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"Gheorghe Asachi" Technical University of Iasi, Romania

ANALYSIS OF THE CONTINUOUS MEASUREMENTS OF PM_{10} AND $PM_{2.5}$ CONCENTRATIONS IN BEIRUT, LEBANON

Wehbeh Farah[1]*, Myriam Mrad Nakhlé[2,5], Maher Abboud[3], Nelly Ziade[4], Isabella Annesi-Maesano[5], Rita Zaarour[6], Nada Saliba[6], Georges Germanos[1], Najat Aoun Saliba[7], Alan L. Shihadeh[8], Jocelyne Gerard[6]

[1]Physics Department, Saint Joseph University of Beirut, Beirut, Lebanon
[2]Biology Department, Saint Joseph University of Beirut, Beirut, Lebanon
[3]Chemistry Department, Saint Joseph University of Beirut, Beirut, Lebanon
[4]Rheumatology Department, Saint Joseph University of Beirut, Beirut, Lebanon
[5]EPAR, Institute Pierre Louis of Epidemiology and Public Health, UMR-S 1136 INSERM & UPMC Paris 6, Sorbonnes Universities, Medical School Saint-Antoine, Paris, France
[6]Geography Department, Saint Joseph University of Beirut, Beirut, Lebanon
[7]Mechanical Engineering Department, American University of Beirut, Beirut, Lebanon
[8]Chemistry Department, American University of Beirut, Beirut, Lebanon

Abstract

Atmospheric concentrations of $PM_{2.5}$ and PM_{10} were measured in Beirut, Lebanon, for a period of 12 months. The daily average concentrations of PM_{10} and $PM_{2.5}$ were found to be 51.3 ± 33.1 and 30.3 ± 9.4 μg.m^{-3}, respectively, with corresponding maximum values of 359.7 and 208.6 μg.m^{-3}. The annual average concentrations of PM_{10} and $PM_{2.5}$ exceeded the World Health Organization's standards by 150% and 200%, respectively. The mean concentration of coarse particles ($PM_{10–2.5}$) was found to be 41% of the average PM_{10}, suggesting that the site was also influenced by re-suspended surface dust and soil. The mean $PM_{2.5}/PM_{10}$ ratio for the entire study period was 0.61 ± 0.12. This indicates that in Beirut, $PM_{2.5}$ accounts for about 61% of PM_{10}. Such a large fraction of fine particles could have considerable effect on health; thus, it is necessary to quantify its impact. Daily concentrations of PM_{10} and $PM_{2.5}$ exceeded the upper threshold limit on 133 and 129 days, respectively, representing 39% and 38% of the entire sample, respectively. These findings indicate the important role dust events play within this area. Concentrations of $PM_{2.5}$ were highly correlated with NO_2, whereas concentrations of PM_{10} and $PM_{10–2.5}$ were not associated with any gaseous pollutant. Regression analysis showed that 93% of $PM_{2.5}$ and 43% of PM_{10} particle mass concentrations were derived from road traffic exhaust in Beirut.

Key words: air quality, dust event, health effect, particulate matter, regression analysis

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1. Introduction

Fine and ultrafine particles are the inhalable fraction of atmospheric particulate matter (PM) that can become embedded within the lungs and lower respiratory system (Oberdorster et al., 2005). Generally, ultrafine particles are related to soot derived from the incomplete combustion of fuels associated with traffic, wood fires used for heating, and incineration. The chemical compositions of these particles define their biological reactivity. Various organic and biological compounds can adhere to these particles and it has been proven that these compounds, which can be found in the lungs of humans, have potentially harmful effects if they are not eliminated by the clearance mechanism of the respiratory system.

* Author to whom all correspondence should be addressed: e-mail: wehbeh.farah@usj.edu.lb; Phone: +96 1142 1374; Fax: +96 1453 2657

Since the early 1990s, thousands of studies have reported associations between airborne particles and a range of respiratory and cardiovascular diseases and even death. For example, Schwartz (1994) reported an association between concentrations of daily total suspended particles and the risk of mortality in Ohio, whereas Dockery et al. (1993) associated premature death in six eastern US cities with fine atmospheric particulates (inhalable particles).

Similar results have been reported in association with fine particles, but this time with regard to hospital admissions. In Birmingham (UK), a study in 1997 showed that following every 10 $\mu g.m^{-3}$ increase in concentration of PM_{10}, respiratory and cerebrovascular hospital admissions increased by 2.4% and 2.1%, respectively (Wordley et al., 1997). Another study revealed an association between the short-term increase in hospital admission rates and $PM_{2.5}$ for all health problems except injuries (Dominici et al., 2006). The largest association regarded heart failure, which had a 1.28% (95% confidence interval; 0.78–1.78) increase in risk per 10 $\mu g.m^{-3}$ increase in same-day $PM_{2.5}$ concentration. Dominici et al. (2006) concluded that short-term exposure to $PM_{2.5}$ increased the risk of hospital admission of people with cardiovascular and respiratory diseases.

Other studies have also found relationships between low levels of fine particles and hospital admissions of people suffering respiratory symptoms. In Vancouver, Canada, where pollutant levels are relatively low, Chen et al. (2004) confirmed a positive relationship between PM_{10}, $PM_{2.5}$, and $PM_{10-2.5}$ and emergency hospitalizations for Chronic Obstructive Pulmonary Disease in people aged over 65 years. Schwartz (1995) constructed daily counts of admissions to all hospitals in New Haven (Connecticut) and Tacoma (Washington) for persons aged 65 years and older with respiratory diseases (ICD-9 460-519). The results showed significant association between the three studied pollutants (SO_2, PM_{10}, and O_3) and admissions to hospitals of the older persons with respiratory problems; however, the strongest evidence of an independent association was for PM_{10}. These significant relationships are also found for children, another group vulnerable to the effects of air pollution and fine particles in particular (Brauer et al., 2002; Braun-Fahrlander et al., 1997; Penard-Morand et al., 2005).

These findings underline the importance of ambient PM and for need to monitor PM_{10} and the associated fraction of $PM_{2.5}$. In this paper, we explore the annual and daily average concentrations of PM_{10} and $PM_{2.5}$ and compare them with the corresponding WHO standards to estimate their effects on health. We also determine the relative contributions of fine, $PM_{2.5}$, and $PM_{10-2.5}$ to total inhalable particles (PM_{10}), and discuss the relationship between levels of PM and concentrations of other gaseous pollutants.

2. Material and methods

2.1. Study area

Beirut, Lebanon's capital, is located on the eastern coast of the Mediterranean Sea (Fig. 1), covering an area of 20.8 km^2 and it has a population of about 361,366 inhabitants (CAS, 2007). Beirut is characterized by two hills that lie to the north and west of the city, separated by a thalweg. Each hill rises about 100 m above sea level and overlooks the Mediterranean Sea.

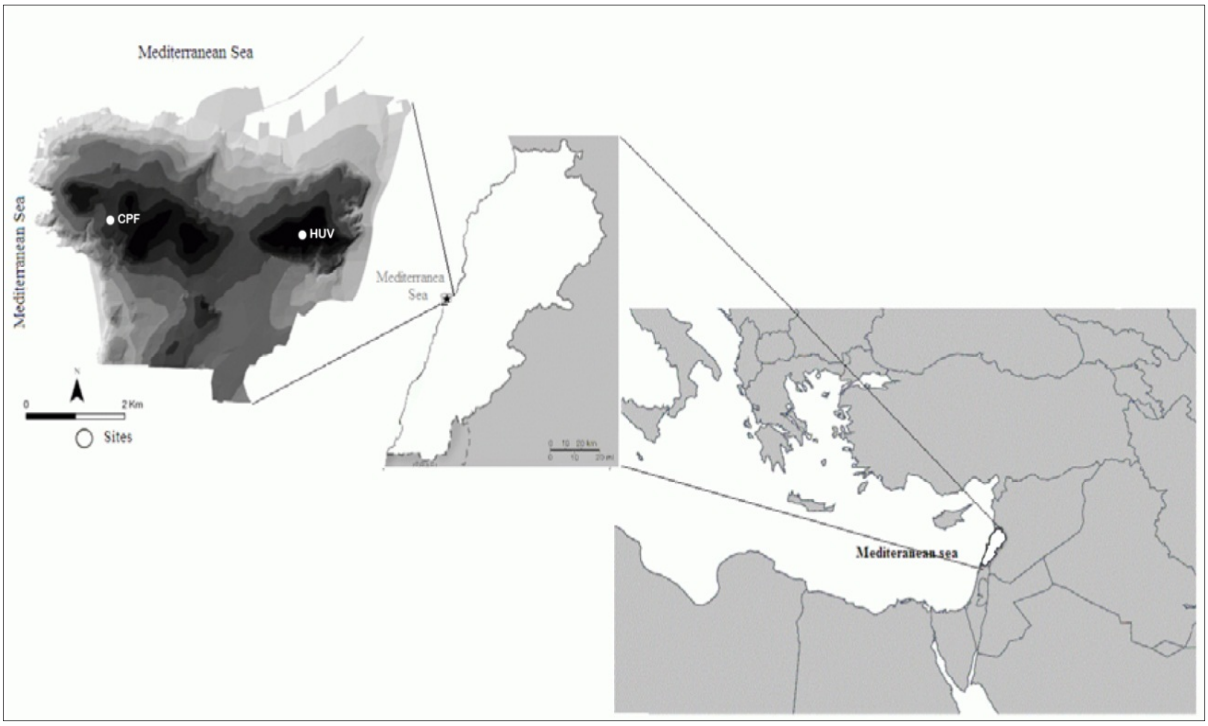


Fig. 1. Locations of Lebanon on the Mediterranean Sea and of the HUV and CPF sites

The typical unplanned urban morphology, high population density, and high concentration of human activities of the developing world, together with the Mediterranean climate and topography of the capital, are major factors that contribute to the degradation of air quality. The main sources of air pollution are vehicular traffic and dust storms, because industrial activity does not exist within the study area. The number of registered vehicles in Lebanon exceeds one million, and the average age of the vehicle fleet is over 10 years (El-Zein et al., 2007). The government exercises little effective control over the quality of fuel, which is imported (El-Zein et al., 2007). However, in 2002, a law was introduced banning the use of diesel fuel for light- and medium-duty engines. The main thermal power station of the country is located 13 km northeast of Beirut, and the airport is located 7 km to the southwest. Pollution data were collected from only one station even though there are several stations within Beirut for the measurement of air quality. However, we chose the most suitable site, which we monitored consistently throughout the study period. Wordley et al. (1997) confirmed that significant variation in pollutant levels could exist between different stations, but that data obtained from one station could be used as proxies for the levels of air pollution required for time series studies.

2.2. Instrumentation and sampling procedure

The concentrations of PM_{10} and $PM_{2.5}$ were measured using an MP101M (Environnement SA, 2013) atmospheric monitoring system. The MP101M is an ambient air-suspended particulate analyzer that uses a beta gauge. A beta gauge consists of a Carbon-14 radioactive source with very low activity, and a Geiger–Müller tube receives the emitted beta radioactive radiations. The detector is fixed below the glass fiber filter tape and it collects air-suspended particulates. Sampling is performed using a vacuum pump attached to a sampling head that is connected to the top of the analyzer. The measurement cycle can be described as follows:

- Stage 1: The tape is blank. The radioactive source is placed in front of the Geiger–Müller detector. At this stage, a specified quantity of beta radiation is absorbed by both the filter and the compressed air located between the radioactive source and the detector.
- Stage 2: The sample is absorbed by the sampling head and collected on the filter tape. Beta radiation emitted by the source is absorbed by the filter, the compressed air, and the fixed particulates.

The particulate concentration is calculated based on the difference between the radiation count at the beginning of the cycle when the tape is blank, and at the end of the cycle when particulates have adhered to the tape. This difference in count is directly proportional to the mass of particulates collected on the tape. The duration of each cycle is 24 h, which is divided into 12 equal periods. Once a cycle has completed, the supply reels rotate and a new cycle begins.

The MP101M has a built-in reference gauge for calibration and the procedure of calibration is repeated every 6 months. This equipment is manufactured according to ISO 10473 standards, certified equivalent to the US EPA-approved reference methods Nos. EQPM-0404-151 and EN 12341.

Measurements of the trace gases were taken by an atmospheric monitoring system for O3 and NO/NO2 (Environnement SA, 2013), the instruments of which were installed within a shelter in Beirut, Lebanon. Ambient air was sampled through ¼-in Teflon sampling tubing and all the recording instruments were connected to an XR workstation data logger, which was used to store their outputs.

The AC32M monitor for NO_2 is based on chemiluminescence (EN 14211) and the O342M monitor is based on the absorption of ultraviolet radiation (EN 14625). A gas dilutor (LNI Schmidlin SA, Model SONIMIX 3012) was used to calibrate the instruments using zero and standard gases. The zero air generator (LNI Shmidlin SA, Model SONIMIX 3052) provided high-purity zero air, while the standard gas consisted of 29 ppm NO balanced with high-purity N_2. The ozone analyzer calibration was conducted using a standard ozone generator regulated by ultraviolet light and integrated in the SONIMIX dilutor.

The daily average concentrations of atmospheric PM_{10}, $PM_{2.5}$, and other pollutants were obtained between January and December 2012. In addition to the continuous measurements of the pollutant levels, measurements of wind direction and speed, and temperature and humidity were routinely monitored at this site to understand the influence of meteorological parameters on pollutant levels. A quality control procedure was established such that the average calculations were accepted if 75% of the quarter-hourly data were valid for any given hour and 75% of the hourly data valid for any given day.

Relationships between PM_{10}, $PM_{2.5}$, and $PM_{10–2.5}$ and other pollutant concentrations were investigated. This was accomplished either by estimating correlations between the different variables (Pearson correlation coefficients) or by conducting regression analysis.

3. Results and discussions

3.1. PM_{10}, $PM_{2.5}$, and $PM_{10–2.5}$ concentrations

The concentrations of PM_{10} and $PM_{2.5}$ were measured on 343 days, out of the 365 days, from January through December 2012. These measurements produced 8232 data points for assessment of the concentration of each pollutant. Statistics for the daily concentrations of PM_{10}, $PM_{2.5}$, and $PM_{10–2.5}$ are shown in Table 1. The coarse particle mass concentration ($PM_{10–2.5}$) was calculated based on the difference between PM_{10} and $PM_{2.5}$. The daily average concentrations of PM_{10} and $PM_{2.5}$ were 51.3 ± 33.1 and 30.3 ± 19.4 μg.m^{-3}, respectively, with corresponding maximum values of 359.7 and 208.6 μg.m^{-3}. The mean concentration of coarse particles ($PM_{10–2.5}$) was found to be 41% of the average PM_{10}, suggesting that the site was influenced by re-suspended surface dust and soil.

The annual average concentrations of PM_{10} and $PM_{2.5}$ exceeded the annual average WHO standards (*i.e.*, 20 μg.m^{-3} for PM_{10} and 10 μg.m^{-3} for $PM_{2.5}$) by 150% and 200%, respectively, suggesting that urgent intervention is required to control particulate pollution in Beirut.

Table 1. Statistics for daily concentrations of PM_{10}, $PM_{2.5}$, and $PM_{10–2.5}$ from January to December 2012

	N total (days)	*Min (μg/m³)*	*Max (μg/m³)*	*Mean (μg/m³)*
PM_{10}	343	16.0	359.7	51.3 ± 33.1
$PM_{2.5}$	343	4.5	208.6	30.3 ± 19.4
$PM_{10-2.5}$	343	1.0	157.7	21.0 ± 17.3

Similar results to the present study have been reported following comparable work performed in other urban and coastal–urban areas throughout Europe and Asia (Chaloulakou et al., 2003; Gerasopoulos et al., 2007; Ho et al., 2003; Marcazzan et al., 2003; Massoud et al., 2011; Pey et al., 2008; Rodriguez et al., 2004). However, the mean concentration of $PM_{2.5}$ observed in December by Meng and Lu (2007) is at least five to six times higher than the values presented in this study.

This large difference is because the concentrations of $PM_{2.5}$ were measured during autumn and winter, when the level of combustion of fossil fuel is very high. In addition, adverse meteorological conditions during these seasons can prevent particulate dispersion, producing high concentrations near the ground, which was not the case in Lebanon in 2012.

3.2. Site representativeness

To assess the health effects more accurately, it is important to examine whether data from a single monitoring site are representative of community exposure. Various studies on the spatial variation of PM have shown that the concentration of particulates is higher at locations affected by traffic emissions compared with traffic-free areas. For example, Buzorius et al. (1999) studied the spatial variations of aerosol concentrations in Helsinki and found that concentrations were higher at locations affected by traffic emissions. Similar results have shown that PM_{10} and $PM_{2.5}$ concentrations measured near a busy road were on average 1.3 times higher than at a background site (Jansen et al., 1997).

Therefore, it is possible that the high concentration levels reported here could be attributed, at least in part, to the location of the monitoring site. To test this hypothesis, a limited number of PM_{10} samples were collected at Beirut Saint Joseph University's Huvelin area (HUV site). This site is located approximately 4 km from the CPF air-quality monitoring station. The CPF site is less affected by traffic emissions and it is more representative of exposure encountered within the Beirut Metropolitan area. Fig. 2 compares the concentrations of PM_{10} observed at the HUV and CPF sites. Although this comparison is based on a limited number of sampling days (170 days), these results strongly support the presumption that PM_{10} concentrations measured at HUV were higher than at the CPF site; concentrations of PM_{10} measured at the HUV site were on average approximately 16% higher. Furthermore, PM_{10} concentrations measured at the HUV and CPF sites exhibited correlation with an r^2 value of 0.82.

3.3. Time series of PM concentrations

Fig. 3 shows the time series plot of daily concentrations of PM_{10} and $PM_{2.5}$ from January 2012 through December 2012.

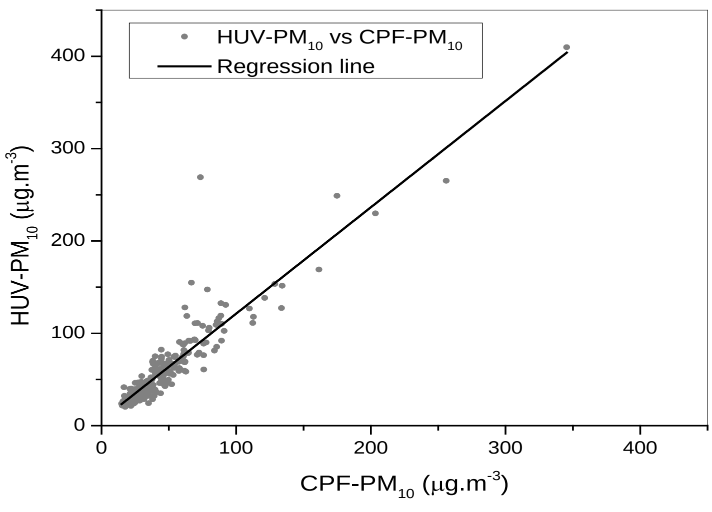


Fig. 2. Comparison between PM_{10} concentration measurements at HUV and CPF sites

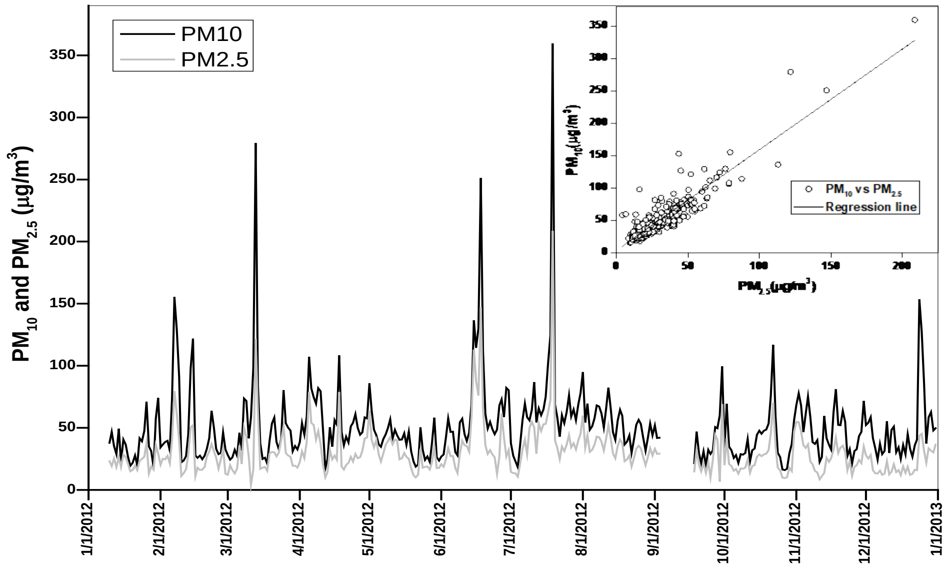


Fig. 3. Temporal trends of daily average PM_{10} and $PM_{2.5}$ concentrations over the study period in Beirut. Inset shows the correlation between PM_{10} and $PM_{2.5}$ concentrations

This Figure shows that the mean values of both PM_{10} and $PM_{2.5}$ reached peaks in February–July, when wind speeds were also the highest, which is consistent with Draxler et al. (2001) and also identified by other investigators (Badarinatha et al., 2010; Querol et al., 2009).

Being an enclosed area, the Middle East is easily affected by dust storms from two sources: the Sahara desert in Africa and the Arabian Desert in Asia. In Lebanon, dust events that carry great quantities of sand and dust from the deserts, usually occur in March and April, but occasionally, they can occur into July.

The relationship between PM_{10} and $PM_{2.5}$ concentrations was analyzed in terms of linear regression and the result revealed that the coefficient of determination (r^2) was relatively high (r^2=0.83), as shown in the inset of Fig. 3. This is expected, because both fine and coarse particles are associated with local traffic.

3.4. PM ratios

Fig. 4 shows the trend in the monthly average of the $PM_{2.5}/PM_{10}$ ratio. This ratio shows the variability of the data, which has a range of 0.45–0.7. The monthly variability in the data suggests that the contributions of fine and coarse particles are derived from different sources. A gradual decrease can be observed in the value of the $PM_{2.5}/PM_{10}$ ratio from September to December, but the mean for the entire study period is 0.61 ± 0.12. This average indicates that in Beirut, $PM_{2.5}$ comprises about 61% of PM_{10}, revealing that the fine particles, which have greater effect of human health, constitute a large fraction of PM_{10}. This finding is similar to that of many other studies. For example, Aldabe et al. (2011), Gerasopoulos et al. (2007), He et al. (2001), and Ye et al. (2003) have reported mean $PM_{2.5}/PM_{10}$ ratios of 0.64, 0.55, 0.63, and 0.63, respectively, for their entire study periods. However, the average $PM_{2.5}/PM_{10}$ ratios observed by Khodeir et al. (2012), Shahsavania et al. (2012), and Saliba et al. (2010) are much lower than those found in the present study.

The primary reason for this difference is that, unlike our study, the pollutants in these other studies were not measured continuously. Thus, the $PM_{2.5}/PM_{10}$ ratios calculated for the entire year include spring and summer. During these seasons, the fine fraction of PM (*i.e.*, $PM_{2.5}$) is highest because various sources release fine particulates primarily during these seasons; therefore, this produces an increase in the $PM_{2.5}/PM_{10}$ ratio.

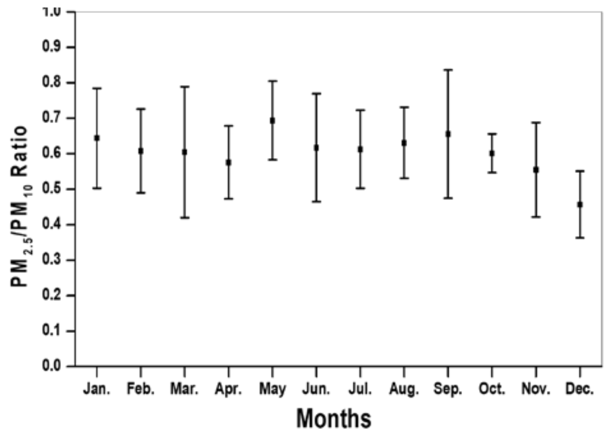


Fig. 4. Monthly $PM_{2.5}/PM_{10}$ ratios during the study period in Beirut

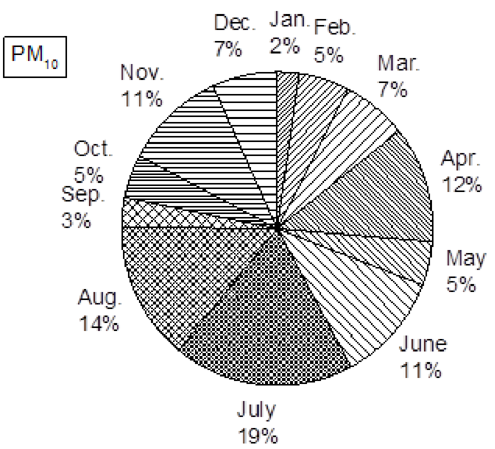
3.5. Statistical analysis of exceedance of the WHO air-quality standard

The daily mean PM_{10} and $PM_{2.5}$ WHO air-quality standards are 50 and 25 $\mu g.m^{-3}$, respectively, and are not to be exceeded on more than 3 days per year. Fig. 5 illustrates the percentage of days exceeding these standards for PM_{10} and $PM_{2.5}$ during the different months of the study period. For PM_{10}, the greatest number of exceedance days (25 days) occurred in July (25 days) followed by August (19 days) and April (16 days). There were 133 days during the observation period on which daily concentrations of PM_{10} exceeded the upper threshold limit, which represents 39% of the sampling period (133 out of 343). For $PM_{2.5}$, the greatest number of exceedance days occurred in April (19 days) followed by May, March, and June (all 16 days). There were 129 days during the observation period on which daily concentrations of $PM_{2.5}$ exceeded the upper threshold limit, which represents 38% of the sampling period (129 out of 343). The highest daily averages of the PM_{10} and $PM_{2.5}$ concentration were observed during spring and summer (March to July). These findings indicate the role played by dust events within this area (Kutiel and Furman, 2003).

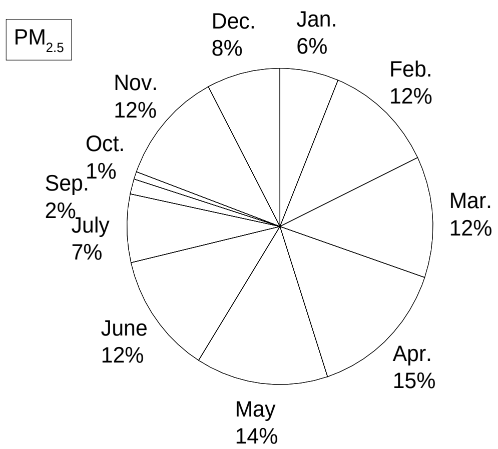
3.6. Relationships between PM and other pollutants

Studies have shown that PM causes greater adverse effects when associated with SO_2, NO_2, CO, and O_3 (*e.g.*, Cheng et al., 1998; Dockery et al., 1993). Gaseous pollutants (except ozone) are associated mostly with local sources, including exhaust emissions, domestic heating during the cold season, and industrial activities. To establish the association between PM and traffic-related gaseous pollutants, data from the HUV site were considered. Simultaneous measurements of NO_2 and O_3 were conducted at the same monitoring site to achieve this objective, and Fig. 6 summarizes the monthly average concentrations of all the gaseous species obtained during the study period. The main source of the high concentration of NO_2 is largely the high volumes of vehicular traffic in Beirut (Afif et al., 2009).

Concentrations of PM_{10}, $PM_{2.5}$, and $PM_{10-2.5}$ were correlated with NO_2 and O_3 measured at the same monitoring site. The most significant correlation was found for $PM_{2.5}$ with NO_2 ($r = 0.7$), whereas PM_{10} and $PM_{10-2.5}$ were found not to be associated with any gaseous pollutant. Strong associations between fine particle mass concentrations and primary gaseous pollutants have been reported previously reported following air-quality surveys in Birmingham, UK, suggesting the importance of road traffic-related emissions (Harrison et al., 1997). The contribution to levels of PM_{10} and $PM_{2.5}$ from vehicular exhausts was estimated using regression analysis (Table 2). NO_2 was used as a vehicular emission tracer because it is assumed that NO_2 is almost entirely attributable to emissions from road traffic.



(a)



(b)

Fig. 5. Percentage of exceedance days for PM_{10} and $PM_{2.5}$ concentrations during the different months of the study period: (a); (b)

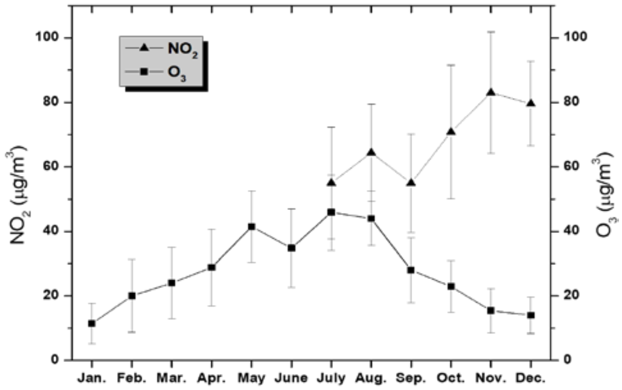


Fig. 6. Monthly average concentrations of O_3 and NO_2 during the study period at the HUV site

Table 2. Regression analysis between PM and NO_2

	Regression relationship	*r*
PM_{10}	$[PM_{10}] = 29 + 0.28\ [NO_2]$	0.39
$PM_{2.5}$	$[PM_{2.5}] = 2.2 + 0.23\ [NO_2]$	0.70
$PM_{10-2.5}$	$[PM_{10-2.5}] = 11.5 + 0.16\ [NO_2]$	0.24

For $PM_{2.5}$, a very small value of the intercept was found (2.2 μg.m^{-3}) for the background together with 28.1 μg.m^{-3} (mean–intercept) of vehicular-derived material, whereas for PM_{10}, the background concentration was 29 μg.m^{-3} with a value of 22.3 μg.m^{-3} representing the traffic-derived material. These results suggest that, on average, 93% of $PM_{2.5}$ and 43% of PM_{10} particle mass concentrations are contributed by the transported pollution of road traffic exhaust from the city.

5. Conclusions

Sampling of PM_{10} and $PM_{2.5}$ was conducted during the period January through December 2012 in Beirut. To the best of our knowledge, this represents the longest record of simultaneous PM_{10} and $PM_{2.5}$ measurements in Beirut. The daily average concentrations of PM_{10} and $PM_{2.5}$ were 51.3 ± 33.1 and 30.3 ± 19.4 μg.m^{-3}, respectively, with corresponding maximum values of 359.7 and 208.6 μg.m^{-3}. The mean concentration of coarse particles ($PM_{10–2.5}$) was found to be 41% of the average PM_{10}, suggesting that the site was influenced by re-suspended surface dust and soil. The annual average concentrations of PM_{10} and $PM_{2.5}$ exceeded the WHO standards (*i.e.*, 20 μg.m^{-3} for PM_{10} and 10 μg.m^{-3} for $PM_{2.5}$) by 150% and 200%, respectively. The mean $PM_{2.5}/PM_{10}$ ratio for the entire study period was 0.61 ± 0.12, indicating that in Beirut, about 61% of PM_{10} comprises $PM_{2.5}$. Such a large fraction of fine particles could have considerable effect on health.

The highest daily averages of PM_{10} and $PM_{2.5}$ were observed in spring and summer (March to July), indicating the important role dust events play within this area. The correlation between PM and NO_2 indicated that vehicular exhaust emissions contribute an average of 93% of $PM_{2.5}$ and 43% of PM_{10} with the remainder derived from other sources. The present study demonstrated the scale and importance of high concentrations of PM.

Therefore, we have initiated the collection of data on health outcomes from seven hospitals in Beirut (80% of hospital beds) to correlate them with air-pollution indicators. This study comprises the framework of the Beirut Air Pollution and Health Effects (BAPHE) project. The outcome of this study is expected to provide compelling evidence for policy makers and local authorities regarding the necessity for the design and implementation of appropriate air-quality control measures in Lebanon.

Acknowledgments

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