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Mobile Aerosol Measurement in the Eastern Mediterranean – A Utilization of Portable Instruments

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ABSTRACT

Air pollution research and reports have been limited in the Middle East, especially in Jordan with respect to aerosol particle number concentrations. In this study, we utilized a simple "mobile setup" to measure, for the first time, the spatial variation of aerosol concentrations in Eastern Mediterranean. The mobile setup consisted of portable aerosol instruments to measure particle number concentrations (cut off sizes 0.01, 0.02, 0.3, 0.5, 1, 2.5, 5, and 10 μm), particle mass concentrations (PM_1, $PM_{2.5}$, and PM_{10}), and black carbon concentration all situated on the back seat of a sedan car. The car was driven with open windows to ensure sufficient cabin air ventilation for reliable outdoor aerosol sampling. Although the measurement campaign was two days long, but it provided preliminary information about aerosols concentrations over a large spatial scale that covered more than three quarters of Jordan. We should keep in mind that the presented concentrations reflect on road conditions. The submicron particle concentrations were the highest in the urban locations (e.g., Amman and Zarqa) and inside cities with heavy duty vehicles activities (e.g., Azraq). The highest micron particle concentrations were observed in the southern part of the country and in places close to the desert area (e.g., Wadi Rum and Wadi Araba). The average submicron concentration was $4.9 \times 10^3 – 120 \times 10^3$ cm^{-3} (5.7–86.7 μg m^{-3}) whereas the average micron particle concentration was 1–11 cm^{-3} (8–150 μg m^{-3}, assume ρ_p = 1 g cm^{-3}). The main road passing through Jafr in the eastern part of Jordan exhibited submicron concentration as low as 800 cm^{-3}. The PM_{10} concentration consisted of about 40–75% as PM_1. The black carbon (BC) concentration variation was in good agreement with the PM_1 as well as the submicron particle number concentration.

Keywords: Particulate matter; Particle number; Black carbon; Urban aerosols; On-street aerosols sampling.

INTRODUCTION

Urban aerosols have a complex dynamic behavior depending on source characteristics and interaction with other material or with the environment itself. For example, they are a mixture between regionally transported and locally emitted particulate matter (e.g., Hussein *et al.*, 2014b). Urban aerosols do not only have impacts on local air quality, but they also have large spatial effects because they are likely transported over large distances where they affect the air quality and the climate. Furthermore, exposure to air pollution might lead to serious health effects (e.g., Samet *et al.*, 2000; Pope *et al.*, 2002; Curtis *et al.*, 2006). As stated by the WHO, the 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.).

In the Middle East and North Africa (MENA), the atmospheric research has not been given enough attention. So far, the aerosol research has been focused on aerosol optical properties (Elminir, 2005; El-Metwally and Alfaro 2013), airborne dust (monitoring, source region, and transport) (Satheesh *et al.*, 2006; El-Askary and Kafatos, 2008; Reid *et al.*, 2008; El-Askary *et al.*, 2009; Dada *et al.*, 2013; Alam *et al.*, 2014; Gherboudj and Ghedira, 2014; Saeed *et al.*, 2014; Basha *et al.*, 2015), transport of anthropogenic aerosols (e.g., Kuwait: impacts of 1991 oil fire plumes in Kuwait) (Lowenthal *et al.*, 1992; Daum *et al.*, 1993; Herring *et al.*, 1996; Rudich 2003; Tazaki *et al.*, 2004; Bonazza *et al.*, 2007), chemical analysis and gaseous pollution (Shaka' and Saliba, 2004; Kouyoumdjian and Saliba, 2006; Saliba

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et al., 2007; Mahmoud *et al.*, 2008; El-Araby *et al.*, 2011; Dobrzhinsky *et al.*, 2012; Boman *et al.*, 2013; Daher *et al.*, 2013; Engelbrecht and Jayanty, 2013; Hassan *et al.*, 2013; Waked *et al.*, 2013a, b; Jafar *et al.*, 2014; Roumie *et al.*, 2015), and particulate matter (PM) (Saliba *et al.*, 2010; Khodeir *et al.*, 2012; Habeebullah, 2013; Munir *et al.*, 2013a, b; Rushdi *et al.*, 2013; Shaltout *et al.*, 2013; Alghamdi *et al.*, 2014a, b; Hussein *et al.*, 2014a; Alghamdi *et al.*, 2015; Hamad *et al.*, 2015). However, very few studies focused on the measurement of particle number concentrations and size distributions (e.g., Tadros *et al.*, 1999; Hussein *et al.*, 2011; Moustafa *et al.*, 2015; Hussein *et al.*, 2016). It is worth to mention two studies that presented an Enhanced Particulate Matter Surveillance Program, which aimed at providing a 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 (Engelbrecht *et al.*, 2009a, b).

According to our knowledge, there are less than ten articles published about PM, some gaseous pollutants, and limited chemical analysis in Jordan (Al-Momani *et al.*, 2005; Abu Allaban *et al.*, 2006; Soleiman *et al.*, 2009; Gharaibeh *et al.*, 2010; Hamasha and Arnott, 2010; Schneidemesser *et al.*, 2010; Abdeen *et al.*, 2014). There were only two studies focused on fine particle number concentrations in Jordan, specifically in Amman and Zarqa (Hussein *et al.*, 2011, 2016; Hussein and Betar, 2017). However, the particle size-fractionated concentrations have never been considered in Jordan. Furthermore, the focus has been on the major cities but not on the major roads or small cities. Therefore, the main objective of this study is to develop a simple "mobile setup" and measure, for the first time, the spatial variation of aerosol concentrations across cities and along highways in Jordan. We utilized portable instruments to measure aerosol particle number and mass concentrations of different particle size fractions. The measurements were performed at a central location (urban background in Amman) and at the same time on a mobile setup that was driven across cities and along main roads in Jordan. Although the measurement campaign was two days long, it provided preliminary information about aerosol concentrations over a large spatial area that covered more than three quarters of the country.

MATERIALS AND METHODS

The measurement campaign was during May 30–31, 2014. We utilized portable instruments in a mobile setup to measure aerosol concentrations (number and mass) across several cities and along main international roads in Jordan (Fig. 1). In addition, we measured aerosol concentrations at a stationary location (urban background) in the capital city Amman, which we considered as a reference location.

Driving Route

The mobile measurement was started each day around 10:00 am with a routine check on the instruments and setting them up in the car. The driving started around midday. On the first day (May 30th), we started from the north eastern part of Amman and drove north passing through Zarqa towards Mafraq. Then, we turned east towards Safawi and turned south towards Azraq, where we stopped over for couple of hours resting and recharging the batteries of the portable instruments. After that we drove towards Petra after passing through Jafr and Ma'an. We arrived at Petra around midnight. The approximate distance traveled on this track was about 500 km.

On the second day (May 31st), we started from Petra and drove towards Aqaba, where we stopped over for half an hour. Then we drove north towards Amman through Wadi Araba and passed by the Dead Sea. This track was also about 500 km. We arrived at the starting point, from where we started on the previous day, in Amman. Thereby, we drove a complete loop around the country.

Aerosol Measurements

Stationary Reference Measurement – Urban Background

The aerosol measurements at the stationary site (reference, urban background), which was based in Amman, consisted of particle number size distributions measured with an Optical Particle Sizer (OPS, TSI model 3330) and a handheld optical particle counter (AeroTrak, TSI model 9306-V2). They shared the same sampling inlet that was located on the third floor of the Department of Physics, the University of Jordan. The inlet was equipped with a diffusion dryer. The campus of the University of Jordan is considered an urban background within the capital city, Amman (Hussein *et al.*, 2011, 2016).

The OPS measured the particle number size distributions (optical diameter 0.3–10 μm, divided into 16 size-bins). The OPS was set to measure the size distributions according to the "TSI default" protocol with the dead-time correction applied throughout the measurement campaign. The sampling time-resolution was 5 minute at a flow rate of 1 L min^{-1}.

The AeroTrak measured the size-specific particle number concentrations within the optical diameter range 0.3–25 μm divided into 6-channels (user defined). These channels were setup as 0.3, 0.5, 1, 2.5, 10, and 25 μm. The sampling time-resolution was 10 seconds at a flow rate of 2.83 L min^{-1}. These size-specific concentrations were then converted to 1-minute average before being used further in the analysis.

Mobile Setup

The mobile aerosol measurements consisted of two portable condensation particle counters (CPC model 3007-2 and P-Trak model 8525, TSI), a laser photometer (DustTrak DRX, TSI model 8533), a handheld optical particle counter (AeroTrak, TSI model 9306-V2), and a portable aethalometer (microAeth, AethLabs model AE51).

Besides the aerosol measurements, we used a Garmin GPS (eTrex 20) to record the speed and location of the car with 1 second time-resolution. We also monitored the temperature and relative humidity with 10 seconds time resolution (Onset Computer Co. HOBO U12-012). All instrument clocks were synchronized each day.

All instruments were situated on the back seat of a sedan car (Suzuki Kizashi, 2012) that has an overhead opening. While driving, we kept the overhead opening and the front

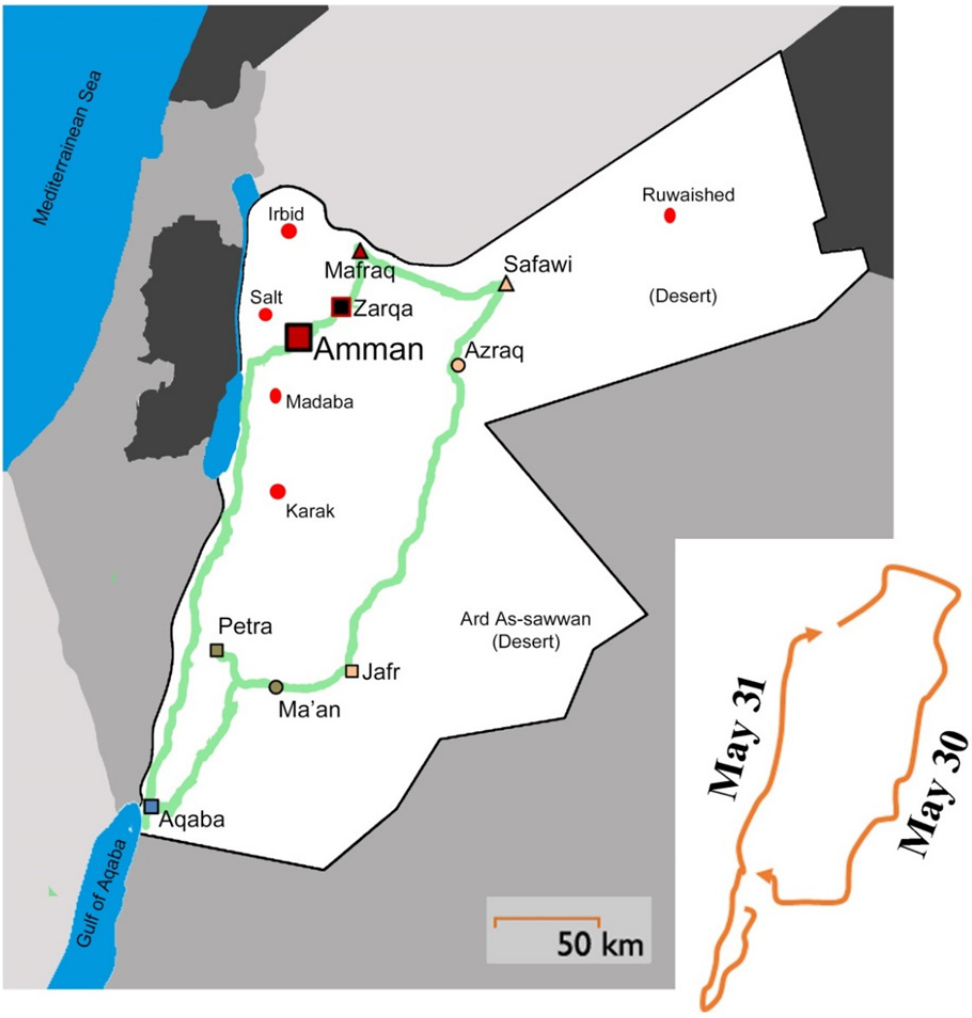

Fig. 1. Map of Jordan that shows the driving track.

windows fully opened whereas the back windows were half opened. This ensured that cabinet indoor air was fully mixed and had a high exchange rate with the outdoor air so that the aerosol measurements represent the outdoor air very well (kindly see Fig. S1). We therefore, did not need special inlets for the aerosol instruments in this simple "mobile setup".

Submicron Particle Number Concentrations

According to the manufacturer, the portable CPC 3007 has a cutoff size of 10 nm and it is capable of measuring submicron particle number concentration with diameters up to 2 µm. The maximum detectable concentration is 10^5 cm^{-3} with 20% accuracy. The sampling flow rate in this type of CPC is 0.1 L min^{-1} (inlet flow rate 0.7 L min^{-1}). We set the time-resolution to 1 second. Technically, the P-Trak 8525 is a similar particle counter with minor differences: cutoff size about 20 nm and maximum concentration 5×10^5 cm^{-3}. The P-Trak was also operated with 1 second time-resolution. The sampling flow rate in this type of P-Trak is 0.1 L min^{-1} (inlet flow rate 0.7 L min^{-1}).

We experimentally validated the cutoff size and the maximum detectable concentration in both the CPC and the P-Trak. We used silver test particles, which were evaporated in a tube furnace (Scheibel and Porstendorfer, 1983). The generated silver particles were polydisperse; therefore, we selected a certain size by utilizing a Hauke-type differential mobility analyzer after bringing them to a charge equilibrium with a radioactive source (241-Am). After the size selection, the particles were brought to a charge equilibrium again with a 63-Ni source and the charged particles were removed with an ion filter to measure instruments' response to neutral particles only. The measured cutoff diameter was found to be 9 nm and 22 nm for the CPC and the P-Trak, respectively. This agrees well with the specification provided by the manufacturer as 10 nm and 20 nm, respectively. The concentration calibration was conducted against a TSI CPC 3776 by varying the concentration of 30 nm silver particles with a diluter. The detection efficiency of the P-Trak was 73%. The maximum detectable concentration for both the portable CPC and the P-Trak was about 4×10^5 cm^{-3}.

Particle Number Size Distribution (0.3–25 µm)

The AeroTrak 9306-V2 in the mobile measurement was used with a similar setup as that used at the stationary site; TSI default channel selection: 0.3, 0.5, 1, 2.5, 10, and 25 µm.

The sampling time-resolution was 10 seconds at a flow rate of 2.83 L min^{-1}. The AeroTrak was factory-calibrated with monodisperse, polystyrene latex (PSL) spheres (TSI, Inc.).

Particulate Mass Concentrations

The DustTrak DR_X 8533 measures particulate matter (PM) mass concentrations in the diameter range of 0.1–15 μm with a maximum concentration limit of 150 mg m^{-3} (Wang *et al.*, 2009). It displays size segregated mass fractions for PM_1, $PM_{2.5}$, respirable, PM_{10}, and total. The sampling flow rate in this type of DustTrak is 3 L min^{-1}. We set the time-resolution at 10 seconds. The DustTrak's zero test was calibrated prior to beginning of each mobile track using an external HEPA filter. The DustTrak was factory-calibrated with Arizona Road Dust (ARD, ISO 12103-1, A1 Dust, Wang *et al.*, 2009). As such, differences in the optical (refractive index) and morphological properties between the ARD and the sample aerosol will affect the mass concentrations reported in this study.

Black Carbon

Black carbon (BC) concentrations were measured with a portable aethalometer (microAeth). The microAeth reports changes in light attenuation at a wavelength of 880 nm as particles are collected on a disposable filter. The sample flow rate was 0.1 L min^{-1} and a 2.5 μm size selective inlet was used. We set the time-resolution at 30 seconds. The filter was replaced each day prior to the measurements. The BC data was post processed to remove any spurious spikes in the concentration (e.g., > 1,000 μg m^{-3}) that were associated with sudden vibration of the instrument.

Aerosol Data Handling

The raw data sets were quality checked before being processed further in the analysis. As a first step in the analysis of the mobile data sets, we converted them to one-minute means. The aerosol data set obtained at the stationary site (urban background) was kept in its original time resolution (5 minutes).

Utilization of several instruments that cover a wide size range and different cutoff diameters allows us to derive particle number and mass concentrations in several size fractions. Therefore, we focused on the following size fractions: submicron particle number concentration (0.01–1 μm), particle number concentrations in three submicron size fractions (10–25 nm, 25–300 nm, and 0.3–1 μm), and micron particle number and mass concentrations (1–10 μm). It is also possible to derive the particle number size distribution in the diameter range 0.01–10 μm.

We also calculated average concentration during different time periods: (1) time periods spent when crossing over each city and (2) time periods spent on the main roads between cities. In total, we had 9 cities: Amman, Zarqa, Mafraq, Safawi, Azraq, Jafr, Ma'an, Petra, and Aqaba. As for the main streets between cities, we had 12 road sections: Amman – Zaqra (through Birayn), Zarqa – Mafraq, Mafraq – Safawi, Safawi – Azraq, Azraq – Jafr – Ma'an, Ma'an – Petra, Petra – Aqaba, Aqaba – Dead Sea, Dead Sea industrial area, and Dead Sea resorts.

Weather Conditions

The Jordan Meteorological Department (JMD) provided the weather data during the measurement campaign. The weather data used for this study was measured at the Amman Civil Airport, which is located in Marka. The airport itself is located at about 11.5 km south east of the stationary site in this study (the University of Jordan campus). While the meteorological data set included hourly averages of several weather parameters, we only picked up the ambient temperature and relative humidity to be presented in this study (Fig. S2).

The wind speed was lower than 6 m/s most of the time but it increased to values higher than 8 m/s during the afternoon of the second day. The local wind direction in Amman varied continuously on the first day, but it was western on the second day. Throughout the measurement campaign, the weather was relatively dry with RH < 35% most of the time (varied between 11 and 35%); it started to increase in the afternoon of the second day. The temperature varied between 19 and 35°C (median 27.5°C).

Both the temperature and relative humidity recorded in the mobile measurement showed a close trend to those observed in Amman. However, the recorded temperature in the mobile measurement was most of the time higher than that recorded in Amman. The relative humidity in the mobile measurement was higher than that in Amman during the first day but it was lower during the second day.

RESULTS AND DISCUSSION

Average Concentrations at the Reference Location

Number Concentrations

The number concentration for particles in the diameter range 0.3–10 μm ($PN_{10-0.3}$) measured with the OPS and the AeroTrak at the stationary reference site in Amman showed excellent agreement between each other with respect to the temporal variation (Fig. S3). However, sometimes the OPS tended to show higher $PN_{10-0.3}$ concentrations than those recorded by the AeroTrak.

According to the OPS measurement, the $PN_{10-0.3}$ was lower than 60 cm^{-3} (as low as 10 cm^{-3}) most of the time, but it increased to values higher than 100 cm^{-3} (as high as 200 cm^{-3}) during the afternoon of the second day of the measurement campaign. As for the AeroTrak measurement, the highest $PN_{10-0.3}$ concentration was about 150 cm^{-3}.

The number concentration of the micron particles (PN_{10-1}) recorded by the OPS and the AeroTrak also showed similar temporal trends (Figs. S3 and 2(a)). In fact, the $PN_{10-0.3}$ concentration was dominated by the $PN_{1-0.3}$ concentration. The differences in the number concentration values between the OPS and the AeroTrak for PN_{10-1} was rather small. According to the OPS measurement, the lowest PN_{10-1} concentration was about 1.5 cm^{-3} (before noon on the first day and late in the night of the second day) and the highest was about 10 cm^{-3} (around noon of the second day). Based on the measurement at the stationary location in Amman, Jordan received a mild dust episode starting from 19:00 on May 30th and remained for about 24 hours. The start of the episode was almost at the same time when we left Azraq

on the first day whereas the end of the episode was almost at the time when we left Aqaba on the second day.

Calculated Mass Concentrations

We calculated the PM concentration at the reference location by assuming spherical particles (ρ_p = 1 g cm^{-3}). Although the OPS showed higher particle number concentrations than those observed by the AeroTrak, the calculated particulate mass of the micron fraction (PM_{10-1}) from the AeroTrak data was higher than that calculated from the OPS particle number size distribution (Fig. 3). According to the OPS data, the PM_{10-1} was less than 80 μg m^{-3} most of the time but it peaked to about 150 μg m^{-3} (around 20:00 on the first day and around noon on the second day); see for example Fig. 3. The lowest PM_{10-1} (around 7 μg m^{-3}) was recorded around midnight of the second day.

It is obvious that the PN and PM concentrations calculated from the particle number size distribution measured with the OPS should be more reliable than that calculated from the AeroTrak data. This is mainly because the OPS recorded the particle number size distribution with 16 particle size channels (diameter, 0.3–10 μm) whereas the AeroTrak has five particle size channels within the same particle diameter range. However, the AeroTrak at the stationary site shall be taken as a reference for the AeroTrak data in the mobile measurement whereas the PM concentrations calculated from the OPS data shall be taken as a reference for the PM concentration measured with the DustTrak in the mobile measurement.

Average Concentrations across Cities and along Main Roads

We extracted the time periods when we drove across the cities and calculated the average particle number and mass concentrations for each city separately. We also averaged the concentrations along the main roads between cities. In the following sections we shall present a comparison between the measurement results by the "mobile seup" and those measured at the reference location for the same time periods. Kindly note that the results presented here about cities should be interpreted as on-street measurements; therefore, they are expected to be higher than those observed at background locations in cities.

Micron Particle Number Concentrations

Recalling the AeroTrak measurement at the reference site, the micron particle number (PN_{10-1}) concentration started to increase from about 2 cm^{-3} (before 19:00 on the first day) to about 5 cm^{-3} (around midnight). It peaked to about 10 cm^{-3} around noon on the second day and leveled at about 6 cm^{-3} until 18:00, when it decreased to about 4 cm^{-3} and remained at that concentration until 23:00. After 19:00 on the first day, Jordan received a mild dust episode that remained for about 24 hours (Fig. 2). This should be taken into consideration when comparing the concentration differences between cities, where sampling occurred during different times.

The average PN_{10-1} concentration varied considerably from a city to another (Tables S1–S2 and Fig. 2). The highest PN_{10-1} concentration was observed in Aqaba (~11 cm^{-3}, during 20:56–21:16). Ma'an was the second highest (~8 cm^{-3}, during 21:27–22:12). Azraq (during 17:16–19:21) and Petra (22:30–11:10 on first day and 15:20–15:51 on the second day) had slightly lower PN_{10-1} concentration than Ma'an: 7 cm^{-3} and 6 cm^{-3}; respectively. The high concentrations of micron particles in these cities can be partly due to the mild dust episode. In addition, the southern part of Jordan (including Ma'an, Petra, and Aqaba) are very close to the

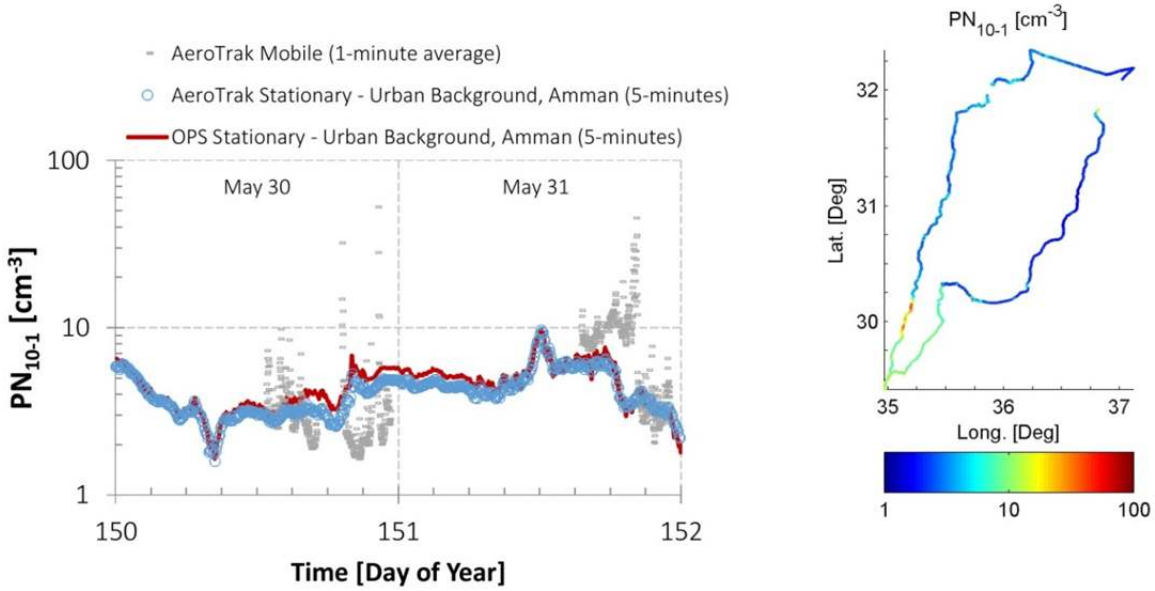

Fig. 2. Number concentrations of micron particles (diameter range 1–10 μm) measured with the OPS and the AeroTrak at the stationary site (urban background, Amman) and compared to the measured concentrations with an AeroTrak operated on the mobile setup. Both AeroTrak concentrations were averaged to 1-minute. The number concentrations were calculated by integrating the measured particle number size distribution over the measured particle size range 1–10 μm.

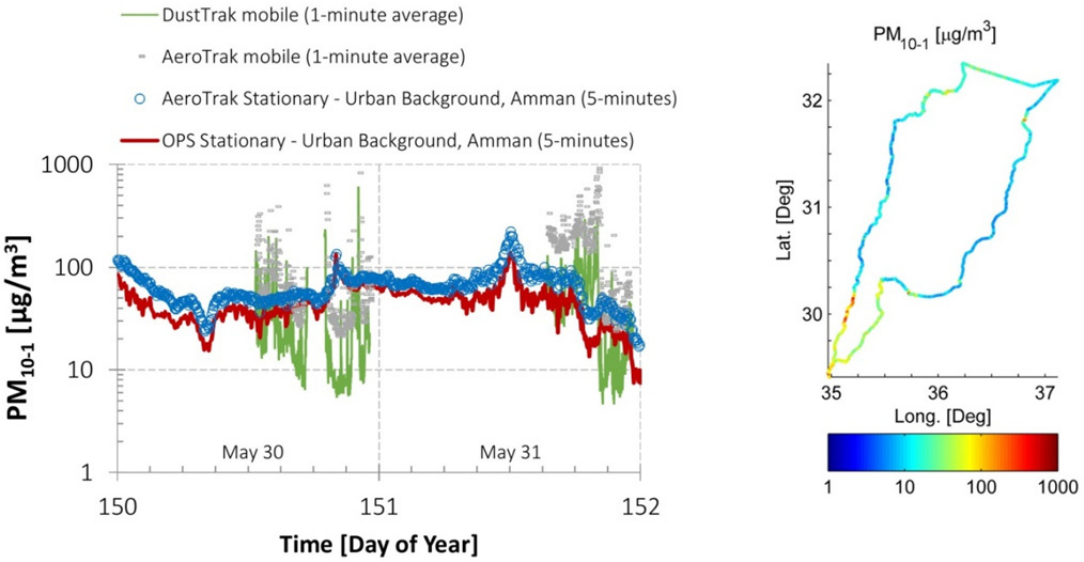

Fig. 3. Mass concentrations of micron particles (diameter range 1–10 µm) Derived from the measured particle number size distributions with the OPS and the AeroTrak at the stationary site (urban background, Amman) and compared to those measured with the Dust Trak DRX and the derived concentrations from AeroTrak measurements operated on the mobile setup.

sand desert areas, where local dust resuspension often occurs. Note that dust episode was observed in Amman starting from ~19:00 on May 30th, which was the time leaving Azraq towards Petra through Jafr and Ma'an.

Safawi (~2 cm^{-3}, during 16:30–16:44) had the lowest PN_{10-1} concentration. The second lowest was observed at Jafr (about 3 cm^{-3}, during 20:56–21:16). It might be that Jafr and Safawi should have similar PN_{10-1} concentration, but the mild dust episode could be the main reason behind the slightly higher PN_{10-1} concentration observed at Jafr. Mafraq (during 15:13–15:29), which is a bigger city than Safawi, had a slightly higher PN_{10-1} concentration than that observed at Safawi. The large cities, Amman and Zarqa, had an intermediate PN_{10-1} concentrations (about 4 cm^{-3}) when compared to the rest of cities included in this study.

The main road from Petra to Aqaba and from Aqaba to the Dead Sea had the highest PN_{10-1} concentrations (more than 8.5 cm^{-3}). Here we have to mention three important notes: (1) we drove on the road from Petra to Aqaba through Wadi Rum, which is a desert area, (2) The road from Aqaba to the Dead Sea passes through the moving sand desert (Wadi Araba), and (3) the mild dust episode was during its maximum strength during the trip from Petra to Aqaba and going out from Aqaba. These facts explain the extremely high PN_{10-1} concentrations observed on this part of the trip. Evidently, during the measurement days the moving sand desert (Wadi Araba) had higher PN_{10-1} concentrations than Wadi Rum. The PN_{10-1} concentrations were below 3.5 cm^{-3} on the rest of the driving track. For example, nearby the Dead Sea industrial facilities the PN_{10-1} concentration was about 3.4 cm^{-3} and on the road between Azraq and Jafr it was 2 cm^{-3}.

Submicron Particle Number Concentrations

The mean submicron particle number ($PN_{1-0.01}$) concentration was the lowest in Safawi (6×10^3 cm^{-3}, during 16:30–16:44); see also Table S1. Safawi was a very small city and very remote in the north eastern part of Jordan. Therefore, the traffic emissions were very small compared to the other cities considered in this study. It is worth to mention here that Azraq (~5.8×10^4 cm^{-4}, during 17:16–19:21) is considered a stop-over for lories whereas Ma'an (~6.1×10^4 cm^{-3}, during 21:27–22:12) is a busy city with heavy duty vehicles related to phosphate mining.

Mafraq (~7.1×10^4 cm^{-3}, during 15:13–15:29) is a medium size Jordanian city whereas Zarqa is the second largest city (~8.2×10^4 cm^{-3}, during 13:42–14:51) after the capital Amman (~1.2×10^5 cm^{-3}, before midnight 22:24–23:17). Although Jafr is a rather small city according to the Jordanian scale, the mean $PN_{1-0.01}$ concentration was about 3.3×10^4 cm^{-3} (during 20:56–21:16), which was slightly less than that was reported for Petra as 3.8×10^4 cm^{-3} but comparable to Aqaba (3.3×10^4 cm^{-3}, during 17:43–19:06).

As for the main roads connecting cities (Table S2), the mean $PN_{1-0.01}$ concentration was the highest nearby the Dead Sea industrial facilities (~4.4×10^4 cm^{-3}, during 20:59–21:54); during that time the main road was down wind the industrial emissions plumes and the heavy duty vehicles activity was considerably high. Although we took a remote road from Amman to Zarqa (through Birayn), the mean $PN_{1-0.01}$ concentration on that road was the second highest (3.8×10^4 cm^{-3}, during 13:11–13:40). The lowest mean $PN_{1-0.01}$ concentrations were observed along the main roads connecting Safawi, Azraq, Jafr, and Ma'an as well as the main road from Aqaba to the Dead Sea. For these roads the mean value was less than 10^4 cm^{-3}. It is interesting to mention here that the $PN_{1-0.01}$ concentration dropped to a value as low as 800 cm^{-3} on the road between Azraq and Jafr. During that time, the traffic activity was very low on that road. The rest of the main roads (Zarqa to Safawi through Mafraq,

Petra to Aqaba, and Dead Sea resorts) had some kind of intermediate mean $PN_{1\text{-}0.01}$ concentrations between 1.8×10^4 cm^{-3} and 2.1×10^4 cm^{-3}.

The complete picture about the $PN_{1\text{-}0.01}$ concentration variation along each city is shown in Figs. 4 and 5. For example, the $PN_{1\text{-}0.01}$ concentrations were the highest in the vicinity of the two largest cities Amman and Zarqa with large spatial-scale. The spatial-scale of high concentrations around the other cities is relatively small when compared to that around Amman and Zarqa. This means that the emissions in those cities are lower than those in Amman and Zarqa. In addition to that, dispersion and dilution of emissions within those cities is more efficient than that in Amman and Zarqa. Therefore, both population density and city topography might have the critical factors in accumulating anthropogenic aerosols over a city.

It is also important to mention that the $PN_{1\text{-}0.01}$ concentration is expected to vary from time to time during the day. Therefore, the concentrations presented here should be compared to the reference site during those specific time periods used to calculate the mean values. For that purpose, we recall the measurement campaign performed just before this for four sites in Amman by Hussein *et al.* (2016). According to that study, the daily pattern at an

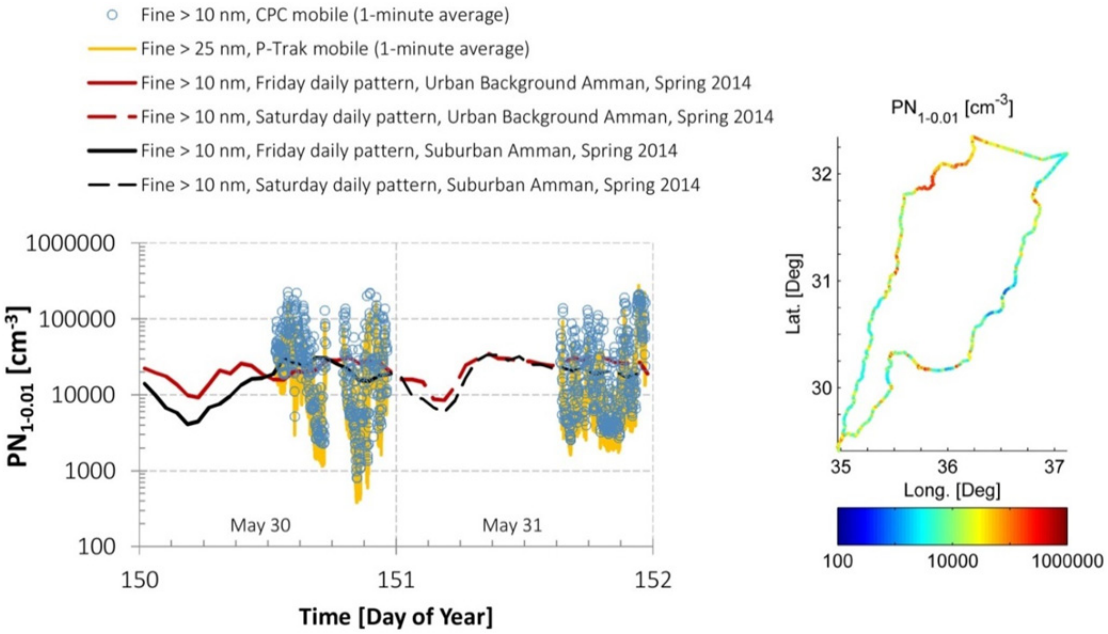

Fig. 4. Submicron particle number ($PN_{1\text{-}0.01}$) concentrations measured CPC (diameter range 0.01–1 μm) and the P-Trak (diameter range 0.025–1 μm) that were operated on the mobile setup and compared with average $PN_{1\text{-}0.01}$ concentrations (diameter range 0.01–1 μm) reported at the stationary site (urban background, Amman), which was reported previously by Hussein *et al.* (2016).

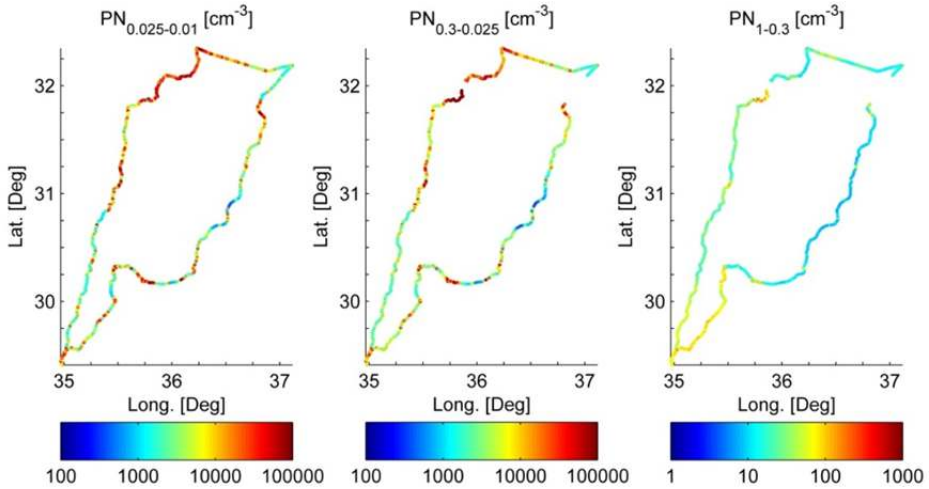

Fig. 5. Submicron particle number concentrations within three size fractions derived from concentrations recorded with the CPC (diameter range 0.01–1 μm), the P-Trak (diameter range 0.025–1 μm), and the AeroTrak that were operated on the mobile setup.

urban background location (University of Jordan campus) and a suburban location (Shafa Badran) on Friday and Saturday were plotted on top of the $PN_{1\text{-}0.01}$ concentration obtained from the CPC and the P-Trak (Fig. 4). The mean concentrations at those locations in Amman varied between 15000 cm^{-3} and 40000 cm^{-3}.

Particulate Mass and Black Carbon Concentrations

The DustTrak measurement recorded the particulate mass concentrations in three size-fractions PM_1, $PM_{2.5}$, and PM_{10} (Fig. 6). Therefore, the submicron particulate mass (PM_1) concentration was taken as is whereas the micron particulate mass ($PM_{10\text{-}1}$) concentration was calculated from the difference between PM_{10} and PM_1 concentrations. The PM_1 concentration was about 40–60% of the PM_{10} concentrations in all cities and on all main roads except for Amman, which was about 75%, and on the road passing by the Dead Sea industries and resorts, which was 69–75%.

It is very clear that PM_1 concentrations were higher across the cities than on the main roads, except for the roads in Wadi Rum and Wadi Araba. This could be due to the enhanced dilution with the clean air. The PM_{10} concentrations were, in general, higher in the southern part of the country and cities with intense heavy duty vehicles than in the northern part of the country. The remote locations such as Safawi and Jafr had the lowest PM concentrations.

As listed in Table S3, Aqaba, Azraq and Ma'an had the highest PM_{10} concentrations (~178 μg m^{-3}, ~145 μg m^{-3} and ~112 μg m^{-3}; respectively) whereas Jafr and Safawi had the lowest PM_{10} concentrations (~19 μg m^{-3} and ~29 μg m^{-3}; respectively). Although, Petra (~98 μg m^{-3}), Zarqa (~94 μg m^{-3}), and Amman (~87 μg m^{-3}) are all located over a large spatial scale, their PM_{10} concentrations were within 10% difference. However, the chemical composition of PM_{10} particles is expected to be different in these cities. For example, the black carbon (BC) concentration in Petra, Zarqa, and Amman was 4.3 μg m^{-3}, 12.3 μg m^{-3}, and 21.3 μg m^{-3}, respectively. Amman and Zarqa are more urbanized than Petra and Aqaba, which are both influenced by the local dust aerosols suspended from the nearby deserts (Wadi Araba and Wadi Rum). Furthermore, Aqaba had slightly more BC concentrations due to emissions (ships and lorries) from the harbors. Because of the heavy duty vehicles activities in Azraq, the BC concentration was the highest, more than 30 μg m^{-3}. The BC concentration in Ma'an was about 11.7 μg m^{-3}, which is close to that recorded in Zarqa as 12.3 μg m^{-3}, however, the PM_{10} concentration in Ma'an was 20% higher than that in Zarqa. Again, indicating different source patterns in these two cities.

The PM_{10} concentrations on the road across Wadi Rum (mean value ~98 μg m^{-3}) and Wadi Araba (mean value ~117 μg m^{-3}) were the highest whereas the main road from Azraq through Jafr towards Ma'an had the lowest PM_{10} concentrations; lower than 17 μg m^{-3} (Table S4). The mean PM_{10} concentrations on the rest of the roads were between 20 μg m^{-3} and 52 μg m^{-3}. With a similar conclusion on the

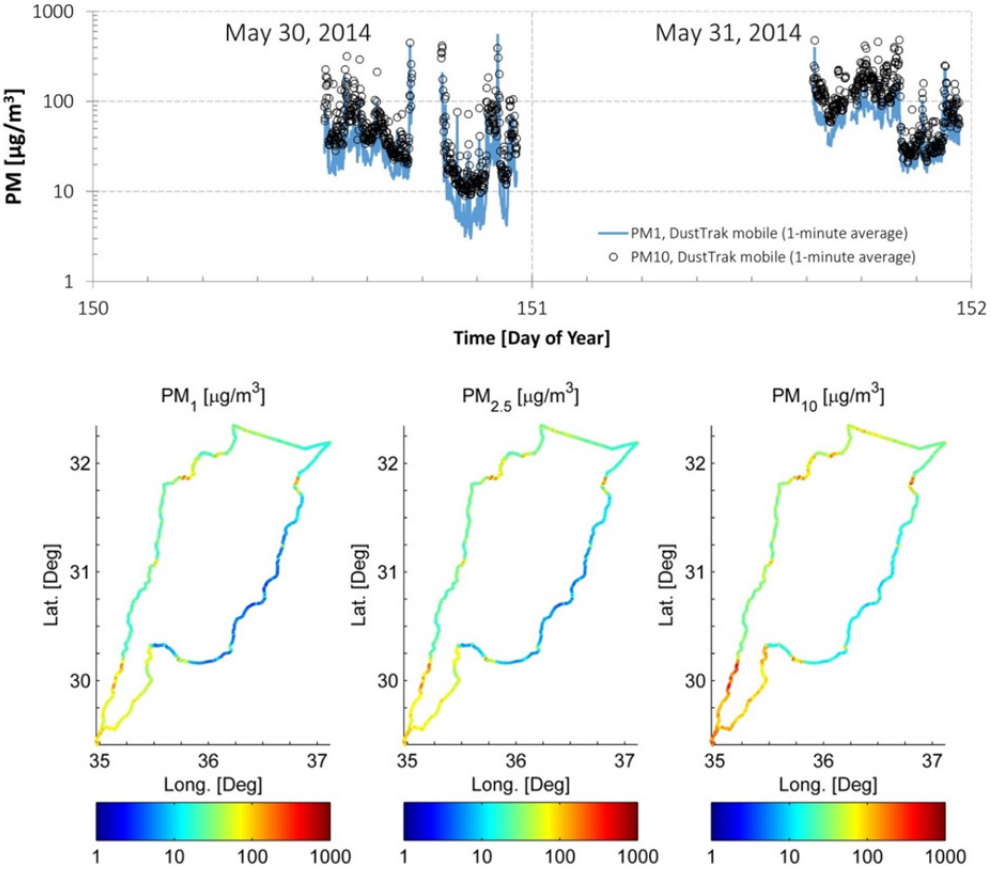

Fig. 6. Particulate matter (PM) concentrations recorded by the DustTrak DRX, which was operated on the mobile setup.

type of emissions on and nearby the roads included in this study, the BC concentration also varied significantly. For example, the road from Aqaba to the Dead Sea had the highest PM_{10} concentrations but had the second lowest BC concentrations (about 1 μg m^{-3}). Furthermore, the road passing by the Dead Sea industry had somehow an intermediate PM_{10} concentrations but the highest BC concentration (5.4 μg m^{-3}). Generally speaking, the BC concentration was in good agreement with PM_1 (Fig. 7).

An Approximation for the Particle Number Size Distribution

The use of different aerosol instruments with different cut off diameters can be used to deduce an approximation for the particle number size distribution. According to our measurement setup, the particle number size distribution can be best represented by six particle size-fractions: 10–25 nm, 20–300 nm, 0.3–0.5 μm, 0.5–2.5 mm, and 2.5–10 μm. The best midpoints of these size fractions can be 20 nm, 80 nm, 0.35 μm, 0.65 μm, 2 mm, and 0.65 μm. The choice was based on several multi-lognormal fittings for the overall average particle number size distributions generated for cities and on roads (Fig. S4).

As discussed in the previous sections, the particle number concentrations across the cities was, in general, higher than that on the main roads connecting the cities. As could be seen from the multi-lognormal fitting, the main difference was found in the ultrafine particle size fraction, which is higher for cities than roads. In fact, the high concentrations across cities in the particle size-fraction between 10–25 nm in diameter is related to fresh aerosols from traffic exhaust emissions.

CONCLUSIONS

In this study, we aim at applying a simple "mobile setup" to measure, for the first time, the spatial variation of aerosol concentrations across cities and along highways in Jordan. We performed an intensive measurement campaign to measure number and mass concentrations of fine and coarse particles as well as black carbon. The measurement setup included a stationary background urban location in Amman and a "mobile setup" driven about 1000 km on the main roads and across cities in Jordan. Although the measurement campaign was two days long, it provided impressive information about aerosols concentrations over a large spatial scale that covered more than three quarters of the country. We have to keep in mind that the presented concentrations reflect on road conditions.

At the stationary urban background location, the mean micron particle number (PN_{10-1}) concentration was mostly about 1.5 cm^{-3}. Assuming spherical particles (ρ_p = 1 g cm^{-3}), the PM_{10-1} was less than 80 μg m^{-3} most of the time. According to the mobile measurement, the average PN_{10-1} concentration varied considerably from a city to another. The highest PN_{10-1} concentration was mainly observed in cities located in the southern region of Jordan (Aqaba ~11 cm^{-3}, Ma'an ~8 cm^{-3}, and Petra ~6 cm^{-3}). The lowest PN_{10-1} concentrations were observed in the remote locations (Safawi ~2 cm^{-3} and Jafr ~3 cm^{-3}). The largest cities (Amman and Zarqa) had an intermediate PN_{10-1} concentrations (about 4 cm^{-3}). On the main roads, the highest PN_{10-1} concentrations (more than 8.5 cm^{-3}) were observed on the roads from Petra to Aqaba (through Wadi Rum) and from Aqaba to the Dead Sea (through Wadi Araba), which are mainly a desert area with moving sand. The PN_{10-1} concentrations were below 3.5 cm^{-3} on the rest of the main roads.

The remote location Safawi also exhibited the lowest mean submicron particle number ($PN_{1-0.01}$) concentrations (~6 × 10^3 cm^{-3}). Cities with heavy duty vehicles activities (Azraq, Ma'an, and Mafraq) had mean $PN_{1-0.01}$ ranging between about 5.8 × 10^4 cm^{-4} and about 7.1 × 10^4 cm^{-3}. The largest cities (Amman and Zarqa) recorded the highest $PN_{1-0.01}$ concentrations (~1.2 × 10^5 cm^{-3} and ~8.2 × 10^4 cm^{-3}, respectively). Although Jafr is a rather small city according to the Jordanian scale, the mean $PN_{1-0.01}$ concentration was about 3.3 × 10^4 cm^{-3}, which was slightly less than that was

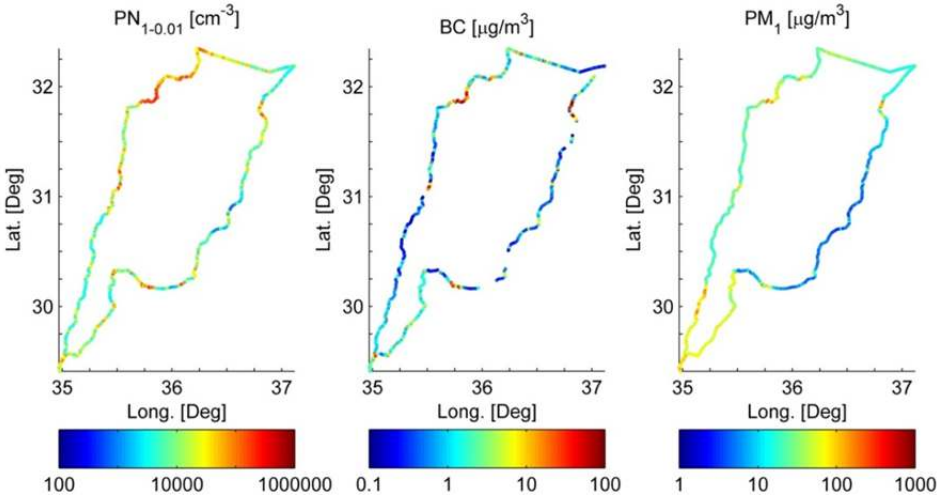

Fig. 7. A comparison between submicron particle number ($PN_{1-0.01}$) concentrations (CPC measurement, diameter range 0.01–1 μm), and the particulate mass concentration (PM1 measured with the DustTrak DRX), and the black carbon concentration (measured with the microAeth); all these instruments were operated on the mobile setup.

reported for Petra as 3.8×10^4 cm^{-3} but comparable to Aqaba (3.3×10^4 cm^{-3}). The mean $PN_{1\text{-}0.01}$ concentrations on the main roads (mean value was less than 4.4×10^4 cm^{-3}) were mainly lower than those observed in the cities. The lowest $PN_{1\text{-}0.01}$ concentrations (< 10^4 cm^{-3}) were observed along the main roads through the eastern part of Jordan (from Safawi to Ma'an through Azraq and Jafr. Interestingly, the $PN_{1\text{-}0.01}$ concentration was as low as 800 cm^{-3} on the road between Azraq and Jafr.

The PM_{10} concentration comprised of about 40–75% as PM_1. Similar to the PN concentrations findings, the PM concentrations were higher across the cities than on the main roads, except for the roads in Wadi Rum and Wadi Araba. Southern cities (Aqaba, Azraq and Ma'an) had the highest PM_{10} concentrations (~178 μg m^{-3}, ~145 μg m^{-3} and ~112 μg m^{-3}; respectively) whereas Jafr and Safawi had the lowest PM_{10} concentrations (~19 μg m^{-3} and ~29 μg m^{-3}; respectively). The PM_{10} concentrations on the road across Wadi Rum (mean value ~98 μg m^{-3}) and Wadi Araba (mean value ~117 μg m^{-3}) were the highest whereas the main road from Azraq through Jafr towards Ma'an had the lowest PM_{10} concentrations (lower than 17 μg m^{-3}).

The black carbon (BC) concentration also varied considerably from one place to another. For example, the road from Aqaba to the Dead Sea had the highest PM_{10} concentrations but had the second lowest BC concentrations (about 1 μg m^{-3}). Furthermore, the road passing by the Dead Sea industry had somehow an intermediate PM_{10} concentrations but the highest BC concentration (5.4 μg m^{-3}). Generally speaking, the BC concentration was in good agreement with PM_1.

The PN, PM, and BC concentrations observed in this study suggest that traffic emissions are the main sources of aerosols in cities, especially those where heavy duty vehicles are used extensively. The southernmost locations are mainly affected by dust aerosols due to local sand re-suspension from desert areas.

The limitations of this study is the short time-scale of the measurement campaign. More efforts need to be followed in order to have more understanding about the air pollution in the MENA region. Currently there is a lack of information about the aerosol temporal and spatial variations, impact of aerosols on weather and vice versa, and trends in dust outbreaks. Such information can be gathered via long-term measurements as well as extensive short-term measurement campaigns. Measurements of the particle size distribution are also needed to understand the dynamic behavior of particulate matter. Furthermore, physical and chemical characterizations are highly needed to better understand the toxicity and health effects as well as the formation and transformation processes of air pollution.

As a recommendation for future investigations, we highly recommend conducting long-term aerosol measurements at several sites throughout the country besides more extensive and repeated mobile measurements.

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SUPPLEMENTARY MATERIAL

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

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