enhanced values of AQI (>100) can result in an increase in hospital admissions for the treatment of cardiovascular and respiratory problems (Bartzokas *et al.*, 2004; Paliatsos *et al.*, 2006). More specifically, several studies have indicated that ambient air pollution is highly correlated with respiratory morbidity amongst children (Jalaludin *et al.*, 2004; Schwartz, 2004).

Among other meteorological parameters, such as air temperature and RH, the effect of wind speed and direction on AQI levels was found to be significant. Thus, the highest AQI values are found in summer (season with the highest temperature, lowest RH, and highest sunshine duration), and are closely associated with strong northerly winds from the Sistan desert. During the period May to August, monthly mean AQI values were above 90, reaching up to ~130 in June-July (Table 4). This is in contrast to findings over Greater Athens Area (Larissi *et al.*, 2010) where, due to complex topography and the accumulation of pollutants, the AQI was larger during calm days and days with weak sea-breeze circulation and lower when strong northeasterly winds dominate. However, the present results reveal that the wind speed over Zahedan in summer acts as an additional tool for enhanced PM levels and deteriorating the air quality.

4. Conclusions

Systematic PM concentrations (PM_{10}, $PM_{2.5}$ and $PM_{1.0}$) were measured in the arid environment of Zahedan in southeast Iran covering the period July 2008 to March 2010. To the best of our knowledge this dataset represents the longest record of simultaneous PM measurements in Zahedan. The present study focused on analyzing the daily, monthly and seasonal variability of PM levels and to establish the role of the northern "Levar" wind in deteriorating the air quality in summer. The results show that the PM_{10} concentrations were considerably higher than the corresponding European Union air quality annual standard and the mean $PM_{2.5}$ concentration (32 μgm^{-3}) also overcame the AQI annual $PM_{2.5}$ standard. Therefore, it is recommended that some effective control measures should be implemented in order to reduce at least the local atmospheric pollution in Zahedan and to protect human health. The analysis of the daily PM concentrations showed that the air quality in Zahedan is mostly affected by dust storms from the Sistan desert, which may be very intense during summer. The PM_{10} and $PM_{2.5}$ levels showed an annual pattern of summer high and winter low, while the $PM_{1.0}$ exhibited opposite pattern. The strong correlation between daily $PM_{2.5}$ and PM_{10} concentrations indicates that they have similar sources and an increase of PM_{10} significantly affects $PM_{2.5}$. The strong correlation and the absence of scatter especially in summer also imply the linear regression model can be used reliably for future predictions, especially for $PM_{2.5}$. Considering the air pollution standards defined by the U.S. Environmental Protection Agency determining that only on one day per year the AQI can be higher than 100, it was found that the values of AQI in Zahedan overcame this level for 86 days out of 399 expressing a fraction of 21.5%. It should be noted that on 25 days (6.3%) the atmospheric conditions were very unhealthy or hazardous for the whole population and this requires more attention by officials, managers and urban planners.

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Table 1: Monthly mean, maximum and minimum PM_{10} and $PM_{2.5}$ concentrations in Zahedan during the period July 2008 to March 2010.

Month	**Monthly Mean**		**Daily minimum**		**Daily maximum**	
Season	PM2.5 (µgm-3)	PM10 (µgm-3)	PM2.5 (µgm-3)	PM10 (µgm-3)	PM2.5 (µgm-3)	PM10 (µgm-3)
January	32	119	14	18	84	444
February	34	121	12	38	112	428
March	28	95	17	48	44	136
April	30	116	13	41	67	242
May	35	150	15	75	89	363
June	33	174	10	42	182	970
July	43	182	16	88	178	643
August	32	151	15	78	73	320
September	24	101	12	70	31	183
October	32	127	17	73	79	297
November	27	103	13	33	53	263
December	29	64	13	23	49	139
Winter	32	107	12	18	111	444
Spring	32	121	13	41	89	363
Summer	38	172	10	42	182	970
Autumn	29	114	12	33	79	297

Table2: Correlation coefficient (r) values between daily mean PM10 and PM2.5 and PM10 and PM1.0 for each season over Zahedan.. [** Correlation is significant at the 0.01 level, N: number of daily values]

Season	PM10 vs PM2.5	PM10 vs PM1.0
Winter (N=125)	0.85**	-0.004
Spring (N=78)	0.90**	0.66**
Summer (N=81)	0.95**	0.86**
Autumn (N=115)	0.82**	0.26**
Whole (N=399)	0.9**	0.33**

Table 3: Determination of health quality with AQI, PM_{10} and number of days with severe pollution in Zahedan during the period July 2008 to March 2010.

Health Quality	Days	(%)	PM10 (µg m-3)	AQI
Good	50	12.5	0-54	0-50
Moderate	263	66	55-154	51-100
Unhealthy for sensitive people	61	15.3	155-254	101-150
Unhealthy	13	3.2	254-354	151-200
Very unhealthy	4	1	355-424	201-300
Hazardous	9	2	>425	301-500

Table 4: Monthly and seasonal mean AQI values in Zahedan during the period July 2008 to March 2010.

Month Season	**Air Quality Index (AQI)**		
	mean	min	Max
January	83	17	325
February	84	35	305
March	77	44	91
April	71	38	144
May	98	61	212
June	110	39	500
July	114	67	500
August	99	62	183
September	74	58	115
October	87	60	172
November	75	31	155
December	55	21	93
Winter	77	17	235
Spring	83	38	212
Summer	109	39	500
Autumn	80	31	172

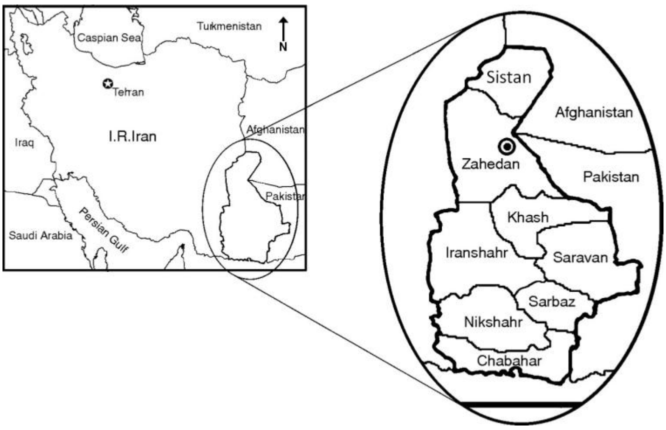

Figure 1. Map of the Zahedan city.

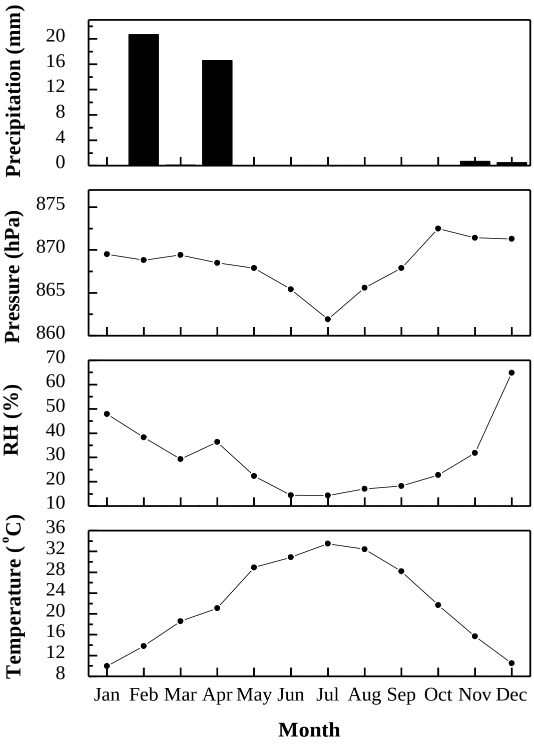

Figure 2. Monthly-mean variation of meteorological variables in Zahedan, Iran covering the period July 2008 – March 2010.

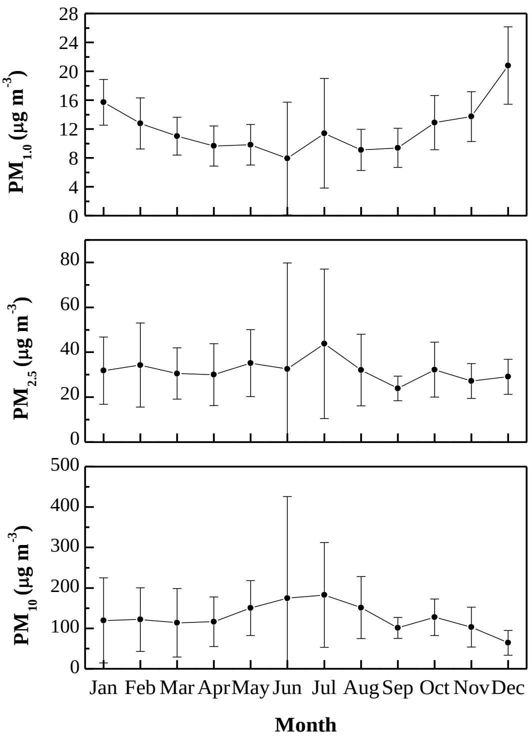

Figure 3. Annual variation of monthly-mean values of PM$_{10,}$ PM$_{2.5}$ and PM$_{1.0}$ at Zahedan during the period July 2008 – March 2010

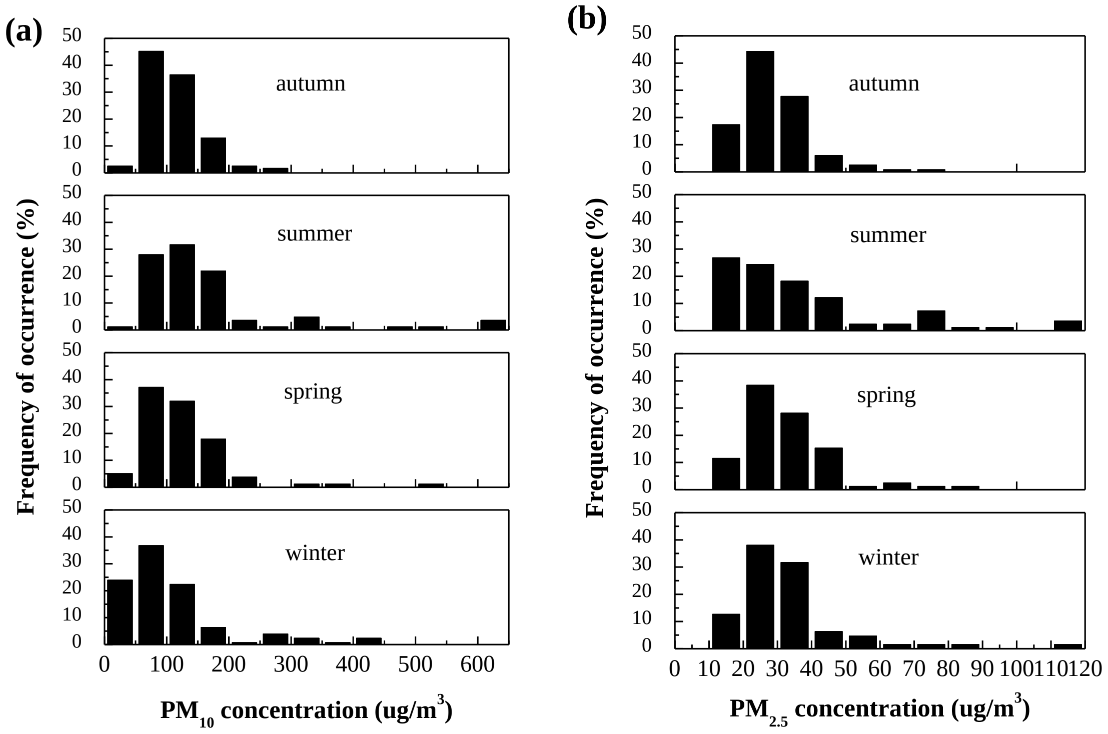

Figure 4. Frequency (%) distribution of the daily PM_{10} (a) and $PM_{2.5}$ (b) for each season in Zahedan.

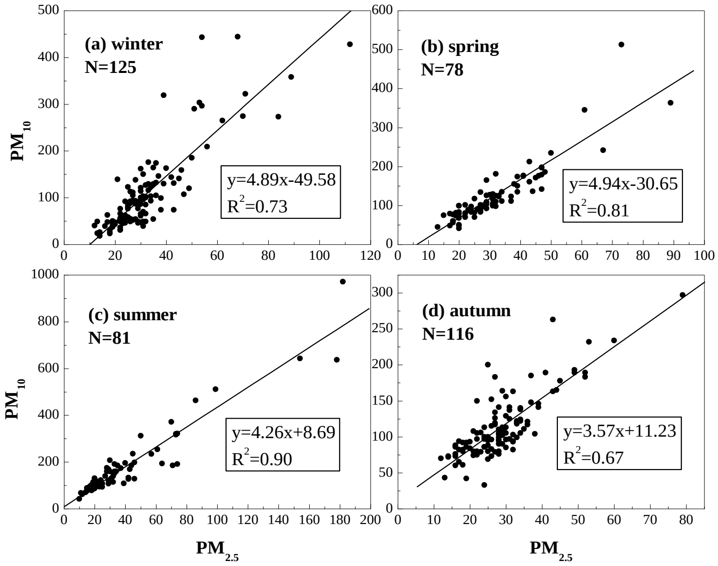

Figure 5. Relationship between $PM_{2.5}$ and PM_{10} for each season using the daily mean values in Zahedan.

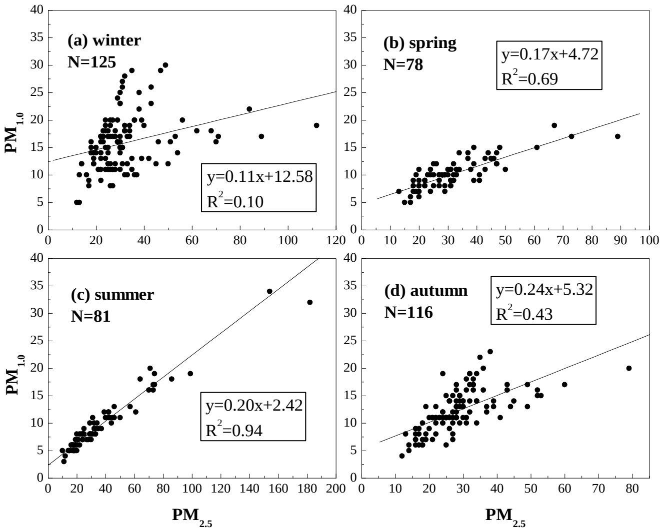

Figure 6. Relationship between $PM_{2.5}$ and $PM_{1.0}$ for each season using the daily mean values in Zahedan.

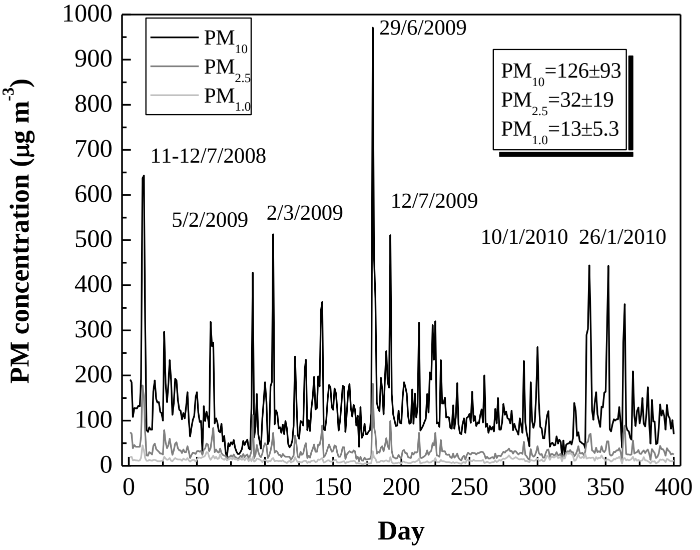

Figure 7. Daily PM concentrations at Zahean during the period 2/7/2008 to 16/3/2010.

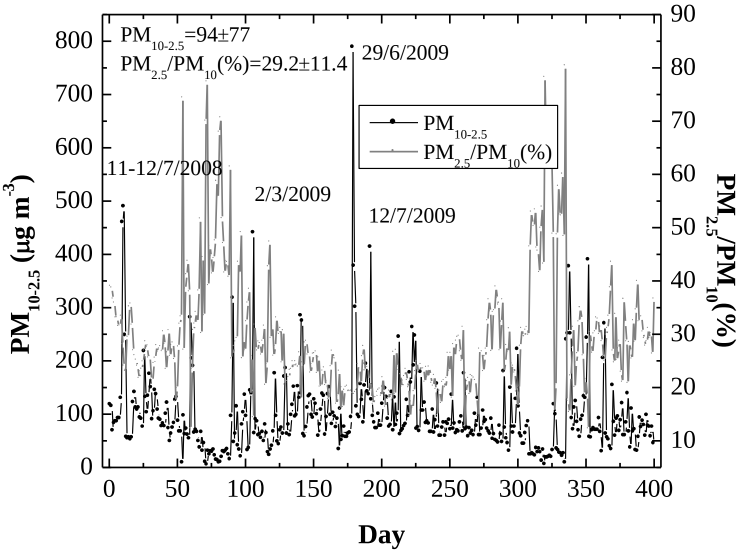

Figure 8. Daily concentration of the coarse-mode particles ($PM_{10-2.5}$) and percentage contribution of the $PM_{2.5}$ to PM_{10}.

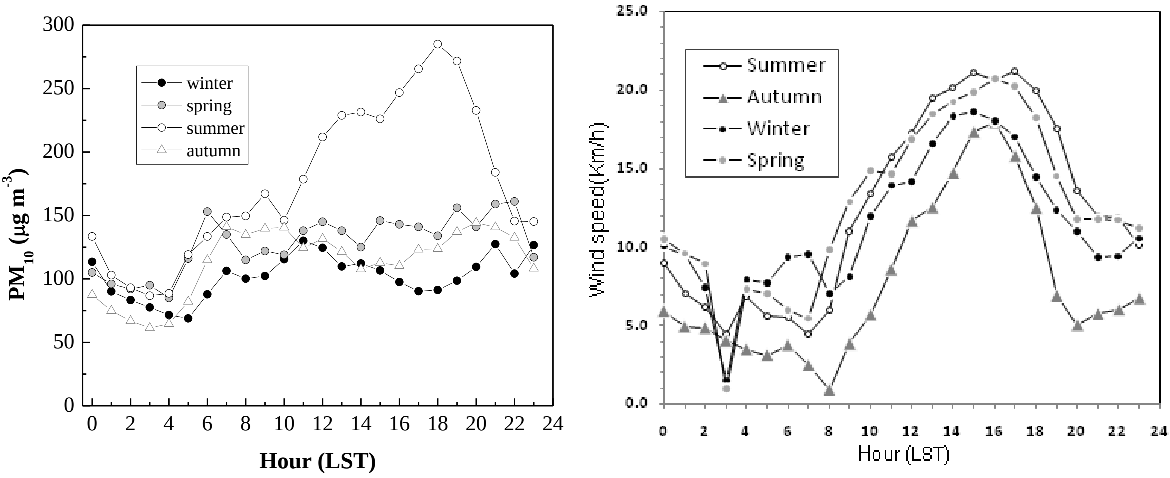

Figure 9. Mean hourly variation of the PM_{10} (top panel) and Wind speed (bottom panel) for each season in Zahedan.

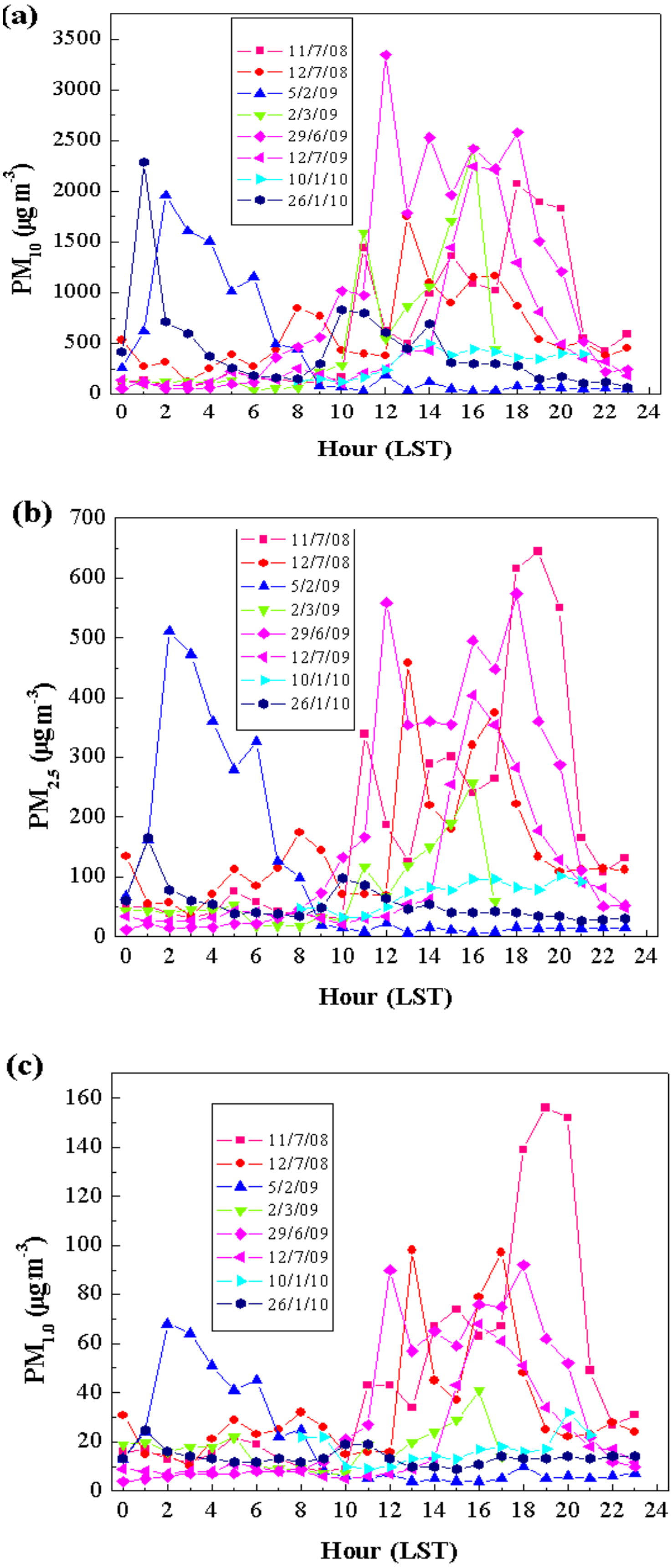

Figure 10. Diurnal variation of PM$_{10}$ (a), PM$_{2.5}$ (b) and PM$_{1.0}$ (c) on selected days with severe pollution over Zahedan.