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Characteristics and composition of the falling dust in urban environment

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Abstract The monthly total amount of dust fall, as well as its chemical and physical characteristics, was systematically investigated in Shuwaikh city, Kuwait. Dust samples were collected on a monthly basis for the entire year of 2009 and analyzed in the laboratory for water-soluble and water-insoluble matter. Water-insoluble matter represented the major portion of the total annual dust. ANOVAs showed significant temporal variation in the concentration of dust fall over the months ($p < 0.05$). Higher dust deposits were encountered between June and August and ranged from 76.4 to 97.6 ± 2.5 (SD) ton km^{-2} $month^{-1}$, where dusty winds and low humidity are a common attribute in such arid areas. The main three soluble matter species measured are nitrate, sulfate, and chloride, and sulfate was found to be the most abundant inorganic species, ranging from 0.72 ± 0.13 to 4.1 ± 0.3 ton km^{-2} - $month^{-1}$. Major insoluble matter species measured are ash, silica, combustible, and tarry. Ash, silica, and combustible account for 63, 19, and 17.8 % of total insoluble dust, and 58.4, 17.7, and 16.6 % of total dust, respectively. Particle size distribution was also investigated, and results showed that dust particles >7 μm were the highest concentration of falling dust. Metrological conditions were found to play a vital role in temporal variations in falling dust.

Keywords Dust fall · Seasonal variation · Water-soluble and water-insoluble matter

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Introduction

Dust storms are one of the most noticeable environmental phenomena in arid and semi-arid regions. Kuwait is located in an arid and semi-arid region, and it is within one of the five major regions where dust originates (Modaihsh 1997). Consequently, dust has been a common natural phenomenon in this area. Dust storms arise when a gust front or other strong wind blows loose sand and dirt from a dry surface. Dust storms have significant influence on global geochemical mass cycles, atmospheric radiation transfer, marine ecosystem, and human health (Gao et al. 1997; Yang 2005; Wang et al. 2005). In recent years, the effects of particles on human health are of greatest concern in urban areas. Epidemiological studies revealed relationships between fine particle concentration and both respiratory and cardiovascular diseases (Pope 2000; Samet et al. 2000). Numerous studies have reported that the adverse health effects caused by concentrations of ultrafine particles are stronger than those created by the mass concentration of the fine particles (Peters et al. 1997; Penttinen et al. 2001). Dust storms can affect climate directly by scattering and absorbing solar radiation (Charlson et al. 1992). Additionally, coagulation and condensation of pollutants on dust particles during transport can further complicate the problem by changing their optical properties (Chou et al. 2003). It was strongly shown that dust particles can react with pollution gases such as SO_2 and NO_X or pollution aerosol by gas/particle interactions during transport, which may alter the nitrogen and sulfur cycles, as well as the acid/base balance (Parungo et al. 1996; Iwasaka et al. 2003; Chung et al. 2003; Li and Shao 2009).

Several studies have investigated the compositions of falling dust. Okada et al. (1990) reported that individual Asian dust particles collected over Japanese islands sometimes had an internal mixture of water-soluble and water-insoluble material, and the water-soluble material mainly contained Ca and S.

Krueger et al. (2004) also found high yields of nitrate formation on calcite and dolomite among individual dust particles from different dust source regions. Traffic and coal burning, accountable for the high levels of NO_x and SO_2, are also the main producers of soil and coal ash mineral particles (Hien et al. 2001, 2004; Begum et al. 2004; Gwilliam et al. 2004). Previous comparative studies of dust particles collected in China and Japan during similar dust storm episodes show that sea salt and sulfur accumulate on dust particles during the transportation from China to Japan (Zhou et al. 1994; Fan et al. 1996). Zhang et al. (2003) studied the mixture of Asian dust particles collected in southwestern Japan in the spring of 2000 by SEM–EDX. They found that mineral materials could enhance particulate sulfate and nitrate formation and restrain chlorine depletion from the sea salt components in mixture particles. Li et al. (2011) has recently investigated aerosol particles collected at a high-elevation mountain site in the North China plain (NCP) during April 2010. The study revealed that sulfate particles can coagulate with dust particles through the physical movement (long-range transport). Additionally, the authors reported the heterogeneous reactions between dust particles and SO_2/NO_2 or their acids, which could result in internally mixed particles. In urban cities, organic compounds are the major constituents of dust after sulfate and nitrates. Tarry matter represents the total organic matter in ambient carbonaceous aerosols, while combustible or unburnt hydrocarbons are a measure of non-volatile compounds in the atmospheric aerosols (Lighty et al. 2000; Johansson et al. 2003).

Particle size distribution measurements have been taken in several European and US cities, e.g., Birmingham (Harrison et al. 1999), Atlanta (Woo et al. 2001), Helsinki (Hussein et al. 2004), Leipzig (Wehner and Wiedensohler 2003), Pittsburgh (Stanier et al. 2004). In terms of seasonal variations, particle number concentrations were slightly lower in summer and higher in winter (Wehner and Wiedensohler 2003; Hussein et al. 2004). In the context of diurnal patterns, particle number concentrations were found to be strongly influenced by the traffic density in the urban area (Tuch et al. 2003; Wehner and Wiedensohler 2003; Hussein et al. 2004; Stanier et al. 2004). Substantial increases of particle number concentration, especially the Aitken mode particles, were observed during traffic peak hours (e.g., Shi and Harrison 1999). Thus, traffic emissions were considered to be one of the most important sources of particles in the urban atmosphere. Tang and Wang (2006) investigated vehicle gaseous emissions (NO, CO, CO_2, and HC) and driver's particle exposures (PM_1, $PM_{2.5}$, and PM_{10}) under very heavy traffic in the urban hot spots in Macao. The measurements were carried out in close proximity to the vehicles, and the inlets of the particle analyzers were positioned at the height of the driver's breathing point. Results showed that motorcycles were higher contributor of particle exposures compared with passenger cars for petrol vehicles, while trucks and buses resulted in higher particle exposures compared with taxis for diesel vehicles. The authors ascribed that to both poor maintenance and the incompetent combustion of fuel or lubricant in motorcycles. Similar trends were also observed in California vehicles (Fruin et al. 2004), New York vehicles (Canagaratna et al. 2004), and Denmark vehicles (Ntziachristos et al. 2000). Tang and Wang (2007) studied the impact of different urban forms, existing currently on the Macao Peninsula, on vehicle transport and street environment using various modeling systems. Results revealed that urban forms 1 and 2, which are characterized with a high percentage (>48.7 %) of narrow roads (≤10 m wide), high density of intersections, and complex road network, restrict the traffic and parking capacities and thus result in reduction in passenger car and motorcycle volumes. This reduction in traffic volumes led to lower noise pollution. With regard to CO emission, the greater street canyon effects in urban forms 1 and 2 resulted in higher CO concentrations. In recent study (Li et al. 2011), it was suggested that dust particles may absorb the acidic gases during the long-range transport and scavenge the fine particles, which ultimately reduce the particle and particle number concentrations and grown particle size.

The impact of meteorological parameters, such as wind speed, wind direction, solar radiation, and precipitation, on the dust constituents and size distributions has gain a least attention in the literature. In one study (Väkevä et al. 2000), it was found that the wind direction weighs heavily in shaping particle number size distributions in the urban background area of Helsinki, Finland. Other studies have reported that long-range transport also plays a vital role in changing the particle number concentrations (Tiitta et al. 2002; Niemi et al. 2004).

Several studies focused on measurement of falling dust included identifying its physical, chemical, and size distribution. Most, if not all, previous studies were conducted in developed countries, with only few observations in Asian countries, including India, Beijing, Korea, and Taiwan. To the author's knowledge, none of these detailed studies were conducted in Middle East countries, which are located in major regions where dust originates. Therefore, the current paper is aimed to systematically study the chemical and physical characteristics of falling dust in Kuwait. Moreover, the relationship between the nature of falling dust and metrological conditions is statistically investigated.

Materials and methods

Site location and sampling method

Dust particles were collected on a monthly basis for the entire year of 2009 in Shuwaikh city, Kuwait. This area (coordinates 29°21′9″N 47°55′31″E) is partly industrial and partly rural. It contains several businesses, including car mechanics, car dealerships, and furniture stores. The Kuwait University

Campus, as well as residential houses, is also located in this area. Therefore, the observation site was quite interesting regarding the measurements of falling dust. Dust fall was collected using open plastic buckets filled with distilled water. These buckets were placed about 3 m above the ground and exposed to the atmosphere for 1 month. All analyses were conducted in duplicate, and each value measured is a mean of at least three replicate determinations. Data on dust fall and its constituents are expressed in ton km^{-2} $month^{-1}$.

Dust fall determination and chemical analysis

Collected dust samples at monthly intervals are analyzed in the laboratory. Insoluble matter, soluble matter, and ash were determined gravimetrically (Lodge 1988). Briefly, all collected samples were filtered using Whatman glass microfiber filters (GF/C) to determine the composition of insoluble matter. Subsequently, the filter paper was dried in an oven at 108 °C for 2.5 h, and afterward kept in a desiccator prior being weighed at least three replicates until the weight of filter paper and insoluble materials became constant. Insoluble matter concentration was quantified using the method by Norela et al. (2009), which is based on the weight differences of filter papers, the area of the dust fall container opening mouth, and number of days (in 1 month); as Eq. (1):

$$\text{Concentration of insoluble matter } \left(\text{g/m}^2\text{/day}\right) = \frac{(W_f - W_i)}{AT} \quad (1)$$

where W_i, weight of the filter without sample (g); W_f, weight of the filter with dry insoluble solids after filtration (g); A, area of dust fall container opening mouth (m^2); T, period of sampling days (days).

For the estimation of soluble matter concentration, the collected samples were placed on the preweighed evaporating dish and then dried in the oven at 108 °C for 2.5 h and subsequently cooled in a desiccator before being weighed. Soluble matter concentration was quantified using the method followed by Latif and Rozali (1991), which is based on the weights differences of the evaporating dish (before and after the drying of the sample), the ratio between volume of water collected and the water used for analysis, the area of the dust fall container opening mouth, and the number of days (in 1 month); as Eq. (2):

$$\text{Concentration of soluble matter } \left(\text{g/m}^2\text{/day}\right) = \frac{\left[(W_f - W_i)\left(\frac{V_1}{V_2}\right)\right]}{AT} \quad (2)$$

where W_i, weight of empty evaporating dish (g); W_f, weight of the evaporating dish with soluble matter (g); A, area of dust fall container opening mouth (m^2); T, period of sampling days (days); V_1, volume of liquid transported to the laboratory (L); V_2, volume of liquid dispensed into the crucible (L).

Total dust deposition was calculated as the sum of insoluble and soluble matter. Tarry matter is an organic matter that has the characteristic of tar or pitch. Tarry content in the water-insoluble matter was determined via acetone extraction. The acetone residue weight represents the tarry matter content. Ash defined as a powdery residue of matter that remains after burning. To determine the ash content, the extracted insoluble matter was then heated in an oven at 850 °C. The residue matter was the ash content, while combustible matter was obtained as the difference between insoluble matter and ash.

Silica contents were determined using FT-IR spectrophotometer (model 510P). The spectrophotometers were checked for malfunctioning by passing standard solutions of all the parameters to be measured; blank samples were passed between measurements to check for any eventual contamination or abnormal response of equipment. Nitrate, sulfate, and chloride contents were analyzed using ion chromatography (DIONEX-600).

Dust particle size

Dust particle size distributions were measured using Andersen hi-vol fractionating samplers (Model 65-000, Andersen 2000, Inc., Atlanta, GA, USA). These consist of a series of 30-cm-diameter (12 in.) aluminum plates with holes offset from the plates and filters in succession. They were designed for placement on the top of an ordinary hi-vol sampler (GMW 2000H, General Metal Works, Cleves, OH, USA) and were operated at the recommended flow rate of 0.57 m^3 min^{-1} (20 cfm).

Dust samples were collected in five separate aerodynamic size ranges as follows: 0.01–1.1 μm (backup), 1.1–2.0 μm, 2.0–3.3 μm, 3.3–7.0 μm, and larger than 7.0 μm. The four upper stages use perforated, circular, Gelman Type A glass fiber filters, as supplied commercially (Andersen 2000, Inc., Atlanta, GA, USA). The backup filter was 20 × 25 cm (8 × 10 in.). Gelman Spectro Grade filters were used throughout the present study.

Results and discussion

Metrological conditions

Temporal variations in meteorological parameters such as wind speed (m s^{-1}), precipitation (mm), temperature (°C), and relative humidity (%) during the study period are shown in Fig. 1a, b. The most frequent meteorological parameters determining the horizontal transport and dispersion of air particles are the mean wind speed and the wind direction (Ziomas et al. 1995). The average monthly wind speed was 4.4 m s^{-1}, with values ranging from 2.9 to 6 m s^{-1}. Northwesterly winds were the most predominant throughout the year, but more so in

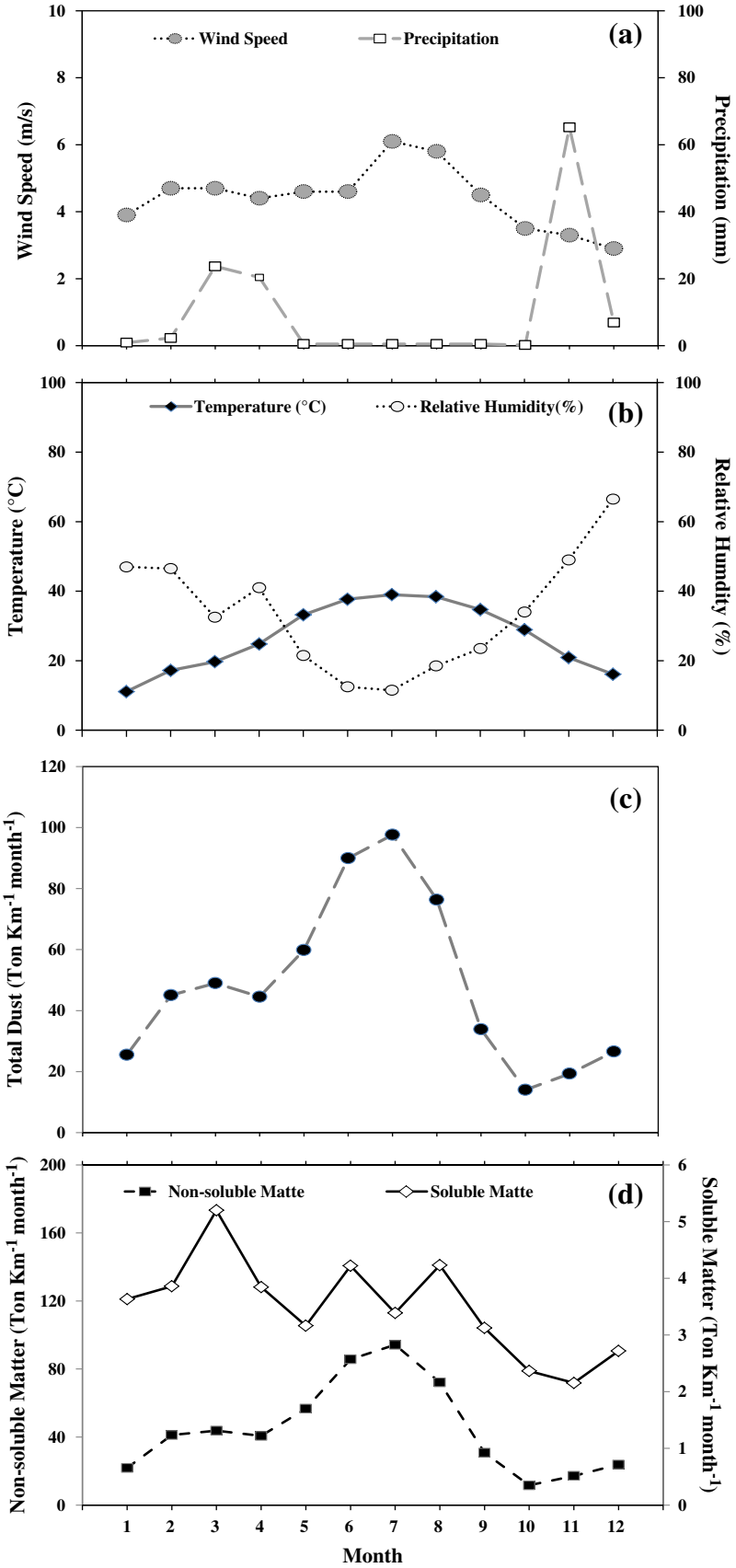

Fig. 1 Temporal variations in monthly average dust fall and metrological parameters

the months of June–August. After northwesterly winds, the most common were southeasterly, which were experienced more often from February to April. This area received approximately 122 mm of rainfall (precipitation) in the year of 2009 (study time), and 53 % (65.2 mm) of the total rainfall was during the month of November. The average monthly relative humidity was 33.7 %, with values ranging from 11.5 to 66.5 % during the investigated period. The maximum relative humidity records were obtained between November and December, while minimum records attained were in June and July. The average temperatures ranged from 11 to 28 °C between October and January, 17–33 °C between February and May, and 35–39 °C between June and September.

Seasonal variations in dust fall

Figure 1c shows the average monthly variation in the dust fall during the period of June through December 2009. The analysis of variance (ANOVA) showed significant temporal variation in the concentration of dust fall over the months ($p < 0.05$). Highest levels of dust deposits were observed between June and August and ranged from 76.4 to 97.6 ± 2.5 (SD) ton km^{-2} month^{-1}, where these months are characterized by dusty winds and low humidity in such arid areas. Additionally, the dust levels rose further by surface erosion and dust resuspension due to prolonged high winds (up to 6 m s^{-1}) and thermal turbulence caused by high temperatures. Minimum dust deposits were observed during October and November and ranged from 14 ± 1.2 to 19. ± 1.4 ton km^{-2} month^{-1}. These lowest valuesare attributed to heavy rainfall during these months, in which it washed out the dust. Falling rain captures aerosol particles via inertial impaction, diffusiophoresis, Brownian and turbulent shear diffusion, thermophoresis, and electric charge effects (Chate and Pranesha 2004). Intermediate values were observed in the months of December, January, and February, with a range of 25.5 ± 1.3–30.5 ± 1.5 ton km^{-2} month^{-1}, which could be ascribed to climatic inversions, as well as constantly changing wind speeds and directions (Lyons and Scott 1990).

Chemical constituents of dust fall

All monthly average measurements of dust-soluble and dust-insoluble matters during the year of 2009 are shown in Fig. 1d. It is evident from Fig. 1d that the water-insoluble matter was comparatively higher (range 11.7 ± 1.9–94 ± 2.1 ton km^{-2} month^{-1}) than the water-soluble matter (range 2.16 ± 0.5–5.2 ± 0.55 ton km^{-2} month^{-1}) over all tested periods. The coefficient of variation (CV) of water-insoluble matter was relatively high (CV = 0.6) compared with water-soluble matter (CV = 0.25) over all tested periods, for the same reasons mentioned in previous sections.

Temporal variation and distribution of chemical components of dust fall, as well as soluble and insoluble matter during the tested period, are shown in Figs. 2 and 3. Descriptive statistics of chemical components of dust fall during the tested period are also shown in Table 1. The main three soluble matter species measured are nitrate, sulfate, and chloride, while the major insoluble matter species measured are ash, silica, combustible, and tarry.

In dust-soluble matter, sulfate was found to be the most abundant inorganic species. The sulfate amount ranged from 0.72 ± 0.13 to 4.1 ± 0.3 ton km^{-2} month^{-1} (average 2.37 ± 0.2 ton km^{-2} month^{-1}) and accounted for 5 and 68 % of the total dust fall and its soluble matter, respectively, during the year of 2009. Another major soluble species is chloride, one of the sea salt's aerosol components. The chloride concentrations ranged from 0.165 ± 0.1 to 0.383 ± 0.11 ton km^{-2} - month^{-1} (average 0.257 ton km^{-2} month^{-1}) and were 0.52 and 7.5 % of the total dust fall and its soluble matter, respectively, during the year of 2009. No significant fluctuations were observed for chloride with respect to month (Tripathi et al. 1991). Nitratewas found to have low concentrations among water-soluble components. The maximum amount detected was 0.012 ± 0.001 ton km^{-2} month^{-1}, with an average of 0.004 ton km^{-2} month^{-1}. On average, three major anthropogenic soluble matter species (sulfate, chloride, and nitrate) accounted for 5.52 and 75.5 % of the total dust fall and its soluble matter, respectively, during the year of 2009.

Among dust-insoluble species, the ash content of dust was highest, ranging from 7.81 ± 0.7 to 57.82 ± 0.92 ton km^{-2} - month^{-1}, with an average of 28.327 ton km^{-2} month^{-1}. The maximum amount was observed in the summer, due to dusty winds having a favorable direction. As for the tracers of soil/dust (Maxwell-Meier et al. 2004), silica were frequently observed in higher concentrations, ranging from 1.39 ± 0.2 to 25.136 ± 0.3 ton km^{-2} month^{-1}, and with an average of 8.613 ton km^{-2} month^{-1}. Significant variations (CV = 0.97) were observed in the amount of silica per month. The combustible fraction of insoluble matter also showed higher values, with an average of 8.03 ± 0.4 ton km^{-2} month^{-1} and with an intermediate variation per month (CV = 0.51). Tarry matter deposition was the lowest (average = 0.011 ± 0.009 ton km^{-2} month^{-1}) among the insoluble matter. It was in the greatest amount in winter (0.022 ± 0.007) and relatively lower in the summer months because of the high frequency of ground inversions in winter and high wind velocity in summer. Overall, ash, silica, and combustible account for 63, 19, and 17.8 % of total insoluble dust, and 58.4, 17.7, and 16.6 % of total dust, respectively.

Source of chemical constituents of dust fall

The source of chemical constituents in falling dust and the impact of metrological conditions on the distribution of chemical constituents were also investigated. Table 2 presents the Spearman correlation coefficient matrices between the amount of chemical components of dust fall

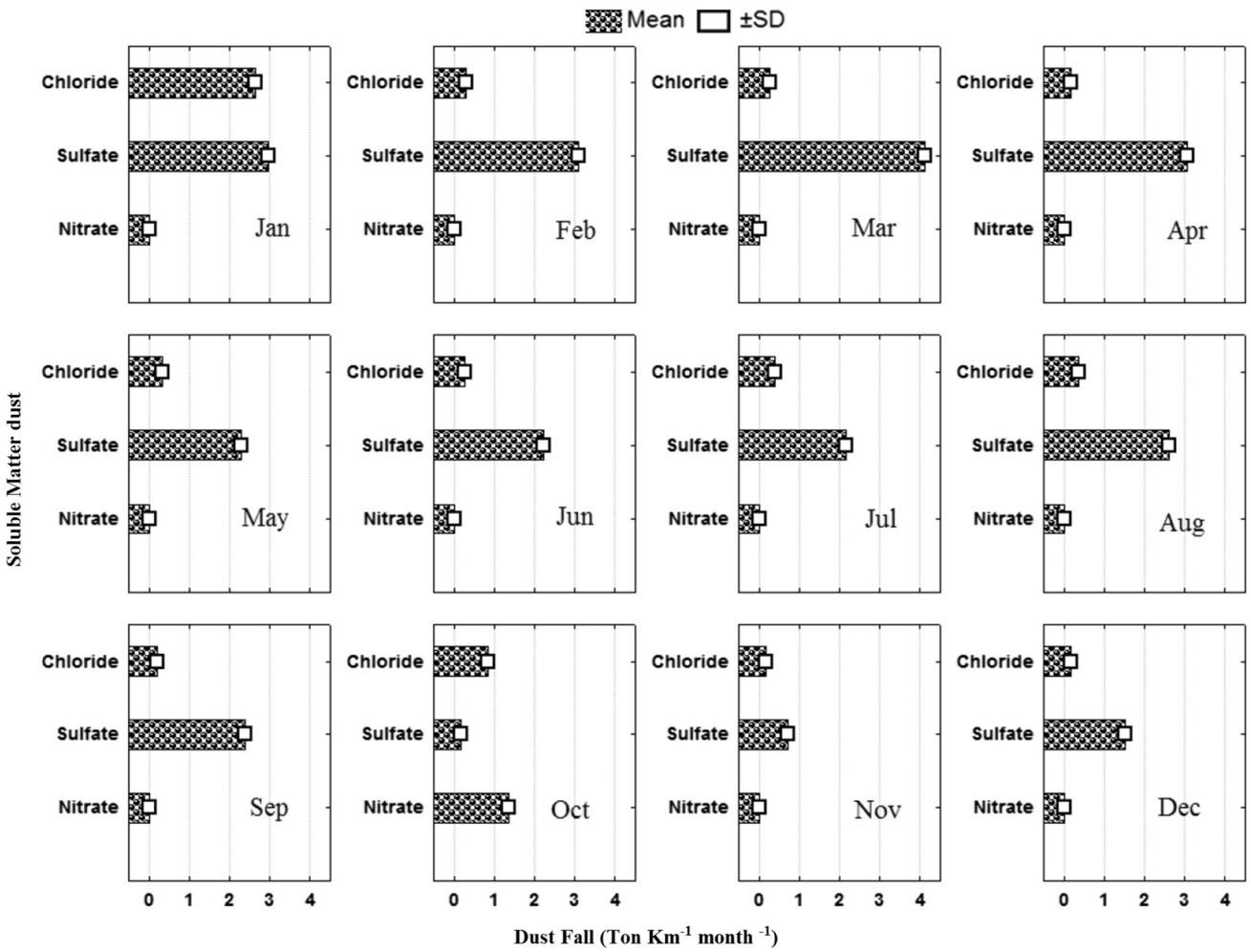

Fig. 2 Temporal variations in monthly average soluble matter in dust fall

and metrological conditions, including wind speed, temperature, relative humidity, and precipitation.

Numerous previous studies have suggested that sulfate and nitrate in dust formed in the atmosphere through homogeneous and heterogeneous reactions (McArdle and Hoffmann 1983; Martin 1984; Hoffmann 1986; Seinfeld 1986; Yang et al. 1991; Quan 1995; Fenter et al. 1995; Zhang 1996; Li and Shao 2009). Heterogeneous reactions involved the transformation of pollution gases, SO_2/NO_X, to sulfate and nitrate, which might take place on the suspended crustal particles remaining in the atmosphere (McArdle and Hoffmann 1983; Martin 1984; Hoffmann 1986). However, heterogeneous conversion is sensitive to relative humidity, and its efficiency decreases with the decrease in humidity. In line with correlation analysis (Table 2), the correlations between sulfate and nitrate concentration and relative humidity were very small, $R = -0.17$ and 0.03, respectively. The findings diminish the possible that nitrate and sulfate species were formed via heterogeneous reactions between mineral dust particles and acidic gases (e.g., NO_X and SO_2). Another possible mechanism of sulfate and nitrate formation is that dust particles absorbed sulfuric and nitric acid (gas or droplets), which were formed through homogeneous reactions of SO_2, OH, O_2, H_2O; and NO_x and OH or N_2O_5 and H_2O occurring in the atmosphere (Seinfeld 1986). Such reactions are independent of the humidity of ambient air (Fenter et al. 1995). This possibility, however, cannot exclude the occurrence of other heterogeneous reactions between mineral dust and aqueous acids once the mineral dust particles absorb the acids. In the tested area, SO_2 and NO_x (NO and NO_2) emissions are usually high, as it is surrounded by various industries. To further investigate the relationship between the emissions of SO_2 and NO_X per month, as well as dust sulfate and nitrate, SO_2 is plotted versus dust sulfate and NO_X isplotted versus dust nitrate, as shown in Fig. 4a, b. Spearman's correlation analysis showed a significant relationship ($R = 0.66$ and $p < 0.05$) between the emission of SO_2 and dust sulfate, which could be the precursor of sulfate formation. Conversely, the Spearman correlation coefficient was low between the emissions of NO_X and dust nitrate. This discrepancy could show that emissions of NO_X are not merely the source of dust nitrate.

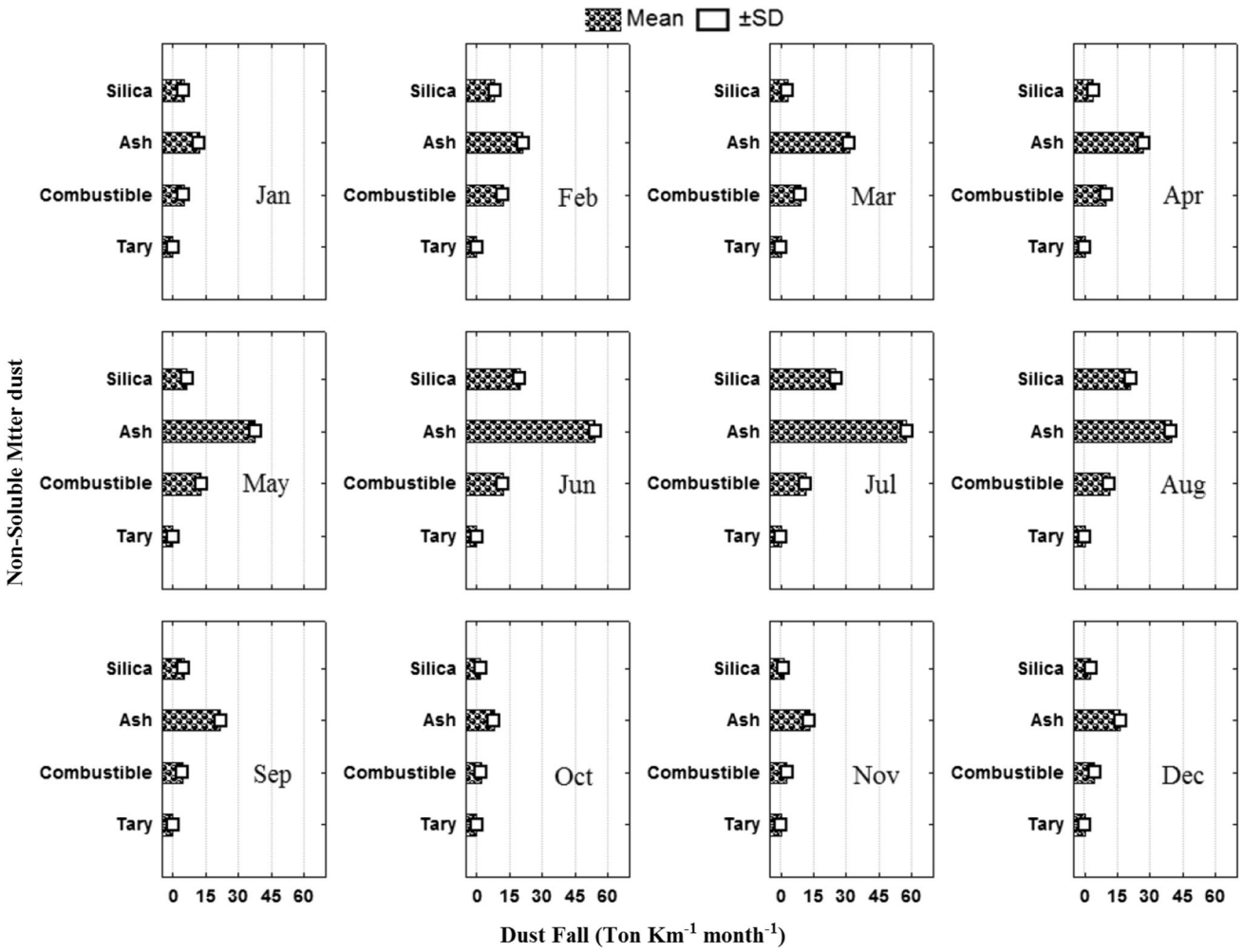

Fig. 3 Temporal variations in monthly average insoluble matter in dust fall

Table 1 Descriptive statistics of dust fall, ton km^{-2} $month^{-1}$

Solubility	Constituents	Mean	Min.	Max.	SD	CV
Soluble matter	Nitrate	0.004	0.001	0.012	0.003	0.83
	Sulfate	2.374	0.724	4.111	0.91	0.38
	Chloride	0.257	0.165	0.383	0.080	0.31
Insoluble matter	Tarry	0.011	0.000	0.022	0.008	0.72
	Combustible	8.03	2.020	12.751	4.071	0.51
	Ash	28.327	7.812	57.822	16.27	0.51
	Silica	8.613	1.391	25.136	8.35	0.97

Previous studies repeatedly reported that the formations of particulate sulfate and nitrate on sea salt particles (Eriksson 1959; McInnes et al. 1994) and dust particles enhanced the production of particulate sulfate and nitrate in the downstream atmosphere (Nishikawa et al. 1991; Dentener 1996; Tang 2004). The sea is about 2–3 km from the tested area, which is where the particles could have originated from, and the wind could have induced the transportation. Temperature and precipitation showed weak correlation in the formation of either nitrate or sulfate, as shown in Table 2. The quantitative estimation revealed that the chloride amount (Fig. 2) was appreciable compared to the amount of sulfate. Chloride is thought to be primarily derived from sea salt aerosols, especially in a marine environment (Zhuang and Chan 1997). Chloride could deposit onto dust particles through the absorption of chlorine-containing gases or sea salt aerosol when the particles passed through the marine atmosphere. Wind speed can induce such transportation. As shown in Table 2, there wasa significant correlation ($R = 0.85$ and $p < 0.05$) between wind speed and dust chloride.

Silica was found in substantial amount in the falling dust, where it accounted for 19 % of total insoluble dust and 17.7 % of total dust. Silica is more likely to be a product of soil erosion or road dust aerosolized by traffic. Wind speed exhibited a significant correlation with silica ($R = 0.73$ and $p < 0.05$). Higher wind speed also causes greater release of dust particles due to erosion and resuspension. The temperature had a consistent pattern, with relative humidity ($R = 0.89$ and $p < 0.05$), and the temperature was inversely

Table 2 Correlation matrices for selected metrological parameters and dust fall constituents

Parameters	Dust fall constituents (ton km^{-2} month^{-1})						
	Nitrate	Sulfate	Chloride	Tarry	Combustible	Ash	Silica
Wind speed (m s^{-1})	0.03	0.47	**0.85**	0.16	**0.74**	**0.79**	**0.73**
Temperature (°C)	−0.07	−0.15	0.39	**0.67**	0.41	**0.72**	**0.69**
RH (%)	0.03	−0.17	**−0.58**	−0.44	−0.53	**−0.78**	**−0.71**
Precipitation (mm)	0.08	−0.30	−0.39	−0.34	−0.35	−0.30	−0.42

Values denote Spearman's coefficient of correlation (R). Significant correlation ($p < 0.05$) is bolded

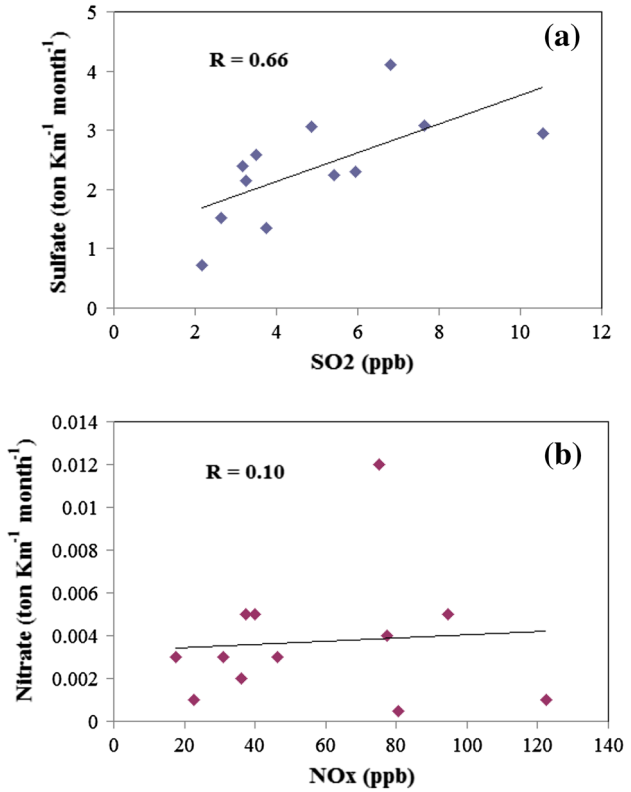

Fig. 4 Correlation analysis between **a** Sulfate and SO_2, **b** nitrate and NO_X

proportional to relative humidity. Both temperature and relative humidity showed a strong correlation with wind speed, using Spearman's correlation coefficient (R) at 0.65 and 0.78, respectively. Accordingly, both temperature and relative humidity induced wind speed, which ultimately enhanced the release of dust particles due to erosion and resuspension; this is consistent with the Mirme and Ruuskanen (1996) study. The ash content was the highest among the soluble and insoluble matters of the falling dust, with an average of 28.327 ton km^{-2} month^{-1}. The likely source of ash is flying ash from the petroleum industry and a power station, as it is increased in summer, which eliminates the possibility from burning coal from adjacent camping activities. It should be mentioned that the dust collection area was far away from the petroleum industry, but in the close vicinity of a power station. In either case, wind speed was very high in summer, reaching 6.1 m s^{-1}. This would, in turn, easily induce the transportation and resuspension of flying ash. A significant correlation was found between wind speed and ash in dust fall ($R = 0.79$ and $p < 0.05$). Additionally, both temperature and relative humidity showed a strong correlation with wind speed, as observed with silica. The combustible fraction showed higher values, with an average of 8.03 ± 0.4 ton km^{-2} - month^{-1}, which accounted for 17.8 % of total insoluble dust and 16.6 % of total dust, respectively. These highest amounts of combustible fractions are the result of frequent running of heavy vehicles and movement of heavy earth-moving machines. Again, strong correlation was found between wind speed and combustible fractions ($R = 0.74$ and $p < 0.05$). The temperature and relative humidity had little effect on the amount of combustible fractions.

Tarry matter showed the lowest amount detected among insoluble matter. In contrast to most species, tarry was found in maximum amount during the winter. This finding may increase the possibility that the source of tarry matter in dust could be the products of burning activities from coal burning, petroleum industry, and power station, as these activities are usually increased in winter months. Another possible source of tarry matter is vehicular exhaust (Li et al. 2009; Zheng et al. 1997). The effect of wind speed and relative humidity was insignificant. It should be emphasized that precipitation exhibited slightly low impact on all the constituents of falling dust.

Comparison of dust fall levels with other cities

The average concentrations of dust fall (ton km^{-2} month^{-1}) for urban city of Shuwaikh, a central location in Kuwait, was compared with those found in urban areas in other cities (Fig. 5). As shown in Fig. 5, the highest dust fall was found in an opencast coalmine area in Bina of India, with an annual amount of dust fall of 96.2 ton km^{-2} month^{-1} (Pandey et al. 2008), while the lowest average dust fall was 0.83 ton km^{-2} month^{-1} and reported in Southern Nevada (USA), with values ranged between 0.36 and 1.3 ton km^{-2} month^{-1} (Reheis and Kihl

1995). The dust fall in Gansu province (China) shows a large annual range of 18.23–69.4 ton km^{-2} $month^{-1}$ in the desert and Gobi area and 9.7–34.84 ton km^{-2} $month^{-1}$ in the loess area (Ta et al. 2004). Shuwaikh city (Kuwait), based on this study, followed Bina of India in dust fall with an average amount of 53.7 ton km^{-2} $month^{-1}$, which is indeed expected as it is located in an arid region, and it is located within one of the five major regions where dust originates. Areas in North and Northwest India exhibited intermediate value (21 ton km^{-2} - $month^{-1}$) of dust fall (Yadav and Rajamani 2006), followed by Nagev desert (Offer and Goossen 2001), Lanzhou (Liu et al. 2004), Texas (Crabtree 2005), Yazd (Naddafi et al. 2006), Arizona (Crabtree 2005), California (Crabtree 2005), and Southern Nevada (Reheis and Kihl 1995), as shown in Fig. 5. The discrepancies of dust fall level among these cities showed that their industrial types and traffic compositions in addition to geographic locations are different from each other. In general, dust fall profile described in Fig. 5 shows that Kuwait is one among the highest urban cities.

Particle size concentration of dust fall

Temporal variations in dust fall concentration as a function of particle size are shown in Fig. 6, and descriptive statistics are also shown in Table 3. As seen from Fig. 6 and Table 3, dust particle size >7 μm showed the highest concentration of falling dust, which accounted for approximately 44 % of total dust particle sizes. The average concentration of particle size >7 μm, as shown in Table 3, was 263.43 ± 76.5 μg m^{-3}. The concentration of particle size >7 μm was found to be 2, 2.5, 4, and 7.5 times greater than particle sizes of 0.01–1.1, 3.3–7, 2–3.3, and 1.1–2.2 μm, respectively. The concentration of particle size of 0.01–1.1 μm was the second highest, where its average was 115.20 ± 53.8 μg m^{-3} and accounted for 21.6 % of total dust particle sizes. This observation is consistent with Baik et al. (1996) in Seoul city, where peak concentration was determined at 0.8 μm. The lowest concentrations (31.62 ± 12.63 μg m^{-3}) detected were for particle size of 1.1–2 μm, where it accounted for only 6 % of total dust particle sizes.

The impact of metrological conditions on dust fall particle size concentration was also investigated. Spearman's correlation coefficient matrices between metrological conditions and particle size concentration are shown in Table 4. Results in Table 4 present a clear association between the concentration of particle size <3 μm and metrological conditions (wind speed, temperature, and humidity). The concentration of particle size >3 μm is less dependent on metrological conditions, as Spearman's correlation coefficients varies between low and intermediates values.

The likelihood of any particle entering the atmosphere depends upon its size, density, and shape. Additionally, the rate at which particles are deposited from the atmosphere by turbulent deposition can be presented in terms of a deposition velocity, which is a function of the aerodynamic diameter (Nicholson 1988). Meteorological variables affect the initial release of this material and its dispersal once airborne, and the influence increases with decreasing particle sizes. The inert release of material from a surface will be contingent upon the balance between two groups of forces. Bonding forces, such as the electrostatic force if the particle and surface are differently charged or surface tension if the surface is wet, will tend to retain the particle on the surface, as will happen for any physical attachment. Bonding effects are most likely to be affected by the temperature and moisture at the surface that the particle rests on. These conditions will be determined by the temperature and humidity of the surrounding air and by the radiation balance of the surface. Particle size distributions have been studied in numerous cities, e.g., Birmingham (Harrison et al. 1999), Atlanta (Woo et al. 2001), Helsinki (Hussein et al. 2004), Leipzig (Wehner and Wiedensohler

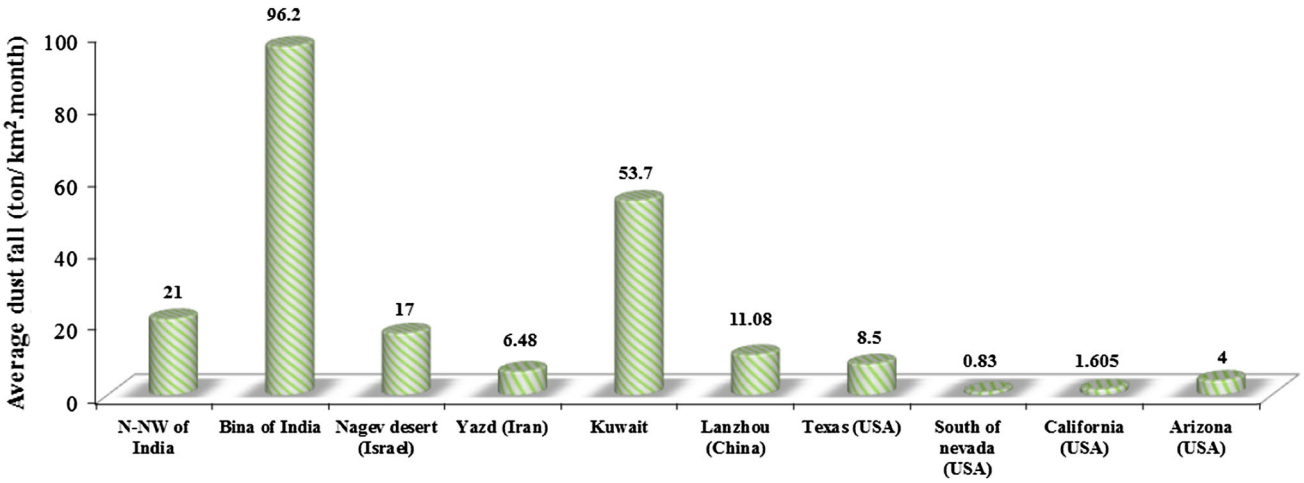

Fig. 5 Comparison of dust fall concentrations for ten cities including Shuwaikh (Kuwait)

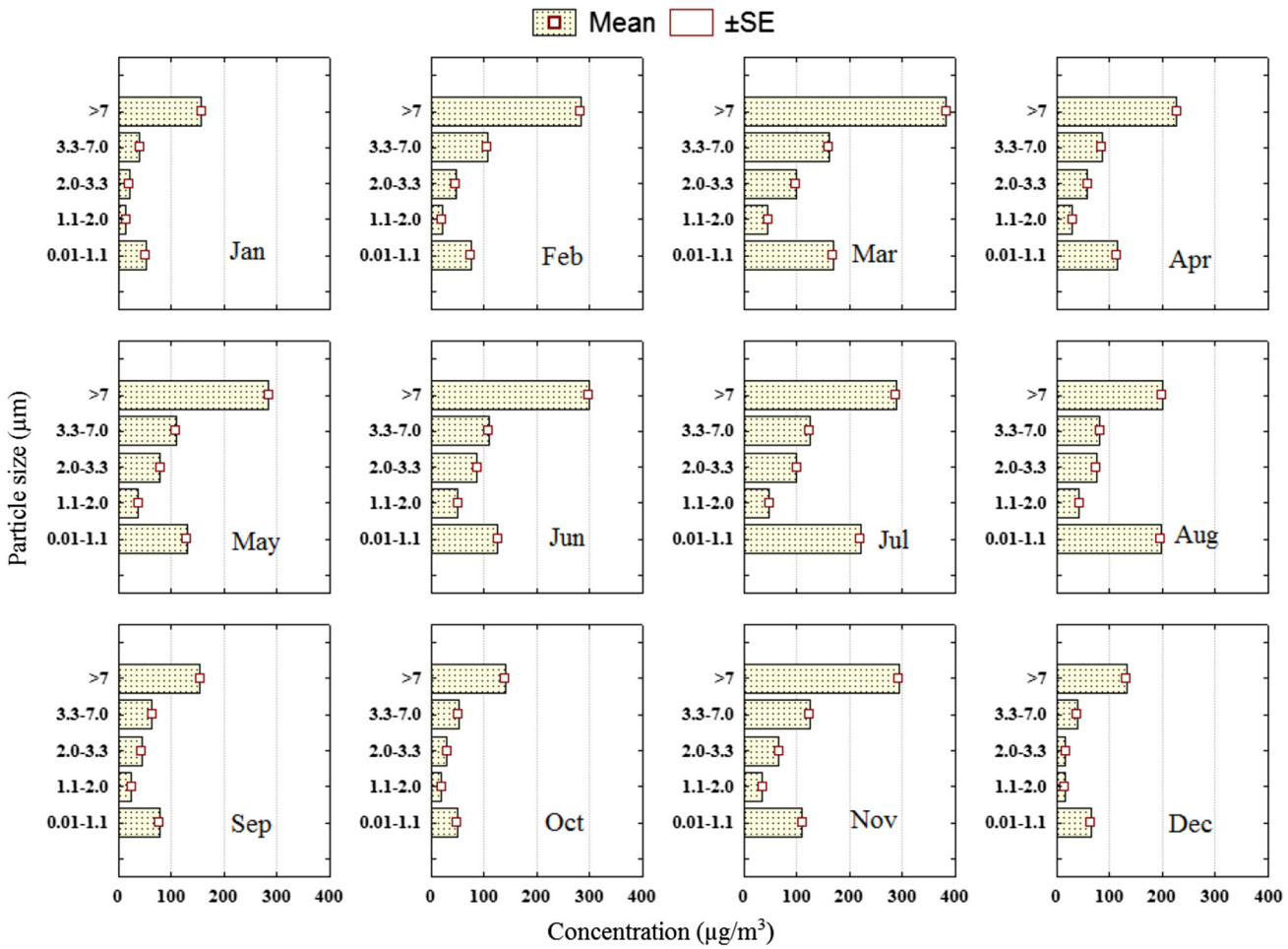

Fig. 6 Temporal variations in monthly average particle size distributions in dust fall

Table 3 Descriptive statistics of dust fall size concentration distribution, µg m^{-3}

Particle size (µm)	Mean	Min.	Max.	SD	CV
0.01–1.1	115.20	48.63	219.77	53.8	0.49
1.1–2.0	31.62	13.85	50.93	12.63	0.42
2.0–3.3	59.77	16.09	99.30	27.78	0.49
3.3–7.0	91.04	37.99	160.58	36.31	0.42
>7	236.43	131.75	382.36	76.50	0.34

Table 4 Correlation matrices for selected metrological parameters and dust particle size distribution

Parameters	Particle size (µm)				
	0.01–1.1	1.1–2.0	2.0–3.3	3.3–7.0	>7
Wind speed (m s^{-1})	**0.82**	**0.66**	**0.7**	0.45	0.4
Temperature (°C)	**0.6**	**0.65**	**0.57**	0.21	0.1
RH (%)	**−0.65**	**−0.75**	**−0.71**	−0.4	−0.33

Values denote Spearman's coefficient of correlation (R). Significant correlation ($p < 0.05$) is bolded

2003), and Pittsburgh (Stanier et al. 2004). Particle number concentrations were found to be strongly influenced by the traffic density in the urban area (Tuch et al. 2003; Wehner and Wiedensohler 2003; Hussein et al. 2004; Stanier et al. 2004). Sheng and Tang (2013) evaluated the risk of exposure to traffic-related air pollutants for the World Heritage Monuments in the historic center of Macao. The air quality was the worst at evening peak hours with north wind direction sector (0°–20°). Wind speed is also has vital role in particle size distribution. The size of particle moved by the wind depends on the size of the particle and the speed of the wind; larger particles are slowly moved by wind compared with small ones. Large particles also tend to settle to the ground by gravity in a matter of hours.

Conclusion

In this study, the seasonal variations in falling dust, as well as its chemical and physical constituents, were thoroughly investigated during the entire year of 2009 in Shuwaikh city, Kuwait.

Representative monthly dust samples were collected and studied in the laboratory. Dust fractions, in both water-soluble and water-insoluble matter, were identified, and it was found that water-insoluble matter constituents the major fraction of the total annual dust. ANOVAs showed significant seasonal variation in the concentration of dust fall over the months ($p < 0.05$). Maximum dust deposits were observed between June and August and ranged from 76.4 to 97.6 $\pm$ 2.5 ton km^{-2} month^{-1}, where dusty winds and low humidity are a common attribute in such arid areas. Major soluble matter species measured were nitrate, sulfate, and chloride, and sulfate was found to be the most abundant inorganic species,averaging 2.37 $\pm$ 0.2 ton km^{-2} - month^{-1}. Major insoluble matter species measured were ash, silica, combustible, and tarry. Ash, silica, and combustible accounted for 63, 19, and 17.8 % of total insoluble dust, and 58.4, 17.7, and 16.6 % of total dust, respectively. Dust particle size >7 μm represented the highest concentration of falling dust. Both chemical characteristics and size distributions of falling dust were influenced by metrological conditions.

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