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Size-Fractionated Number and Mass Concentrations in the Urban Background Atmosphere during Spring 2014 in Amman – Jordan

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Abstract: The number size distribution of urban aerosols was never measured in Amman, Jordan. In this study, we aim at investigating the mean number size distribution (optical diameter 0.3–10 µm) and size-fractionated particle number and mass concentrations during spring 2014 in the urban background atmosphere of Amman, Jordan. The overall mean particle number concentration of coarse particles (PN_{10-1}) was 1.8±2.9 cm^{-3} and the corresponding mass concentration PM_{10-1} was 22.1±44.3 µg/m^3. The overall mean submicron particle number concentration ($PN_{1-0.01}$) was 26800±12800 cm^{-3} and the corresponding mass concentration $PM_{1-0.01}$ was 4.7±1.9 µg/m^3. The calculated 24-hour PM_{10} concentrations were 3.7–126.4 µg/m^3. According to the Jordanian 24-hour PM_{10} concentrations limit value (120 µg/m^3), there was only one exceedance that observed on April 16th. The mean particle number size distribution during that period was characterized by three main lognormal modes: ultrafine, accumulation and coarse modes. The geometric mean diameters (D_{pg}) were 0.05 µm, 0.125 µm and 1.7 µm, respectively for the ultrafine mode, accumulation mode and coarse mode. The corresponding mode number concentrations were 12000 cm^{-3}, 300 cm^{-3} and 2.6 cm^{-3}.
Keywords: *Particle distribution, Multi-lognormal fitting, Portable aerosol instruments.*

Introduction

Urban aerosols have a complex dynamic behavior, because they are a mixture of regionally transported aerosols and a wide range of locally emitted aerosols [1]. Besides being externally mixed, their composition can vary depending on the source type, geographical region and state of development and dynamic processes involved in their transformation. Urban aerosols do not only impact the local air quality (e.g. loss of visibility), but they also have a large spatial-scale effect, because they are likely transported over large distances, where they affect air quality and climate. Exposure to urban aerosols might lead to serious health effects [2–5]. As stated by the WHO, health effects of urban aerosols are usually assessed by monitoring exposure to certain particulate matter classes (such as PM_{10} and $PM_{2.5}$), in addition to some gaseous pollutants (such as carbon oxides, nitrogen oxides, … etc.).

The aerosol research in the Middle East and North Africa (MENA) region has been limited to PM concentrations, some gaseous pollutants, elemental and chemical analysis, long-range transport, mineral dust and dust episodes and optical depth [6–48]. Studies focused on particle number concentrations and particle number size distributions are very rare in the MENA region [49, 50]. It is worth to mention two studies that presented an Enhanced Particulate Matter Surveillance Program; this program aimed at providing scientifically founded information on the physical and chemical properties of dust collected during a period of approximately 1 year in Djibouti, Afghanistan, Qatar, United Arab Emirates, Iraq and Kuwait [51, 52]. It was shown that air quality of coastal regions in North Egypt is affected by the flow bringing long-range transported anthropogenic air pollution from Europe towards North Africa as well as the flow of desert dust from North Africa towards Europe [53].

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According to our knowledge, there are less than ten articles published about PM, some gaseous pollutants and limited chemical analysis in Jordan [54–61]. For instance, Al-Momani *et al.* [56] and Gharaibeh *et al.* [57] focused on heavy metals and elemental analysis of aerosol samples in Al-Hashimya and Irbid, respectively. Soleiman *et al.* [61] indicated that high ozone concentrations in Jordan are due to transboundary transport of ozone precursors from East Mediterranean coast into Jordan. Hamasha and Arnott [58] reported black carbon concentrations at six sites in Irbid city. Abu Allaban *et al.* [55] focused on dust re-suspension from limestone quarries nearby a town located north east of Amman and reported PM_{10} concentrations as high as 600 μg/m^3 with most of the airborne PM in the coarse fraction. However, there are only two studies which focused on fine particle number concentrations in Jordan, specifically in Amman city [62, 63].

The main objective of this study is to present, for the first time, the size-fractionated particle number and mass concentrations in Amman during the spring season of the year 2014. We also presented, for the first time, the mean particle number size distribution by merging two aerosol data-sets: (1) submicron particle number concentration and (2) particle number size distributions (diameter 0.3–10 μm).

Materials and Methods

Site Description

The campus of the University of Jordan [32.0129N, 35.8738E] is situated in the northern part of Amman, Jordan. It is about 10 km far from the city center (Fig. 1a). The campus is surrounded by a populated residential area with a small road network. One of the main highways is parallel to the western side of the campus. The main source of air pollution at this site is traffic emissions and small scale combustion processes from restaurants in and around the campus. The Department of Physics, where the aerosol measurements took place, is located in the middle of the campus (Fig. 1b).

Aerosol Measurement

The aerosol measurement was performed with an Optical Particle Counter (OPS, TSI model 3330) and a portable Condensation Particle Counter (CPC, TSI model 3007). The OPS was located inside a laboratory in the second floor, whereas the CPC was located inside an office in the first floor. The aerosol inlets of both instruments were led through the windows to sample the outdoor air from the southern side of the Department of Physics (Fig. 1c). The height from the ground of the sampling inlet used for the OPS was about 10 meters, whereas that for the CPC was about 5 meters. Both instruments were calibrated prior to the measurement campaign.

The OPS measurement was conducted continuously during March 6 – April 30, 2014. The OPS 3330 measures the particle number size distribution (optical diameter 0.3–10 μm, 13 size-bins). The OPS was set to measure the particle number size distributions with the dead-time correction applied. The sampling time resolution and flow rate were 5 minutes and 1 L/min, respectively. A diffusion drier was used in the aerosol tubing of the OPS. The penetration efficiency through the tubing and the diffusion drier was experimentally determined.

The CPC measurement was conducted in two parts: March 6–17 and April 14–30, 2014. The instrument was operating somewhere else during March 18 – April 13. The CPC 3007 is capable of recording the submicron particle number concentration in the diameter range 0.01–1 μm. We operated the CPC with a 5-minute averaging time resolution. The sampling inlet was about 1 meter copper tube (4 mm inner diameter). The use of a short sampling line would have minimal effects on the nominal flow rate, cut-off size and particle losses. The penetration efficiency through the tubing was experimentally determined.

Weather Conditions

We obtained the weather data from the Jordan Meteorological Department (JMD). It was recorded at Amman Civil Airport, which is located in Marka about 11.5 km south-east of the University of Jordan campus. The weather data base included hourly averages of the ambient temperature, relative humidity, wind direction and speed, precipitation and pressure.

During the measurement campaign, the wind speed was as high as 11.6 m/s (median ~2.7 m/s and average ~3 m/s). The prevailing wind direction was mainly between -135^o and +45^o. The median value of the temperature was ~18.3 ºC (maximum value did not exceed 33 ºC and minimum value was as low as 4 ºC). The relative humidity varied between 7% and 91% (average ~40% and median ~36%). The mean pressure was around 925 mbar.

FIG. 1. (a) A map of Amman showing the campus of the University of Jordan (shaded), (b) the campus of the University of Jordan and (c) the sampling site at the Department of Physics.

Data Handling

The aerosol data-base in this study consisted of: (1) submicron particle number concentrations in the diameter range 0.01–1 µm and (2) particle number size distributions (0.3–10 µm, 13 size-bins). The aerosol data-base was first corrected for tubing particle losses. Then, we processed it to calculate hourly averages. We merged the particle number size distributions (0.3–10 µm, 13 size-bins) and the submicron particle number concentrations (0.01–1 µm) to form a particle number size distribution in the particle diameter range 0.01–10 µm. In that sense, we created an additional particle size-bin (0.01–0.3) µm with an assumed geometric mean particle diameter set at 0.06 µm. The number concentration in that particle size-bin (0.01–0.3 µm) was obtained as follows:

$$PN_{0.3-0.01} = PN_{1-0.01} - PN_{1-0.3} \quad (1)$$

where $PN_{1-0.01}$ is the particle number concentration measured with the CPC and $N_{1-0.3}$ is the particle number concentration in the particle diameter range 0.3–1 µm measured with the OPS, which is calculated by integrating the particle number size distribution in that particle diameter range:

$$PN_{1-0.3} = \int_{0.3}^{1} n_N^0 \, d\log_{10}(D_p) \quad (2)$$

where $n_N^0 = dN/d\log_{10}(D_p)$ is the particle number size distribution and D_p is the particle diameter.

The particulate mass concentrations can be also calculated by assuming spherical particles and integrating the particle number size distribution as follows:

$$PM_{D_{p2}-D_{p1}} = \int_{D_{p1}}^{D_{p2}} \frac{\pi}{6} D_p^3 \rho_p n_N^0 d\log_{10}(D_p) \quad (3)$$

where ρ_p is the particle density. In this article, we summed spherical particles with unit density.

Multi-lognormal Fitting

The particle number size distribution $dN/dlog(D_p)$ can be mathematically described with the multi-lognormal distribution function [64, 65], which is the sum of several log-normal modes,

$$\left.\begin{aligned}\frac{dN}{d\log_{10}(D_p)} = \sum_{i=1}^{m} \frac{N_i}{\sqrt{2\pi}\log_{10}(\sigma_{g,i})} \times \\ \exp\left(-\frac{1}{2}\left[\frac{\log_{10}(D_p/D_{pg,i})}{\log_{10}(\sigma_{g,i})}\right]^2\right)\end{aligned}\right\} \quad (4)$$

where the left hand side is the normalized particle number concentration, i is an index for mode number with a number concentration N_i, a geometric mean diameter $D_{pg,i}$ and a standard deviation $\sigma_{p,i}$.

We used Eq. (4) to fit the particle number size distribution by assuming three main modes: an ultrafine mode, an accumulation mode and a coarse mode. In general, and as assumed by Hussein et al. [66], the fine particles can have three main modes (i.e., the ultrafine mode consists of a nucleation mode and an Aitken mode). In this study, we can't assume anything about these two ultrafine modes, because the first particle size-bin spans over the range 0.01–0.3 µm. In general, it is sometimes enough to a single mode for ultrafine particles (e.g. Whitby, 1978).

Results and Discussion

Average Concentrations

The instruments used in this study provide particle number size distribution (optical diameter 0.3–10 µm) measured with the OPS and submicron particle number concentration (diameter 0.01–1 µm) measured with the CPC (Figs. 2 and 3). Based on the hourly averaged data-base, the mean number concentration of particles in the diameter range 0.3–10 µm (i.e., $PN_{10-0.3}$) was about 41.1±25.9 cm^{-3} (median value ~35.7 cm^{-3}) with a maximum as high as 204 cm^{-3} (Fig. 2a). The corresponding particle mass concentration was about 23.6±44.7 µg/m^3 (median ~11.0 µg/m^3) with a maximum of about 907.1 µg/m^3 (Fig. 2b). It is important to mention here that the maximum $PN_{10-0.3}$ and $PM_{10-0.3}$ were not observed at the same time. For instance, the maximum $PN_{10-0.3}$ was observed during the nighttime on March 25, whereas the maximum $PM_{10-0.3}$ was observed during the morning on April 20.

The interesting part here is to consider the concentrations for micron and submicron particles separately (Fig. 4). The overall mean number concentration of coarse particles (PN_{10-1}) was about 1.8±2.9 cm^{-3} (median value ~0.9 cm^{-3}) with a maximum as high as 41.3 cm^{-3} (Fig. 4a). The corresponding mass concentration PM_{10-1} was about 22.1±44.3 µg/m^3 (median value 9.7 µg/m^3) with a maximum as high as 903.9 µg/m^3 (Fig. 4b).

The overall mean submicron particle number concentration ($PN_{1-0.01}$) was about 26800±12800 cm^{-3} (median ~26100 cm^{-3}) and the maximum as high as 89500 cm^{-3}, which was recorded on March 16 (Fig. 4a). The corresponding mass concentration $PM_{1-0.01}$ was about 4.7±1.9 µg/m^3 (median value 4.6 µg/m^3) with a maximum as high as 13.9 µg/m^3 (Fig. 4b). We could also give an estimate for the 24-hour PM_{10} concentrations. In total, we had 29 days for that (March 6–17 and April 14–30). The 24-hour PM_{10} concentrations varied between 3.7 µg/m^3 and 126.4 µg/m^3. According to the Jordanian 24-hour PM_{10} concentrations limit value (120 µg/m^3), there was only one exceedance which was on April 16th. Based on the hourly average, the PM_{10} concentrations were 0.6–465.5 µg/m^3 (average 36.2±46.5 µg/m^3 and median 22.6 µg/m^3).

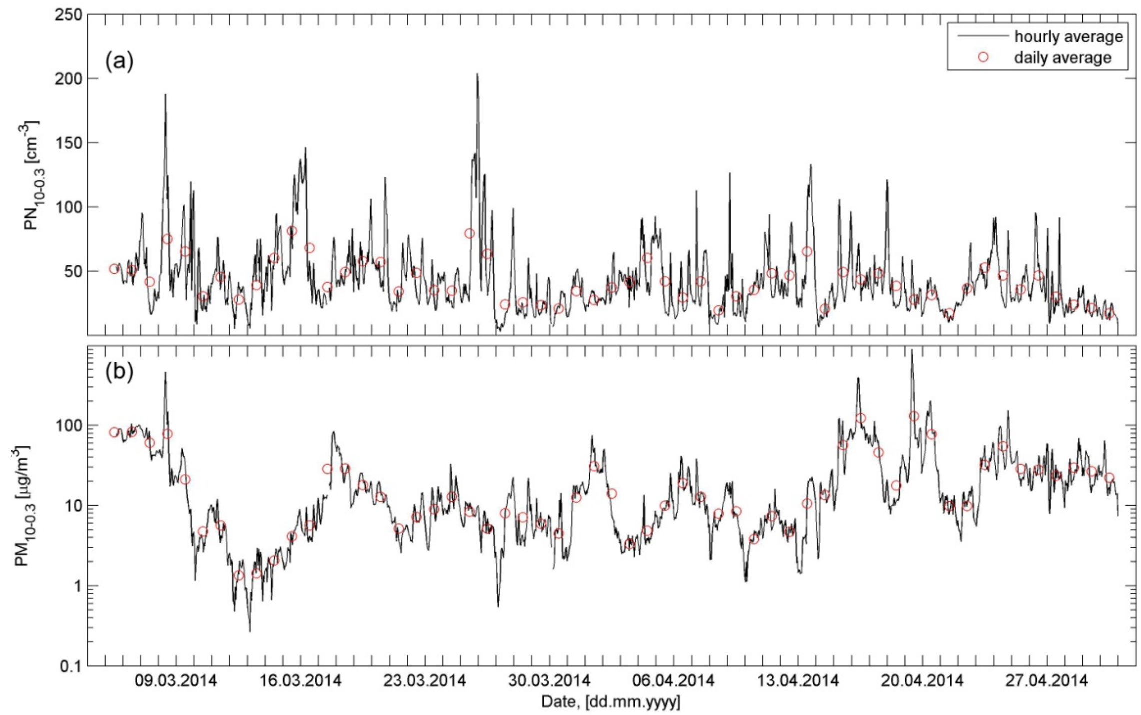

FIG. 2. Aerosol particle concentrations in the diameter range 0.3–10 µm measured with the Optical Particle Counter (a) number concentration and (b) mass concentration calculated by assuming spherical particles with unit density.

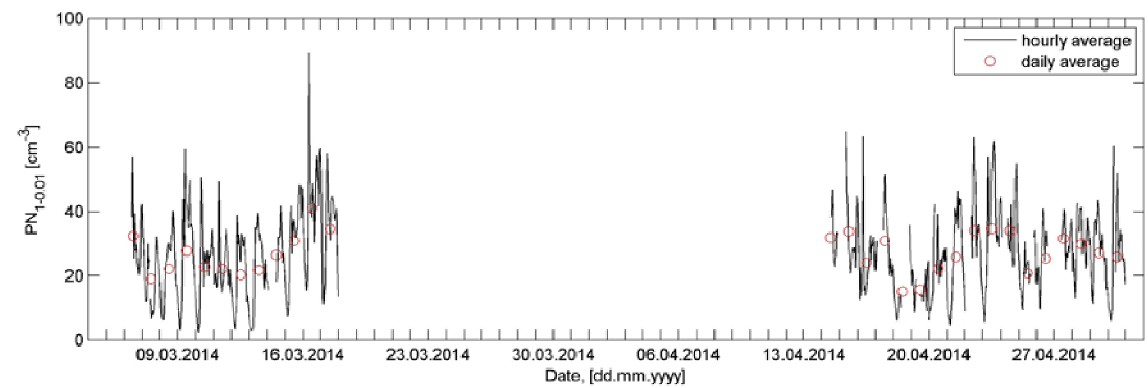

FIG. 3. Submicron particle number concentrations measured with the Condensation Particle Counter.

Average Particle Number Size Distribution

As explained before in the data handling section, we can generate the particle number size distribution by adding an additional particle size bin for particles in the diameter range 10–300 nm. The appropriate geometric mean diameter for this particle size bin is 60 nm. This is based on urban particle number size distributions measured elsewhere (e.g. Hussein *et al.*, 2004). The overall mean particle number size distribution is shown in Fig. 5 and the corresponding particle mass distribution is shown in Fig. 6.

As described in the multi-lognormal fitting section, we performed the multi-lognormal fitting according to Hussein et al. (2005) by assuming three major modes: ultrafine, accumulation and coarse modes. The multi-lognormal fitting was also performed for the particle surface area and mass distributions as an additional control check on the fitting quality. With the particle size resolution, we can’t assume more than two fine particle modes (i.e., ultrafine mode and accumulation mode). Usually, the ultrafine particles have two main modes: nucleation mode and Aitken mode.

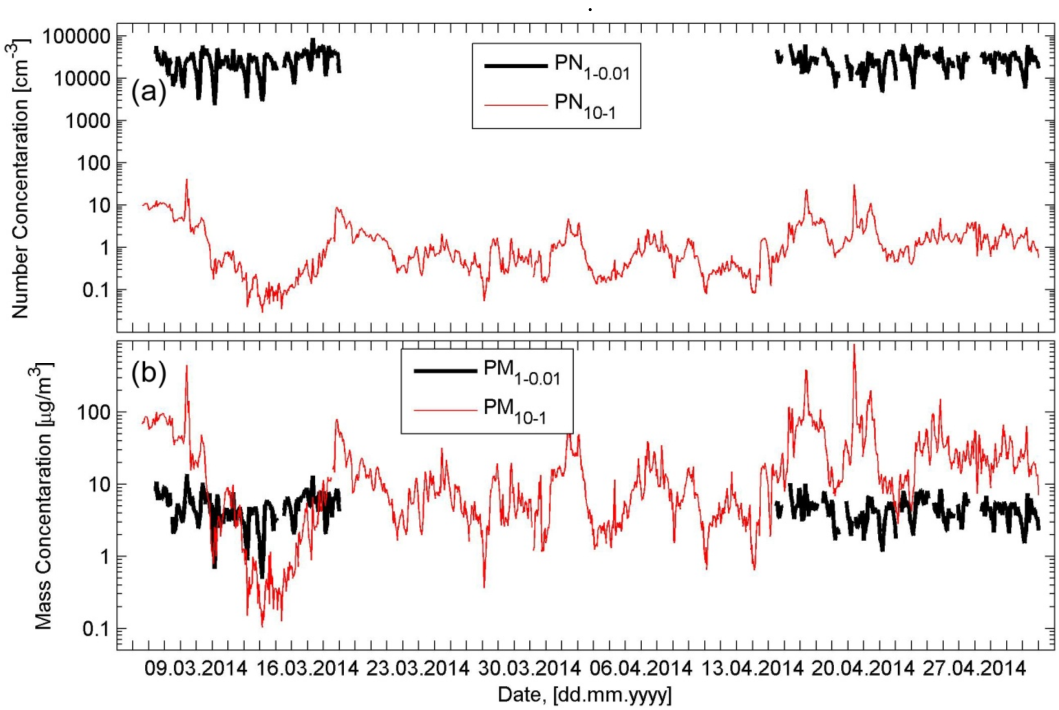

FIG. 4. Aerosol particle concentrations in two main fractions (submicron and coarse): (a) number concentrations and (b) mass concentrations.

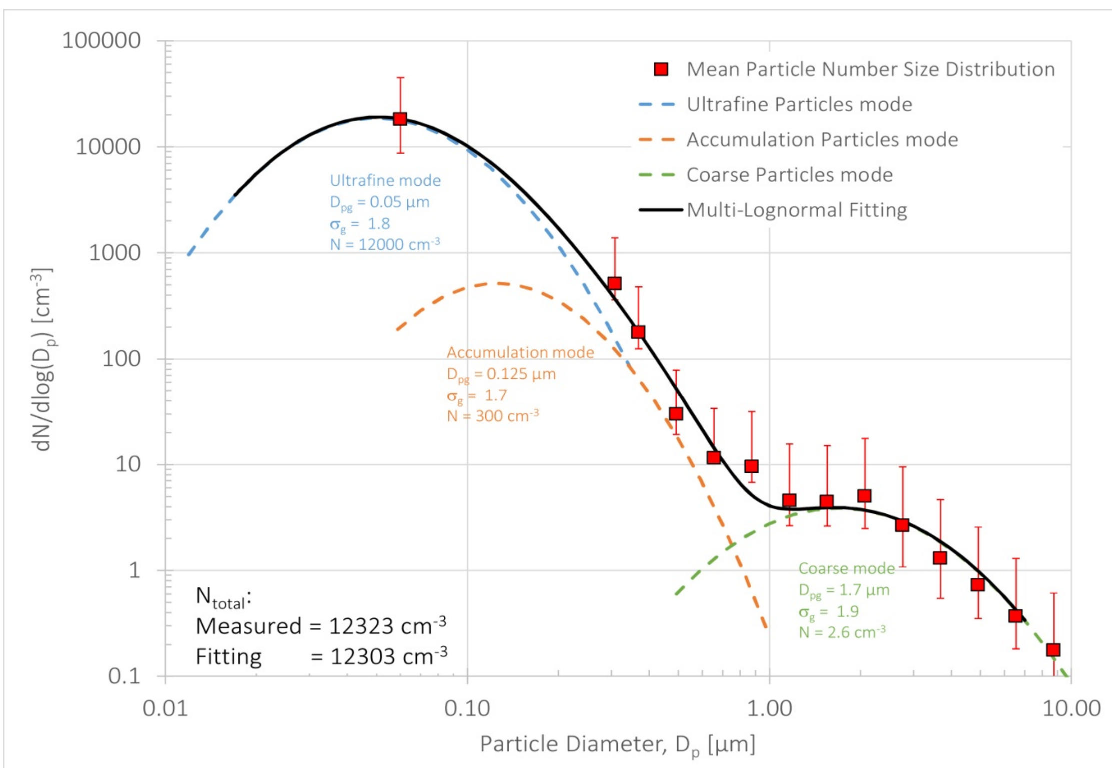

FIG. 5. Average particle number size distribution and its multi-lognormal fitting showing the modal structure. The particle number size distribution was obtained by merging the Optical Particle Counter (OPS) and the Condensation Particle Counter (CPC) data-sets.

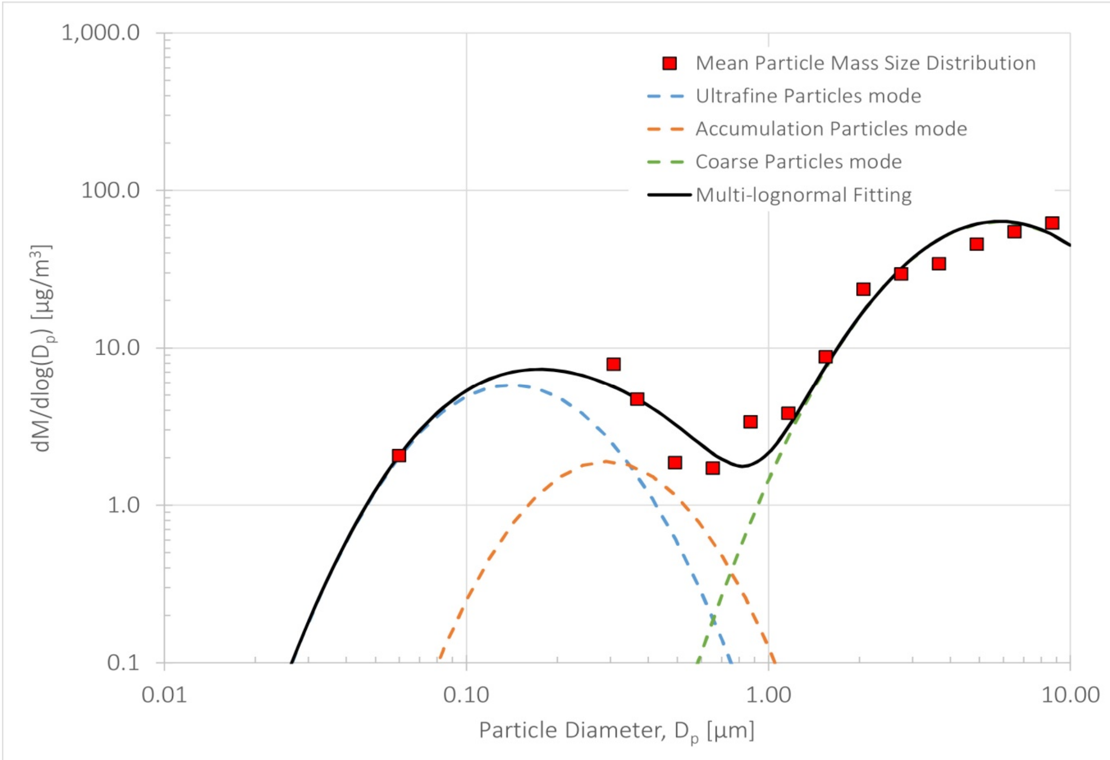

FIG. 6. Average particle mass distribution converted from the average particle number size distribution (Fig. 5) by assuming spherical particles with unit density.

According to the best multi-lognormal fitting, the mode geometric mean diameters (D_{pg}) were about 0.05 µm, 0.125 µm and 1.7 µm for the ultrafine mode, accumulation mode and coarse mode; respectively. The corresponding mode number concentrations were 12000 cm^{-3}, 300 cm^{-3} and 2.6 cm^{-3}. The difference in the total number concentration between the fitting and the measurement was very small (Fig. 5).

Conclusions

Most of the aerosol research in Jordan was focused on particulate matter concentration (PM), some gaseous pollutants and limited chemical analysis. In general, the aerosol research on particle number concentrations and particle size distributions has not been given enough attention in the Middle East and North Africa (MENA) region. Therefore, we defined the main objectives of this study to present the size-fractionated particle number and mass concentrations in Amman during the Spring season of 2014. We also presented, for the first time, the mean particle number size distribution by merging two aerosol data-sets: (1) submicron particle number concentration and (2) particle number size distributions (diameter 0.3–10 µm).

In this study, we measured the particle number size distributions (optical diameter 0.3–10 µm) and utilized submicron particle number concentrations investigated in one of our previous studies (Hussein *et al.*, 2015). We calculated the size-fractionated particle number concentrations in two main ranges: submicron (diameter 0.01–1 µm) and coarse (diameter 1–10 µm). We also derived the particle number size distributions by merging the measured size distribution data-set (0.3–10 µm) with the submicron particle concentration data-set. We also calculated the corresponding particle mass size distribution by assuming spherical particles with unit density. This also enabled us to obtain the size-fractionated mass concentrations in the above-mentioned particle diameter ranges (i.e., submicron and coarse).

The overall mean particle number concentration of coarse particles (PN_{10-1}) was 1.8±2.9 cm^{-3} with a median value ~0.9 cm^{-3} and a maximum as high as 41.3 cm^{-3}. The corresponding mean mass concentration (PM_{10-1}) was 22.1±44.3 µg/m^3 (median ~9.7 µg/m^3 and maximum 903.9 µg/m^3). The overall mean submicron particle number concentration ($PN_{1\text{-}0.01}$) was 26800±12800 cm^{-3} with a median value ~26100 cm^{-3} and a maximum as high as 89500 cm^{-3}. The corresponding mean particle mass concentration ($PM_{1\text{-}0.01}$) was 4.7±1.9 µg/m^3 (median ~4.6 µg/m^3 and maximum 13.9 µg/m^3).

We also calculated the PM_{10} concentrations. Based on the hourly average, the PM_{10} concentrations were 0.6–465.5 µg/m^3 (average 36.2±46.5 µg/m^3 and median 22.6 µg/m^3). The 24-hour PM_{10} concentrations were 3.7–126.4 µg/m^3. According to the Jordanian concentrations limit value 24-hour PM_{10} (120 µg/m^3), there was only one exceedance that was observed on April 16th.

The mean particle number size distribution in the diameter range 0.01–10 µm was characterized by three main lognormal modes: ultrafine, accumulation and coarse modes. The geometric mean diameters (D_{pg}) were 0.05 µm, 0.125 µm and 1.7 µm, respectively for the ultrafine mode, accumulation mode and coarse mode. The mode number concentrations were 12000 cm^{-3}, 300 cm^{-3} and 2.6 cm^{-3}; respectively.

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