Atmósfera 21(2), 171-189 (2008)

Seasonal and spatial variation of atmospheric particulate matter in a developing megacity, the Greater Cairo, Egypt

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Received July 25, 2006; accepted October 2, 2007

RESUMEN

Como ejemplo de una mega ciudad en desarrollo se evaluó el área del Gran Cairo, Egipto (GC) en relación con las partículas (PM) y el plomo (Pb) atmosféricos. Las partículas se colectaron durante 2001-2002 en dos tamaños de fracción, $PM_{2.5}$ y PM_{10} de 17 sitios representativos de diferentes características (industriales, urbanas, residenciales y ambiente no alterado). Las concentraciones de partículas fueron en general altas, con promedios anuales de 85 ± 12 $\mu g\ m^{-3}$ para $PM_{2.5}$ y de 170 ± 25 para PM_{10}. En una escala anual, los niveles elevados de PM se deben a varias fuentes que incluyen el tráfico, la incineración de desechos, partículas de polvo transportadas por el viento desde el desierto fuera del GC, y dentro del GC desde la colina Moqattam. En una escala estacional, las concentraciones de PM son más elevadas en el sector industrial durante la primavera, la estación polvosa, debido al efecto combinado de las tormentas de polvo y las emisiones antrópicas en el GC. Las concentraciones estacionales más bajas se registraron en el verano en los sitios no alterados. Hubo un incremento notable en los niveles de PM durante el periodo de octubre a diciembre debido a la incineración de desechos de las cosechas de arroz en el área del delta del Nilo (al norte del Cairo). La relación $PM_{2.5}/PM_{10}$ más alta (0.59) que se registró corresponde al sector urbano, mientras que la más baja (0.32) es del sector residencial. Las muestras de $PM_{2.5}$ y PM_{10} también se analizaron para Pb con el fin de determinar la influencia de diferentes fuentes de emisión. Las concentraciones promedio mensuales de Pb en $PM_{2.5}$ ($Pb_{2.5}$) y PM_{10} (Pb_{10}) variaron entre 0.4 y 1.8 $\mu g\ m^{-3}$ en los sitios no industriales. Las concentraciones fueron significativamente mayores en las áreas industriales, en las que se observó un máximo de 16 $\mu g\ m^{-3}$. Las concentraciones elevadas de Pb y PM determinadas contribuyen a la contaminación ambiental local. El GC está sujeto a concentraciones elevadas de partículas durante todo el año. No hay un límite anual para las concentraciones de PM_{10} en la ley ambiental egipcia, pero al compararlas con los promedios de 24 h, las

PM_{10} representan riesgos de largo plazo a la salud ya que tienen efectos ambientales locales y regionales. Los muestreos de alto volumen de PM_{10} considerados como promedios diarios muestran que los límites de calidad del aire se excedieron 60.47, 79.07 y 62.96 % en los sitios Heliopolis (35), Maadi (6) y 6 de Octubre (13) durante el periodo de medición de 2001 y 100, 91.7 y 89.8 % en Shoubra El-Kheima (20), El-Qolay Sq (1) y Abbasiya (36) durante el periodo de 2002. La evaluación de los datos presentados en este trabajo servirá como base para futuras modelaciones regionales y globales y para la clasificación de las fuentes.

ABSTRACT

As an example of a developing megacity the Greater Cairo (GC) area in Egypt has been evaluated with respect to atmospheric particulate matter (PM) and lead (Pb). Particulate matter was collected during 2001-2002 in the two size fractions $PM_{2.5}$ and PM_{10} at 17 sites representing different activities (industrial, urban, residential and background condition). The PM concentrations were generally high, with yearly average $PM_{2.5}$ and PM_{10} values of 85 ± 12 and 170 ± 25 $\mu g/m^{-3}$, respectively. On an annual scale, the high PM levels were due to many sources that included traffic, waste burning and wind blown dust particles emitted from the desert outside GC and the Moqattam hill inside GC. On a seasonal scale, the PM concentrations were highest in the industrial sector during spring, the dusty season, due to the combined effect of dust storm events and anthropogenic emissions over GC. The lowest seasonal concentrations were recorded in the summer season at the background sites. There was a marked increase in PM levels during the period October to December due to burning of waste from harvested rice in the agriculture area in the Nile Delta (north of Cairo). The highest $PM_{2.5}/PM_{10}$ ratio was recorded in the urban sector (0.59) while the lowest ratio was recorded in the residential sector (0.32). The $PM_{2.5}$ and PM_{10} samples were also analyzed for Pb in order to address the influence of different emission sources. The monthly average concentrations of Pb in both $PM_{2.5}$ ($Pb_{2.5}$) and PM_{10} (Pb_{10}) varied between 0.4 and 1.8 ± $\mu g\ m^{-3}$ at the non industrial sites. The concentrations were significantly higher in the industrial areas, where concentration up to a maximum of 16 ± $g\ m^{-3}$ could be observed. Both the high lead and PM concentrations measured are contributing to local environmental pollution. GC is subjected to high concentrations of particulates most of the year. There is no annual limit for PM_{10} concentrations in the Egyptian law of environment, but comparing to the 24 hour average, PM_{10} is representing health risks on the long-term that will give both regionally and globally environmental effects. High volume samplers measuring PM_{10} as daily average shows that the air quality limit value has been exceeded at sites Heliopolis (35), Maadi (6) and 6th October (13) during 60.47, 79.07, and 62.96% of the measuring period of 2001, and at Shoubra El-Kheima (20), El-Qolaly Sq (1), and Abbasiya (36) during 100.0, 91.7, and 89.8% of the measuring period of 2002. Thus, the evaluation of the data presented in this paper will serve as a basis for future regional and global modelling and source apportionment.

Keywords: Megacity, lead, air quality, air pollution, dust storm, PM_{10}, $PM_{2.5}$.

1. Introduction

The megacities of the world are facing serious air quality problems (Molina and Molina, 2004). The Greater Cairo (GC) area in Egypt is the largest city in Africa and the Middle East with a population of over 15 million people, and it is one of the 15 largest cities in the world. Urbanization and industrialization have increased very rapidly, particularly in the second half of the last century, causing increased levels of air pollutants and environmental hazards (Robaa and Hafez, 2002; Robaa, 2003). The air pollutant levels are not only an environmental issue within the city itself, but also affect regional and global environment. The GC area serves as an example of a developing megacity. Transportation (more than ~1.5 million vehicles), industries and waste burning are common major sources of gaseous and particulate air pollution in megacities (Molina and Molina, 2004). Particulate matter (PM) concentration is significantly enhanced by further contributions of wind blown dust from the surrounding arid areas.

The severe air pollution combined with meteorological conditions and seasonal variations motivated detailed characterization of the air quality situation in GC. Of particular interest in the present study are the PM and Pb concentrations in GC during 2001-2002 starting from January to December. Previous investigations have shown high levels of PM_{10} (three times WHO standards ~ 60 ± $\mu g\ m^{-3}$). For example, a study by Rodes *et al.* (1996) measured PM concentrations in Cairo during the period from December 1994 to November 1995, and the annual average PM_{10} concentrations were concluded to exceed 150 $\mu g\ m^{-3}$ at most measurement sites.

Pb in particulate matter is known to cause severe health problems and the concentration levels reported in previous studies were high by any standards. For example Ali *et al.* (1986) measured an annual mean lead concentration of 4.2 $\mu g\ m^{-3}$ at a site near traffic, with a highest monthly average value observed in July (5.4 $\mu g\ m^{-3}$) and lowest in January (3.7 $\mu g\ m^{-3}$). Hassanien *et al.* (2001) showed an improvement where they observed a decrease by 40 % in Pb concentration in the urban sector of GC from 1994 to 1997 as a result of Pb reduction from traffic (diesel buses and gasoline cars). Even if the conditions have improved, reported Pb concentrations in GC are still higher than those recorded in other parts of the world (Querol *et al.*, 1999; Watson and Chow, 2001; El-Tahir *et al.*, 2004). The environmental effects of Pb in GC have been demonstrated by measurements of Pb levels in the blood of Cairo traffic policemen (Kamal *et al.*, 1991), and in studies on crops grown near highways (Belal and Saleh, 1978; Noweir, 1990).

There are great needs for better characterization of seasonal and long-term variations in PM and Pb concentrations in GC, as well as a better understanding of the governing effects of meteorology and changes in urban development. This paper presents mass concentrations of $PM_{2.5}$, PM_{10} and their Pb content obtained from measurements at 17 sites in GC over the period 2001-2002. These sites are classified into different areas according to local activities, i.e. industrial, urban, residential and background. The seasonal variations in concentrations are presented, and discussed in relation to natural and anthropogenic activities taking place during different parts of the year.

2. Experimental

2.1 Site description and climate

Greater Cairo is situated south of the delta in the Nile basin. The population exceeds 15 millions concentrated over an area of about 200 km^2, i.e. an area 4 km wide and stretching 50 km along the banks of the Nile river. Climatologically, GC is in the subtropical region. The city is characterized by the presence of the Moqattam hill (inside GC) to the east and southeast, and desert areas (outside GC) extending in the west and east directions. Among the outstanding weather events are dust and sand storms that frequently occur in spring (March to May) and autumn (September to November) (Zakey and Omran, 1997). In spring, hot desert cyclones known as the “Khamasin” depressions pass over the desert. These cyclones are always associated with strong hot and dry winds that are often laden with dust and sand that increase PM levels. In winter (December to February) the general climate is cold, humid and rainy; while during the summer season (June to August) the predominant weather is hot and dry.

Figure 1 shows the map of GC including the measurements sites. The measurement took place at 31 sites within GC of which 17 sites have PM_{10} and $PM_{2.5}$ measurements and the other sites have gaseous measurements only (NO_2, SO_2, O_3). The selected sites for PM measurements represent different activities and are spatially distributed over GC. Summary and activity classifications of the selected sites are shown in Table I. The sites of Shoubra El-Kheima (20), Giza (30), Abbasiya (36), and Kaha (26) were chosen to represent the industrial, urban, residential and background, respectively.

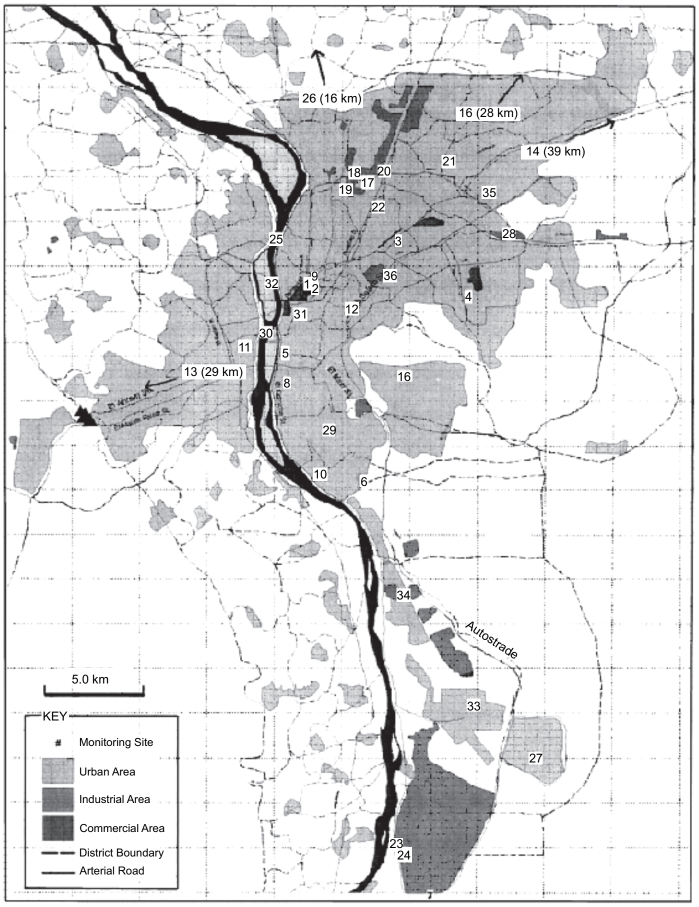

Fig. 1. Map of Greater Cairo with the stations and significant land features.

Table I. Classification of the 17 selected sites; sites Shoubra El-Kheima (20), Giza (30), Abbasiya (36), and Kaha (26) were selected as representatives for industrial, urban, residential and background activities, respectively.

Site No.	Site Name	Latitude (°N)	Longitude (°E)	Site classification
1	El-Qolaly Sq.	30.06	31.243	Urban
6	Maadi(Degla)	29.961	31.274	Residential
7	Tebbin south	29.752	31.314	Industrial
13	6th October	29.938	30.915	Residential/Industrial
19	El-Sahel	30.11	31.262	Industrial
20	Shoubra El-Kheima	30.113	31.269	Industrial
21	Matariya	30.123	31.315	Urban
22	El-Wayli	30.099	31.277	Urban
26	Kaha	30.276	31.196	Background
30	Giza	30.035	31.22	Urban
31	Tahrir Square	30.045	31.237	Urban
32	Zamalek	30.06	31.223	Residential
33	Helwan	29.848	31.333	Residential
34	El-Massara	29.903	31.295	Urban
35	Heliopolis	30.107	31.337	Urban
36	Abbasiya	30.065	31.285	Residential
37	Abu Zabal	30.123	31.369	Industrial

2.2 Sampling and analysis

Twenty four month (January to December) of PM samples were collected during the period 2001-2002. Air Metrics^{TM} samplers were used at each site to collect atmospheric PM for gravimetric and Pb analysis. In some of our sites we measure the PM using another techniques so-called beta gauge method, these sites are El-Qalay (1), Tebbin south (7) and Abbassaeya (36). The samplers were fitted with PM_{10} and $PM_{2.5}$ heads, which are designed to select particles of aerodynamic diameter less than 10 µm and 2.5 µm respectively. Both $PM_{2.5}$ and PM_{10} were sampled at all sites on 47 mm quartz fibre filters. The samplers were programmed to continuously collect a PM sample over a 24 h period ("0000" to "2400" (h)) and samples were retrieved from the sites on a scheduled program of every sixth day. At a few sites PM_{10} was measured during selected episodes with high time resolution (hourly) using ß-attenuation detectors.

The PM mass deposited on the filters was determined by weighing the filters before and after sample collection using a microbalance. Prior to both the initial and final weighing, the filters were conditioned in a desiccation cabinet for at least 24 hours to stabilize the weight. The filter conditioning and weighing operations were performed in a room in which the air temperature and relative humidity were controlled within the ranges 17-23 °C and 45-55%, respectively.

After the final weighing, Pb was extracted from the PM by digesting the filters in hot nitric acid solution. Flame atomic absorption spectroscopy (FAAS) was used to determine the Pb concentration using the Pb absorption line at 217 µm. The analytical detection limit of this method corresponds to an atmospheric concentration of 0.17 $\mu g\ m^{-3}$ of particulate Pb in a 24 h sample. Before beginning analysis of samples, the FAAS response is calibrated using a reagent blank solution and standard lead solutions at five different concentration levels. A series of continuing calibration checks is performed during the analysis of each set of samples to verify that the FAAS calibration conditions do not shift beyond acceptable limits. The calibration of the FAAS is considered acceptable if the response for the blank sample is within ± 0.10 µg of Pb and the response for the 2.48 µg of Pb standard is in the range of 2.25-2.75, i.e. the deviation from the standard values is ≤ 10%.

The data recovery/completeness values reported are expressed as a percentage of the total number of measurements that yielded a valid result. The annual average recoveries for PM and lead data are within an acceptable range (sampling events > 60%). However, data recoveries for a few sampling events were below acceptable levels. In particular, low $PM_{2.5}$ and PM_{10} data recoveries of 35.7% and 36.8%, respectively, were obtained from the 27 August 2001 sampling event. In this case, data loss appears to result from a systematic error in the sample weights, possibly due to improper conditioning of the samples prior to gravimetric analysis (see Table II).

Table II. Monitoring data recovery summary.

Statistic	Data recovery (as %)			
	$PM_{2.5}$	PM_{10}	$Pb_{2.5}$	Pb_{10}
Annual average recovery %	80.6	87.6	70.0	80.7
Maximum event recovery %	98.0	98.0	94.3	97.4
Minimum event recovery %	35.7	42.18	46.4	60.6
Sampling events < 70% recovery	4	3	18	5
Sampling events < 60%	1	1	2	0

3. Results and discussion

3.1 Mass concentrations of PM_{10} and $PM_{2.5}$

In 1994, the government of Egypt promulgated a law for the environment (EGL/94). The provisions of this law become effective in March 1998. EGL/94 specifies maximum limits for pollutants in ambient air (outdoors), workplace atmosphere, and source emissions. The limits established by EGL/94 for PM_{10} and lead are shown in Table III.

Table III. Limits established by EGL/94 for PM_{10} and lead.

Pollutant	Environment	Maximum limit	Average period
PM_{10}	Ambient air	70 µg m^{-3}	24 h
	Source emissions	None	-
Lead	Ambient air	1 µg m^{-3}	1 year
	Source emissions	20 µg m^{-3}	-

Figure 2 shows the average mass concentrations of PM_{10} and $PM_{2.5}$ measured at each of the 17 sites during the measurement period. Each average and corresponding standard deviation represents approximately 120 samples. The daily PM_{10} concentrations were in the range 82-253 µg m^{-3} as shown in Table IV. These values are all higher than the 24 h limit of 70 µg m^{-3} set by EGL/94 as shown in Table III and as such the limit is exceeded in all samples from all the sites. Among the sites, Tebbin south (7) recorded the highest mass concentration due to the cement and iron industrial activities in this area. The $PM_{2.5}$ concentrations in the samples were also high in all areas and ranged from 55 to 131 µg m^{-3}.

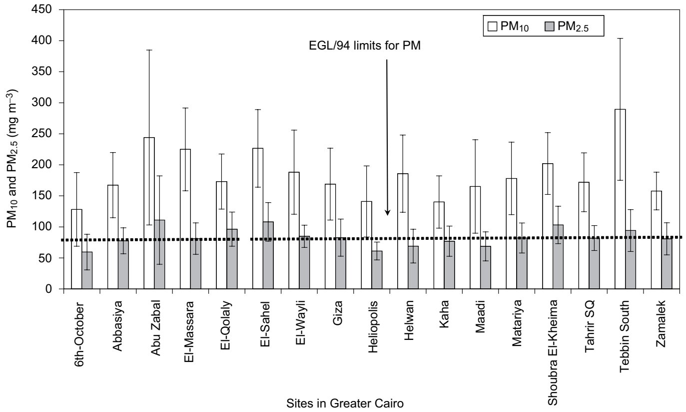

Fig. 2. Site-to-site variation of $PM_{2.5}$ and PM_{10} in Greater Cairo during the period 2001-2002. The dashed line indicates the EGL/94 limit and error bars represent the statistically standard deviation of the 120 samples.

Table IV. Summary of measurement data for the four representative sites. All concentrations are given in µg m^{-3} and the calculated standard deviations are based on 120 samples.

		Background	Residential	Urban	Industrial	All sites
			Concentrations (µg m^{-3})			
PM_{10}	Mean	140 ± 40	170 ± 35	170 ± 42	200 ± 39	170
	Range	82-200	120-210	100-230	150-250	82-253
$PM_{2.5}$	Mean	77 ± 20	78 ± 16	83 ± 22	100 ± 23	85
	Range	56 -120	57-110	55-130	69-130	55-131
Pb_{10}	Mean	0.9 ± 0.2	1.3 ± 0.7	1 ± 0.32	5.8 ± 3.9	2.3
	Range	0.5-1.8	0.8-1.8	0.7-1.5	1.0-16	0.5-16
$Pb_{2.5}$	Mean	0.7 ± 0.2	1.0 ± 0.3	0.8 ± 0.2	3.9 ± 2.7	1.6
	Range	0.4-1.1	0.6-1.5	0.6-1.1	0.8-11	0.4-11
			Ratios			
$PM_{2.5}/PM_{10}$	Mean	0.56 ± 0.1	0.47 ± 0.08	0.49 ± 0.08	0.52 ± 0.1	0.50
	Range	0.3-0.7	0.3-0.6	0.35-0.6	0.4-0.7	0.30-0.70
Pb_{10}/PM_{10}	Mean	0.007 ± 0.003	0.008 ± 0.003	0.007 ± 0.002	0.03 ± 0.02	0.01
	Range	0.004-0.01	0.004-0.01	0.004-0.01	0.004-0.07	0.004-0.07
$Pb_{2.5}/PM_{2.5}$	Mean	0.010 ± 0.004	0.014 ± 0.006	0.011 ± 0.003	0.04 ± 0.02	0.02
	Range	0.004-0.018	0.007-0.02	0.006-0.02	0.006-0.08	0.004-0.08
$Pb_{2.5}/Pb_{10}$	Mean	0.82 ± 0.1	0.78 ± 0.1	0.8 ± 0.2	0.7 ± 0.1	0.80
	Range	0.63-0.9	0.45-0.9	0.59-1.2	0.6-0.6	0.45-1.25

Figure 3 shows the $PM_{2.5}/PM_{10}$ mass ratio from the 24 hours samples at all sites. The ratios ranged from a minimum of 0.3 to a maximum of 0.7 with a mean of 0.5, indicating that $PM_{2.5}$ contributed significantly to PM_{10} in all samples. The PM mass ratios for the four sites representing background, urban, residential and industrial conditions are summarized in Table IV. The mass ratio $PM_{2.5}/PM_{10}$ gives an indication of the relative importance of natural and anthropogenic sources to PM (Querol *et al.*, 2004). A low $PM_{2.5}/PM_{10}$ mass ratio indicates a relatively large contribution from natural sources since they tend to dominate in the particle size range 2.5-10 µm. The monthly mean values of $PM_{2.5}$ and PM_{10} are shown in Figure 4.

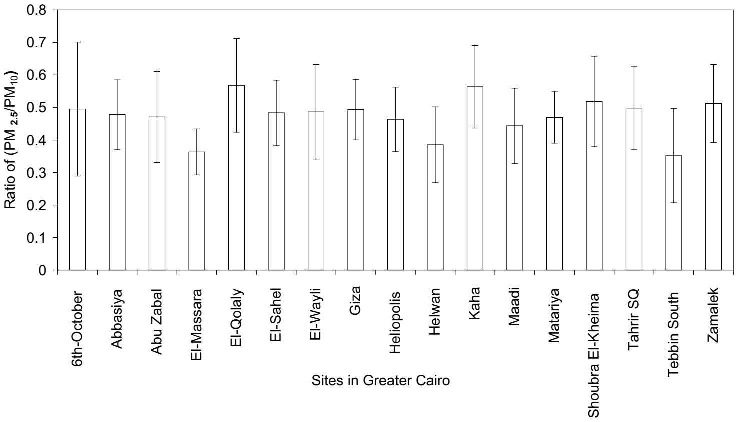

Fig. 3. Calculated $PM_{2.5}/PM_{10}$ ratio for the 17 measurement sites.

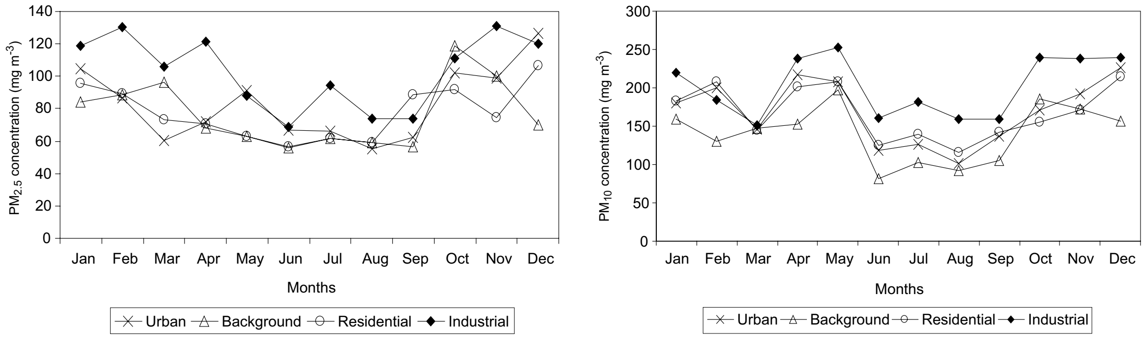

Fig. 4. Monthly variation of a) $PM_{2.5}$ and b) PM_{10} for the four representative sites (urban, industrial, background and residential) in GC during the period 2001-2002.

Basically, the seasonal variation is similar for all sites, with the annual low occurring during the summer months. The $PM_{2.5}$ concentrations partially follow the pattern observed for PM_{10} with low concentrations during summer season. The increase in $PM_{2.5}$ concentration after the summer season is, however, more pronounced than for PM_{10}. The higher values of PM_{10} in April and May may be due to the dust storm episode from 11 to 14 May 2001, as shown in Figures 5a and 6a. Thus, the main explanations for the seasonal variation may be deduced from these figures.

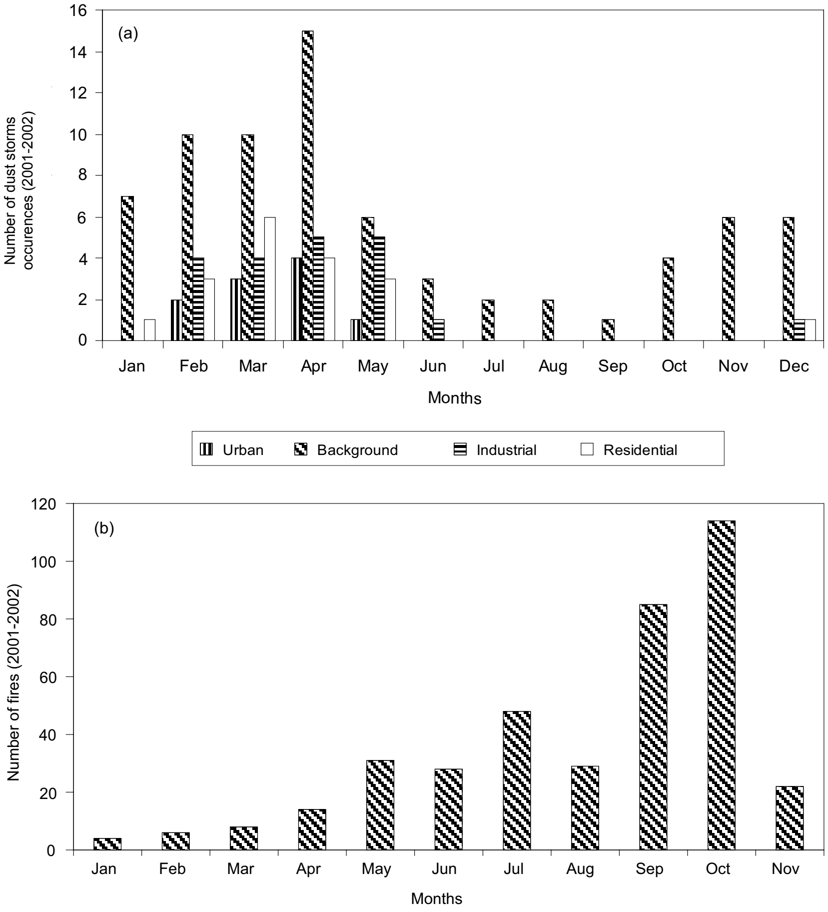

Fig. 5. a) Monthly number of detected dust storms at the selected sites in GC during 2001-2002. The numbers of dust storms were counted according to Zakey and Omran (1997). b) Monthly number of detected fires in the Nile Delta and Greater Cairo region during four years (2001-2004). The numbers of fires were calculated using data from the Terra satellite (Roy *et al.*, 2002).

Figure 5 shows the seasonal variation on numbers of dust storms in GC (Fig. 5a) and the numbers of detected fires due to burning of waste from harvested rice in the Nile delta (Fig. 5b) The fires were detected with the moderate resolution imaging spectroradiometer (MODIS) aboard the Terra satellite, with 1 km resolution by monitoring radiation in the 3.9 µm channel that saturates at 500 K. During night the detection system also uses the 1.65 and 2.15 µm channels. The periods of dust storms (March-April) and waste burning (September-November) can be linked to the seasonal variation of PM_{10} and $PM_{2.5}$ shown in Figure 4. Thus, aerosols from dust storm events and waste burning enhanced the levels of $PM_{2.5}$ and PM_{10} significantly. Coarse particles from dust storm events contribute to increase the levels of PM_{10}, most of this particles fall back to ground with dry deposition and sedimentation, while the fine and accumulated ones are transported in the atmosphere to play the direct effect on radiation (Zakey *et al*., 2006). Aerosols from waste burning produces finer particles that may contribute more to $PM_{2.5}$. As an example, Figure 6 shows the episodic nature of these two sources, where e.g. the PM_{10} levels can reach extreme values during some hours. Both, the wind direction and wind speed are crucial parameters for these severe conditions. In addition to these two seasonal effects, low winter-time temperatures often result in stable weather conditions that aggravate the effects of particle emissions from urban traffic and industrial activities as shown in Figures 7 and 8**.**

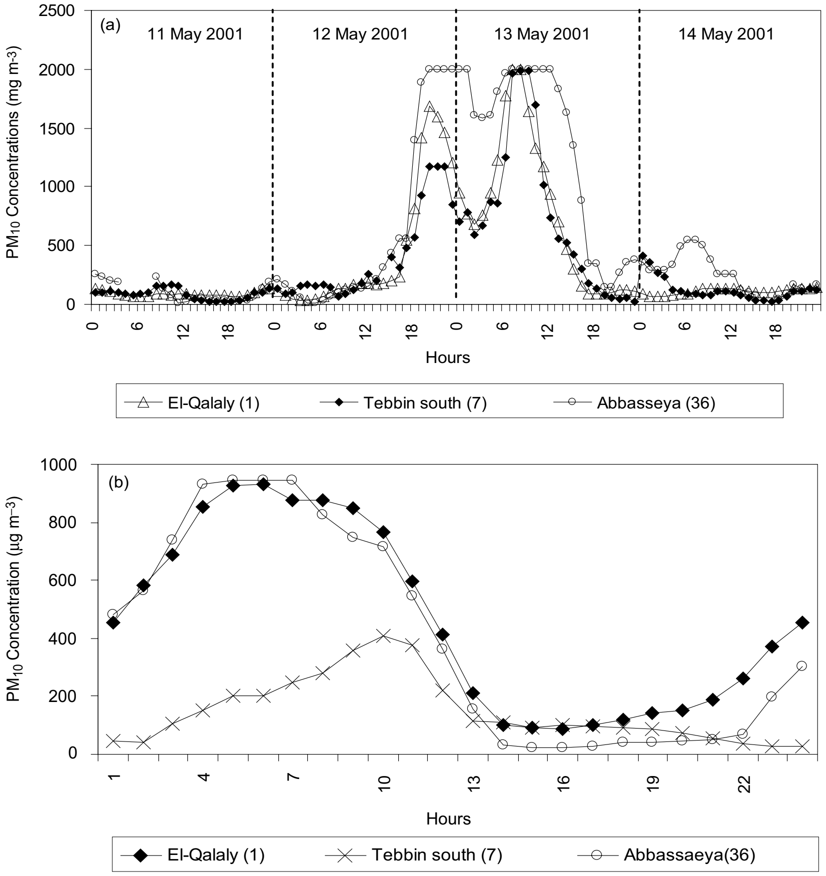

Fig. 6. a) Hourly PM_{10} concentration at three sites in GC during one of the severe dust storms over GC (11-14 May 2001). The analyzer was saturate if the concentration reaches above 2000 µg m^{-3}, what may be due to the experimental procedures. b) Hourly PM_{10} at three sites in GC during an apisode of rice waste burning (3 November 2001).

Figure 7 shows the wind direction frequency distribution for selected sites. The most prevailing wind direction is from north in GC area, but this direction is slightly shifted north-west in delta. Wind from north occurred during 65% of the time at Abbasiya (36), 74 at Tabbin (7), 49 at Shoubra (20), and 66% at Giza (30). The highest wind speed occurred at Tabbin, Shoubra and Giza, exceeding 10 m s^{-1}.

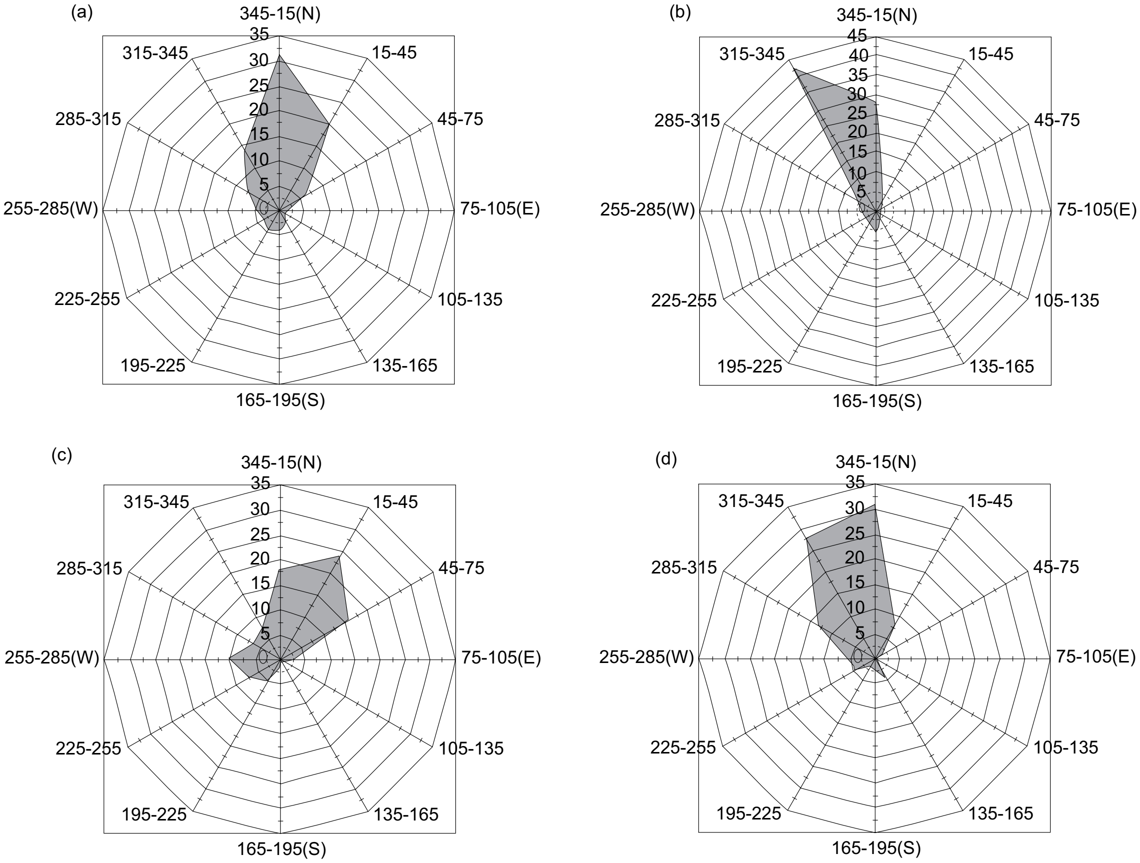

Fig. 7. Wind direction frequencies (%) for twelve 30-degree sectors measured at a) Abbasiya, b) Tebbin, c) Shoubra El-Kheima, and d) Giza.

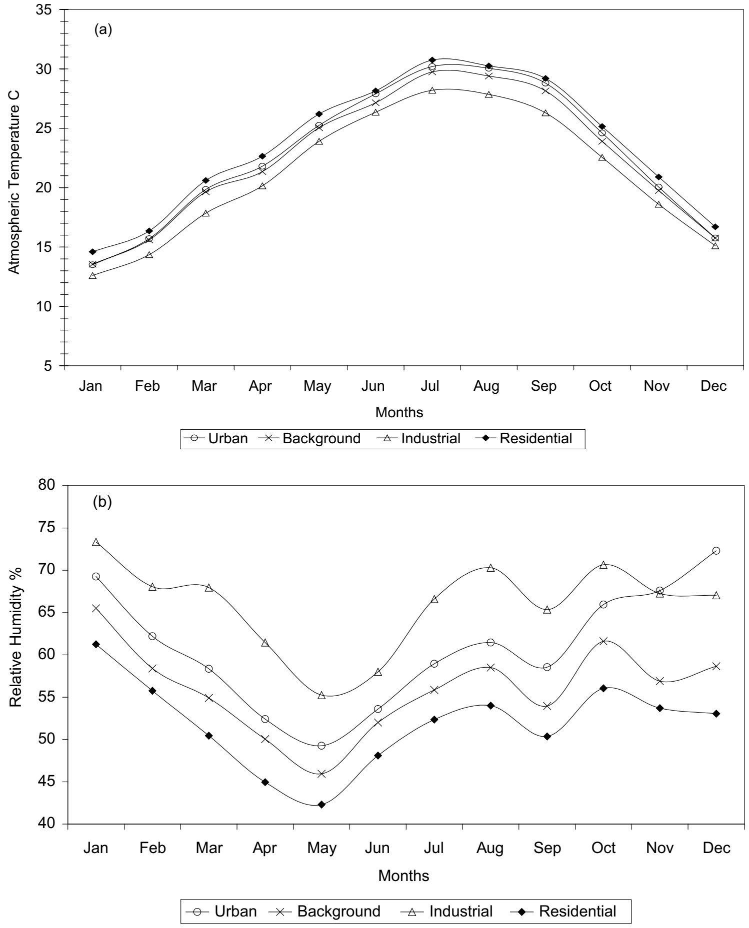

Fig. 8. Monthly mean temperature (a) and monthly mean values of relative humidity (b) in different sectors in Geater Cairo during the period 2001-2002.

Table V gives an overview of the correlation coefficients (r^2) of the monthly average values of PM_{10} and $PM_{2.5}$ between all sites. Most sites show a positive correlation because they are either responding to regional sources affecting the whole area, like waste burning or dust storms, or to well distributed point sources like traffic. As can also be seen from the analysis of the lead data, the industrial sites are not as well correlated as the other due to increased numbers of potential point sources of particulate matter. Especially the correlation coefficients between Abu Zabal (37) and most of the other sites are low. This site is up-wind of GC and the low correlation stresses further that the site is mostly exposed to local industrial activities.

Table V. Correlation (r^2) between the sites for the monthly average values of particulate matter.

PM_{10}

No.	1	6	7	13	19	20	21	22	26	30	31	32	33	34	35	36	37
01	1.00																
06	0.14	1.00															
07	0.34	−0.09	1.00														
13	−0.15	0.60	−0.15	1.00													
19	0.40	0.18	0.56	0.04	1.00												
20	0.55	0.50	0.25	0.25	0.59	1.00											
21	0.15	0.80	0.17	0.59	0.57	0.72	1.00										
22	0.57	0.55	0.28	0.18	0.74	0.53	0.69	1.00									
26	0.44	0.26	0.23	0.44	0.43	0.84	0.64	0.46	1.00								
30	0.42	0.74	0.05	0.53	0.43	0.82	0.90	0.65	0.77	1.00							
31	0.33	0.49	0.10	0.20	0.46	0.87	0.77	0.48	0.76	0.87	1.00						
32	0.57	0.16	0.32	−0.20	0.54	0.25	0.26	0.76	0.24	0.25	0.27	1.00					
33	0.33	0.42	−0.14	0.09	0.35	0.12	0.33	0.67	0.03	0.28	0.17	0.76	1.00				
34	0.42	0.64	−0.19	0.50	0.05	0.65	0.67	0.41	0.62	0.09	0.72	0.10	0.20	1.00			
35	0.08	0.55	−0.28	0.30	0.25	0.62	0.76	0.45	0.58	0.84	0.85	0.12	0.21	0.77	1.00		
36	0.37	0.69	−0.11	0.40	0.31	0.73	0.83	0.62	0.67	0.97	0.86	0.25	0.30	0.91	0.92	1.00	
37	0.37	0.11	0.26	0.08	0.16	0.52	0.10	−0.14	0.29	0.25	0.25	−0.41	−0.42	0.21	−0.02	0.11	1.00

$PM_{2.5}$

No.	1	6	7	13	19	20	21	22	26	30	31	32	33	34	35	36	37
01	1.00																
06	0.89	1.00															
07	0.34	0.24	1.00														
13	0.24	0.05	−0.35	1.00													
19	0.81	0.63	0.28	0.34	1.00												
20	0.66	0.56	0.54	0.34	0.59	1.00											
21	0.79	0.73	0.20	0.51	0.88	0.75	1.00										
22	0.73	0.73	0.26	0.34	0.69	0.86	0.84	1.00									
26	0.44	0.32	0.57	0.03	0.70	0.66	0.67	0.67	1.00								
30	0.88	0.83	0.22	0.42	0.77	0.63	0.84	0.78	0.43	1.00							
31	0.53	0.55	0.74	−0.38	0.55	0.62	0.49	0.52	0.69	0.32	1.00						
32	0.78	0.72	0.40	−0.18	0.75	0.54	0.58	0.63	0.54	0.56	0.79	1.00					
33	0.56	0.55	0.36	0.35	0.23	0.72	0.43	0.65	0.12	0.68	0.20	0.26	1.00				
34	0.64	0.75	0.07	0.31	0.34	0.60	0.61	0.73	0.20	0.72	0.23	0.39	0.72	1.00			
35	0.69	0.83	0.20	0.18	0.48	0.76	0.69	0.90	0.39	0.76	0.48	0.58	0.75	0.79	1.00		
36	0.73	0.85	0.21	0.07	0.53	0.56	0.69	0.76	0.42	0.71	0.48	0.53	0.51	0.59	0.83	1.00	
37	0.21	−0.18	0.29	−0.36	0.12	−0.27	−0.33	−0.25	−0.04	0.02	−0.07	−0.12	0.05	−0.32	−0.16	−0.22	1.00

3.2 Lead concentrations

Figure 9 shows the average concentrations of lead in PM_{10} (Pb_{10}) and in $PM_{2.5}$ ($Pb_{2.5}$) observed at the 17 measurement sites during 2001-2002. The average Pb_{10} concentrations are between 1 and 2 µg m^{-3} at most sites, with a couple of exceptions showing higher average values, i.e. the industrial sites. Thus, the lead concentrations at most of the sites exceed the EGL/94 annual limit of 1 µg m^{-3}. The monthly variation of Pb_{10} shows higher values at the industrial sites (ranged from 6 to 16 times the EGL/94 limit), while the others urban, residential and background sites recorded values around the EGL/94 limit, the same behavior is noticed for $Pb_{2.5}$ as shown in Figure 10**.**

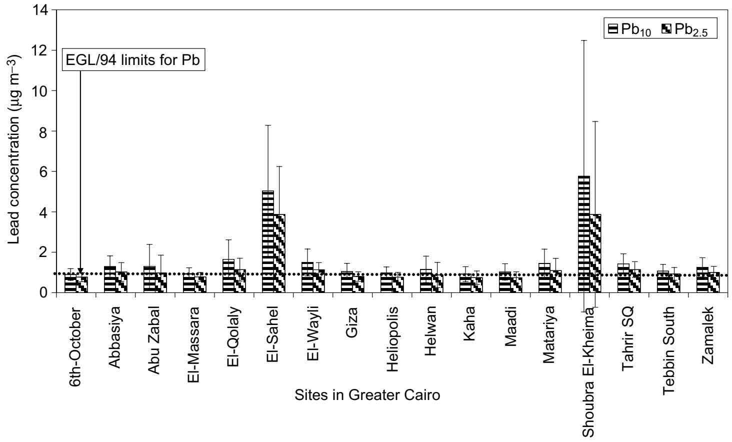

Fig. 9. Site-to-site variation of lead concentrations (µg m^{-3}) in PM_{10} and $PM_{2.5}$ in Greater Cairo during the period 2001-2002. The dashed line indicates the EGL/94 limit and error bars represent the standard deviation.

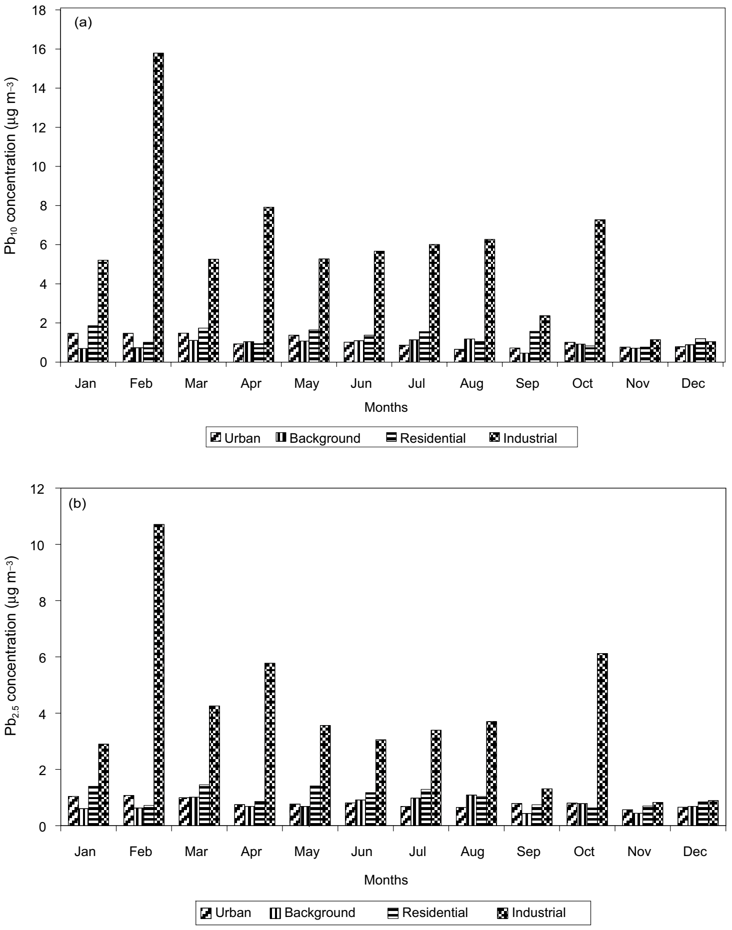

Fig 10. Monthly variation of Pb_{10} and $Pb_{2.5}$ concentrations in µg m^{-3} in different sectors (urban, industrial, background, and residential) in Greater Cairo during the period 2001-2002. a): Pb_{10} mass concentrations. b): $Pb_{2.5}$ mass concentrations.

It was concluded that Pb is associated with the fine fraction since the $Pb_{2.5}$ concentrations are comparable to the values of Pb_{10}. The ratios of $Pb_{2.5}$ to Pb_{10} presented in Table IV are high with an average of 85%. Since associated to the fine fraction the Pb emissions can spread over a larger area, thus affecting a significant part of the population. It stands clear that the air quality in the region can benefit significantly if the Pb emissions from the industrial point sources are reduced. The yearly average concentration of above 1 $\mu g\ m^{-3}$ for all sites within the GC area, where there lives 15 million people, is giving an indication that 74.9% of the urban sector, 100 of the industrial sector, 43 of the residential sector and 12% of the background sector are facing lead exposure. The lead sources and consecutive exposure to the inhabitants in GC has further been evaluated and presented in a report by the Egyptian Environmental Affair Agency (EEAA, 2002). In this report they conclude that the major industrial sources of lead were from diesel combustion and lead smelters. Furthermore, it was noted from data in that report that there are 100% of people living in industrial areas which are directly affected by these elevated Pb levels.

Lead may be emitted from several sources, including fuel and motor oil combustion, brake wear, and re-suspension of enriched road dust. Figure 11 indicates that the sources of lead in GC are: 1) Mazout (diesel) combustion, 2) Secondary lead smelting, 3) Secondary copper processing, 4) Lead-acid battery production, and 5) Portland cement manufacturing. The ratio from the Portland cement manufacturing, secondary copper production and lead-acid battery production was very small, and a significant ratio was recoded from secondary lead smelting. The lead from mazout is the dominant source of Pb in the GC as shown in figure 9, contributing up to 43% of PM_{10} Pb at the industrialized.

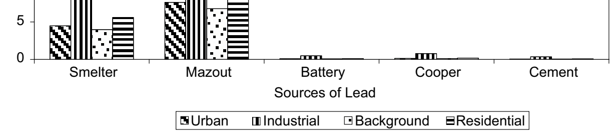

Fig. 11. Estimated contributions from different sources to the lead concentrations in PM_{10} observed in different sectors in Greater Cairo area.

3.3 Comparison with other studies

Table VI shows values of $PM_{2.5}$ and PM_{10} from some previous studies. Abu-Allaban *et al.* (2002) presented measurements from 1999. These values are comparable to the present results. However, the industrial areas recorded significantly lower values comparing to the previous measurements due to the improvements of some industrial activity, for example, the filter systems of the cement industry and the decreasing number of smelter workshops.

Table VI. Reported data from selected publications illustrating the relation between measurements in Greater Cairo and other sites. All data are from records longer than 1 year and the data are 24 h averages.

City	$PM_{2.5}$	PM_{10}	Reference
Greater Cairo			
- Industrial-Shobra	216.1	265.1	Abu-Allaban *et al*. (2002)
- Background-Kaha	49.7	93	Abu-Allaban *et al*. (2002)
- Residential-Zamalek	61.9	127.2	Abu-Allaban *et al*. (2002)
- Urban-Qualaly	84.6	219.9	Abu-Allaban *et al*. (2002)
- Industrial-Shobra	100 ± 23	200 ± 39	This study
- Background-Kaha	77 ± 20	140 ± 40	This study
- Residential-Zamalek	78 ± 16	170 ± 35	This study
- Residential-Abbasiya	77.6 ± 21	167.2 ± 53	This study
- Urban-Qualaly	83 ± 22	170 ± 42	This study
- Urban-Giza	82.7 ± 30	169 ± 58	This study
Athens, Greece	40.2	75.5	Chaloulakou *et al.* (2003)
India			
- Industrial site		384 ± 139	Sharma *et al*. (2003)
- Background site		62 ± 11	
- Traffic site		401 ± 60	
- Commercial site		281 ± 170	
- Residential site		226 ± 142	
Beirut, Lebanon	39.9	118.8	Shaka and Saliba (2004)
Dhaka, Bangladesh,	167.4-10.9	289.8-15.4	Biswas *et al*. (2003)
Eastern Spain			Rodríguez *et al*. (2004)
- Rural		22.0	
- Industrial		33.26	
- Urban (Barcelona)	33.92	49.51	
London, UK			Harrison *et al*. (2004)
- Road site	22.32		
- Background site	14.35		
México City, México		52	Baldasano *et al*. (2003)
Milan-Italy			Lonati *et al*. (2005)
- Traffic site	204.5		
- City center	32.8		
Taichung, Taiwan	42.8	62.2	Fang *et al*. (2003)
Zurich	17.8	23.4	Gehrig and Buchmann (2003)

In comparison to measurements from Lebanon, Italy, Greece and Spain, the values of annual PM_{10} and $PM_{2.5}$ from the GC sites are much higher and are due to the larger population in Cairo. Concentrations obtained at some traffic sites, e.g. Milan, Italy, can reach and exceed the levels obtained in Cairo area. However, in most European cities the abatement of urban pollution has given effects, and significant lower levels are present, e.g. Athens, Zurich and London. Table VI also includes measurements from some megacities in the world. Even if Cairo is not the most polluted megacity in the world, the location of Cairo in a desert area has an effect on the air pollution levels from the additional dust source.

4. Concluding remarks

Two years measurements of PM (PM_{10}, $PM_{2.5}$) in GC in different environments (industrial, urban, residential and background) have been evaluated. The results indicated that the average concentration of PM_{10} ($PM_{2.5}$) was 1.3 (1.6), 1.8 (1.7), 1.6 (1.6), 1.6 (1.4) times lower in summer than in winter at industrial, urban, residential and background sites, respectively. The low values recorded during the summer season are due to the absence of dust episodes and waste burning in combination with good dispersion. Generally, the severe air pollution situation in GC is enhanced by the naturally occurring dust storms and the anthropogenic waste burning in the Nile delta. Both of these issues are regional in character and may influence the climate in the region, where the aerosols are a key factor of radiative forcing and cooling of the atmosphere over Europe and Africa (Solmon *et al*., 2006; Zakey *et al*., 2006). In the perspective of human health, the fine aerosols $PM_{2.5}$ are more effective in causing respiratory illness and premature death than larger aerosols due to their ability to penetrate deeper into the lung (Kaiser, 2005).

The high Pb content in particle samples can be directly related to industrial activities where the sources of combustion of mazout, and lead smelting can be traced and abated. This will reduce the Pb exposure for a large part of the population in the area. The homogeneously distributed fine particle fraction from urban sources present in the GC area is mostly from traffic. The observed reduction of Pb content in the urban aerosol due to phase out of leaded petrol shows the effect on air quality on implementation of environmental actions.

Acknowledgements

This work was supported by MISTRA, the Swedish Foundation for Strategic Environmental Research. The Charmin board of Egyptian Meteorological Authority and the Egyptian Environment Affairs Agency are acknowledged for supporting and promoting this evaluation by supplying data.

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