CHAPTER 4

AIRBORNE PARTICULATE MATTER CONCENTRATION OVER THE SISTAN

4.1 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 has an adverse effect on respiratory and cardiovascular systems (Nastos *et al*., 2010), which can result in 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 U.S 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 to 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.

In this Chapter the temporal variation of PM_{10} and $PM_{2.5}$ concentrations are analysed in the atmosphere above the cities of Zabol and Zahedan in southeastern Iran focusing mainly on the following five objectives: (1) 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; (2) comparing the observed PM_{10} and $PM_{2.5}$ concentration levels to the corresponding EU and USA ambient particle standards; (3) 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, (4) revealing the role of wind speed, especially in summer, to the PM levels and, (5) revealing the fraction of days that are unhealthy for the population based on AQI values. It should be noted that such studies are lacking from this region and that this is the first that examines the seasonal evolution of PM concentrations and AQI, aiming also to relate the peak values in PM to dust exposures from the nearby Sistan desert.

4.2 Assessment of PM concentration in the city of Zahedan

4.2.1 Study area and meteorology

The measurements were carried out in the city of Zahedan located in the southeastern part of Iran (60.52^{o} East, 29.32^{o} North, 1384 m above mean sea level) close to the Iranian borders with Pakistan and Afghanistan (Fig. 4.1). 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.

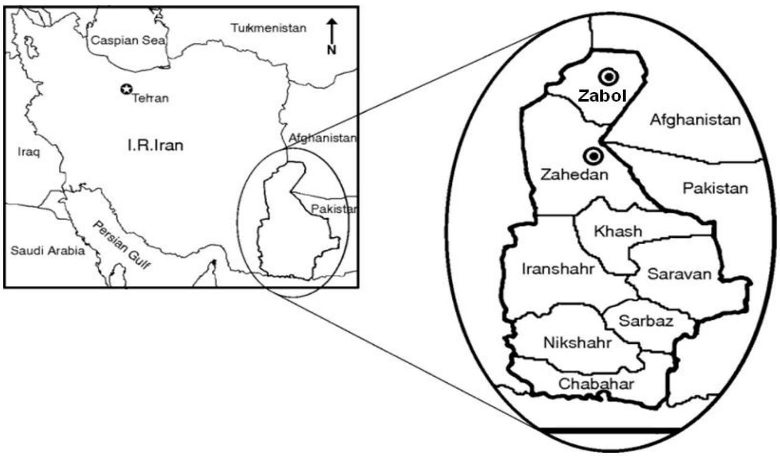

Figure 4.1: Position of the cities Zahedan and Zabol in Iran.

The climate is semi-arid to arid, with a low annual average precipitation of 84 mm occurring mainly in winter (December to February). Monthly mean values of temperature, RH, atmospheric pressure and accumulated precipitation in Zahedan during the study period (July 2008 to March 2010) are plotted in Fig. 4.2. 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 to 65%) and very low values in summer (below 20%), which are indicative of an arid environment. The atmospheric pressure is generally steady (~869 hPa) from January to April, and then decreases significantly during summer, and increases again in autumn.

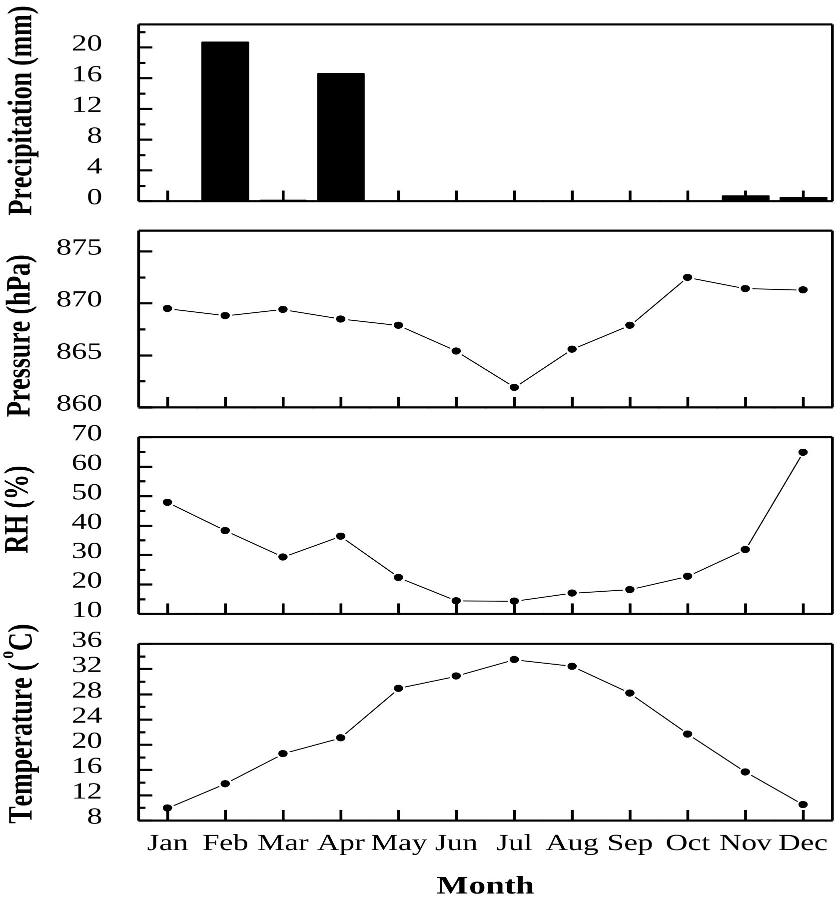

Figure 4.2: Monthly-mean variation of meteorological variables in Zahedan, Iran covering the period July 2008 to March 2010.

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 the 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 (July 2008 to March 2010) the rainfall was restricted to winter and spring, while the maximum acccumulated rainfall in February (20 mm) is indicative of the typical arid environment.

4.2.2 Particulate Matter (PM) measurements

PM concentrations at near-surface level in the city of Zahedan were systematically measured using the Environmental Dust Monitor model 180 (EDM-180). The 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 μg.m^{-3}) for 3 particle sizes, namely PM_{10}, $PM_{2.5}$ and $PM_{1.0}$, with a relatively high temporal resolution (5-minutes) of recordings. The recording station is located at the outskirts of the city, in a sparsely-populated area without any industries or any direct influence from anthropogenic emissions. The 5-minutes 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.

4.2.3 Results and discussion

4.2.3.1 Seasonal and monthly variability in PM concentrations

Fig. 4.3 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.

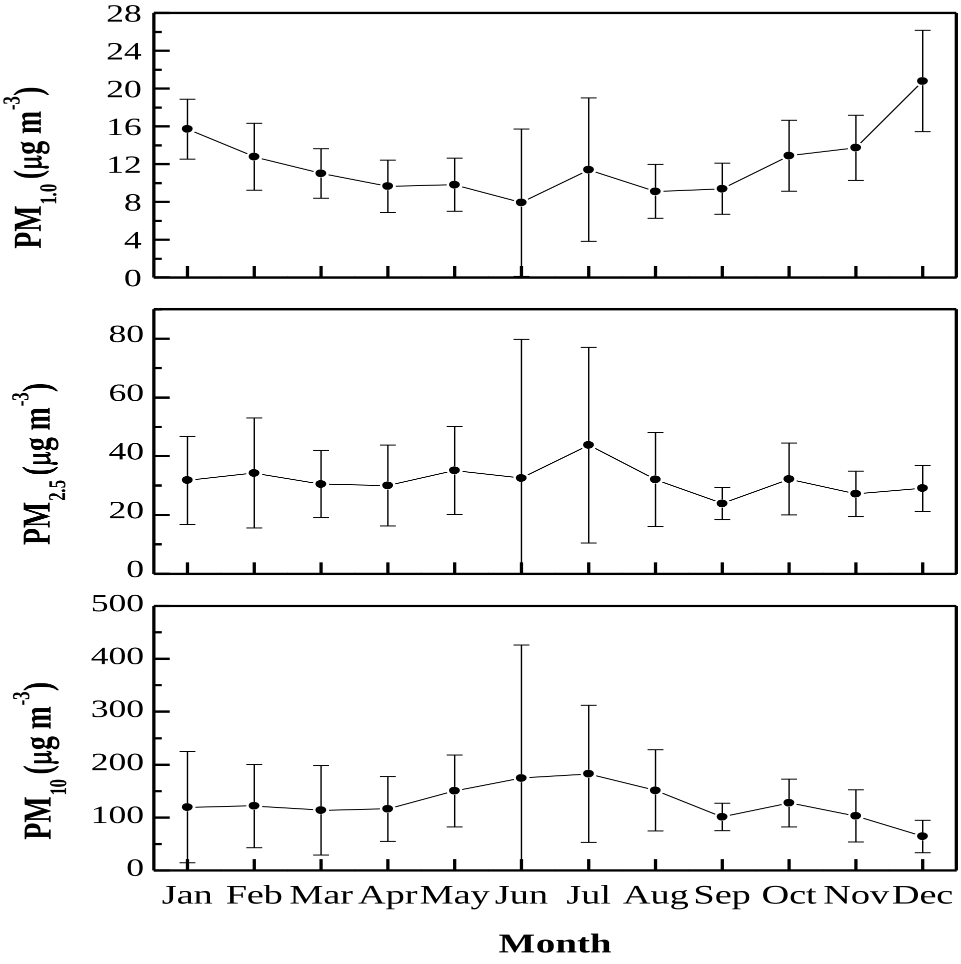

Figure 4.3: Annual variation of monthly-mean values of PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ at Zahedan during the period July 2008 to March 2010.

The annual pattern of PM_{10} shows a significant increase in summer where monthly mean concentrations of up to ~170-180 µg.m^{-3} were recorded in June and July (Table 4.1). PM_{10} concentrations during winter months are significantly lower, with 64µg.m^{-3} measured in December. January and February exhibit PM_{10} concentrations of above 100µg.m^{-3}, which persist until April when PM_{10} levels increase as a result of the Levar wind. The highest PM_{10} concentration (970µg.m^{-3}) is recorded during June (Table 4.1) 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 µg.m^{-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 combustion, 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}) is also expected to originate from eolian and traffic-driven re-suspension of dust, since the scarce rainfall favors the accumulation of road dust in summer.

Table 4.1: 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**	
	PM2.5 (µgm-3)	PM10 (µgm-3)	PM2.5 (µgm-3)	PM10 (µgm-3)	PM2.5 (µgm-3)	PM10 (µgm-3)
Season						
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

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 μg.m^{-3} (January) to 88.9 μg.m^{-3} (December), with an annual mean value of 75.5 μg.m^{-3}. In Barcelona, Spain, the ambient PM_{10} and $PM_{2.5}$ were in the range of 39 to 42 μg.m^{-3} and 25 to 29 μg.m^{-3}, respectively over the period 2003-2006 with 97 daily values exceeding 50 μg.m^{-3} (Perez et al., 2008), while the mean annual PM_{10} concentration ranges from 20 to 37 μg.m^{-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 endangers human health.

The frequency of occurrence for PM_{10} and $PM_{2.5}$ concentrations for each season is depicted in Fig. 4.4(a), (b), respectively. In spring and summer ~33% of the PM_{10} values were between 100 and 150 μg.m^{-3}, with higher frequency for lower values in spring. In summer, the frequency distribution shifts towards larger values, with values even above 500 μg.m^{-3} and negligible PM_{10} values below 50 μg.m^{-3}. On the other hand, a considerable fraction (24%) of PM_{10} values < 50 μg.m^{-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 μg.m^{-3}, while in summer the largest frequency shifts towards lower values (10-20 μg.m^{-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 > a 100 μg.m^{-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 rather increases the $PM_{2.5}$ levels. Also note that the mean $PM_{2.5}$ in winter (32 μg.m^{-3}) is similar to that of spring and larger than that of autumn, despite the fact that winter PM_{10} is the lowest (Table 4.1). 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 μg.m^{-3}) (Table 4.1). An important finding revealed from Fig. 4b is the absence of $PM_{2.5}$<10 μg.m^{-3}, while mean monthly $PM_{2.5}$ values (Table 4.1) are similar or even lower, than those reported for urban Athens (Chaloulakou *et al.*, 2003).

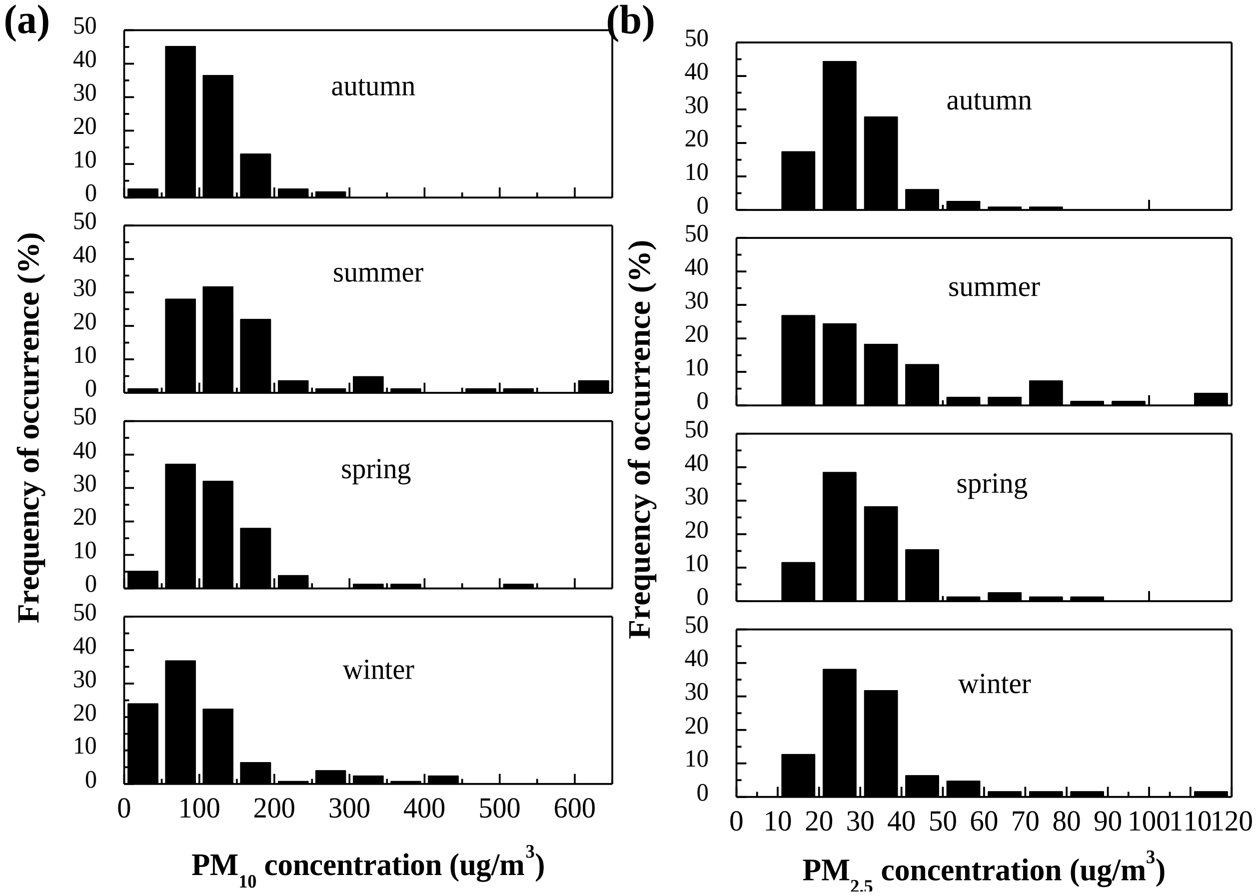

Figure 4.4: Frequency (%) distribution of (a) the daily PM_{10} and (b) $PM_{2.5}$ for each season in Zahedan.

Relationships between daily mean $PM_{2.5}$ and PM_{10} concentrations were calculated using linear regression analysis for each season (Fig. 4.5) and with the Pearson's coefficient of correlation (Table 4.2). 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 $PM_{2.5}$ for the whole dataset is associated with 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 4.2).

Table 4.2: Correlation coefficient (r) values between daily mean PM_{10} and $PM_{2.5}$ and PM_{10} and $PM_{1.0}$ for each season over Zahedan. [** Correlation is significant at the 0.01 level, N: number of daily values]

Season	PM_{10} vs $PM_{2.5}$	PM_{10} vs $PM_{1.0}$
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^{**}

This indicates that sub-micron aerosols during winter are of local anthropogenic origin, while 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 also be 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. 4.6).

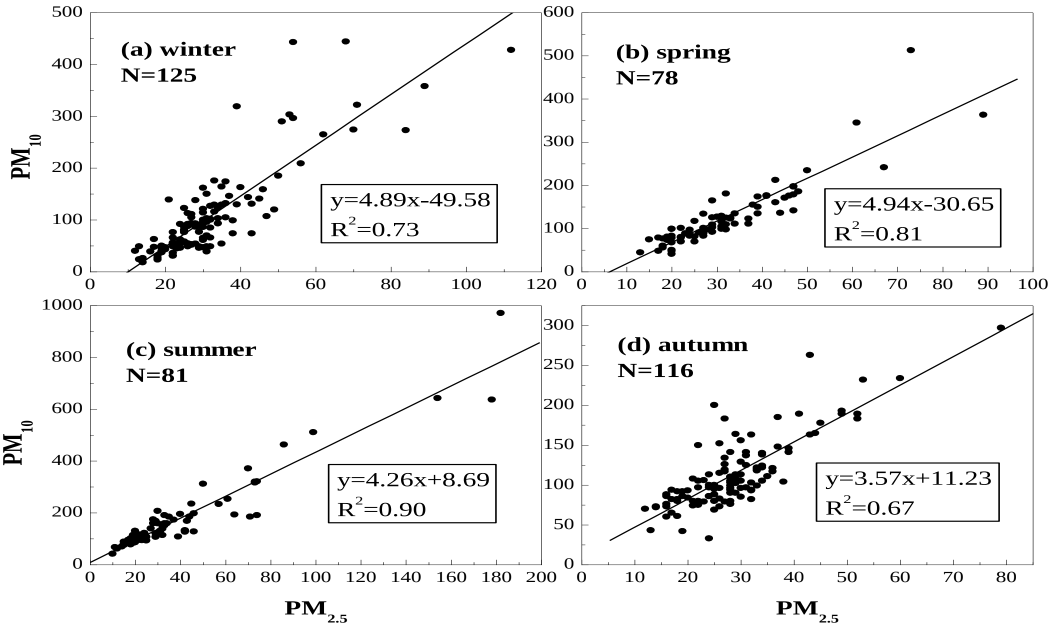

Figure 4.5: Relationship between $PM_{2.5}$ and PM_{10} for each season using the daily mean values of $PM_{2.5}$ and PM_{10} in Zahedan.

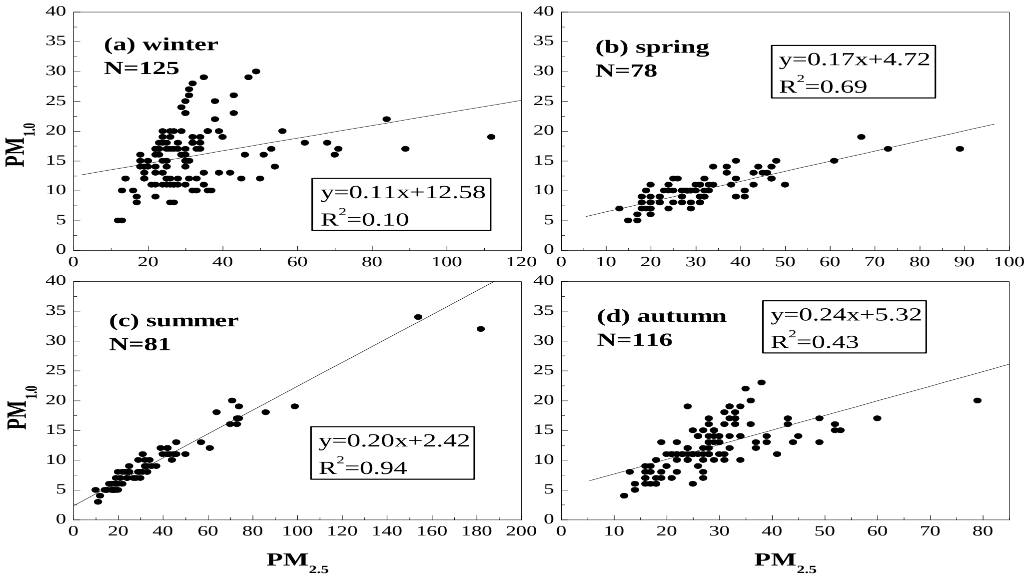

Figure 4.6: Relationship between PM$_{2.5}$ and PM$_{1.0}$ for each season using the daily mean values of PM$_{2.5}$ and PM$_{1.0}$ in Zahedan.

4.2.3.2 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. 4.7. A threshold value of 400 μg.m^{-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 being very unhealthy and even hazardous for 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 the fact 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 at the ground level.

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 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 adopted from 1st January 2005 it is permissible that the daily-average threshold of $50\mu g.m^{-3}$ at any station is exceeded for a maximum of 35 times per year, while the annual average PM_{10} should not exceed $40\mu g.m^{-3}$. These are ambitious goals considering the current levels of PM_{10} observed in Zahedan (Fig. 4.7, Table 1), since on 361 out of 399 days (90.5%) the PM_{10} levels were found to be above the daily EU threshold value of $50\ \mu g.m^{-3}$.

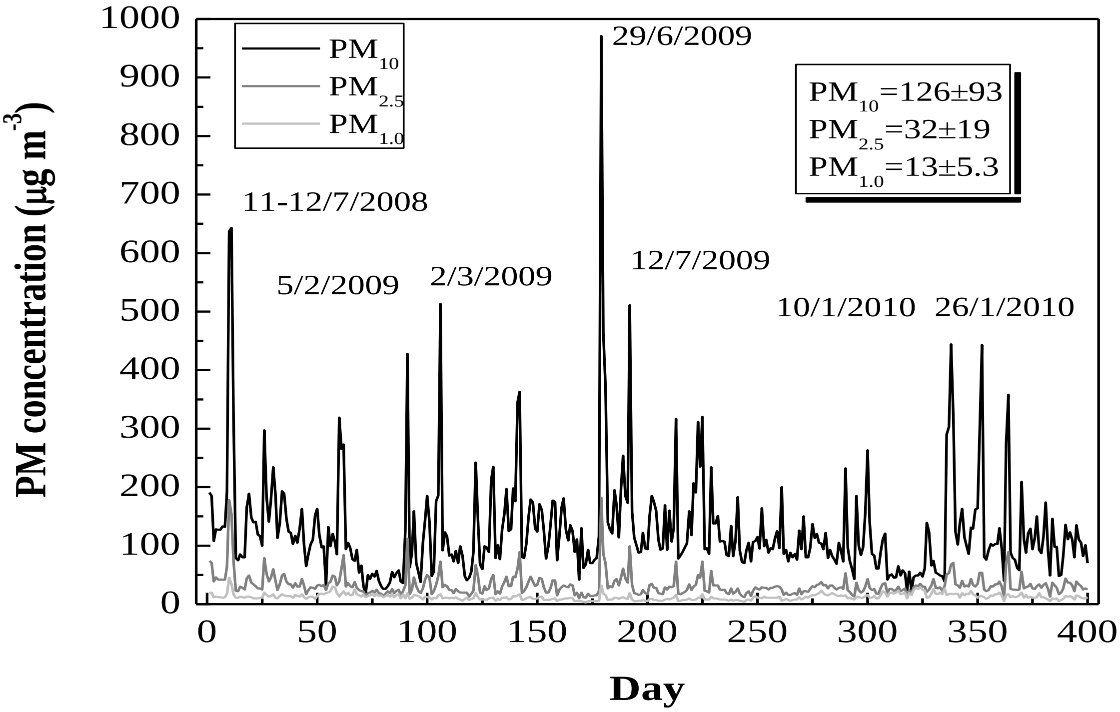

Figure 4.7: Daily particulate matter (PM) concentrations at Zahedan during the period 2/7/2008 to 16/3/2010.

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. 4.8). Comparing Figs. 4.7 and 4.8 it is observed that on 5 out of the 8 days with extreme PM_{10} values, coarse-mode concentrations of above $400\ \mu g.m^{-3}$ were reached, while all these events occurred in spring and summer. In Zahedan $PM_{2.5}$ values ranged from 10 - 182 $\mu g.m^{-3}$, while coarse particles ranged from 4 to 788 $\mu g.m^{-3}$ with a mean value of 94±76 μg.m^{-3}. Although the range and mean of $PM_{2.5}$ are 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 for the latter location. Fig. 4.8 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 μg.m^{-3} to ~200 μg.m^{-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 in Zahedan, while the fraction of coarse-mode particles ($PM_{10-2.5}$) ranges from 72% to 85% during dust events.

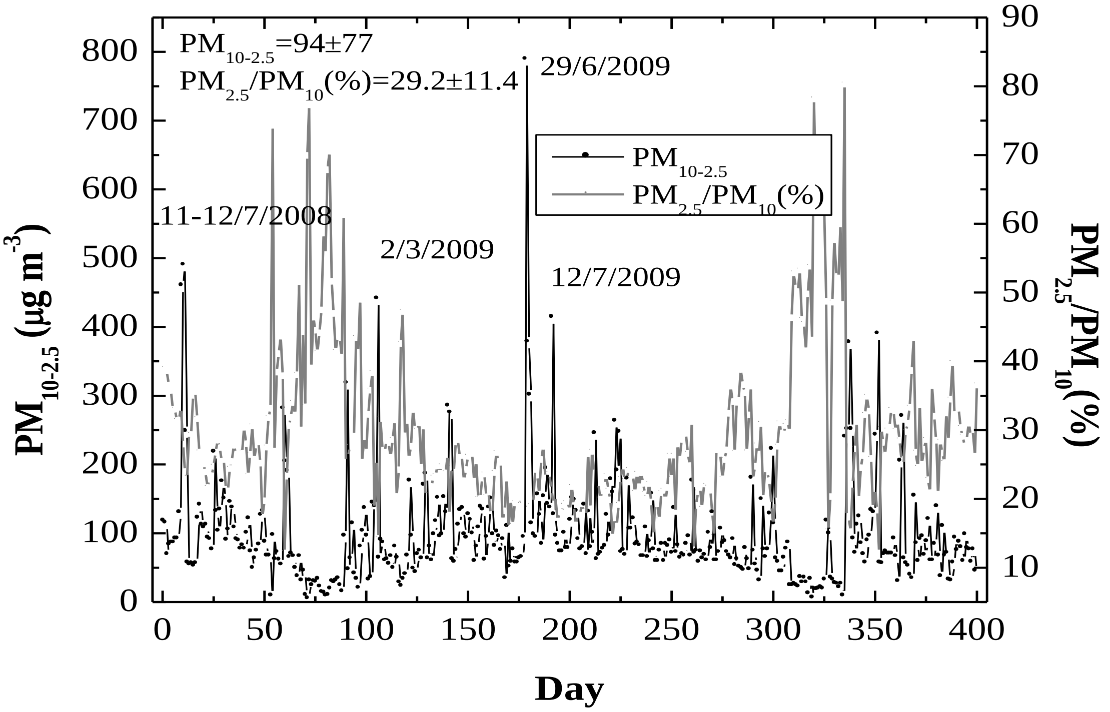

Figure 4.8: Daily concentration of the coarse-mode particular matter ($PM_{10-2.5}$) and percentage contribution of the $PM_{2.5}$ to PM_{10} at Zahedan during the period 2/7/2008 to 16/3/2010.

Fig. 4.9 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 at these times. 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 slight steadily 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 (see fig 4.9)) reach the study region after 4 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. 4.9 right 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 $\mu g.m^{-3}$ for the other days for PM_{10} and 29 against 33 $\mu g.m^{-3}$ for $PM_{2.5}$), which is the day of rest in the Muslim culture; lower PM levels were also found on weekends as against weekdays.

Days with extremely high PM_{10} concentrations (>400 $\mu g.m^{-3}$), as illustrated in Fig. 4.7, are further examined regarding diurnal variability of PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ (Fig. 4.10a, 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, explaining the extremely large PM_{10} concentrations (up to 1000 $\mu g.m^{-3}$) 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 can be attributed to local emissions (e.g. thermal heating and fossil-fuel combustion).

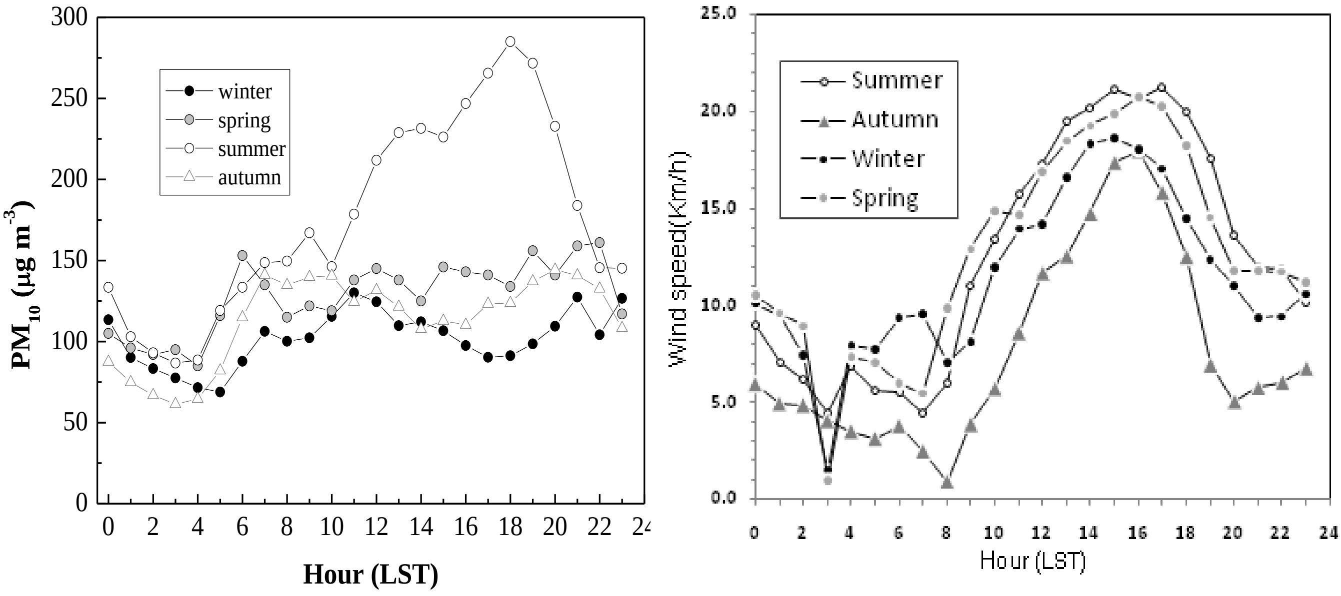

Figure 4.9: Mean hourly variation of PM_{10} (left panel) and wind speed (right panel) for each season in Zahedan.

During severely polluted days in spring, and mainly in summer, the diurnal variability in PM_{10} concentrations follows an opposite pattern with low values in the 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. 4.10a) controls the summer seasonal diurnal variability (Fig. 4.9), 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 - 20 $km.hr^{-1}$).

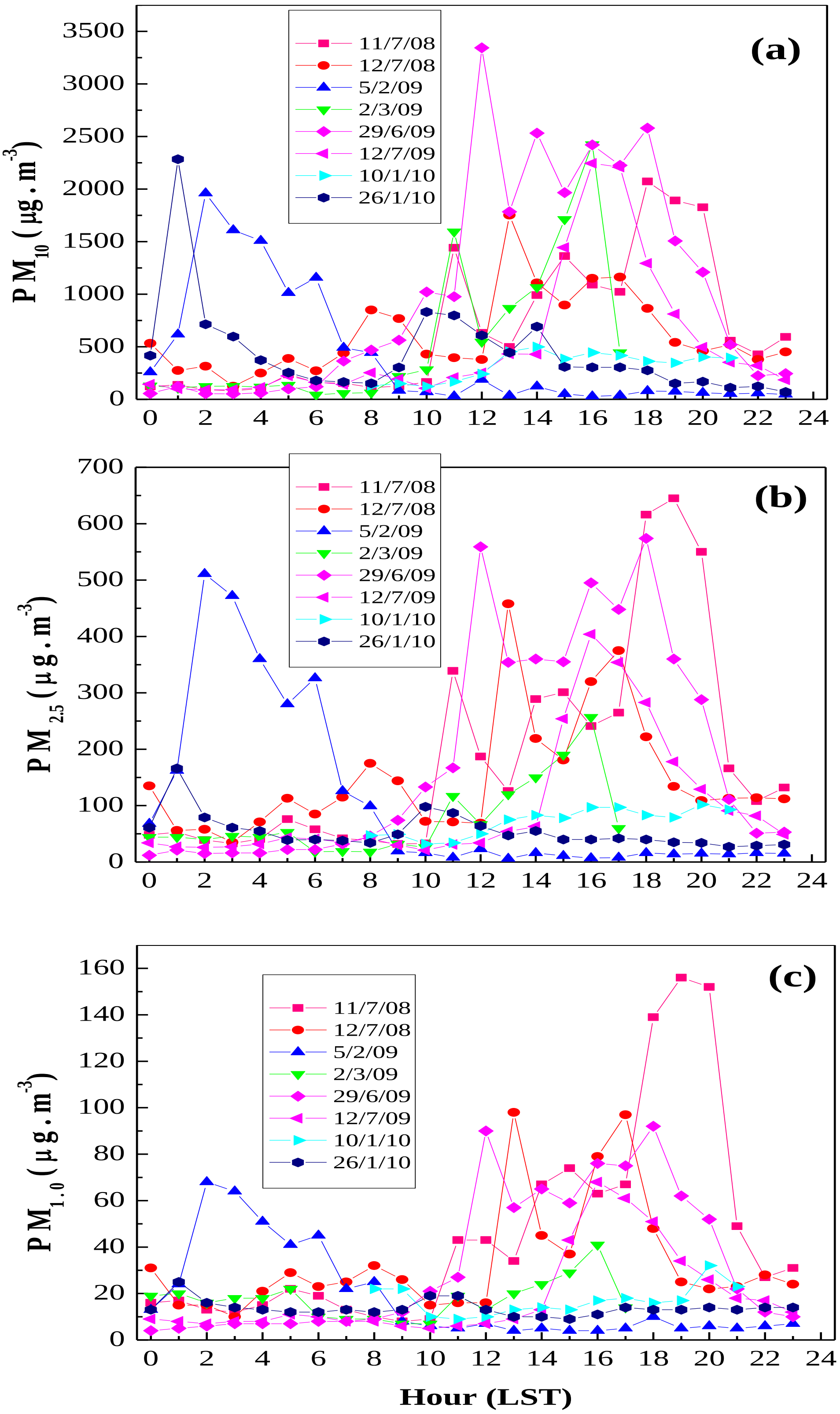

Figure 4.10: Diurnal variation of PM_{10} (a), $PM_{2.5}$ (b) and $PM_{1.0}$ (c) on selected days with severe pollution over Zahedan.

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 the 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 also 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 levels prescribed by EU standards.

4.2.3.3 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, is divided into six categories, and its health indicators are mentioned in Table 4.3, 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} $\mu g.m^{-3}$), is associated with a serious risk of respiratory symptoms and aggravation of lung diseases, 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.*, 2010a):

$$I = \frac{I_{high} - I_{low}}{C_{high} - C_{low}}(C - C_{low}) + I_{low} \tag{4.1}$$

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 (> 155µg.m^{-3}). Sixty one days were regarded as unhealthy for sensitive people, 17 days were unhealthy or very unhealthy and 9 days were hazardous (Table 4.3). 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).

Table 4.3: Indication of health quality with the AQI, PM_{10} and number of days with severe pollution in Zahedan during the period July 2008 to March 2010.

Health Quality	Days	(%)	PM_{10} (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

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 4.4). This is in contrast to findings over the Greater Athens Area (Larissi *et al.*, 2010b) where, due to complex topography and the accumulation of pollutants, the AQI was higher 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 air quality.

Table 4.4: Monthly and seasonal mean Air Quality Index (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

4.3 PM concentration over the city of Zabol

Zabol (Fig. 4.1) is the biggest city in the Sistan region, close to the Iranian border with Pakistan and Afghanistan, in the southeastern part of Iran. This city has a population of more than 100,000. During the summer season, the city is under the influence of the Levar northerly winds, causing frequent dust and sand storms (Goudie and Middleton, 2000; Middleton, 1996) and contributing to the deterioration of the air quality (Rashki *et al.*, 2011). The Hamoun Lakes are located about 15 km north of Zabol. Desiccation of the Hamoun lakes, especially after 1999, has caused formation of a fine layer of sediment that is easily lifted by the wind; therefore Zabol is influenced by severe dust storms. The strong winds, especially during the summer season, blow fine sands off the exposed lake bed and deposit this detritus within residential areas in Zabol and surroundings.

4.3.1 PM_{10} measurements

In order to provide a first ever in-situ analysis of the air quality and to compare the results with those obtained at Zahedan (located about 200 km south of Zabol), PM_{10} concentration measurements were obtained by using an automatic Met One BAM 1020 beta gauge monitor (Met One, Inc.,) over Zabol (Rashki *et al.*, 2011). The instrument measures PM_{10} concentrations (in $\mu g.m^{-3}$) with a temporal resolution of one hour. The measurements were carried out at the Environmental Institute in Sistan located at the outskirts of Zabol during the period September 2010 to September 2011 (total of 373 days). The recording station is close to the Hamoun basin and is placed in the main pathway of the dust storms of the Sistan region. The hourly measured PM_{10} data were daily-averaged, from which the monthly values and seasonal variations were obtained (Table 4.5). For further assessing the air quality over Zabol, the PM_{10} concentrations were used to calculate an AQI.

Table 4.5: Monthly mean, daily maximum and daily minimum PM_{10} concentrations in Zabol during the period September 2010 to July 2011.

	Monthly Mean	**Daily minimum**	**Daily maximum**
Season	PM10 (µgm-3)	PM10 (µgm-3)	PM10 (µgm-3)
January	196	29	597
February	147	13	787
March	262	21	2698
April	224	97	515
May	322	71	1276
June	627	100	1875
July	847	110	2007
August	807	155	2448
September	564	88	1046
October	531	100	2339
November	200	66	737
December	476	84	3094
Winter	273	13	3094
Spring	270	21	2698
Summer	716	100	2448
Autumn	484	66	2339

The results show extremely large PM_{10} concentrations at Zabol (see Fig. 4.11), but it should be borne in mind that the instrumentation used for the PM10 monitoring is different between Zabol and Zahedan for any comparative purposes. Even the mean values are much higher than the most risky and dangerous maximum levels provided by the USEPA (397 μgm^{-3}). During each month, and especially during the period June to October, the area suffers from severe pollution since even the lower PM_{10} values are above 100 μg. m^{-3}, while the maximum ones are usually above 1000 μg.m^{-3}. On the other hand, extreme PM_{10} measurements associated with severe dust events may also occur in other months, for example like December.

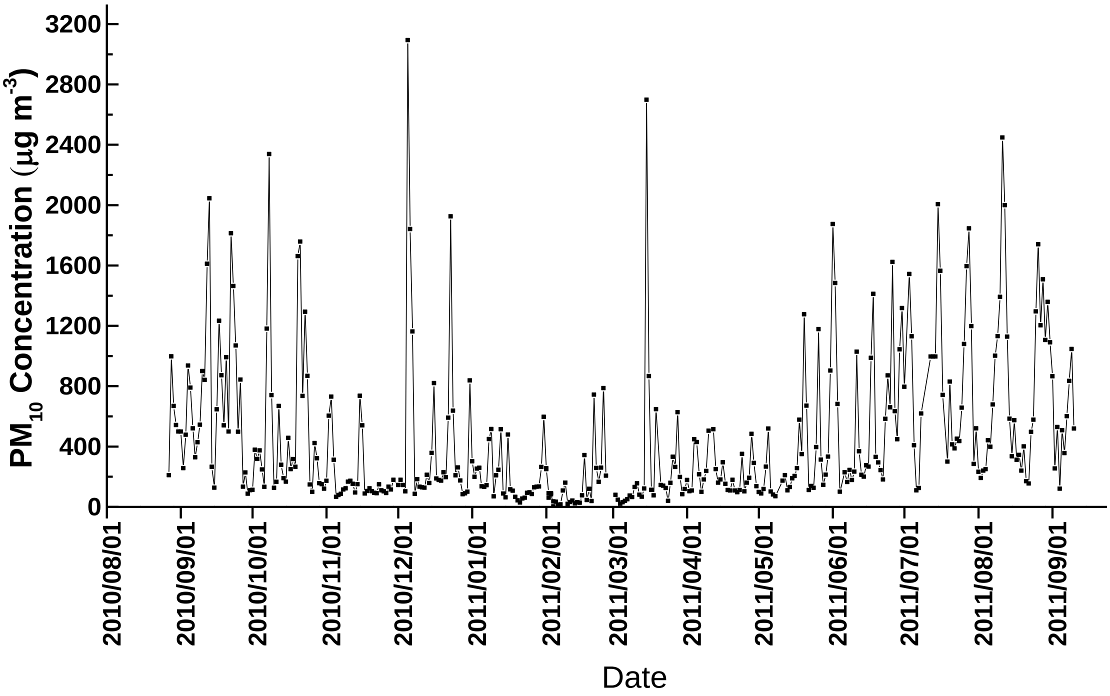

Figure 4.11: Daily PM_{10} concentrations at Zabol during the period 28/8/2010 to 10/9/2011.

Daily PM_{10} concentrations during major dust storms are about 10 to 20 times above the standard levels, and are much higher (~1000 to 2000 μg.m^{-3}) than those measured for intense dust storms at Zahedan (~400 to 600 μg.m^{-3}). Regarding the monthly mean PM_{10} concentrations, the results show extremely large values (>500 μg.m^{-3}) during the period June to October, reaching up to 743 μg.m^{-3} in July. The annual variation of PM_{10} in Zabol is similar to that recorded at Zahedan (Rashki *et al*., 2011), but with much higher values at the former site, in the order of ~160 to 170 μg.m^{-3} in winter and spring and ~510 μg.m^{-3} in summer. These large differences in PM_{10} concentrations between the two neighboring (Fig. 4.1) cities are attributed to severe dust storms that directly affect Zabol, which is located along the main pathway of intense dust plumes, while Zahedan is usually influenced by the margins of the dust storms originating from Hamoun.

The frequency of occurrence of PM_{10} concentrations for each season is depicted in Fig. 4.12. In summer ~60% of the PM_{10} values were higher than 425 $\mu g.m^{-3}$, while the lower PM_{10} values occur in winter and spring with larger frequency in the 55-154 $\mu g.m^{-3}$ interval. Autumn also presents high frequency in the >425 $\mu g.m^{-3}$ interval that might be due to continues the Levar wind in September.

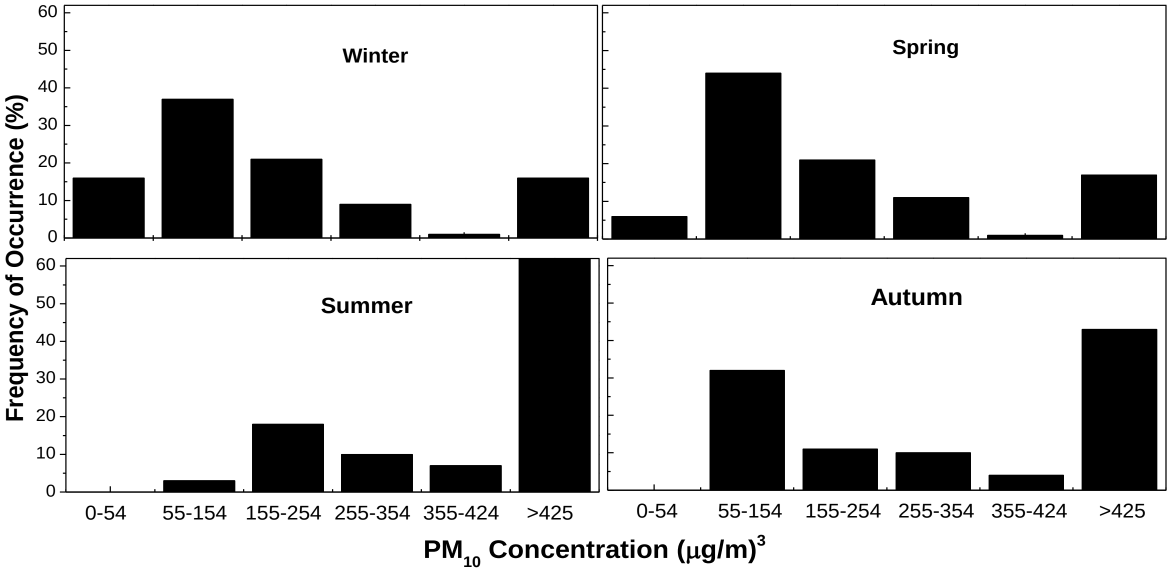

Figure 4.12: Frequency (%) distribution of the daily PM_{10} values for each season in Zabol.

4.3.2 Air quality index

In order to identify the impact of air pollution on human health, air pollution indices are commonly used, of which the AQI is the most well known (EPA, 1999; Mohan and Kandya, 2007; Larissi *et al.*, 2010a). The AQI is divided into six categories, varying from 0 to 500, with different health impacts as listed in Table 4.6. The AQI for Zabol was calculated for the period September 2010 to July 2011 using the same technique as for Zahedan. This will make comparisons of air quality between the two cities possible.

Assessment of air quality in Zabol shows that 243 days out of 370 (65%) exhibit air pollution levels of above the air quality standards (>155 μgm^{-3}), a fraction that is much higher than that (26.5%) reported for Zahedan. The most significant finding is the 129 days (34.9%) that are characterized as hazardous (Table 4.6), which in combination with the adverse effects on human health, make it clear that environmental conditions in the

Sistan region are rather poor for human well-being. On the other hand, only 5.7% of the days are associated with low pollution levels when the air quality is considered satisfactory and air pollution poses little or no risk. Several studies have shown that ambient air pollution is highly correlated with respiratory morbidity, mainly amongst children (Bartzokas *et al*., 2004; Nastos *et al*., 2010; Samoli *et al*., 2011).

Table 4.6: Health quality as determined by the Air Quality Index (AQI), PM_{10} and number of days with severe pollution in Zabol during the period September 2010 to July 2011

Health Quality	AQI	PM10 (µg. m-3)	Days	(%)
Good	0-50	0-54	21	5.7
Moderate	51-100	55-154	106	28.6
Unhealthy for sensitive people	101-150	155-254	66	17.8
Unhealthy	151-200	254-354	36	9.7
Very unhealthy	201-300	355-424	12	3.2
Hazardous	301-500	425<	129	34.9

The results gathered from hospitals in the Sistan region showed that during dust storms respiratory patients increased significantly, especially those affected by chronic obstructive pulmonary disease and asthma. The percentage of these diseases increases in summer (June and July) (Miri *et al*., 2007). Apart from the dust storms, re-suspended dust within the urban environment is a strong source of PM10 concentrations, while urban-anthropogenic and industrial activities are considered to have a much lower effect on the air pollution over Zabol.

Mean diurnal variation of PM_{10} concentrations for each season in Zabol indicates a clear pattern for all seasons except winter, with the maximum of the diurnal variation being observed in the middle of the day ((~08:00 to 11 LST) while in winter PM_{10} values reach a maximum in the afternoon hours to early morning (~16:00 to 02:00 LST). 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. However, the maximum PM_{10} concentrations normally occur between 08:00 LST and 11:00 LST. The diurnal PM_{10} variability in all seasons except winter is closely associated with the intensity of the wind speed measured at the Zabol meteorological station (see Fig. 4.13). This wind, being northerly in direction, carries large quantities of dust from the Hamoun dry lake bed. The mean diurnal wind speed variation is similar for all seasons; however, the wind favors the increase of aerosol load in summer and autumn (maximum PM_{10} for higher wind speeds).

Note that the Hirmand River and some other ephemeral provide some water in winter and spring to the Hamoun lake beds. Therefore in early summer, the Hamoun lakes are wet and at the end of summer and early autumn are always completely dried out. On the other hand, the Levar wind continues also in September and so high wind speeds cause huge dust storms (Fig. 4.13).

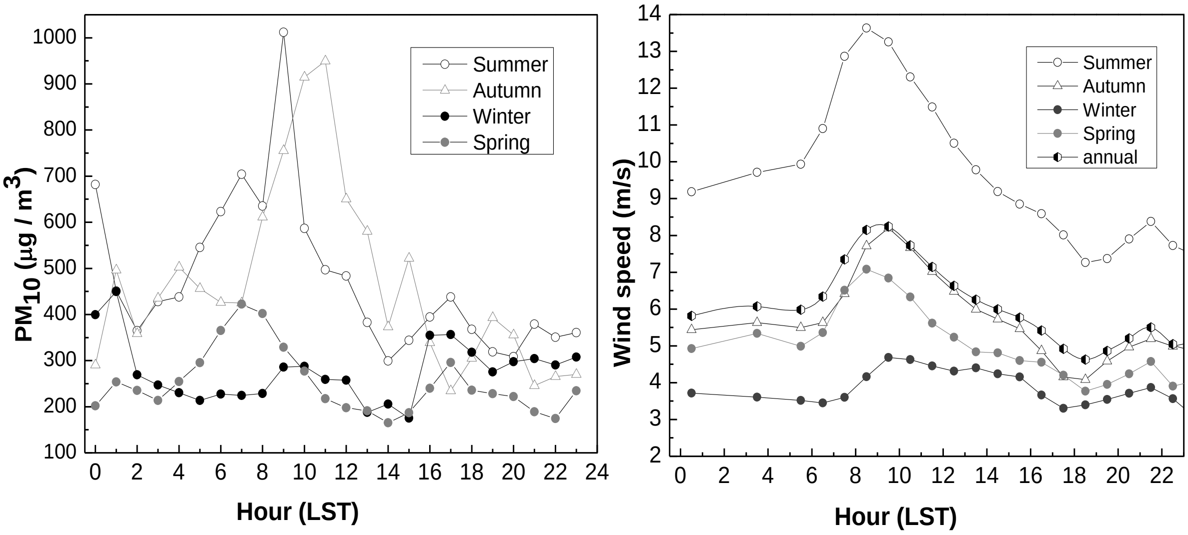

Figure 4.13: Mean hourly variation of the PM_{10} (left panel) and wind speed (right panel) for each season in Zabol.

4.4 Conclusions

Systematic PM concentrations were measured in two cities affected by the Sistan dust storms, Zabol and Zahedan, in southeast Iran covering the period September 2010 to September 2011 and July 2008 to March 2010, respectively. The present Chapter focused on analyzing the daily, monthly and seasonal variability of PM levels and to establish the role of the "Levar" wind in deteriorating the air quality.

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 $PM_{2.5}$ standards. The analysis of the daily PM concentrations showed that the air quality is affected by dust storms from the Sistan desert, which may be very intense during summer.

The drainage of the Hamoun wetlands, in association with the intense Levar winds in summer, is the main factor responsible for the frequent and massive dust storms over the Sistan region. Hamoun, as an intense dust source region, caused a dramatic increase in PM_{10} concentrations and a deterioration of air quality (65% of the days were considered unhealthy for sensitive people and 34.9% as hazardous) in Zabol city.

The PM_{10} and $PM_{2.5}$ levels in Zahedan showed an annual pattern of summer high and winter low, while the $PM_{1.0}$ exhibited the opposite pattern. The maximum PM_{10} concentrations occurred between 8:00 to 11:00 LST in Zabol and between 12:00 and 20:00 LST in Zahedan, indicating that Sistan dust storms reach Zahedan after 6 to 9 hours. The strong correlation between daily $PM_{2.5}$ and PM_{10} concentrations indicated 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 that 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 may the AQI 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.