



Characterization and Elemental Composition of Atmospheric Aerosol Loads during Springtime Dust Storm in Western Saudi Arabia

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ABSTRACT

Dust storm is a common phenomenon and a severe environmental hazard in western Saudi Arabia. In this study, simultaneous measurement of PM₁₀, PM_{2.5} and PM_{1.0} and elemental compositions analysis of PM_{2.5} in Jeddah city during springtime (March 2012) dust storm (DS) and non-dust storm (non-DS) periods were carried out to investigate the impact of DS on the levels, characterization and elemental compositions of atmospheric particles. Results indicate that PM fractions concentrations were higher in DS environment compared to non-DS. The diurnal variation of PM fractions concentrations was uni-modal in non-DS environment and bimodal in DS. PM_{1.0}/PM₁₀, PM_{2.5}/PM₁₀ and PM_{2.5}/PM_{2.5-10} ratios were relatively lower in DS, indicating that sand-dust events in spring carry much more coarse than fine particles to Jeddah. PM₁₀, PM_{2.5} and PM_{1.0} in DS and PM₁₀ and PM_{2.5} in non-DS might originate from similar sources. PM₁₀, PM_{2.5}, PM_{1.0} in DS and PM₁₀ in non-DS were correlated negatively with relative humidity and positively with wind speed. PM_{2.5} and PM_{1.0} in non-DS were correlated positively with relative humidity and negatively with wind speed. The crustal elements accounted for 44.62 and 67.53% of the total concentrations of elements in non-DS and DS, respectively. The elements concentrations increased in DS, with highest DS/non-DS ratios for Ca, Si, Al and Fe. This indicates that the soil originating species contributed mainly in DS particles. The enrichment factors values and non-crustal fractions in both non-DS and DS indicate that the main sources of Na, Mg, Si, K, Ca, Ti, Cr, Mn, Fe, Rb and Sr are of a crustal type, whereas S, Cl, Co, Cu, Zn, Ga, As, Pb and Cd are anthropogenic. V and Ni in DS only are emitted from anthropogenic sources. The enrichment factors of these anthropogenic elements were lower in DS. They might originate mainly from local sources in Jeddah.

Keywords: PM₁₀/PM_{2.5}/PM_{1.0}; Diurnal variation; Elemental composition; Dust storm; Jeddah.

INTRODUCTION

Atmospheric aerosol is a complex mixture of anthropogenic and natural origin. Industrial activities, energy production, construction, urban waste treatment and vehicle exhausts constitute anthropogenic sources of particulate matter (PM) in the atmosphere (Bilos *et al.*, 2001). Main sources of natural atmospheric PM are dust storm (DS), volcanic activities and oceans. Dust events are defined as natural events with substantial PM concentrations, usually

occurring frequently in desert lands and their surrounding areas in arid and semi-arid regions and primarily resulting from low vegetation cover and strong surface winds (Wang *et al.*, 2005; Miri *et al.*, 2009). DS is a kind of severe natural disaster and plays an important role in the Earth system (Ravi *et al.*, 2011; Shao *et al.*, 2011). In most cases it results from turbulent winds, including fronts and convective haboobs (Miller *et al.*, 2008), which raise large quantities of dust from desert surfaces and reduce visibility to less than 1 km. Sometimes dust reaches concentrations in excess of 6000 µg/m³ in severe events (Song *et al.*, 2007). It can affect daily life for short time intervals ranging from a few hours to a few days. Upon entering the atmosphere, especially when transported over heavily polluted regions, the chemical and surface nature of mineral dust particles undergo significant changes, in turn influencing a number

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of atmospheric processes (Usher *et al.*, 2003; Formenti *et al.*, 2011). Nine regions contribute to the total global production of desert dust. These regions include North Africa (Sahara), South Africa, the Arabian Peninsula, Central Asia, Western China, Eastern China, North America, South America and Australia (Prospero *et al.*, 2002; Tanaka and Chiba, 2006). Al-Dousari *et al.* (2013) showed that there were seven major sources of DS trajectories in the world including the west and south Sahara Desert, the east of Sahara Desert, east Sudan and Ethiopia, the northern Arabia, Gobi Desert, Taklimakan Desert, and Australian Desert. Precipitation, vegetation cover, wind velocity, and soil particle size of dust-generating sources are the main factors influencing the amount of dust in the atmosphere (Ta *et al.*, 2004).

DS was reported to have health as well as environmental effects. It has been reported that dust emissions have impacts on human health even at great distances from their source. This is because of the long distances over which dust plumes can travel (Zhu *et al.*, 2007). The number of emergency visits to hospitals was reported to increase within 1 to 3 days after DS events (Chung *et al.*, 2005). Mineral dusts associated with the dust events can also potentially carry different infective agents and transport them over long distances. Dust events can produce large-scale transport of pathogens and thereby affect downwind populations and ecosystems (Kellogg and Griffin, 2006). Wind-blown desert dusts commonly carry high amounts of toxins and thereby endanger the organisms and ecosystems exposed to the dust (Sandstrom and Forsberg, 2008). Dust events have been related to increased deposition rates of radioactive material (Akata *et al.*, 2007). Metal elements can bind to dust particles and therefore affect respiratory function (Hong *et al.*, 2010). The regional dust is not only significantly harmful to health, but also to the ecological environment, agricultural activities (suppressing plant growth by blocking plant pores and disrupting photosynthesis), land use and soil formation, reduced soil fertility in dust storm source areas, chemical/elemental fluxes between continents and oceanic biogeochemical cycles, delivery of iron to the oceans, reduction of solar radiation that reach the ground, effect on air temperature, reduction of visibility that limits various activities, increases traffic accidents, and may increase the occurrence of vertigo in aircraft pilots (Prospero *et al.*, 2008; Goudie, 2009; Tagaris *et al.*, 2010; Maghrabi *et al.*, 2011; Chang *et al.*, 2013; Chiu *et al.*, 2013; Gan *et al.*, 2013; Delfino *et al.*, 2014).

Parts of the Middle East, especially Saudi Arabia, are affected by DS during some seasons. The frequency of DS occurrence peaks during the pre-monsoon season (March–May), when dust aerosols are transported by south westerly winds from the arid and semi-arid regions around the Arabian Sea (Middleton, 1986; Ackerman and Cox, 1989). Some of these regions include the alluvial plains of Iraq, the plateau of Eastern Jordan, the Jazirah of Eastern Syria, the plains of Dhofar, the adjacent interior eastern Yemen, and the Empty-Quarter desert centred in Saudi Arabia (Maghrabi *et al.*, 2011). In these regions, DS is a very frequent phenomenon.

In Saudi Arabia, DS is considered to be one of the most

severe environmental hazards. Due to topography, drought, light textured topsoil and scanty vegetative cover, Saudi Arabia is susceptible to the dust and DS. Several investigators have studied desert dust in the Middle East and Arabian Peninsula, including Saudi Arabia (Pease *et al.*, 1998; Smirnov *et al.*, 2002; Alharbi and Moied, 2005; Badarinath *et al.*, 2010). All the previously mentioned studies used either surface or satellite observations to characterize the large-scale dust loading of the atmosphere over the Arabian Peninsula. However, there are limited studies about the effect of DS on the levels, characterization and element composition of atmospheric aerosol in western part of Saudi Arabia (Jeddah).

We were able for the first time to clearly define the possible source(s) of DS, concentrations and diurnal variations of PM_{10} , $PM_{2.5-10}$, $PM_{2.5}$, and $PM_{1.0}$, elemental composition of $PM_{2.5}$ during non-DS and DS periods in an urban area of Jeddah city. This will be useful to provide sound information on the importance and effects of DS on the air quality of the study

MATERIALS AND METHODS

Study Area

Jeddah is the second largest city in Saudi Arabia and the most significant commercial center, located in the middle of the western Red Sea coast of the country, the city is surrounded by mountains in the north-east, east and south-east. According to the recent census collected by the Central Department of Statistics and Information of the Ministry of Economy and Planning, Saudi Arabia in 2010, Jeddah houses more than 3.40 million inhabitants which represent 14% of national population. The growth of the city over the last thirty years has been rapid and diverse, and continues to date. The annual growth rate of Jeddah's population in 2010 accounts around 3.7% (3.9%) with reference to 1992 (2004) census (Almazroui *et al.*, 2013). Regrettably, due to lack of awareness and proper regulations, these development activities were accompanied by environmental degradation, and over the years the air quality has progressively deteriorated. Like almost everywhere else in the world, the Jeddah's environment and its citizen's health are affected by both mobile and stationary sources. Here, more than 1.40 million vehicles are running in the streets of Jeddah city (Khodeir *et al.*, 2012). Vehicle fuels used in Jeddah are mainly unleaded gasoline and diesel. The stationary sources in this city include an oil refinery, a desalinization plant, a power generation plant and several manufacturing industries. South Jeddah, where the dust monitor was installed, is an urban area with industrial activities, narrow streets and relatively high traffic density.

General Description of DS

The back trajectories are a common way to study the transport of aerosol from source regions to receptor sites and interpretation of how aerosol or other atmospheric components vary over space and time. The main idea behind the back trajectories is that there exists a link between air mass path and the aerosol observations at the receptor site

(Jeddah King Abdulaziz University). In the present study, PSU/NCAR mesoscale forecast prediction model (known as MM5V3) was used to study the dust storms that occurred in the period 1–31 March 2012 (Dudhia and Bresch, 2000). The backward trajectories are computed based on hourly three dimensional MM5V3 output wind fields on a 36×36 km horizontal grid. The forecast model MM5V3 output includes u and v components of the wind, temperature, geopotential height, and pressure at different atmospheric levels starting from surface to 100 millibars, typically from operational model runs; which are used to compute backward trajectories for air parcels at specified heights above the ground. The six hourly data for initial and lateral boundary conditions were provided by the World Area Forecast System (WAFS) files on the National Center for Environmental Prediction (NCEP) Office with a resolution of 1.25×1.25 degrees and are used to run the MM5V3. In order to compute backward trajectories at the surface in the present study, MM5V3 was run to provide 5 days - hourly forecasted windfield. MM5 is used as source of meteorological input data for dust models such as CARMA-dust model (Barnum and Winstead, 2004). The model was run operationally to forecast dust storms in Northern Africa, the Middle East and Southwest Asia. The model has been evaluated and showed effectiveness to make short, medium and long-range forecasts of dust storm with Probability of Detection of dust storm occurrence exceeding 68 percent over Northern Africa, 61 percent over Southwest Asia and 48 percent over Saudi Arabia.

Aerosol Sampling and Monitoring

Particulate matter concentrations (PM_{10} , $PM_{2.5}$ and $PM_{1.0}$) were monitored with one minute average by an optical scattering spectrometer (Environmental Dust Monitor (EDM-179), Grimm Aerosol, Germany) in an urban area “Gholeil” in south Jeddah city during March 2012, the period during which the highest frequency of dust events is occurred. To assess the effect of dust events on elemental composition of particles, the $PM_{2.5}$ sampler (Automated Cartridge Collector Unit (ACCU) was used to collect dust samples in non-DS and DS periods, at the same site, for elemental composition analysis. The samples were collected using a calibrated vacuum pump (Gast, USA) to draw 10 L/min. The flow rate of a calibrated vacuum pump was measured before and after sampling time. The differences were found to be very small (0.1 L/min), so, it is considered that no overload of filter media occurred for the sampling condition. Daily 24-hr samples (3–4 per week (total samples = 15)) were collected on Teflon filters (GelmanTeflo, 37 mm, 0.2 μ m pore-size) from midnight to midnight. Field blanks were collected through putting another set of Teflon filters in the sampling site for the same duration with the same steps without operating the air sampler. Sampling inlets were installed at a height of 6 m above ground, to minimize local influences of surrounding obstructive vegetation, topography, or buildings.

Elemental and Gravimetric Analysis of $PM_{2.5}$

The description for gravimetric and elemental analysis via energy dispersive X-ray fluorescence, ED-XRF, of all

PM samples is provided in Maciejczyk *et al.* (2005). Briefly, Filter masses were measured on a microbalance (model MT5, Mettler–Toledo Inc., Highstown, NJ). The mass of particulate collected on each filter was determined by the difference in weight before and after sampling, then, particulate concentration was calculated from the volume of air filtered. $PM_{2.5}$ samples were analyzed for 24 elements by nondestructive XRF (model EX-6600-AF, Jordan Valley) using five secondary fluorescers (Si, Ti, Fe, Ge, and Mo), and spectral software XRF2000v3.1 (U.S. EPA and ManTech Environmental Technology, Inc.). Blank samples were analyzed for total element concentrations. Four field and four laboratory blank samples were used to evaluate external elemental contamination introduced by sample handling. The actual detection limits of measured elements depend on the filters and other parameters. We used 3 times of the uncertainties (3x) of each element in our measurements. Any elements with concentrations lower than 3x uncertainties is considered not detectable. The detection limits were 14.14, 4.24, 3.68, 3.54, 2.83, 2.40, 2.26, 2.26, 1.41, 1.41, 0.99, 0.85, 0.71, 0.99, 0.71, 0.85, 0.85, 0.85, 0.85, 1.13, 8.49 and 1.56 ng/cm^2 for Na, Mg, Al, Si, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Rb, Sr, Cd and Pb, respectively. We used commercially available thin film standards for calibration. They deposit a know amount, in ng/cm^2 , of specific element on a thin film. Usually 2 points plus blank to calibrate each element were used.

Meteorological Data

The wind speed, wind direction, temperature (T), and relative humidity (RH) during the period of study were obtained from the air monitoring station located in King Abdulaziz University: Lat. 24.67°N and Lon. 45.33°E. These meteorological parameters were measured continuously using Lufft WS600-UMB Compact Weather Station, simultaneously with measurements of atmospheric PM concentrations.

Statistical Analysis

Data were analyzed using SPSS version 17 (SPSS, Chicago, Illinois, USA). Pearson correlation coefficient was used to test the correlation between PM_{10} , $PM_{2.5}$, $PM_{1.0}$, temperature, relative humidity and wind speed (Norman and Streiner, 2000).

RESULTS AND DISCUSSION

Origin of DS

The type of soil was deduced from the 17- type of soil included in US Geological Survey (USGS). Accordingly, four types of soil (sand, loamy sand, sandy loam, silt loam) are the main sources of dust in the present study (Figs. S1–5(a)). To identify the sources of dust emission, which caused dust storms on Jeddah city, backward trajectory for forecasted five days including the day before the storm and the day of storm and three days after was applied. The duration of each track was 12 hours and started from 8 am for 12 hours prior.

Five situations of dust storm were recorded in the

present study. These dust storms occurred on 3, 13, 17, 18 and 22 March 2012.

Situation 1 (Northeast Winds)

Backward trajectory for forecasted five days (2–7 March) indicated wind coming from northeast crossing over clay and loamy areas (Fig. S1). It is characterized by frictional speed higher than the critical increasing dust and sand to the atmosphere, especially south of Jeddah. This is confirmed by satellite image on March 3, which shows the presence of a cloud of dust covering a longitudinal area of the Red Sea.

Situation 2 (South Winds)

Backward trajectory on the storm day and the days followed this prediction (10, 11, 12, 13 and 15 March) (Fig. S2). It can be seen that the sources of dust are the southern areas of Jeddah. Instability is also present due to the increased friction velocity above critical values.

Situation 3 and 4 (East to Northeast Winds)

Backward trajectory on 17–21 March indicated wind coming from east to northeast, with higher friction velocity than the critical values (Figs. S3 and S4). This is confirmed by satellite images showing the presence of many areas on the coast of the Red Sea that are considered sources of dust. This dust appears as clouds of smoke crossing the Red Sea from east to west.

Situation 5 (North and East Winds)

This situation (21–25 March) represents the extension of the third and fourth situations. Fig. S5 shows that friction velocity was lower than the critical value with further confirmation that the sources of dust were from north and east of Jeddah (Fig. 5(b)). This explains that such a situation was widespread and that the sources of dust that reaching Jeddah are not from close but from distant sources. It appeared in the satellite image as a homogenous dust cloud.

PM Fractions

Temporal Trends of Different Particle Sizes Concentrations

The temporal trends in daily average values of the PM₁₀, PM_{2.5–10}, PM_{2.5}, and PM_{1.0} concentrations over the study period are presented in Fig. 1. The trends in daily values of PM fractions followed the same pattern. The concentrations of PM fractions were higher in DS environment than non-DS. Four daily peak concentrations were observed during the period of study. Under the effect of moderate DS, moderate peaks were observed on 1, 3, and 13 March. A sharp peak occurred on 19 March during which the intense DS attacked the sampling site on 18–26 March. The daily average concentrations ranged from 82 to 2308 µg/m³ for PM₁₀, 53 to 1715 µg/m³ for PM_{2.5–10}, 27 to 594 µg/m³ for PM_{2.5} and 9 to 97 µg/m³ for PM_{1.0} during the period of study (Fig. 1). The maximum half hour concentrations were 3986, 3135, 868 and 131 µg/m³ for PM₁₀, PM_{2.5–10}, PM_{2.5} and PM_{1.0}, respectively. Table 1 shows the summary statistics for PM fractions concentrations during non-DS, DS and all the period of study. The overall mean values of PM₁₀, PM_{2.5–10}, PM_{2.5}, and PM_{1.0} were 165, 116, 49 and 16 in

non-DS, 909, 663, 247 and 41 in DS and 453, 328, 126 and 25 µg/m³ in the whole period of study, respectively. The DS/non-DS concentration ratios were 2.59 for PM_{1.0}, 5.02 for PM_{2.5}, 5.72 for PM_{2.5–10} and 5.51 for PM₁₀. Jeddah city is exposed to bouts of DS that lead to increase the levels of PM fractions, especially coarse particles (PM_{2.5–10}), in the atmosphere. A large input of dust from the upstream regions during sand-dust events is the main reason for the high coarse aerosol concentration in Jeddah. The comparison of PM_{2.5} and PM₁₀ concentrations between the present study and other related studies is shown in Table 2. All these studies revealed that the concentrations of PM_{2.5} and PM₁₀ in DS periods were significantly higher than those in non-DS periods (Mori et al., 2003; Chen et al., 2004; Lee et al., 2009; Hong et al., 2010; Bian et al., 2011; Li et al., 2011; Wang et al., 2011; Zhao et al., 2011; Tsai et al., 2012; Chuang et al., 2013). In the present study, the average concentrations of PM₁₀ and PM_{2.5} in non-DS and DS (Table 1) were clearly much higher than the World Health Organization (WHO) PM₁₀ (50 µg/m³ for 24 h) and PM_{2.5} (25 µg/m³ for 24 h) (WHO, 2006).

Diurnal Variations of Different Particle Sizes

The study of diurnal variations of air pollutants can provide valuable information about the sources, transport and chemical formation/destruction effects of such pollutants. Weather processes such as local dust blowing and sand-dust intrusions from upstream regions have a strong impact on PM concentrations in Jeddah as mentioned above. The average diurnal variations in PM fractions during both non-DS and DS periods are shown in Fig. 2. A uni-modal PM₁₀, PM_{2.5–10} and PM_{2.5} peaks at about the same time (1300 h) were seen in non-DS period. The three PM fractions show a similar diurnal pattern; their concentrations raised gradually in the morning and reached maximum levels around noon and afternoon. After that time, their concentrations decreased progressively until evening, and maintained low values over night hours. Thus, PM₁₀, PM_{2.5–10} and PM_{2.5} fractions originated from common sources, and their concentrations mainly depended on the variations of local emissions such as traffic emissions, re-suspension generated by traffic and other human activities. For PM_{1.0} in non-DS period, maximum concentrations occurred in the morning hours close to rush hour. These differences in the occurrence time of the maximum concentration between submicron (PM_{1.0}), fine (PM_{2.5}) and coarse (PM₁₀) particles in non-DS may be due to their different diffusion behaviors in the atmospheric boundary layer. PM_{1.0} particles, due to their small mass, can suspend in air for long time and their concentrations became affected mainly by atmospheric diffusion conditions. At noon and afternoon, the dissipation of the boundary layer inversion and the development of a mixing layer are helpful for PM_{1.0} particles to diffuse, which result in a minimal concentration. Pathak et al. (2010) and Rashki et al. (2013) suggest that local anthropogenic emissions and vertical mixing in the boundary layer play a major role in controlling diurnal PM concentrations. In the present study, the diurnal variability in PM₁₀, PM_{2.5–10}, PM_{2.5} and PM_{1.0} in DS showed a similar trend, with two peaks at 1000 h and

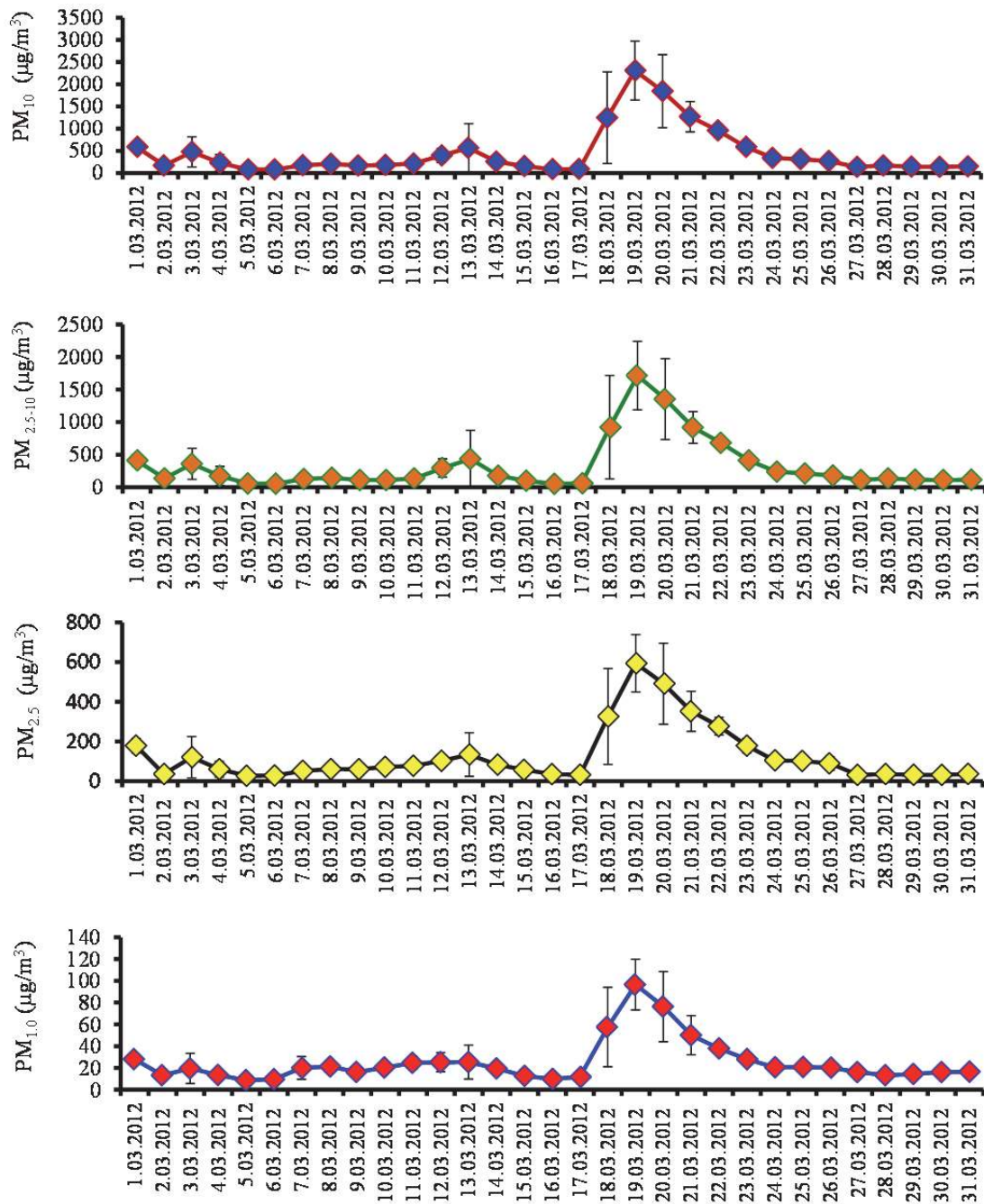


Fig. 1. Temporal trends in daily average concentrations of PM₁₀, PM_{2.5-10}, PM_{2.5} and PM_{1.0} during the period of study.

Table 1. Concentration ($\mu\text{g}/\text{m}^3$) of different particle sizes and ratios between them during non-dust storm, dust storm and all period of study.

Particulate	Non dust storm days					Dust storm days					All days				
	Min.	Max.	Median	Mean	SD	Min.	Max.	Median	Mean	SD	Min.	Max.	Median	Mean	SD
PM ₁₀	82	270	170	165	56	312	2308	590	909	641	82	2308	213	453	537
PM _{2.5-10}	53	181	114	116	39	211	1715	423	663	477	53	1715	146	328	397
PM _{2.5}	27	89	36	49	20	101	594	179	247	165	27	594	71	126	141
PM ₁	9	25	16	16	4	19	97	28	40	25	9	97	20	25	20
PM ₁ /PM ₁₀	0.06	0.13	0.10	0.10	0.02	0.04	0.07	0.05	0.05	0.01	0.04	0.13	0.08	0.08	0.03
PM ₁ /PM _{2.5}	0.22	0.51	0.34	0.34	0.09	0.14	0.25	0.16	0.17	0.03	0.14	0.51	0.25	0.28	0.11
PM _{2.5} /PM ₁₀	0.21	0.40	0.32	0.30	0.06	0.24	0.32	0.27	0.28	0.03	0.21	0.40	0.29	0.29	0.05
PM _{2.5} /PM _{2.5-10}	0.26	0.66	0.47	0.44	0.13	0.31	0.48	0.37	0.39	0.05	0.26	0.66	0.41	0.42	0.11

Table 2. Comparison of PM_{2.5}, PM₁₀, and PM_{2.5}/PM₁₀ in the present study during non-dust storm and dust storm periods with those of some other studies.

Site	Sampling periods	PM ₁₀		PM _{2.5}		PM _{2.5} /PM ₁₀		Reference
		Dust storm	Non-dust storm	Dust storm	Non-dust storm	Dust storm	Non-dust storm	
Jeddah (Saudi Arabia)	1–31 March 2012	909	165	247	49	0.28	0.30	This study
Hengchun (Taiwan)	14–22 March 2010	55	30	23	13	0.40	0.44	Tsai et al. (2002)
Beijing (China)	19–23 March 2010	780	195					Li et al. (2011)
Tianjian (China)	20–23 March 2010	500		90		0.18		Bian et al. (2011)
Dongsha Island (Taiwan)	21–23 March 2010			109	16–18	0.59		Wang et al. (2011)
Seoul (Korea)	May 13–June 15, 2007	62		36				Hong et al. (2010)
Seoul (Korea)	April 2007–March 2008			83	37			Lee et al. (2009)
Pingtung City (Taiwan)	19–28 March 2000	232	128	86	88	0.37	0.68	Chen et al. (2004)
	8–18 April 2001	156	79	70	54	0.45	0.69	

1800 h (Fig. 2). These two peaks can be referred to wind speed, since high wind speed was noticed at these two specific hours (reaching a value of 40 km/h). The similar diurnal distribution of PM fractions indicates that the impact of DS on the concentrations of PM₁₀, PM_{2.5–10}, PM_{2.5} and PM_{1.0} particles is significant. This is confirmed by the significant high correlations between PM₁₀, PM_{2.5–10}, PM_{2.5} and PM_{1.0} in DS (Table 3).

Ratios between Different Particle Sizes

Since different sizes of atmospheric particles probably originate either from different sources or by different activities within the same sources (Oanh et al., 2006), the ratios of PM_{2.5}/PM₁₀, PM_{1.0}/PM₁₀, PM_{1.0}/PM_{2.5}, and PM_{2.5–10}/PM₁₀ were used to indicate the relative importance of natural and anthropogenic origin of PM with different sizes (Querol et al., 2004; Sun et al., 2004). Higher PM_{2.5} to PM₁₀ ratios (larger than 0.60) are generally ascribed to relatively high contribution from secondary particles and from the combustion sources (Perez et al., 2008), while lower ratios indicate significant contribution from primary sources such as resuspended soil/road dust and from other mechanical activities (Chan and Yao, 2008). In the present study, the temporal variations of PM_{2.5}/PM₁₀, PM_{1.0}/PM₁₀, PM_{1.0}/PM_{2.5}, and PM_{2.5}/PM_{2.5–10} ratios are shown in Fig. 3. The daily ratios ranged from 0.21 to 0.40 for PM_{2.5}/PM₁₀, 0.26 to 0.66 for PM_{2.5}/PM_{2.5–10}, 0.04 to 0.13 for PM_{1.0}/PM₁₀ and 0.14 to 0.51 for PM_{1.0}/PM_{2.5} during the period of study. On average, the ratio of PM_{1.0}/PM₁₀, PM_{1.0}/PM_{2.5}, PM_{2.5}/PM₁₀ and PM_{2.5}/PM_{2.5–10} were found to be 0.10, 0.34, 0.30 and 0.44 in non-DS, 0.05, 0.17, 0.28 and 0.39 in DS and 0.08, 0.28, 0.29 and 0.42 during the period of study, respectively, (Table 1). The relatively lower PM_{1.0}/PM₁₀, PM_{2.5}/PM₁₀ and PM_{2.5}/PM_{2.5–10} ratios in DS than non-DS indicate significant contribution of coarse particle during sand-dust events. The average values of PM_{2.5}/PM₁₀ ratio in Jeddah in both non-DS and DS indicate that PM₁₀ consisted mainly of coarser particles (PM_{2.5–10}). This can be referred mainly to the geographical location of Jeddah and the topographic characteristics of its upstream regions. These unique geographical and topographic characteristics make Jeddah vulnerable to the invasion of sand and dust (mainly coarse particles) from sand-dust events in the upstream regions. Therefore, compared with other cities, coarse particle pollution in Jeddah is more severe. The comparison PM_{2.5}/PM₁₀ ratios between the present research and related studies are shown in Table 2. They revealed that the PM_{2.5}/PM₁₀ values were decreased in DS than non-DS period due to increase the coarse particles (PM_{2.5–10}) in DS (Chen et al., 2004; Tsai et al., 2012).

Relationship between Different Particle Sizes

The relationships between PM₁₀, PM_{2.5} and PM_{1.0} measured at the study area may reveal the consistency of the sources for PM emissions. The results of correlation analysis between the three PM fractions are displayed in Table 3. Statistically significant ($p < 0.01$) correlation coefficient (r) is highlighted in bold. As shown in Table 3, PM₁₀ has significant positive correlation with PM_{2.5}, moderate ($r =$

0.73) in non-DS and high ($r = 0.99$) in DS periods. This suggests that these two PM fractions might originate from

similar sources, and the variation in $PM_{2.5}$ has a significant influence on the observed variability in PM_{10} in non-DS

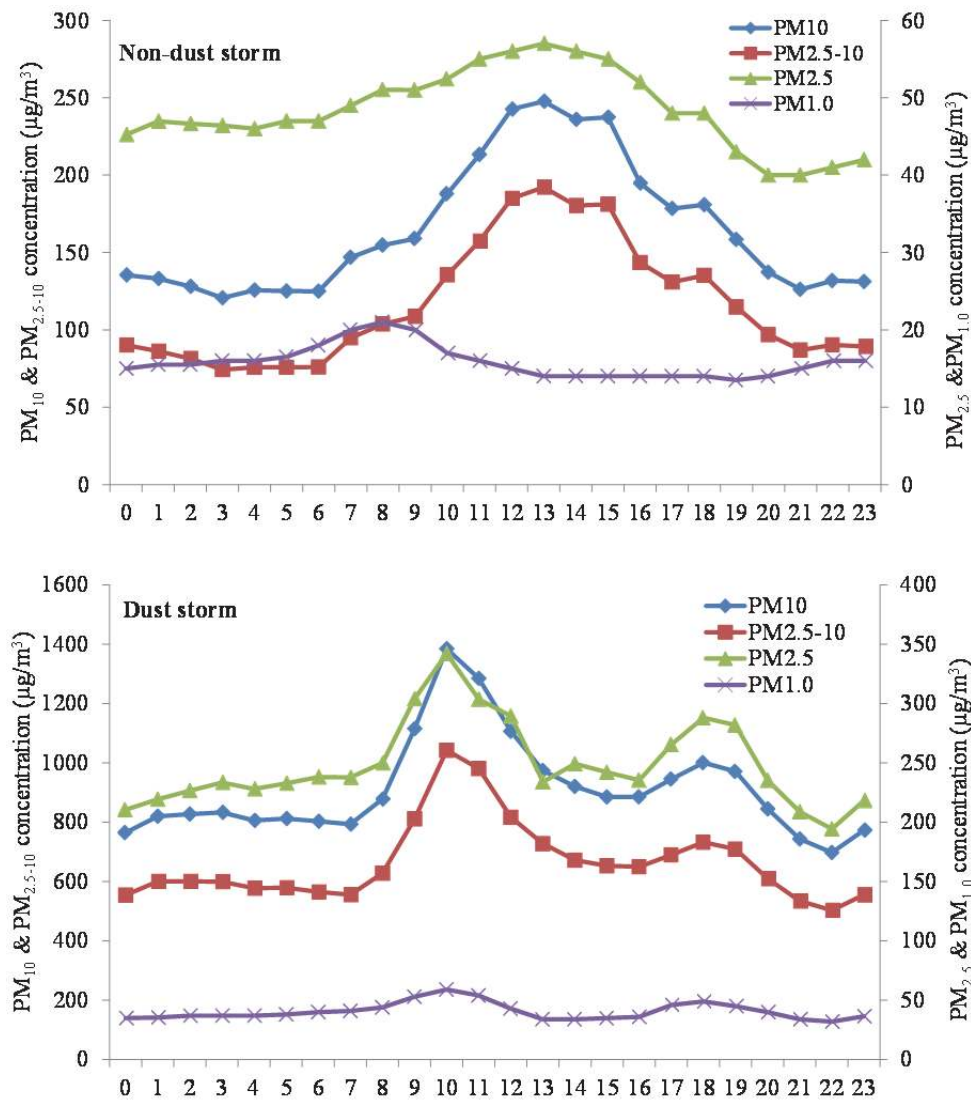


Fig. 2. Diurnal variations of PM_{10} , $PM_{2.5-10}$, $PM_{2.5}$ and $PM_{1.0}$ concentrations during non-dust storm and dust storm.

Table 3. Correlation^a matrix of PM fractions and meteorological parameters in non-DS and DS periods.

Non-DS	PM_{10}	$PM_{2.5}$	$PM_{1.0}$	T (°C)	RH%	Wind speed
PM_{10}	1.00					
$PM_{2.5}$	0.73	1.00				
$PM_{1.0}$	0.45	0.70	1.00			
T (°C)	0.53	0.30	0.09	1.00		
RH%	-0.32	0.19	0.27	-0.36	1.00	
Wind speed	0.15	-0.20	-0.46	0.29	-0.48	1.00
DS	PM_{10}	$PM_{2.5}$	$PM_{1.0}$	T (°C)	RH%	Wind speed
PM_{10}	1.00					
$PM_{2.5}$	0.99	1.00				
$PM_{1.0}$	0.97	0.98	1.00			
T (°C)	0.18	0.14	0.19	1.00		
RH%	-0.61	-0.55	-0.60	-0.61	1.00	
Wind speed	0.19	0.14	0.10	0.22	-0.30	1.00

^aBold (significant ($p < 0.01$)).

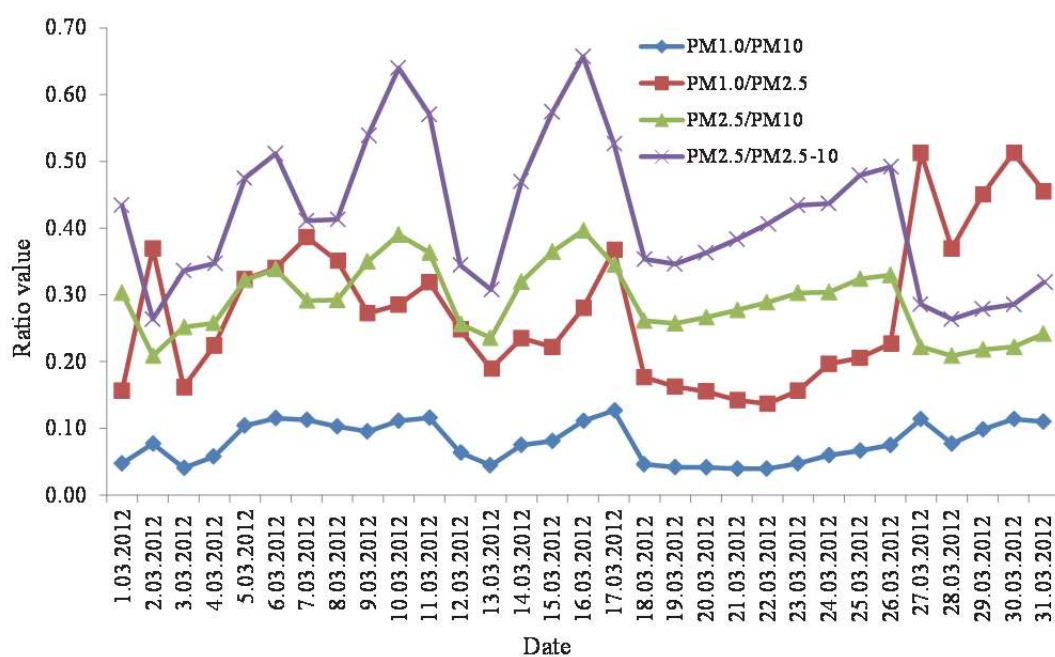


Fig. 3. Trends in daily average $PM_{1.0}/PM_{10}$, $PM_{1.0}/PM_{2.5}$, $PM_{2.5}/PM_{10}$ and $PM_{2.5}/PM_{2.5-10}$ concentration ratios during the period of study.

and DS. The regression relationship between PM_{10} and $PM_{1.0}$ concentrations showed weak ($r = 0.45$) correlation in non-DS and high ($r = 0.97$) correlation in DS. This suggests that the ambient PM_{10} and submicron $PM_{1.0}$ particles in non-DS might originate from different and various sources; since submicron aerosols are of local anthropogenic origin, while coarse aerosols have a strong natural component. In contrast, during DS, increase of PM_{10} from natural sources may also have an impact on $PM_{1.0}$ aerosol concentrations, since transported dust can be also of fine mode (Rashki *et al.*, 2013). $PM_{2.5}$ has a moderate significant positive correlation with $PM_{1.0}$ ($r = 0.70$) in non-DS and high ($r = 0.98$) in DS periods, indicating common sources of origin. Previous studies (Vallius *et al.*, 2000; Li and Lin, 2003) found that $PM_{1.0}$ and $PM_{2.5}$ were well-correlated and might have similar sources. Generally, the correlations between the measured three PM fractions in the study area during non-DS and DS suggest that the source and concentration are influenced by complex interaction between local meteorological conditions, natural and anthropogenic sources.

Influence of Local Meteorological Elements on PM Concentrations

Air pollutant concentrations are mainly controlled by local meteorological conditions when local emission is constant. The air quality at any place varies from time to time, though the emissions may not undergo any variations, due to the dependence of air quality on the dynamics of the atmosphere and the vital role of meteorological situation in governing the fate of air pollutants. Fig. S6 shows the time series of RH and PM fractions during the period of study. From this figure, the highest concentrations of PM were observed during the period of lower RH. The correlation coefficients of meteorological parameters, i.e., temperature, relative

humidity and wind speed, with PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ are given in Table 3. The mass concentrations of PM_{10} , $PM_{2.5}$, $PM_{1.0}$ in DS and PM_{10} in non-DS period showed negative correlation with relative humidity. Thus in case of higher relative humidity, the PM gets settled down or washed out by precipitation (Deshmukh *et al.*, 2013). The negative relationship between PM fractions and relative humidity suggests that relative humidity removes atmospheric particulates and diminishes the amount of re-suspended soil dust by making the soil humid (Hien *et al.*, 2002). In the Indian cities, negative relationship of relative humidity with PM mass concentrations was also found (Katiyar *et al.*, 2002; Singh *et al.*, 2010). On the other hand, the positive relationship between relative humidity and $PM_{2.5}$ and $PM_{1.0}$ in non-DS in the present study may be due to the depressing effect on diffusion of fine particles under high relative humidity. The depressing effect is more significant for smaller particles (Wang *et al.*, 2009). In the present study, the correlation between PM mass concentrations and wind speed was also investigated during the non-DS and DS period. Surface wind speed was positively correlated with the concentrations of PM_{10} , $PM_{2.5}$, $PM_{1.0}$ in non-DS and DS (except for $PM_{2.5}$ and $PM_{1.0}$ in non-DS). This indicates that high wind speed generally was associated with weather processes of DS bringing a large amount of dust with different sizes from upstream regions to the study area. High wind speed can also aggravate sand-dust pollution due to local dust blowing in Jeddah. High wind speed and high temperature, both increase turbulence and resuspension of the dust particles (Kim *et al.*, 2009). In an arid region like Saudi Arabia, high wind speed with no rain for months, surrounding deserts and wind blowing into inhabited areas from the neighbouring desert lands lead to high concentrations of PM (PME, 2012; Munir *et al.*, 2013). On the other hand,

negative correlations between wind speed and $PM_{2.5}$ and $PM_{1.0}$ in non-DS period suggest that fine ($PM_{2.5}$ and $PM_{1.0}$) particles can be diffused and transported by wind more easily than coarse particles under normal condition and consequently result in lower $PM_{2.5}$ and $PM_{1.0}$ concentrations. Strong winds flush pollutants out of the system and low winds allow pollution levels to rise (Chaloulakou *et al.*, 2003).

Elemental Compositions of $PM_{2.5}$

The chemical composition of atmospheric aerosol is necessary to clarify the likely source regions and provide valuable information about potentially harmful trace elements. The average concentrations of 23 elements in $PM_{2.5}$ during non-DS and DS periods are presented in Fig. 4. The element contents in DS were higher than that in non-DS. The sum of element concentrations in non-DS and DS periods were 5075.6 and 17102.2 ng/m^3 , respectively. Among the 23 elements species, S has the maximum fraction in both non-DS (2390 ng/m^3) and DS (4658 ng/m^3) periods. The distribution and relative concentration of the individual measured elements were found to follow the following pattern: $S > Si > Ca > Fe > Al > Na > Pb > K > Mg > Cl > Zn > Ti > Cd > As > V > Mn > Cu > Sr$ and $Ni > Co > Rb$ and $Cr > Ga$ in non-DS, and $S > Si > Ca > Fe$ and $Al > Mg > Na > Pb > K > Cl > Ti > Zn > Mn$ and $Cd > As > V > Cu > Sr$ and $Ga > Ni > Co > Rb$ and Cr in DS. The crustal elements Si, Ca, Na, Al, Fe, K, and Mg accounted for 44.62 and 67.53% of the total concentrations of elements in $PM_{2.5}$ in non-DS and DS, respectively. The relatively higher contribution of crustal elements in DS than non-DS indicates that the soil-sourced species were much more contributive to DS particle due to re-suspension of local road dust and mixing materials containing long range transported crustal elements and other pollution species (Ho *et al.*, 2003; Zhang *et al.*, 2010; Liu *et al.*, 2014). In the present study, the concentrations of all elements increased in DS. The highest DS/ non-DS ratios were 6.27(Ca), 5.99 (Si), 5.88 (Al) and 5.17 (Fe). These results ascertain that the soil originated species were

much more contributing in DS particles than non-DS. DS not only delivers large amounts of crustal aerosols but also carries significant quantities of trace metal pollutants (Shen *et al.*, 2009; Tan *et al.*, 2012). Also, Wang *et al.* (2005) and Tsai *et al.* (2012) found that, the crustal element contents increased in total suspended particulate (TSP), $PM_{2.5}$ and $PM_{2.5-10}$ during DS.

If the atmospheric aerosol of Jeddah during DS originated from distant sources, the components of the dust sampled in DS and non-DS periods might be different. To test this hypothesis, the Al/Si concentration ratios for the $PM_{2.5}$ collected samples during the DS/non-DS periods were calculated. The Al/Si concentration ratios during DS (0.38) and non-DS (0.39) were nearly similar. The lack of obvious variation in the Al/Si ratio means that not only the sources of Al and Si are local but also their source(s) are common and /or located along the same transport pathway (Tecer *et al.*, 2012). When Al concentrations are high, Si concentrations also are high or vice versa. In the present study, the transportations of entirely different crustal aerosol by means of regional or long range transport to the study area are not clear, and further studies are needed.

Enrichment Factor Analysis

Both natural and anthropogenic processes are the sources of mineral components and trace metals in aerosol. Enrichment factors (EFs) can give an insight into differentiating an anthropogenic source from a natural origin, and hence, can also assist in the determination of the degree of contamination (Han *et al.*, 2006). The enrichment factor for a generic element X with respect to a reference crustal element Y is defined as $EF_X = (X/Y)_{air} / (X/Y)_{crust}$, where the ratio (X/Y) is the concentration ratio of X and Y in either aerosol sample or earth crust. In the present study, Al was used as the reference element Y, and the earth crust chemical composition was taken from Taylor (1964) and Taylor and McLennan (1985). Our calculation of EFs was done assuming that contributions of man-made

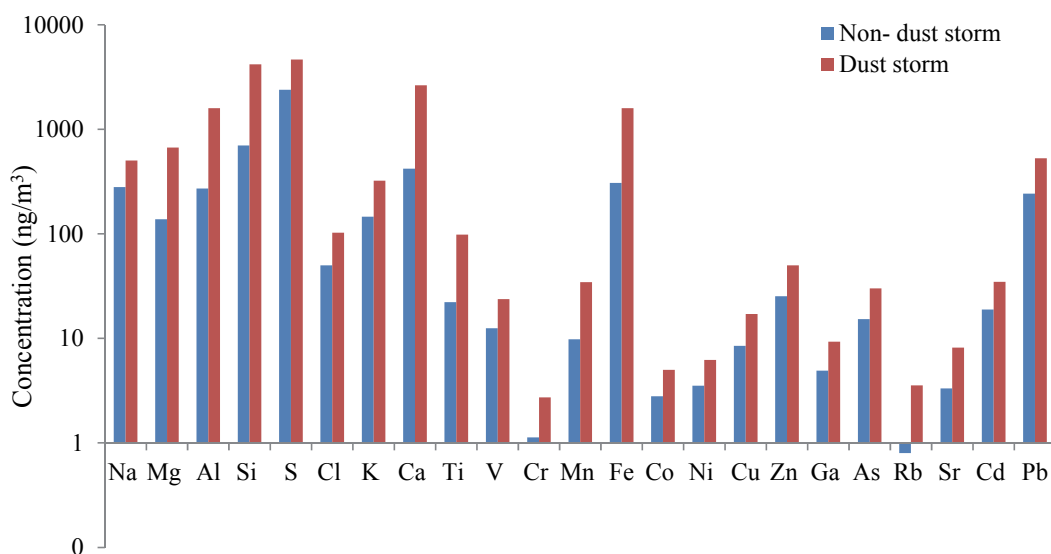


Fig. 4. The average concentrations of measured elements in non-dust storm and dust storm at the study area.

sources to Al are insignificant in the study area. The use of average crust values provides meaningful comparison to many other studies that commonly use this technique. The average local soil profiles are not available and will be investigated in the follow up study. The mean EF values of each element in both non-DS and DS samples were calculated and are listed in Table 4. It is well accepted that EF values lower than 5 are indicative of crustal importance. Accordingly, Na, Mg, Si, K, Ca, Ti, Cr, Mn, Fe, Rb and Sr in non-DS and DS and Ni in DS are of crustal type (e.g., soil and re-suspended dust), while anthropogenic sources have a lesser contribution (Hien *et al.*, 2001; Hao *et al.*, 2007). The deserts surrounding Jeddah city were evidently the sources of these mineral crust elements in non-DS and DS aerosol. Among the elements, Cl and Zn (DS), Ni and V (non-DS) and Co, Cu and Ga (non-DS and DS) were observed moderately enriched. The atmospheric PM_{2.5} in the study area was found to be extremely enriched by S, As, Cd and Pb in non-DS and DS and Zn and Cl in non-DS. The extremely high EF values for these elements indicate that they are present in atmospheric aerosol in concentrations too high to be explained in terms of normal crustal weathering processes. Consequently, these elements are mainly originating from the anthropogenic sources (Han *et al.*, 2006; Xu *et al.*, 2012). Generally, the EFs for all measured elements in Jeddah except Si and Ca were relatively lower in DS than non-DS. These data suggest that the local pollution sources in Jeddah contributed to these elements mostly. In urban environments, the sources of enriched anthropogenic elements are the emissions of

combustion from mobile sources (vehicle-exhaust emissions) and industrial activities (Cao *et al.*, 2009; Hsu *et al.*, 2010).

The fraction of elements coming from non-crustal sources [(C_x)*] can be calculated by the following formula (Mason, 1966):

$$(C_x)^* = \{(C_x)_{\text{air}} - (C_{\text{Al}})_{\text{air}} \cdot (C_x/C_{\text{Al}})_{\text{crust}}\} / (C_x)_{\text{air}} \quad (1)$$

where:

(C_x)_{air}: the concentration of an element X in the air

(C_{Al})_{air}: the concentration of Al in the air

(C_x)_{crust}: the concentration of an element X in the crust

(C_{Al})_{crust}: the concentration of Al in the crust.

The percentages of crustal and non-crustal fractions of the detected elements in PM_{2.5} during non-DS and DS are shown in Table 4. About 100% of Si in non-DS and Si, Ti and K in DS are entered to the air from the Earth crust. About 100% of S, Cl, Zn, Ga, As, Cd and Pb during non-DS and S, As, Cd and Pb in DS were of anthropogenic origins. Important man-made emission sources for these elements are combustion processes, traffic emissions and construction activities (Lough *et al.*, 2005; Handler *et al.*, 2008; Hassan *et al.*, 2013).

CONCLUSIONS

This paper discusses the impact of DS on the levels, characterization and elemental compositions of atmospheric particles in an urban area of Jeddah coastal city during March 2012. Results indicate that PM fractions concentrations

Table 4. Enrichment factor, crustal and non-crustal fractions (%) of elements in atmospheric PM_{2.5} aerosol of the study area in non-dust storm and dust storm.

Element	Non-Dust storm			Dust storm		
	EF	Crustal	Non-crustal	EF	Crustal	Non-crustal
Na	3.60	27.8	72.2	1.10	90.9	9.1
Mg	1.80	55.6	44.4	1.48	67.5	32.5
Al	1.00	100.0	0.0	1.00	100.0	0.0
Si	0.76	100.0	0.0	0.77	100.0	0.0
S	2791.61	0.0	100.0	924.99	0.1	99.9
Cl	116.80	0.9	99.1	40.72	2.5	97.5
K	2.12	47.3	52.7	0.80	100.0	0.0
Ca	3.08	32.4	67.6	3.28	30.4	69.6
Ti	1.18	84.5	15.5	0.89	100.0	0.0
V	28.15	3.6	96.4	9.06	11.0	89.0
Cr	3.42	29.2	70.8	1.41	71.0	29.0
Mn	3.13	31.9	68.1	1.88	53.2	46.8
Fe	1.66	60.2	39.8	1.46	68.5	31.5
Co	34.01	2.9	97.1	10.31	9.7	90.3
Ni	14.25	7.0	93.0	4.29	23.3	76.7
Cu	46.93	2.1	97.9	16.04	6.2	93.8
Zn	109.76	0.9	99.1	36.88	2.7	97.3
Ga	99.21	1.0	99.0	32.01	3.1	96.9
As	2581.37	0.0	100.0	860.52	0.1	99.9
Rb	2.70	37.0	63.0	2.04	49.1	50.9
Sr	2.69	37.2	62.8	1.13	88.9	11.1
Cd	28698.77	0.0	100.0	8983.83	0.0	100.0
Pb	5879.46	0.0	100.0	2065.25	0.0	100.0

were higher in DS than non-DS. The diurnal variation of PM fractions concentrations was uni-modal in non-DS and bimodal in DS period. $PM_{1.0}/PM_{10}$, $PM_{2.5}/PM_{10}$ and $PM_{2.5}/PM_{2.5-10}$ ratios were relatively lower in DS than non-DS, indicating that sand-dust events in spring carry more coarse than fine particles to Jeddah. The relationships between PM fractions indicate that PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ in DS and PM_{10} and $PM_{2.5}$ in non-DS might originate from similar sources. S has the maximum fraction in both non-DS and DS periods. PM_{10} , $PM_{2.5}$, $PM_{1.0}$ in DS and PM_{10} in non-DS were negatively correlated with relative humidity and positively correlated with wind speed. $PM_{2.5}$ and $PM_{1.0}$ in non-DS were correlated positively with relative humidity and negatively with wind speed. The crustal elements (Si, Ca, Na, Al, Fe, K, and Mg) accounted for 44.62 and 67.53% of the total concentrations of elements in non-DS and DS, respectively, indicating that soil-sourced species were much more contributive to DS particle. The elements concentrations increased in DS, with highest DS/non-DS ratios of 6.27(Ca), 5.99 (Si), 5.88 (Al) and 5.17 (Fe) indicating that the soil originated species contributed mainly in DS particles. The lack of obvious variation in Al/Si ratio during DS and non-DS means that not only the sources of Al and Si are local but also said that their source(s) are common and/or located along the same transport pathway. The enrichment factors (EFs) values and non-crustal fractions indicate that the main sources of Na, Mg, Si, K, Ca, Ti, Cr, Mn, Fe, Rb and Sr in both non-DS and DS are of a crustal type (e.g., soil and re-suspended dust), whereas S, Cl, Co, Cu, Zn, Ga, As, Pb and Cd in both non-DS and DS and V and Ni in DS are mostly emitted from anthropogenic sources. Although the concentrations of anthropogenic elements increased in DS, their enrichment factors were lower than those in the non-DS, which indicate that they were mostly originating from local anthropogenic pollution sources in Jeddah area.

ACKNOWLEDGEMENT

This work was funded by King Abdulaziz University (KAU), Jeddah, under grant number 47/432. The authors thank KAU for technical and financial support.

SUPPLEMENTARY MATERIALS

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

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Received for review, June 19, 2014

Revised, September 25, 2014

Accepted, November 24, 2014

Supplementary Materials

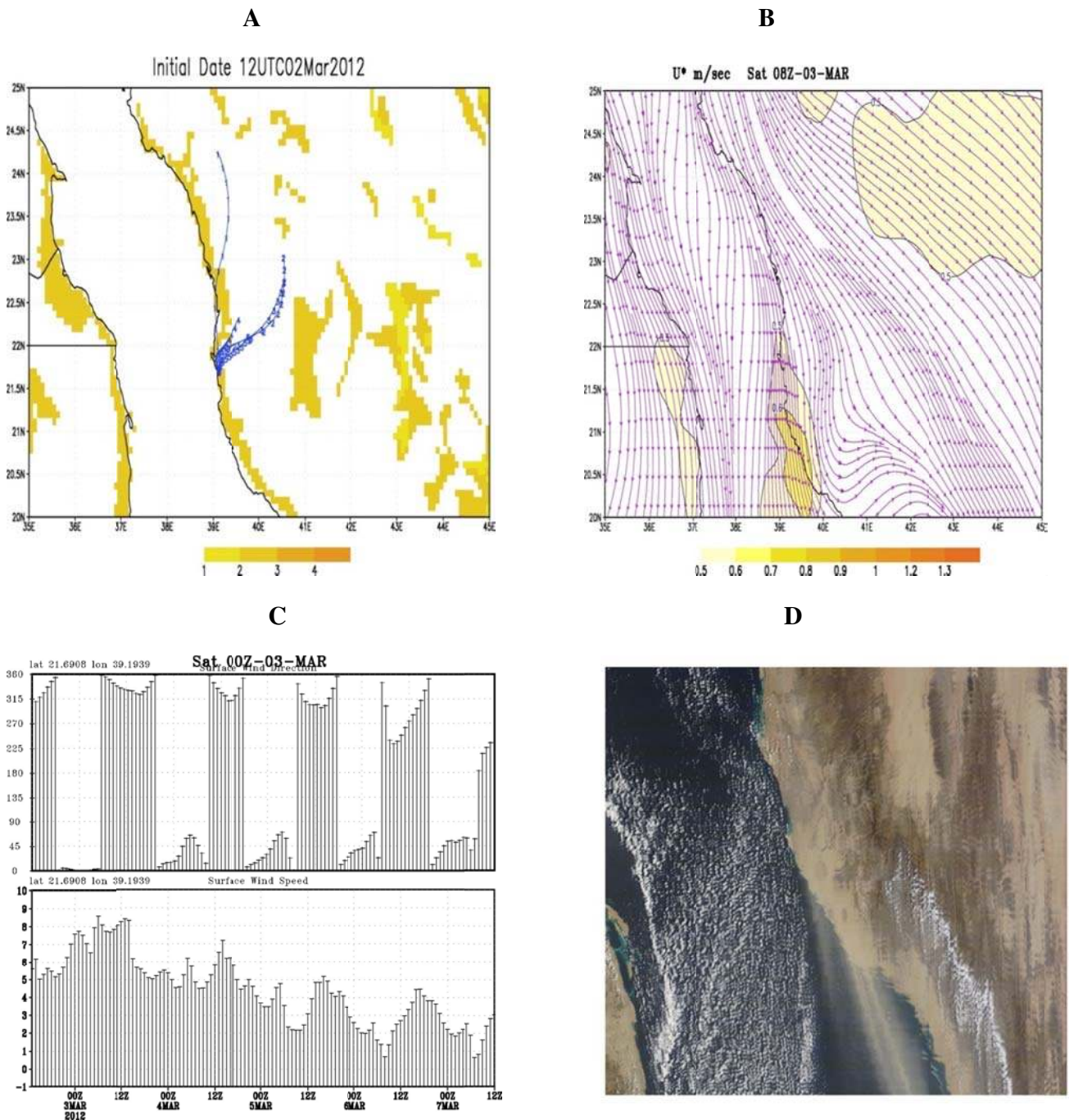


Fig. S1. A) Forecasted 5 days back trajectories at surface reaching Jeddah at 08 UTC for 12 hours length (Initial date is 12 UTC 02 Mar 2012). The trajectory is labeled in a sequential number according to the forecasted days. The main source locations of dust emission according to the soil type are shown. B) Distribution of threshold values for friction velocity. C) Time series of five days forecasted wind speed and direction. D) MODIS Image showing dust plume spread in south direction and the main source of dust.

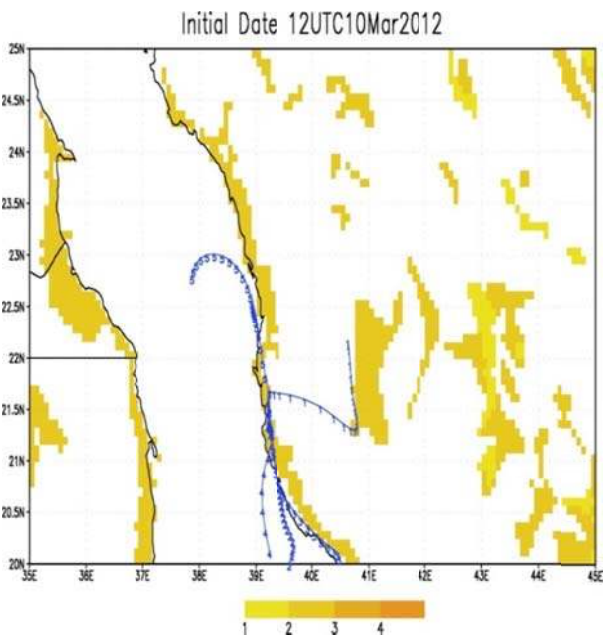
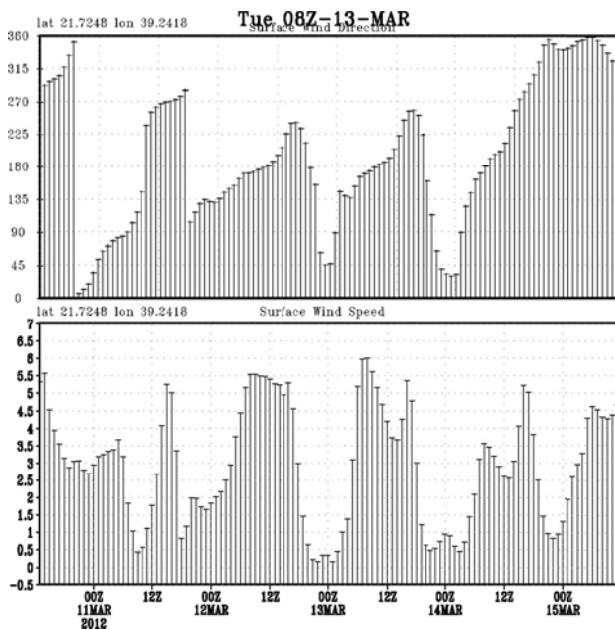
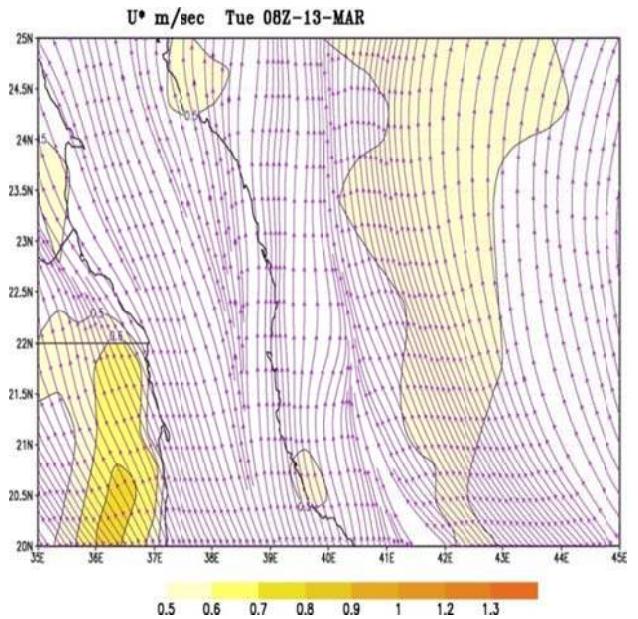
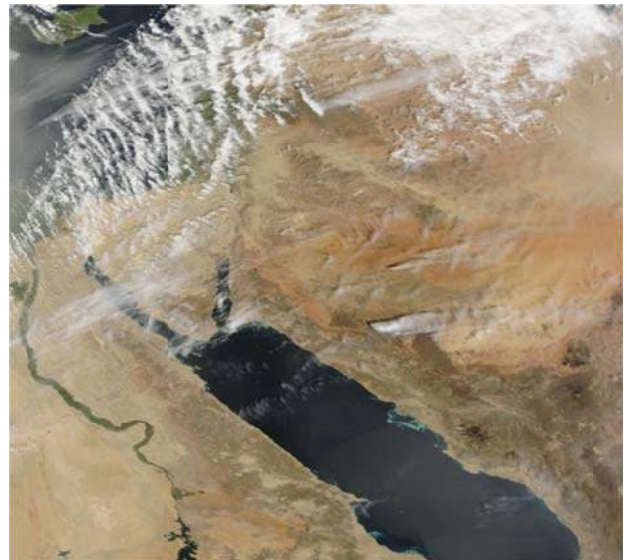
A**C****B****D**

Fig. S2. A) Forecasted 5 days back trajectories at surface reaching Jeddah at 08 UTC for 12 hours length (Initial date is 12 UTC 10 Mar 2012). The trajectory is labeled in a sequential number according to the forecasted days. The main source locations of dust emission according to the soil type are shown. B) Distribution of threshold values for friction velocity. C) Time series of five days forecasted wind speed and direction. D) MODIS Image showing dust plume spread in south direction and the main source of dust.

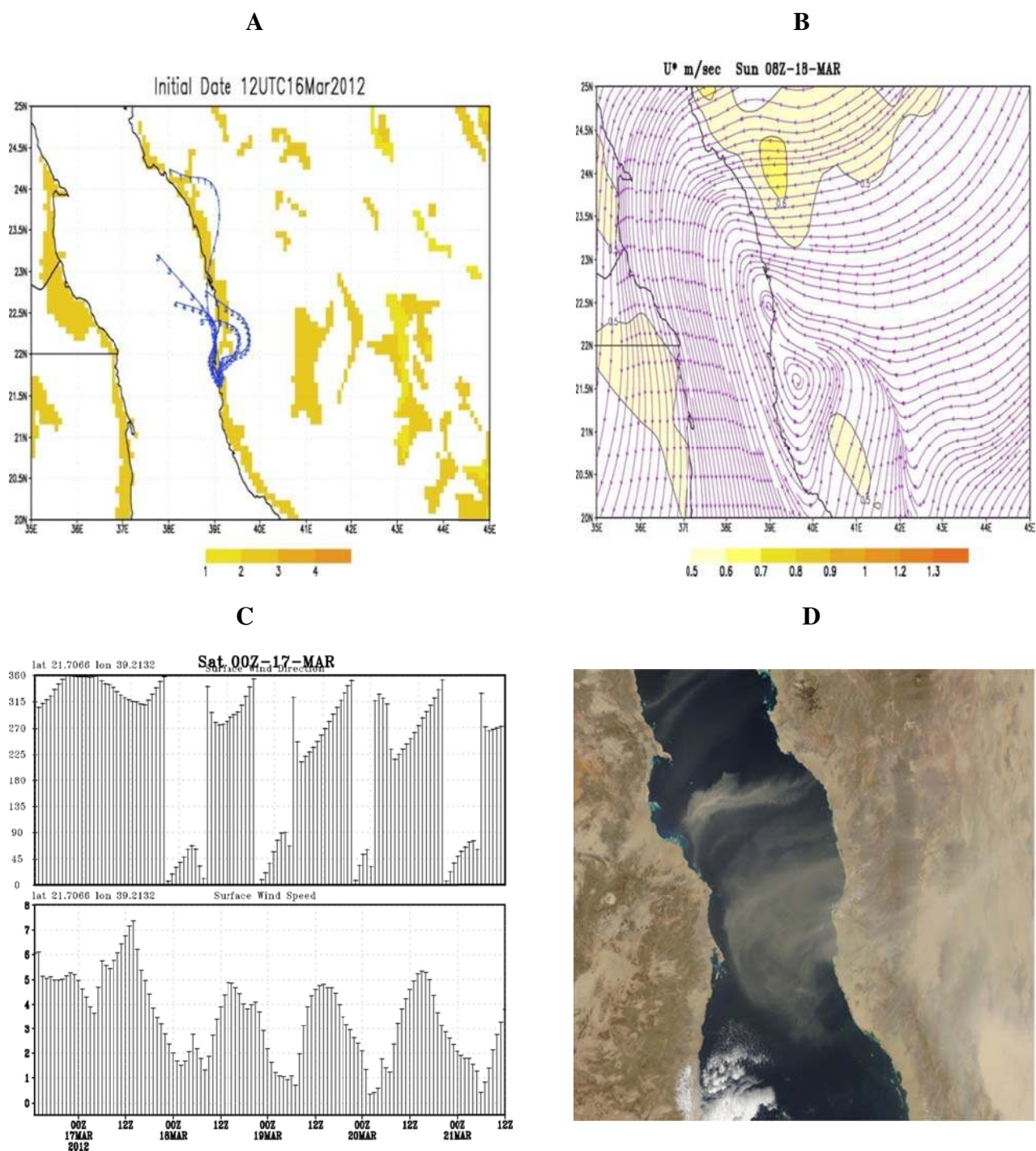


Fig. S3. A) Forecasted 5 days back trajectories at surface reaching Jeddah at 08 UTC for 12 hours length (Initial date is 12 UTC 16 Mar 2012). The trajectory is labeled in a sequential number according to the forecasted days. The main source locations of dust emission according to the soil type are shown. B) Distribution of threshold values for friction velocity. C) Time series of five days forecasted wind speed and direction. D) MODIS Image showing dust plume spread in south direction and the main source of dust.

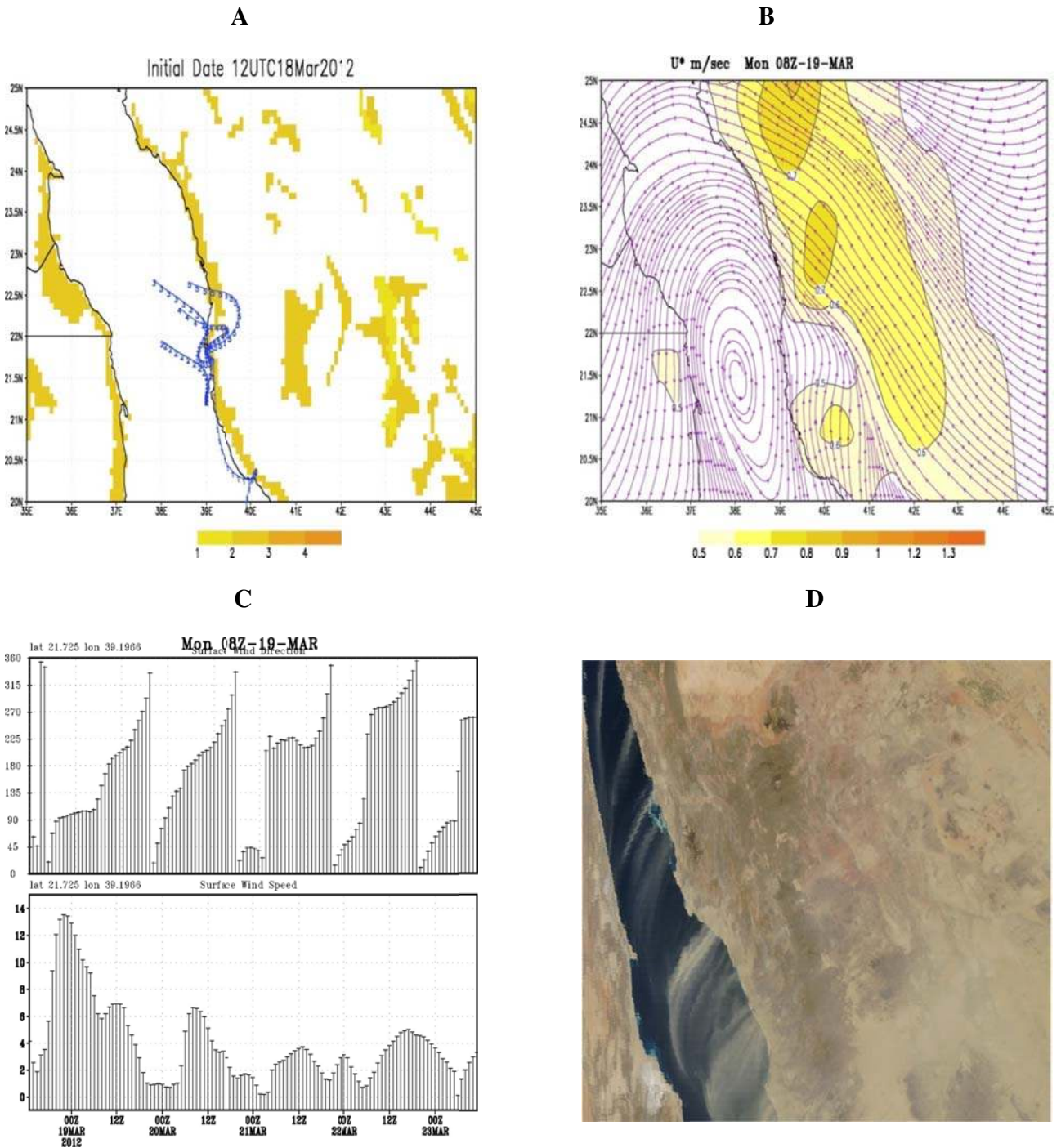


Fig. S4. A) Forecasted 5 days back trajectories at surface reached Jeddah at 08 UTC for 12 hours length (Initial date is 12 UTC 18 Mar 2012). The trajectory is labeled in a sequential number according to the forecasted days. The main source locations of dust emission according to the soil type are shown. B) Distribution of threshold values for friction velocity. C) Time series of five days forecasted wind speed and direction. D) MODIS Image showing dust plume spreadin southwest direction and the main source of dust.

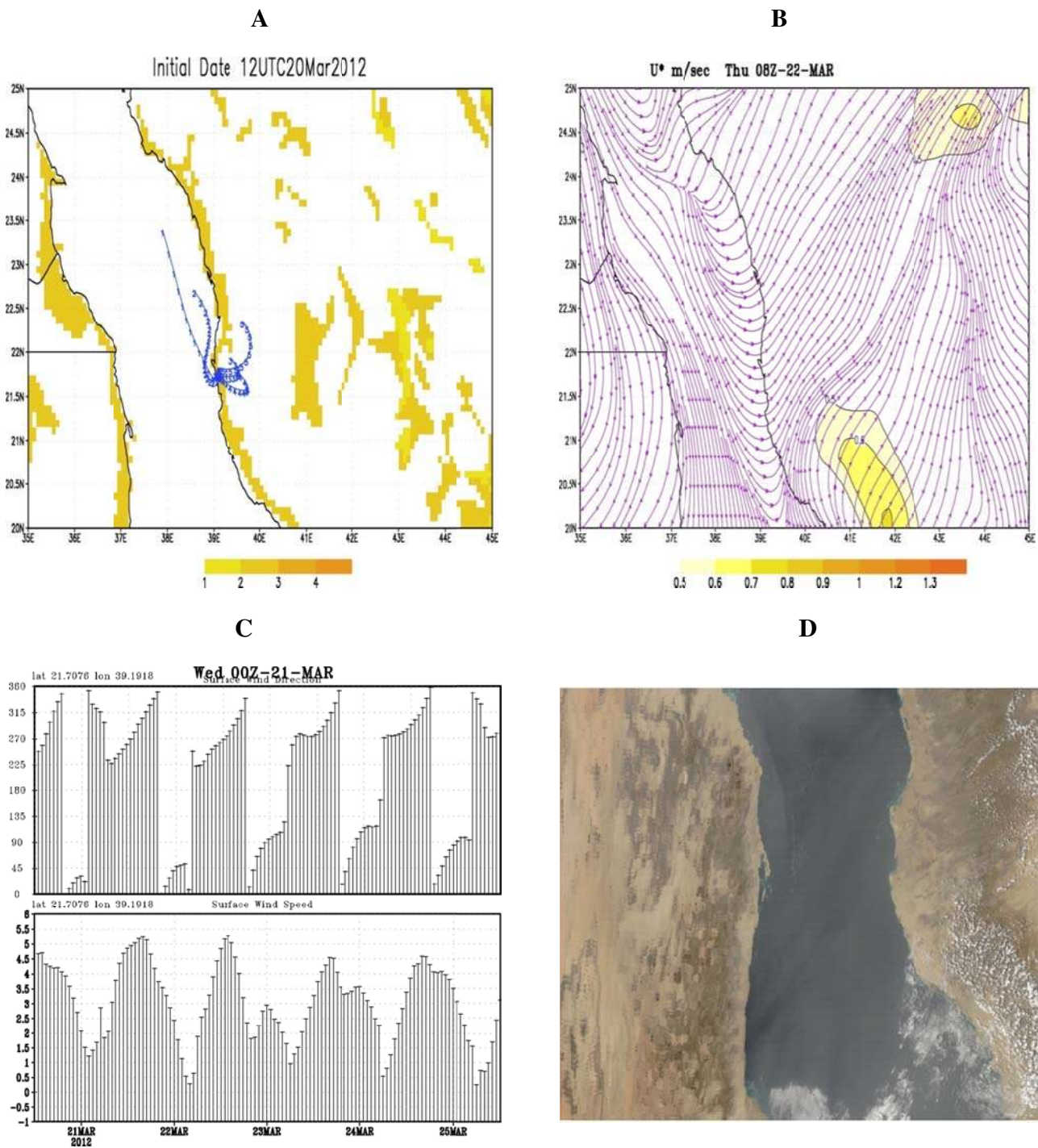


Fig. S5. A) Forecasted 5 days back trajectories at surface reached Jeddah at 08 UTC for 12 hours length (Initial date is 12 UTC 20 Mar 2012). The trajectory is labeled in a sequential number according to the forecasted days. The main source locations of dust emission according to the soil type are shown. B) Distribution of threshold values for friction velocity. C) Time series of five days forecasted wind speed and direction. D) MODIS Image showing wide spread dust storm spread Saudi Arabia.

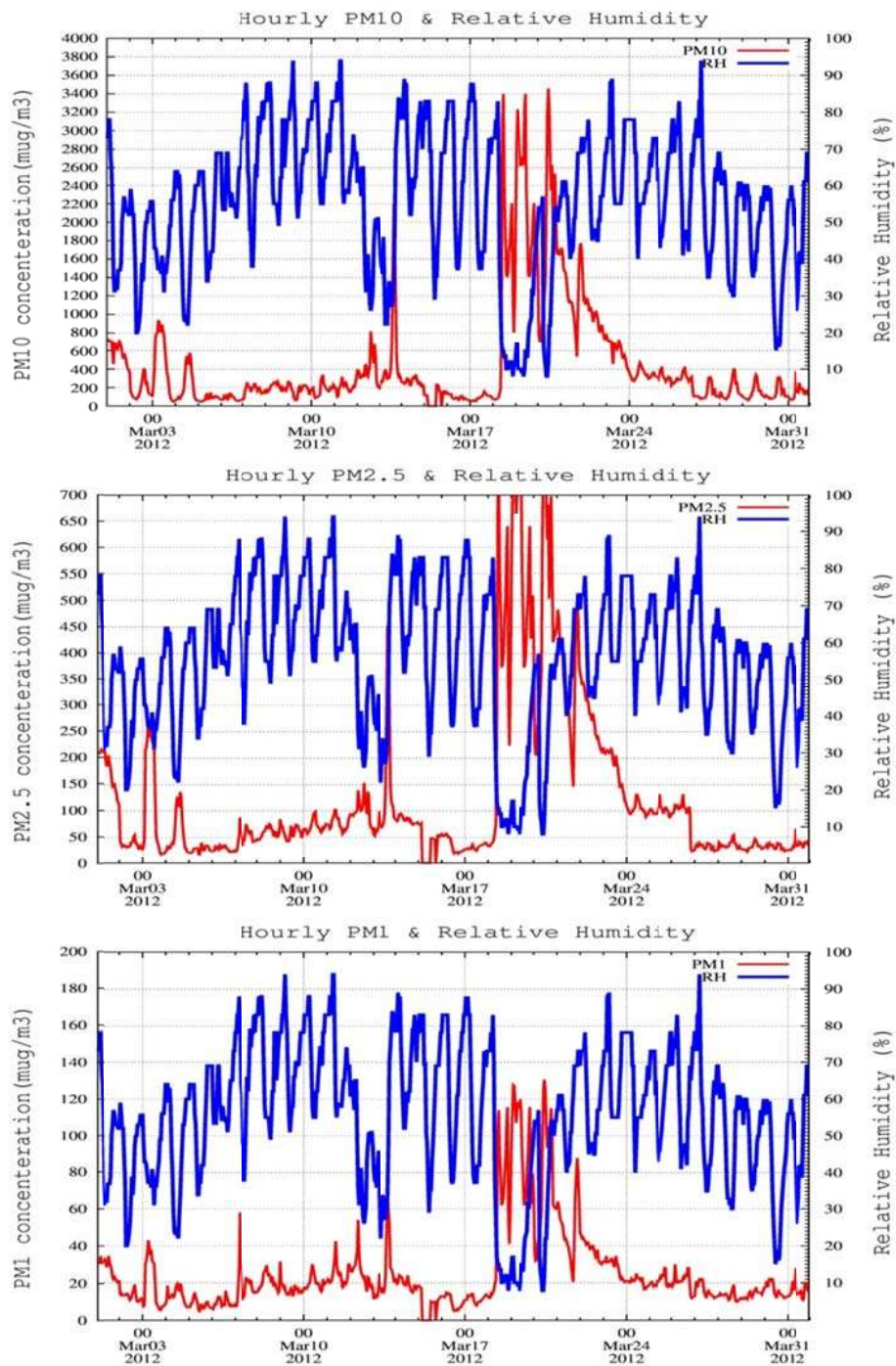


Fig. S6. Time series of RH and PM₁₀, PM_{2.5} and PM₁ fractions during the period of study.