Aerosol and Air Quality Research, 11: 109–119, 2011

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2010.08.0066

Local Air Pollution versus Short–range Transported Dust Episodes: A Comparative Study for Submicron Particle Number Concentration

Tareq Hussein[1*], Rasha Abu Al-Ruz[1], Tuukka Petäjä[2], Heikki Junninen[2], Dia-Eddin Arafah[1], Kaarle Hämeri[2,3], Markku Kulmala[2]

[1] *The University of Jordan, Department of Physics, Amman 11942, Jordan*
[2] *University of Helsinki, Department of Physics, P. O. Box 48, FI-00014 UHEL, Helsinki, Finland*
[3] *Finnish Institute of Occupational Health, Topeliuksenkatu 41 a A, FI-00250, Helsinki, Finland*

ABSTRACT

We measured the submicron particle number concentrations in the urban/suburban atmosphere of Amman–Jordan during the spring of 2009. The main objective was to distinguish the differences in the submicron particle number concentrations with/without dust episodes. In the absence of dust episodes the concentrations showed distinguished daily patterns, which were similar at both the urban and the urban atmosphere with lower concentrations (at least 1:2) at the suburban site. The daily pattern during the first five working days (Saturday–Wednesday) was different than that that on either Thursday or Friday. During the morning rush hours the number concentrations were as high as 120×10^3 and 75×10^3 $1/cm^3$ at the urban and suburban sites during those workdays, respectively. These concentrations were about 21 and 14 times what was observed during the background conditions (5.5×10^3 $1/cm^3$ between midnight and early morning) at both sites. This suggests that traffic emissions are one of the main sources in the urban/suburban atmosphere of Amman. The number concentration of submicron aerosol particles, which originated from the nearby highway, at the urban site decreased exponentially with the wind speed. During a dust episode the total number concentration of submicron particles was about 1/5 of what is typically observed during workdays without dust episodes. The lower concentrations were attributed here for two reasons: increased wind speed and coagulation of locally emitted urban particles with the regional dust particles. These observations in the absence of dust episodes agree well with other studies for highly populated cities. The limitation of this study is the lack of information about the particle number size distribution that can reveal the modal structure of aerosol particles in Amman.

Keywords: Urban; Suburban; Back-trajectory; Dispersion; Daily-pattern.

INTRODUCTION

Recent studies have examined the affects of aerosols on regional and global climate through both direct and indirect effects (e.g. Haywood and Boucher, 2000; Lohmann and Feichter, 2005). It has been largely recognized that air quality and exposure to air pollution have severe consequences and direct growing effects on human health such as diseases of the respiratory and cardiac systems (e.g. Peters *et al.*, 1997; Atkinson *et al.*, 1999; Künzli *et al.*, 2000; Samet *et al.*, 2000; Pope *et al.*, 2002; Curtis *et al.*, 2006). The effects have become of large interest in urban areas where the population density and human activities are highly concentrated. In general, aerosol particles in urban areas consist of several fractions including long-range transport, suspension and re-suspension from road surface, primary/secondary formation due to traffic combustion and non-combustion emissions, emissions from industrial activities, etc.

The Hashemite Kingdom of Jordan is a country under continuous development that faces a rapid increase in air pollution due to rapid increase in population density and industrial activities. Research on aerosols is rather sparse in Jordan. Very few studies have only focused on atmospheric aerosols because of the lack of air quality data as well as the absence of routine monitoring of ambient air pollution. For example, Abu Allaban *et al.* (2006) have focused on dust re-suspension from limestone quarries nearby a town located north east of Amman. They reported PM_{10} concentrations as high as 600 μg/m^3 with most of the airborne PM was in the coarse fraction. The main reason was explained by loading trucks that play a major role in re-suspending road dust, with an observed PM_{10} emission rate of > 6000 mg/km. Hamasha and Arnott (2009)

* Corresponding author. Tel.: 962-6-5355000 Ext. 22060; Fax: 962-6-5300253
E-mail address: t.hussein@ju.edu.jo

investigated the air quality at six sites within Irbid-Jordan through measurement and analysis of time series of black carbon light absorption coefficients. Soleiman *et al.* (2009) indicated that emissions from the highly populated and industrialized Israel-Gaza coast are transported inland and lead to elevated levels of ozone over Jordan. They also reported that southerly winds carry air pollutant from local transportation emissions (e.g. ship, trucks, etc.) and possibly from some industrial areas towards the north end of the Red Sea, while northerly winds are associated with the transport of regional ozone. Air pollution from local transportation was also observed during traffic rush hours in the form of elevated nitrogen oxide (NO) concentrations.

In all previous research activities and studies, none has, however, focused on the capital city, Amman, neither they included measurements of particle number concentrations. Therefore, the purpose of this study was to investigate the number concentration of submicron particles in urban and suburban atmosphere of Amman during the spring season (April 15–22, 28–30 and May 1–5) of the year 2009. We specifically focused on the following aspects: (1) characteristics dispersion of submicron particle number concentrations and difference between urban and suburban areas in the absence of dust episodes and (2) the influence of short-range transported dust episodes on the characteristics of submicron particle number concentrations. We had additional information about the local weather conditions and we obtained back-trajectory information from the HYSPLIT model simulation.

MATERIALS AND METHODS

Site Description

The Hashemite Kingdom of Jordan is located in the Middle East at latitude 29º–33º North and longitude 37º–39º East. Jordan has a unique location from the environmental point of view because of several topographical reasons:

- The southern-eastern part of the country is mainly a desert area, known as the “Badia”. Beyond this is the Arabian desert of Iraq and Saudi Arabia and to the North/West is the Fertile Crescent part of Syria, Lebanon, and Israel/Palestine.
- The northern-western part is comprised of high mountains (Balqa, Ajloun, and Jarash).
- The Dead Sea and the Jordan Valley are located on the western part with an altitude of about 400 m below the sea level.
- The southern part of Jordan has a small opening to the Red Sea.
- At a distance of less than 100 km to the West is the Mediterranean Sea that is considered to be the main source of marine air masses.

This unique location of the country with different types of landscapes provide quite a wide range of different air masses that originate from the desert (East and South-East), vegetation (North and North-West), and marine (West).

The population of Jordan is about six million of which one third are living in the capital city, Amman, that covers an area of about 50 × 35 km^2. The capital city itself is located in the North-Western part and it comprises of a complex terrain of several mountains that makes it challenging to evaluate the air quality the city.

We performed a measurement campaign to measure submicron particle number concentrations at two sites in Amman (Fig. 1). The first site was located on the campus of the University of Jordan, which was a suburban area representing the north-western part of the city. The second site was located in an urban area, Al-Hashmi Al-Shamali, representing the eastern part of the city. The eastern part was by all means more densely populated area when compared to the north-western side with less organized building distribution.

The aerosol measurements at the suburban site (Campus of the University of Jordan) were conducted during April 15–22, 2009 accounting for 8 days. We had to omit about 3 days of data due to severe weather conditions of dust episodes and difficulties to access the instrument outside the working hours at the University of Jordan. The aerosol measurements at this site took place on the rooftop of the Department of Physics; a building consisted of three floors and located in the middle of the campus. Generally, the university campus may be classified as a suburban site; it was located in the north-western part of Amman at about 10 km from the city center (Fig. 1). The campus was surrounded by small streets, populated area, towards the western side was located one of the main highways connected the capital city to other cities such as Salt, Ajloun, and Jarash. The university campus itself is a fairly flat landscape mixed of pine tree forest and buildings (3–4 floors).

The aerosol measurements at the urban site (Al-Hashmi Al-Shamali) were conducted during April 28–May 5, 2009 accounting for another 8 days. The collected data at this site were of better quality because we had only one short dust episode and the instrument was easily accessible on contrary to the university campus site which was not accessible in the nighttime. This site can be classified as an urban area; it was located in the eastern part of Amman at about 2 km from the city center (Fig. 1). The aerosol measurements at this site took place on the rooftop of a family building. The building itself was situated on a slope of a mountain that constrained the building structure to have four floors from one side and two floors from the other side. Towards the south-west of this mountain is another mountain on which the Royal Palaces were situated. It is worth noting that both mountains were of relatively similar heights and they formed a valley. In the valley there was one of the main roads (Al-Istiklal) that connected the eastern parts to the western parts of the capital city.

Aerosol Measurement

The aerosol measurements were performed with a portable Condensation Particle Counter (CPC, TSI model 3007). In order to be able to sample the air at 1–meter above the rooftop of each measurement site we extended the sampling inlet with a 5–meter copper tube (4–mm

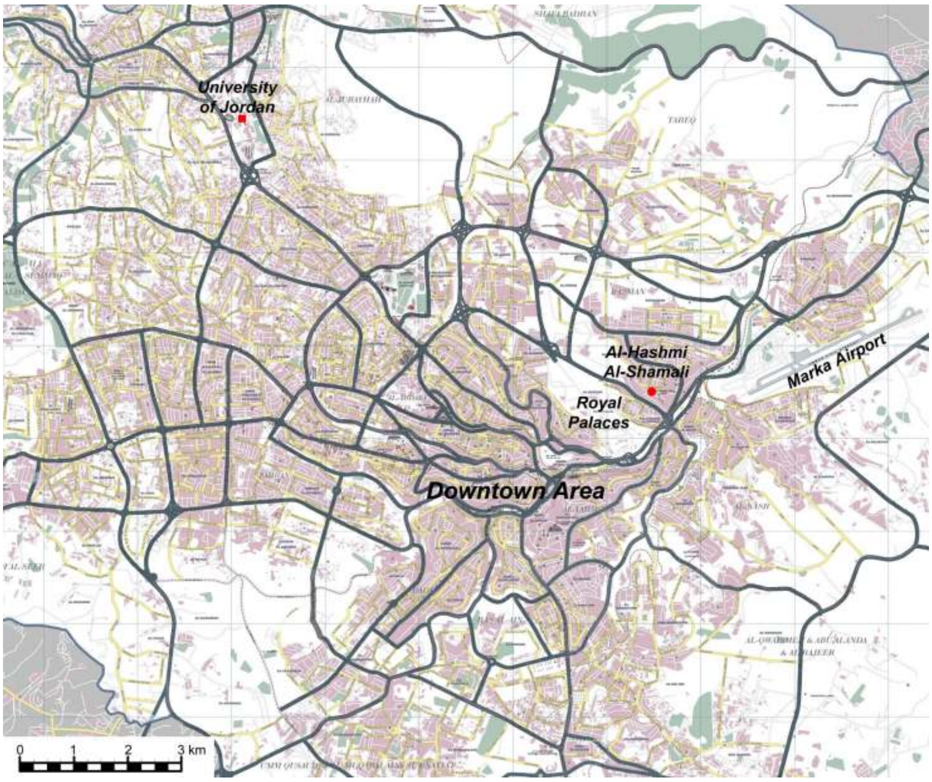

Fig. 1. A detailed map for the Greater Region of Amman showing the main roads (black lines) and the measurement sites: suburban on the University of Jordan campus (square) and urban site in Al-Hashmi Al-Shamali (circle). The map also shows the minor roads and land use.

inner diameter). The use of long sampling line slightly reduced the nominal flow rate of the CPC with about 5%; and thus, after accounting for the laminar flow diffusion losses in the sampling line the cut-off size was estimated to be around 12 nm (Gormley and Kennedy, 1949; Hämeri *et al.*, 2002). Hämeri *et al.* (2002) reported that this CPC model shows a linear response for particle concentrations up to 1×10^5 1/cm^3 and the approximate effect of coincidence is 20% at 3×10^5 1/cm^3 (Hämeri *et al.*, 2002), which was the maximum concentrations recorded during these experiments.

In general, the non-optimal sampling efficiency and unknown number size distribution cause errors in estimating the particle losses in the sampling lines. According to our setup, these cannot be accounted for the measured total number concentration. To get a rough idea for the undersampling, we performed few calculations assuming different modal distributions. For example, in a highly polluted atmosphere, such as New Delhi and similar large urban centers, where a large portion of the total number concentration is in the Aitken and accumulation modes, the undersampling is expected to be around 20% in case of the urban atmosphere (e.g. Mönkkönen *et al.*, 2005; Petäjä *et al.*, 2007). On the other hand, in clean conditions such as a boreal forest environment in Southern Finland, where the relative contribution of nucleation mode to the total number concentration can be considerably higher, the estimated under sampling can be up to 30% (Mäkelä *et al.*, 2000). During the measurement campaign, we made a rough estimation for the practical particle transport efficiency through several tests: we alternatively sampled the air with and without the sampling line several times of 5-minutes long each. The observed number concentrations with the sampling tube were 10–15% less than those done without the sampling tube during that particular instant. Based on this result as well as the high total number concentrations observed in Amman during this study, the most of the sampled particles are not in the nucleation mode but in the Aitken and accumulation modes. When interpreting the total number concentrations presented in this paper, this undersampling needs to be taken into account with caution.

Weather Conditions

At a distance of about 3 km to the East of the urban site was located Amman Civil Airport in Marka where we had access to the weather data provided by the Jordan Meteorological Department (JMD). Records of the meteorological variables included temperature, relative humidity, wind direction and speed, cloud cover, and pressure record. The time resolution of the records was four times a day. The record time-resolution is, however, too sparse to be used to investigate the dependence of the number concentration on weather conditions. Nevertheless, we justified our analysis by considering the wind speed to indicate situations of enhanced particle dispersion.

According to this weather observation, the prevailing wind direction was mainly Western (± 45°) and did not show significant differences between days with and without dust episodes. The wind speed varied between 1.5 m/s and 7.2 m/s, with a median value of 4.1 m/s. In the presence of dust episodes the wind speed was generally higher reaching a maximum value of about 12.7 m/s. The temperature had a clear daily pattern with a maximum as high as 30°C observed around midday and a minimum as low as 10°C registered around midnight. The relative humidity varied between 11% and 83% with an inverse daily pattern with respect to temperature. It was also noticed that the temperature increase during daytime was typically followed by an increase in wind speed; such situations are expected to markedly enhance the boundary layer mixing and dispersion.

Back Trajectories of Air Masses

Trajectory analysis is a useful tool to investigate the history of air masses. We used the HYSPLIT model (Version: September) with archived data that was available on the NOAA/ARL (Draxler and Hess, 1998). HYSPLIT is a single particle Lagrangian trajectory dispersion model. We calculated the 48-hours back-trajectories and produced one trajectory each 3 hours back in time at 100 m arrival height above ground level. Current literature suggests that the error in a trajectory is within 15–30% of the travel distance (Stohl, 1998; Draxler and Hess, 2004).

RESULTS AND DISCUSSION

We had 8 days of valid aerosol data at the urban site (Fig. 2(a–c)) and about 5 days at the suburban site (Fig. 2(d–f)). The 24-hour mean of the total particle number concentration varied between 23400 and 68600 1/cm^3 at the urban site during April 28–May 3, compared to the variation between 24900 and 36800 1/cm^3 during April 16–21 at the suburban site. We shall consider a period between May 3 and 5 separately because of the occurrence of a dust episode on May 4. The lowest concentrations at the urban site were observed on Friday (daily mean of 23400 1/cm^3) and during conditions that favored dispersion and efficient boundary layer mixing such as during high wind speed and high ambient temperature. On the other hand, the highest concentrations were observed at both sites when the prevailing wind speed was low; for example May 3 at the urban site with a daily mean of 68600 1/cm^3 and on April 21 at the suburban site with a daily mean concentration of 36800 1/cm^3.

Particle Number Concentrations Characteristics in the Absence of Dust Episodes: Daily Patterns

We observed clear daily patterns for the submicron particle number concentration during the measurement period excluding the time periods of dust episodes. The first five workdays (Saturday–Wednesday) had a unique pattern that was different than the ones observed on Thursday or on Friday. We, therefore, treated these days separately (Fig. 3). These daily patterns were clearly apparent at both the urban and suburban sites with lower concentrations at the suburban site; the ratio was at least 1:2 between these sites.

Fig. 3(a) illustrates the daily pattern during Saturdays–Wednesdays. The daily pattern on these days was characterized by a sharp concentration peak between 06:00–10:00 and another wider peak that started around 18:00 and ended at 02:00 on the following day. The lowest number concentration during these days was observed between 03:00–06:00, right before the morning traffic rush hour. During daytime (10:00–15:00), the particle number concentration showed a rather flat profile with fluctuations around the mean value. The maximum particle number concentration during the morning was about 118500 1/cm^3 at the urban site and about 75000 1/cm^3 at the suburban site. The lowest particle number concentration; i.e. background, was approximately 5300 1/cm^3 at the suburban site. The sharp peak that occurred in the morning was most likely related to the morning rush hour of the traffic activity. The nighttime high concentrations might be due to the combined effect of increased activity of the heavy traffic and ambient conditions, low temperature and low wind speed (stable boundary layer) as well as low boundary layer height capturing all the particulate emissions in a rather shallow surface layer.

Fig. 3(b) illustrates the daily pattern on Thursdays. This daily pattern was similar to that observed during the other workdays (Saturday–Wednesday) but with lower concentrations during nighttime at both sites. On average lower particle concentration can be related to the fact that there was less heavy duty traffic activity on Thursdays because the following day is a national holiday. The particle number concentrations were rather similar at both sites during Thursday afternoon and evening even though the concentrations were generally higher at the urban site during the first half of Thursday. This observed similarity between the sites could be addressed to the general activity within the city that could, on one hand, reduce the traffic in the city and, on the other hand, increase the human activities in the sub-urban areas as a result of free time during the last workday, which is Thursday.

Friday, being the official holiday in Jordan, had a distinguished daily pattern for the particle number concentrations. The concentrations were generally the lowest, the morning peak was not observed, and the number concentrations were rather similar at both the urban and suburban sites (Fig. 3(c)). It is also interesting to see here that the number concentration during Friday night were similar to those observed on workdays (Saturday–Thursday) during the same conditions. This is expected because the heavy duty traffic start again on Friday night as the next day is a workday. In fact, this strongly supports and justifies the idea of traffic emissions as being one of the most important sources of pollution in Amman.

A similar weekly pattern was observed by Xia *et al.* (2009) for the aerosol optical depth. The Middle East had a distinct cycle, where the minimum aerosol optical depth typically occurred during Thursday-Friday whereas in Europe and the US this happened during weekends (Xia *et al.*, 2009). Noticing that the count of the heavy duty traffic during the nighttime hours is lower than the daytime total traffic count indicates the enormous impact of heavy duty traffic emissions (diesel engines) in Amman.

Dispersion of Submicron Aerosol Particles

Because the weather measurement was sparse it was not possible to make proper analysis for the particle number concentrations with the meteorological parameters. The only possibility was to analyze the particle number

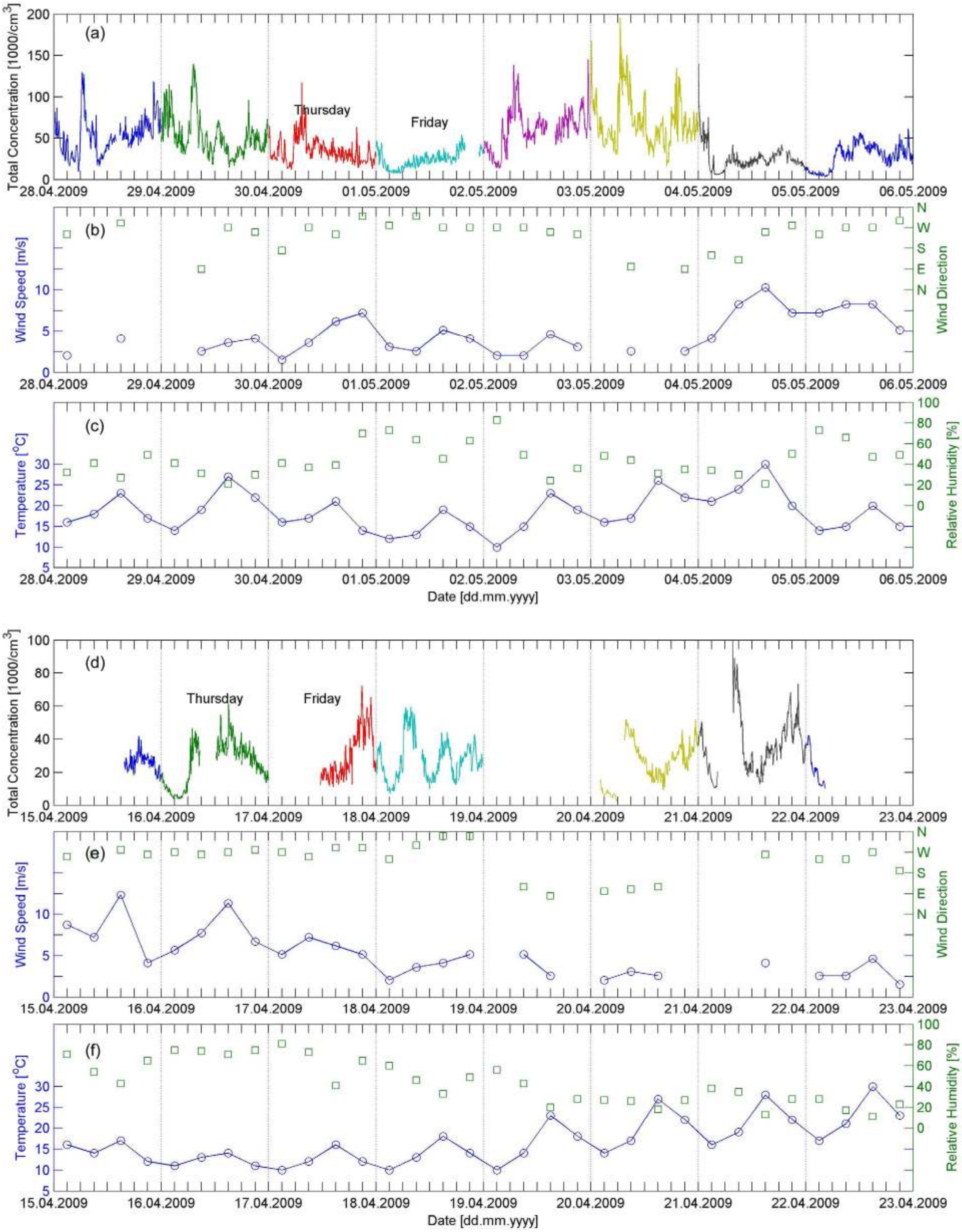

Fig. 2. Particle number concentrations (5-minutes means) with relevant weather conditions (a–c) at the urban site and (d–f) at the suburban site.

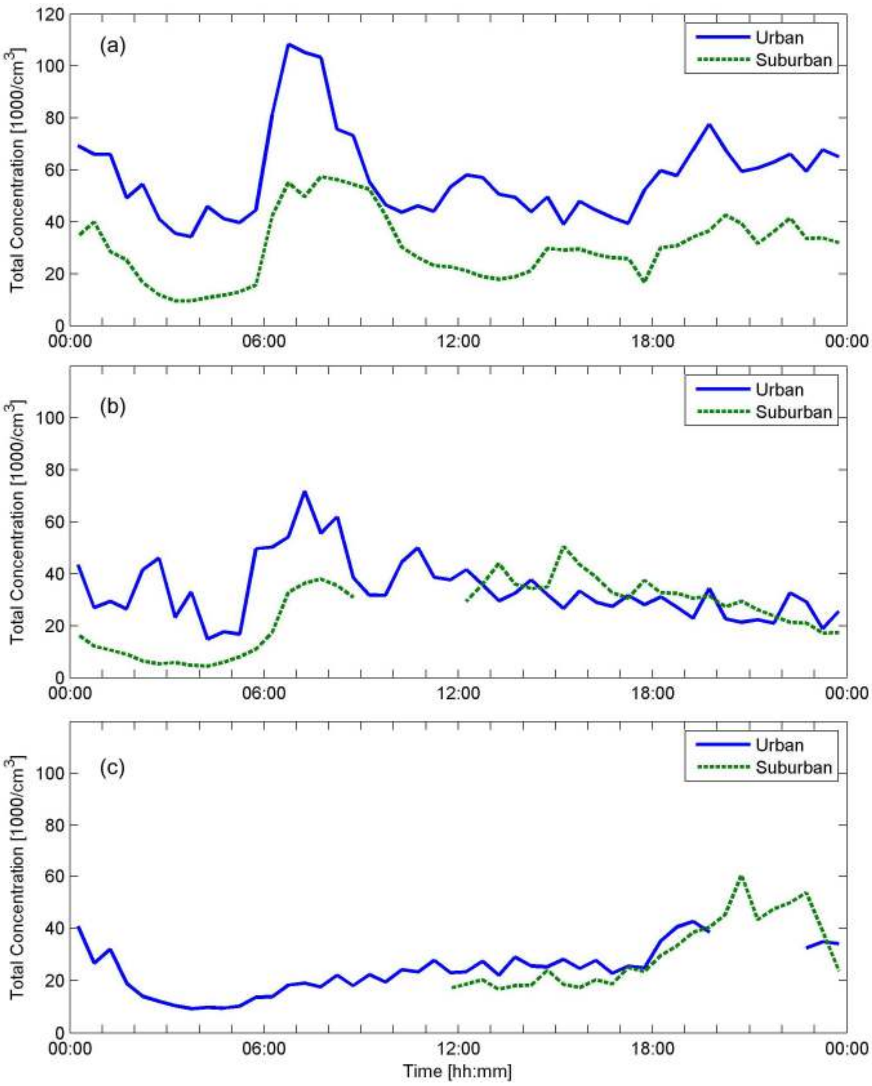

Fig. 3. Daily patterns of the particle number concentrations (30-minutes means) at urban and suburban sites: (a) Saturdays–Wednesdays, (b) Thursdays, and (c) Fridays.

concentrations with respect to the local wind speed at the urban site. The wind direction was mostly Western (± 45°) with occurrence probability of 81%. This provides suitable conditions to make pollutant dispersion at the urban site that arrived from the nearby highway (Al-Istiklal).

In accordance with the weather measurements we calculated the mean particle number concentrations for a time-window ± 30 minutes around the time-records of the weather measurements. This is based on the assumption that the weather condition did not change significantly during a one-hour period. In order to eliminate the temporal and spatial variation of main sources, which we presume to be mainly traffic emissions, we considered daytime (08:30–09:30 and 14:30–15:30), nighttime (20:30–21:30), and background conditions (02:30–03:30) during workdays in the absence of dust episodes.

The main findings showed that the particle number concentration had an exponential decay pattern with the local wind speed (Fig. 4). Similarly, this finding was also reported in other urban/suburban environments (e.g. Harrison *et al.*, 2001; Charron and Harrison, 2003; Gidhagen *et al.*, 2004; Harrison *et al.*, 2004; Hosiokangas *et al.*, 2004; Hussein *et al.*, 2006, 2007; Olivares *et al.*, 2007; Krecl *et al.*, 2008; Järvi *et al.*, 2009). Most of these studies confirmed that such a decreasing trend with the wind speed is an indication of the closeness of the air pollution sources, which are typically the traffic emissions in cities.

In general, the observed number concentrations in Amman were higher than what is usually reported in European cities. Ruuskanen *et al.* (2001) reported total number concentrations of 26000, 27900, and 21700 1/cm^3 respectively in Alkmaar, Erfurt, and Helsinki during weekdays. Even lower concentrations can be found in some European cities; Birmili *et al.* (2009) reported total particle number concentrations between 6000 and 14000 1/cm^3 during morning rush hours of weekdays nearby a highway in Berlin, Germany. Obviously, they also showed that the concentrations were lower during weekends and also anti-correlated with the wind speed. More importantly,

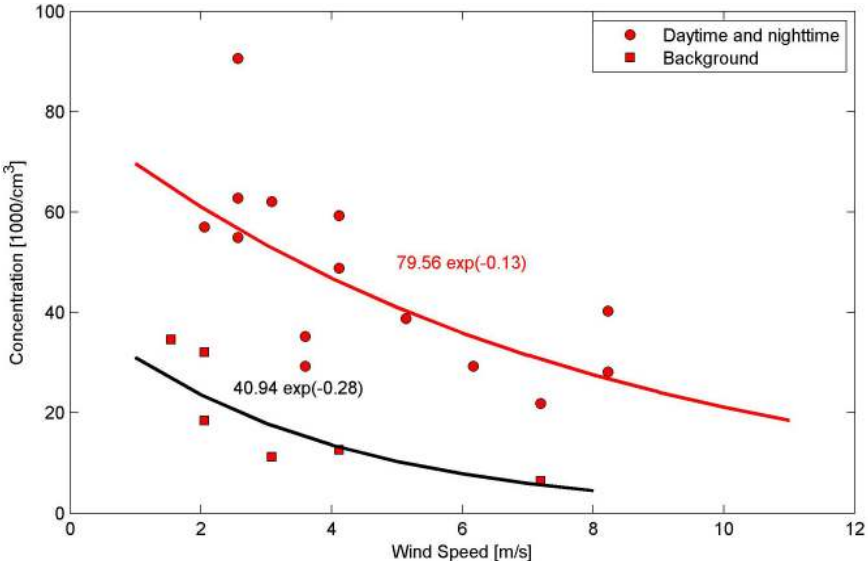

Fig. 4. Particle number concentrations versus local wind speed at the urban site. *Here the specified time periods are as follows: daytime (08:30–09:30 and 14:30–15:30), nighttime (20:30–21:30), and background conditions (02:30–03:30).*

Dingenen *et al.* (2004) compiled inter-European particle number concentrations in different environments where four urban sites experienced seasonal total number concentrations between 10000 and 25000 1/cm^3 and at kerbside sites the number concentration was between 40000 and 60000 1/cm^3.

Dust Episode

Amman and the neighboring areas experienced several dust episodes during April and May 2009. The dust episode that occurred on May 4th was monitored successfully. This episode gave us the opportunity to investigate the effects of such dust episodes on the concentrations of submicron aerosol particles. As will be illustrated in this section, the above mentioned characteristics of the submicron particle number concentrations where significantly different during a dust episode.

Back-trajectories of Air Masses during the Dust Episode

The start and end time of this dust episode was also confirmed from the air mass back-trajectory analysis; though the dust loading in the atmosphere took several hours to be built up and washed out before and after the air masses crossing over Amman region. For example, the air mass history before the early morning of May 3rd was steadily from the Mediterranean over Israel and the West Bank (Fig. 5). Then suddenly changed to circulate and spend more than 48 hours at a very low altitude over south-east Jordan, which is a desert area. The air masses remained the same until noon of May 4th when they started to gradually change to originate from Senai Desert and their altitude increased. By the end of May 4th and also during May 5th, the air masses were from the Mediterranean again.

Local Wind Speed during the Dust Episode

During May 3rd (one day before the dust episode) the wind speed was below 2.6 m/s. It was also recorded that the wind speed increased steadily from ~2.6 m/s to ~10 m/s during the first half of May 4th and then retained rather constant value ~7.5 m/s during May 5th (one day after the dust episode). The wind speed, as illustrated in Fig. 4, does affect the particle concentration: the faster the wind is the lower the particle number concentration is. But as will be discussed below, the number concentration is expected to be further lowered due to the existence of high coagulation sink between the dust particles and ultrafine particles, which are the dominant ones in the urban atmosphere.

Evolution of Particle Number Concentration during the Dust Episode

Recalling back the observed particle number concentrations during May 3–5 (Fig. 2(a)), there was a sudden decrease in the number concentration around 03:00 of May 4th. This is the moment of the dust episode crossing over Amman. The particle number concentration dropped from about 5×10^4 1/cm^3 to about 10^4 1/cm^3. During May 4th the morning peak of the particle number concentration, which is a result of the morning traffic rush hours, was not observed clearly and the daytime particle number concentration varied between 15×10^3 and 30×10^3 1/cm^3. Compared to just one day before the dust episode, the daily particle number concentration varied between 25×10^3 and 80×10^3 1/cm^3 and the maximum value of about 150×10^3 1/cm^3 was achieved during the morning traffic rush hours. Similar observations were reported for a dust episode measured in Beijing–China where the total particle number concentrations dropped from about 6×10^4 1/cm^3 to about 6×10^3 1/cm^3 and at the same time the volume concentration of super micron particles (diameter between 1 and 10 µm) reached a value more than 400 µm^3/cm^3 (Wehner *et al.*, 2004).

The total number concentration of submicron particles was lower during the dust episodes when compared to other days due to two reasons. First, the local wind speed

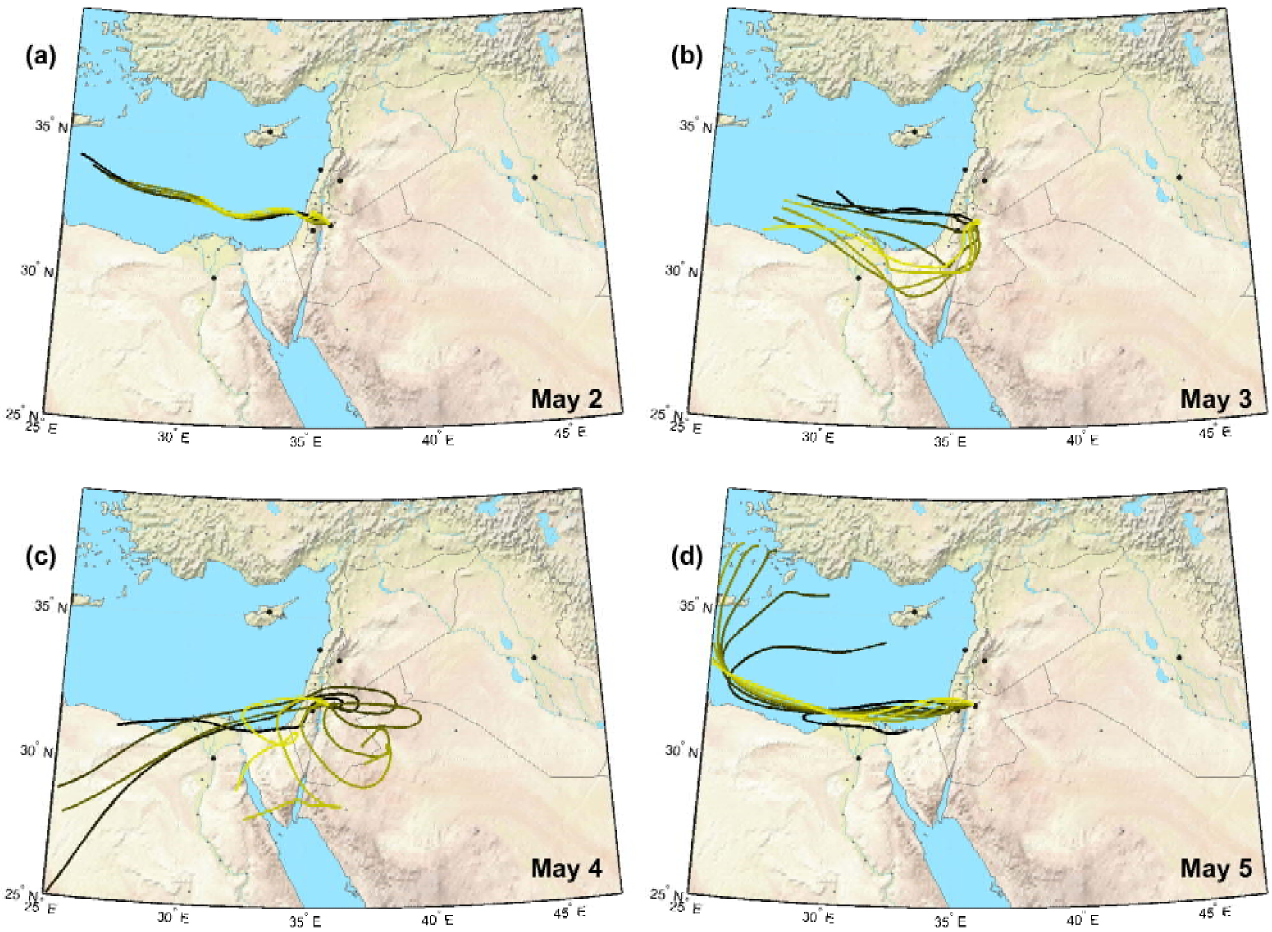

Fig. 5. Air masses back-trajectories calculated every three hours during the past 48-hours before arriving in Amman; these figures illustrate the conditions before, during, and after the dust episode observed on May 4th: (a) May 2nd, (b) May 3rd, (c) May 4th, and (d) May 5th. The evolution of back-trajectories is from black to yellow.

was higher during an episode that enhances the dispersion of aerosol particles and dilutes local air pollution with incoming air over the city. Second, the dust particles would act as coagulation sink for smaller ones and, thus, reduce the number concentration of locally emitted urban aerosol particles. Typically, the urban/suburban number concentration of fine particles is dominated by ultrafine particles (e.g. Hussein *et al.*, 2004, 2005). This fact has been confirmed in several studies, both experimentally and theoretically (Wehner *et al.*, 2000; Jung *et al.*, 2002; Mönkkönen *et al.*, 2004; Cheng *et al.*, 2005; Meija *et al.*, 2008; Wu *et al.*, 2008; Birmili *et al.*, 2009; Oliveira *et al.*, 2009). As much as 98% of the total number concentration is accounted for the accumulation mode particles during Divali festival period, when e.g. fireworks produced submicron particles in large quantities. When the activities are in a smaller scale, nucleation mode particles are scavenged, but some of the Aitken sized particles remain (Wehner *et al.*, 2000). Similarly, the number size distribution and total particle number concentration is affected by dust storms, when super-micron particles are strongly affected (Wehner *et al.*, 2004; Zhang *et al.*, 2006). As the super-micron concentration increases the relative contribution of submicron concentration decreases (Cheng *et al.*, 2005). After such a dust storm, when the wind speed decreases the super-micron concentration drops quite rapidly in the boundary layer due to high deposition velocities of the super-micron particles; this indicates that dust particle do not typically travel from more than few tens of kilometers (Arimoto *et al.*, 1995). If the dust penetrates to higher elevations in the atmosphere it can be transported thousands of kilometers (e.g. Prospero, 1996) whereas the boundary layer underneath does not necessarily reflect this.

SUMMARY AND CONCLUSION

We measured the submicron particle number concentrations with a portable condensation particle counter at two sites (urban and a suburban) in Amman–Jordan during the spring of 2009: during April 15–22 at the suburban site and during April 28–30 and May 1–5 at the urban site. We aimed at investigating the differences in the submicron particle number concentrations with/without dust episodes. More specifically we focused on the daily pattern of particle number concentrations, aerosol dispersion, and the influence of dust episodes on these characteristics.

The findings here confirmed that the particle number concentration of submicron aerosol particles is characterized by a daily pattern in the urban and suburban atmosphere of Amman. The daily pattern was unique during the first five workdays (Sunday–Wednesday) which was different than ones on Thursday or Friday. The number concentration at the suburban site was at least half of what was observed at the urban site. The distinguished characteristics of the daily pattern during Saturday–Wednesday, Thursday, and Friday suggests that traffic emissions can be one of the main sources in the urban and suburban atmosphere of Amman. For example, during the morning rush hours, when the traffic activity is at its maximum within a city, the number concentrations were as high as 120×10^3 and 75×10^3 1/cm^3 respectively at the urban and suburban sites during workdays. These concentrations were about 21 and 14 times what was observed during the background conditions, which showed particle number concentrations around 5.5×10^3 1/cm^3 at both sites. Our speculations from both the measurement setup and with comparison with previous studies indicate that most of the submicron particles at the urban site were mainly in the Aitken and accumulation modes. The number concentration of submicron aerosol particles, which originated from the nearby highway, at the urban site decreased exponentially with the wind speed.

The number concentration observed in the urban atmosphere of Amman can be as high as what can be in densely populated cities in Europe and about 2–3 times what can be observed in small urban environments such as Helsinki. The distinguished daily pattern is also similar to what can be observed in other environments where the traffic is the main source. This in turn, reflects the weekly pattern of the number concentrations being highest on the first five workdays (Saturday–Wednesday) of the week followed by the last workday (Thursday) and finally the weekend (Friday). The dispersion of submicron aerosol particles is pretty much similar to what was previously observed at other urban and suburban environments in Europe.

The dust loading in the atmosphere took several hours to be built up and washed out before and after the air masses crossing over Amman region. In general, the total number concentration of submicron particles during a dust episode over Amman can be about 1/5 of what is typically observed during workdays without dust episodes. The low concentrations during dust episodes suggests that dust particles act as a coagulation sink for the submicron particles where their concentrations are reduces significantly, and thus, the total number concentration is also reduced. In addition, the wind speed during the observed dust episode was high enough to dilute the locally produced urban particles and disperse them efficiently. On the following days of a dust episode the number concentration gradually builds up in the urban atmosphere indicating the loading of aerosols from local sources within the city.

After all, the limitation of this study is the lack of information about the particle number size distribution that can reveal the modal structure of aerosol particles in Amman. It is, therefore, recommended to conduct more intensive campaigns in the near future to understand the dynamics of aerosol particles in the urban/suburban atmosphere of Amman and also during dust episodes.

ACKNOWLEDGMENTS

On the way to end this work, we would like to thank the crew at the Jordan Meteorological Department for providing the local weather information at the Amman Civil Airport. The personal, especial Zaied Eldekis, at the Workshop of the University of Jordan and Prof. Adnan Abu-Surrah from the Hashimate University are very much acknowledge for helping in the experimental part. We especially thank Mr. Fathi Hussein for allowing the measurement at his house and also for participating in following up the measurement during the nighttime.

REFERENCES

Abu-Allaban, M., Hamasha, S. and Gertler, A. (2006) Road Dust Re-suspension in the Vicinity of Limestone Quarries in Jordan. *J. Air Waste Manage. Assoc.* 56: 1440–1444.

Arimoto, R., Duce, R., Ray, B., Ellis, W., Cullen, J., and Merril, J. (1995). Trace Elements in the Atmosphere over the North Atlantic. *J. Geophys. Res.* 100: 1199–1213.

Atkinson, R.W., Bremner, S.A., Anderson, H.R., Strachan, D.P., Bland, J.M. and de Leon, A.P. (1999). Short-term Associations between Emergency Hospital Admissions for rRespiratory and Cardiovascular Disease and Outdoor Air Ppollution in London. *Arch. Environ. Health* 54: 398–411.

Birmili, W., Alaviippola, B., Hinneburg, D., Knoth, O., Tuch, T., Borken-Kleefeld, J. and Schacht, A. (2009) Dispersion of Traffic-related Exhaust Particles near the Berlin Urban Motorway – Estimation of Fleet Emission Factors. *Atmos. Chem. Phys.* 9: 2355–2374.

Charlson, R., Schwartz, S., Hales, J., Cess, R., Coakley, J., Hansen, J. and Hofmann, D. (1992). Climate Forcing by Anthropogenic Aerosols. *Science* 255: 423–430, doi: 10.1126/science.255.5043.423.

Cheng, T., Lu, D., Chen, H. and Xu, Y. (2005). Physical Characteristics of Dust Aerosol over Hunshan Dake Sandland in Northern China. *Atmos. Environ.* 39: 1237–1243.

Curtis, L., Rea, W., Smith-Willis, P., Fenyves, E. and Pan, Y. (2006). Adverse Health Effects of Outdoor Air Pollutants. *Environ. Int.* 32: 815–830.

Dingenena, R.A., Raes, F., Putaud, J.P., Baltensperger, U., Charron, A., Facchini, M.C., Decesari, S., Fuzzi, S., Gehrige, R., Hansson, H.C., Harrison, R.M., Hüglin, C.H., Jones, A.M., Laj, P., Lorbeer, G., Maenhaut, W., Palmgren, F., Querol, X., Rodriguez, S., Schneider, J., ten Brink, H., Tunved, P., Torseth, K., Wehner, B., Weingartner, E., Wiedensohler, A. and Wåhlin, P. (2004). A European Aerosol Phenomenology—1:

Physical Characteristics of Particulate Matter at Kerbside, Urban, Rural and Background Sites in Europe. *Atmos. Environ.* 38: 2561–2577.

Draxler, R.R. and Hess, G.D. (1998). An Overview of the HYSPLIT 4 Modeling System for Trajectories, Dispersion and Deposition. *Aust. Meteorol. Mag.* 47: 295–308.

Draxler, R.R. and Hess, G.D. (2004). Description of the HYSPLIT 4 Modeling System, NOAA Technical Memorandum ERL ARL–224.

Gidhagen, L., Johansson, C., Langner, J. and Olivares, G. (2004). Simulation of NO_x and Ultrafine Particles in a Street Canyon in Stockholm, Sweden. *Atmos. Environ.* 38: 2029–2044.

Gormley, P.G., and Kennedy, M. (1949). Diffusion from a Stream Flowing through a Cylindrical Tube. *Proc. R. Irish Acad.* 52: 163–169.

Hamasha, K. and Arnott, W. (2009). Photoacoustic Measurements of Black Carbon Light Absorption Coefficients in Irbid City. *Environ. Monit. Assess.* 166: 485–494, doi: 10.1007/s10661-009-1017-3.

Hämeri, K., Koponen, I.K., Aalto, P.P. and Kulmala, M. (2002). Technical Note: The Particle Detection Efficiency of the TSI-3007 Condensation Particle Counter. *J. Aerosol Sci.* 33: 1463–1469.

Harison, R. and Yin, J. (2000). Particulate Matter in the Atmosphere: Which Particle Properties are Important for Its Effects on Health? *Sci. Total Environ.* 249: 85–101.

Harrison, R.M., Jones, A.M. and Barrowcliffe, R. (2004). Field Study of the Influence of Meteorological Factors and Traffic Volumes upon Suspended Particle Mass at Urban Roadside Sites of Differing Geometries. *Atmos. Environ.* 38: 6361–6369.

Haywood, J.M. and Boucher, O. (2000). Estimates of the Direct and Indirect Radiative Forcing Due to Tropospheric Aerosols: A Review. *Rev. Geophys.* 38: 513–543.

Hosiokangas, J., Vallius, M., Ruuskanen, J., Mirme, A. and Pekkanen, J. (2004). Resuspended Dust Episodes as an Urban Air-quality Problem in Subarctic Regions. *Scand. J. Work Environ. Health* 30: 28–35.

Hussein, T., Hämeri, K., Aalto, P.P. and Kulmala, M. (2005). Modal Structure and Spatial-temporal Variations of Urban and Suburban Aerosols in Helsinki Area. *Atmos. Environ.* 39: 1655–1668.

Hussein, T., Karppinen, A., Kukkonen, J., Härkonen, J., Aalto, P.P., Hämeri, K., Kerminen, V.M. and Kulmala, M. (2006). Meteorological Dependence of Size Fractionated Number Concentrations of Urban Aerosol Particles. *Atmos. Environ.* 40: 1427–1440.

Hussein, T., Kukkonen, J., Korhonen, H., Pohjola, M., Pirjola, L., Wriath, D., Härkönen, J., Teinilä, K., Koponen, I.K., Karppinen, A., Hillamo, R. and Kulmala, M. (2007). Evaluation and Modeling of the Size Fractionated Aerosol Particle Number Concentration Measurements nearby a Major Road in Helsinki – Part II: Aerosol Measurements within the SAPPHIRE Project. *Atmos. Chem. Phys.* 7: 4081–4094.

Hussein, T., Puustinen, A., Aalto, P.P., Mäkelä, J.M., Hämeri, K. and Kulmala, M. (2004). Urban Aerosol Number Size Distributions. *Atmos. Chem. Phys.* 4: 391–411.

Järvi, L., Hannuniemi, H., Hussein, T., Junninen, H., Aalto, P.P., Hillamo, R., Mäkelä, T., Keronen, P., Siivola, E., Vesala, T. and Kulmala, M. (2009). The Urban Measurement Station SMEAR III: Continuous Monitoring of Air Pollution and Surface-atmosphere Interactions in Helsinki, Finland. *Boreal Environ. Res.* 14: 86–109.

Jung, C.H., Kim, Y.P. and Lee, K.W. (2002). Simulation of the Influence of Coarse Mode Particles on the Properties of Fine Mode Particles. *Aerosol Sci. Technol.* 33: 1201–1216.

Krecl, P., Ström, J. and Johansson, C. (2008). Diurnal Variation of Atmospheric Aerosol during the Wood Combustion Season in Northern Sweden. *Atmos. Environ.* 42: 4113–4125.

Künzli, N., Kaiser, R., Medina, S. and Studnicka, M. Chanel, O. and Filliger,P., Herry, M., Horak, F., Puybonnieux-Texier, V., Quénel, P., Schneider, J., Seethaler, R., Vergnaud, J.C. and Sommer, H. (2000). Public-health Impact of Outdoor and Traffic-related Air Pollution: A European Assessment. *Lancet* 356: 795–801.

Lohmann, U. and Feichter, J. (2005). Global Indirect Aerosols Effects: A Review. *Atmos. Chem. Phys.* 5: 715–737.

Mäkelä, J.M., Koponen, I.K., Aalto, P. and Kulmala, M. (2000). One-year Data of Submicron Size Modes of Tropospheric Background Aerosol in Southern Finland. *J. Aerosol Sci.* 31: 595–611.

Mejıa, J.F., Morawska, L. and Mengersen, K. (2008). Spatial Variation in Particle Number Size Distributions in a Large Metropolitan Area. *Atmos. Chem. Phys.* 8: 1127–1138.

Mönkkönen, P., Koponen, I.K., Lehtinen, K.E.J., Hämeri, K., Uma, R. and Kulmala, M. (2005). Measurements in a Highly Polluted Asian Mega City: Observations of Aerosol Number Size Distribution, Modal Parameters and Nucleation Events. *Atmos. Chem. Phys.* 5: 57–66.

Mönkkönen, P., Koponen, I.K., Lehtinen, K.E.J., Uma, R., Srinivasan, D., Hämeri, K. and Kulmala, M. (2004). Technical Note: Death of Nucleation and Aitken Mode Oarticles: Observations at Extreme Atmospheric Conditions and Their Theoretical Explanation. *J. Aerosol Sci.* 35: 781–787.

Olivares, G., Johansson, C., Ström, J. and Hansson, H.C. (2007). The Role of Ambient Temperature for Particle Number Concentrations in a Street Canyon. *Atmos. Environ.* 41: 2145–2155.

Oliveira, C., Alves, C. and Pio, C.A. (2009). Aerosol Particle Size Distributions at a Traffic Exposed Site and an Urban Background Location in Oporto, Portugal. *Quim. Nova* 32: 928–933.

Petäjä, T., Kerminen, V.M., Dal Maso, M., Junninen, H., Koponen, I.K., Hussein, T., Aalto, P.P., Andronopoulos, S., Robin, D., Hämeri, K., Bartriz, J.G. and Kulmala, M. (2007). Sub-micron Atmospheric Aerosols in the

Surroundings of Marseille and Athens: Physical Characterization and New Particle Formation. *Atmos. Chem. Phys.* 7: 2705–2720.

Peters, A., Wiclumann, H.E., Tuch, T., Heinrich, J. and Heyder, J. (1997). Respiratory Effects Are Associated with the Number of Ultrafine Particles. *Am. J. Respir. Crit. Care Med.* 155: 1376–1383

Pope, C.A. III, Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K. and Thurnston, G.D. (2002). Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution. *J. Am. Med. Assoc.* 287: 1132–1140.

Prospero, J.M. (1996). Saharan Dust Transport over the North Atlantic Ocean and Mediterranean: An Overview, In *The Impact of Desert Dust Across the Mediterranean*, Guerzoni, S. and Chester, R. (Eds.), Kluwer Academic Publishers, Dortrecht, The Netherlands, p. 133.

Ruuskanen, J., Tuch, Th., Ten Brink, H., Peters, A., Khlystov, A., Mirme, A., Kos, G.P.A., Brunekreef, B., Wichmann, H.E., Buzorius, G., Vallius, M., Kreyling, W.G. and Pekkanen, J. (2001). Concentrations of Ultrafine, Fine and $PM_{2.5}$ Particles in Three European Cities. *Atmos. Environ.* 35: 3729–3738.

Samet, J., Rappold, A., Graff, D., Cascio, W., Berntsen, J., Huang, Y.C., Herbst, M., Bassett, M., Montilla, I., Hazuch, M., Bromberg, Ph. and Devlin, R. (2009). Concentrated Ambient Ultrafine Particle Exposure Induces Cardiac Changes in Young Volunteers. *Am. J. Respir. Crit. Care Med.* 179: 1034–1042

Soleiman, A., Abu-Allaban, M., Bornstein, B., Luria, M. and Gertler, A. (2009). A Ttransboundary Air Quality Study of Pollution over the Gulf of Aqaba. *11th Conference on Atmospheric Chemistry 2009*.

Stohl, A. (1998). Computation, Accuracy and Application of Trajectories – A Review and Bibliography. *Atmos. Environ.* 32: 947–966.

Wehner, B., Wiedensohler, A. and Heintzenberg, J. (2000). Submicrometer Aerosol Size Distributions and Mass Concentration of the Millenium Fireworks 2000 in Leipzig, Germany. *J. Aerosol Sci.* 31: 1489–1493.

Wehner, B., Wiedensohler, A., Tuch, T.M., Wu, Z.J., Hu, M., Slanina, J. and Kiang, C.S. (2004). Variability of the Aerosol Number Size Distribution in Beijing, China: New Particle Formation, Dust Storms, and High cContinental Background. *Geophys. Res. Lett.* 31: L22108, doi: 10.1029/2004GL021596.

Wu, Z., Hua, M., Lin, P., Liu, S., Wehner, B. and Wiedensohler, A. (2008). Particle Number Size Distribution in the Urban Atmosphere of Beijing, China. *Atmos. Environ.* 42: 7967–7980.

Xia, X., Eck, T.F., Holben, B.N., Philippe, G. and Chen, H. (2008). Analysis of the Weekly Cycle of Aerosol Optical Depth Using AERONET and MODIS Data. *J. Geophys. Res.* 113: D14217, doi: 10.1029/2007JD009604.

Zhang, D., Iwasaka, Y., Matsuki, A., Uenoc, K. and Matsuzakic, T. (2006). Coarse and Accumulation Mode Particles Associated with Asian Dust in Southwestern Japan. *Atmos. Environ.* 40: 1205–12:15.

Received for review, August 6, 2010
Accepted, January 17, 2011