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Temporal Variations of Submicron Particle Number Concentrations at an Urban Background Site in Amman-Jordan

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Abstract

This paper presents the temporal variation of fine particle number concentrations and their dependence on some weather parameters (T, P, and RH) during August 2016 – May 2017 at an urban background site in Amman. The measurement was conducted with a condensation particle counter with one-minute time resolution. The daily mean concentrations showed a clear annual cycle (annual average of ~8×10^3 cm^{-3}) with high concentrations (~2.8×10^4 cm^{-3}) during winter and low concentrations (~1.2×10^4 cm^{-3}) during summer. This annual cycle was inversely correlated with the daily mean temperature (T), but was proportional with the daily mean relative humidity (RH); however, the concentration cycle had about a twenty-two day shift with respect to T and RH cycles. Further analysis based on the hourly mean aerosol database revealed a weekly cycle and distinguished daily patterns for three types of days: (1) Sunday–Wednesday, (2) Thursday, and (3) Friday–Saturday. The workdays had the highest daily mean concentrations, and their daily pattern had the highest concentrations during morning rush hours. The weekend type daily pattern had the highest concentrations during midday and late night. Both pattern types had the lowest concentrations between the times 03:00 – 06:00. These temporal variations (annual, weekly, and daily) reflect the anthropogenic emissions, especially those emitted from combustion traffic-related activities in the city. The aerosol database was of a long-term type (about eight months in total), which encourages the researchers to perform more extensive measurements for a longer term to fill in the missing gaps and reveal more accurate temporal characteristics of the fine particle number concentrations.

Keywords: seasonal, diurnal Pattern, meteorological dependence, traffic emissions.

1. Introduction

Aerosol particles play an important role in the climate via their direct effect, which is represented by the ability to absorb and reflect radiation, or via the indirect effect acting as Cloud Condensation Nuclei (CCN) or Ice Nuclei (IN) (e.g. Myhre et al., 2013; Haywood and Boucher, 2000; Lohmann and Feicher, 2005). Aerosols might also affect human health because some types of aerosols have been classified as toxic and carcinogenic causing mortality and morbidity (Pop et al., 2002; Vinzents et al., 2005; Krewski, 2009; Lepeule et al., 2012; Burnett et al., 2012).

Urban areas are major sources of aerosols as a result of activities associated with large population densities and their anthropogenic activities (Fenger, 1999). Among the major sources are combustion emissions that are mainly accompanied with traffic and industrial activities. Urban aerosols have a complex mixture of those that are locally emitted and those from long- range transport (e.g. Hussein et al., 2014). Therefore, the physical and chemical properties of urban aerosols often have a complex trend in time and space. Meteorological conditions remarkably affect aerosols properties and concentrations (e.g. Wehner and Wiedensohler, 2003; Wu, et al., 2008; Zhao et al., 2015; Vakeva et al., 2000; Hussein et al., 2006).

An important feature of aerosol concentrations is their temporal variation with different time scales: daily, weekly, and seasonal (e.g. Rahman et al., 2017; Hussein et al., 2016; Hussein et al., 2004; Jin et al., 2005; Wehner and Wiedensohler (2003). Jin et al., (2005) indicated that seasonality is evident in aerosol optical thickness measurements, with a minimum in January and a maximum in April to July, and demonstrated the diurnal variations of aerosols which were detectable but largely affected by local and regional weather conditions, such as surface and upper-level winds, also he reported that for calm clear days, aerosols peak during the two rush hours in the morning and evening. Wehner and Wiedensohler (2003) showed the weekly and daily aerosol concentration variations in an urban area of Leizpzig (Germany), and concluded that Meteorological conditions remarkably affect the particle concentrations. Rahman, et al. (2017) investigated the diurnal trend of the particle number concentrations, and they showed that vehicular emissions and new particle formation events increased the total particle number concentrations. Understanding urban aerosol temporal variations can help in developing climate models to calculate the climate forcing of aerosol particles, in addition to the possibility of using the long-term aerosol concentration data for correlation with epidemiological data; such a study can reveal the effects of these concentrations on respiratory diseases in urban areas.

There have been many studies in the eastern

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Mediterranean region interested in aerosols. They focus on the PM and some chemical characterization and aerosol transport (e.g. Abdeen et al., 2014; Alghamdi et al., 2014a, 2014b, 2015; Boman et al., 2013; Daher et al. 2013; El-Araby et al., 2011; Engelbrecht and Jayanty, 2013; Gherboudj and Ghedira, 2014; Hamad et al., 2015; Hussein et al., 2014; Hussein et al., 2011; Hassan et al., 2013; Habeebullah, 2013; Khodeir et al., 2012; Kouyoumdjian and Saliba, 2006; Rushdi et al., 2013; Shaltout et al., 2013; Waked et al., 2013; Saliba et al., 2010; Al Dousari et al., 2017; Basha et al., 2015; Doronzo et al., 2015; Alam et al., 2014; Jaafar et al., 2014; Saeed et al., 2014; Dada et al., 2013; El-Askary et al., 2009; El-Askary and Kafatos, 2008; Reid et al., 2008; Saliba et al., 2007; Satheesh et al., 2006). However, those researches didn't shed the light on the particle number concentrations, long-term database, and particle number size distribution. In Jordan, which is considered to be at a central location in the eastern Mediterranean region, there have been several aerosol studies concerning particle number concentrations. For example, Hussein et al. (2011) investigated the number concentration of submicron particles in urban and suburban atmospheres of Amman during a short-term measurement aiming to compare the concentrations before and after a dust episode.

In a recent study, Hussein et al. (2016) have measured the fine number concentrations and deduced their spatial and diurnal variation in the two most populated cities (Amman and Zarqa). However, the measurement campaigns were too short to predict the seasonal pattern. The research was extended by Hussein and Betar (2017) to present the size-fractionated particle number and mass concentrations in Amman during short-term investigations and deduce an estimate for the urban particle number size distribution. Most recently, Hussein et al. (2017) developed a simple mobile setup and measured the spatial variation of aerosol concentrations across cities and highways in Jordan. Although their study covered a large geographical area of Jordan, it was very short.

In this study, the main objective is to investigate the temporal variation of submicron particle number concentrations at an urban background site in Amman, Jordan. The researchers focused on three temporal scales: seasonal, weekly, and daily. This is very important to further understand the temporal characteristics of the emission of submicron aerosols in Amman, and will provide useful information (e.g. relationship with some meteorological parameters) which is also important for modeling the urban air quality based on proxies.

2. Materials and Methods

2.1. Aerosol Measurements

The researchers measured the particle number concentrations of submicron aerosols at an urban background site in Amman, Jordan. The site is located on the third floor of the Department of Physics in the middle of the University of Jordan campus. The aerosol measurement was performed over the period from August 1, 2016 to June 22, 2017.

The aerosol instrument was a portable condensation particle counter (CPC 3007-2, TSI). The cutoff size of this CPC was 10 nm, and it was capable of measuring submicron particle number concentration for aerosols with diameters up to 1 μm. According to the specifications provided by the manufacturer, the maximum detectable concentration was 10^5 cm^{-3} with a 20 % accuracy. The sampling flow rate was 0.1 lpm (inlet flow rate 0.7 lpm). The aerosol inlet consisted of short Tygon tubes (4 mm inner diameter) connected to a diffusion drier (TSI model 3062-NC). The diffusion drier is used to remove the excess of moisture from the aerosol sample. Since the aerosol never comes in contact with the desiccant material, there is a minimal aerosol loss. The main inlet (~1-meter-long and 8 mm inner diameter) was led through the wall to sample the outdoor aerosols. The aerosol transport efficiency through the aerosol inlet was estimated experimentally, and the aerosol data were corrected accordingly.

The measurement time-resolution was set to one-minute average scans. After correcting the raw data for aerosol losses in the experimental setup, the processed aerosol data were then converted to statistical analysis. This hourly averaged database was then used to calculate the daily and monthly statistical values. The statistical analysis included average, standard deviation, standard error, minimum, 5 %, 25 %, median, 75 %, 95 %, max, valid number of data points, and percentage of valid data points.

The hourly averaged database was also used to generate the daily pattern of the particle number concentrations. The daily pattern is usually calculated by taking the average (or any statistical parameter) separately for every hour of a certain weekday (Mondays, for instance). Then workdays and weekends/holidays are considered separately as two distinct groups.

2.2. Weather Conditions

The weather conditions were measured continuously on the roof top of the Department of Physics since February 2015. The measurement was conducted with a weather station (Weather Station WH-1080, Clas Ohlson: Art.no. 36-3242). The time resolution of the measurement was five minutes. The weather station consists of an automatic data logger, which is controlled by its own software installed on a personal computer, and sensors connected wirelessly with the data logger. The sensors measure ambient temperature, absolute pressure, relative humidity, wind speed and direction, and precipitation.

For the purpose of the analysis made for this study, the researchers only included the temperature and the relative humidity from July 1, 2016 to June 30, 2017. The daily average temperature varied between 1.3 °C and 30.5 °C with an overall average of 17.3±7.4 °C, and the relative humidity was in the range of 16 % – 100 % (median 59 %). The daily average wind speed was 4.9±2.4 km/h.

3. Results and Discussion

3.1. Seasonal Variation of the Submicron Aerosol Concentrations

Throughout the measurement period, the daily average concentration of the submicron aerosols was in the range of 6.9×10^3 – 4.1×10^4 cm^{-3} with a yearly average of 1.94×10^4 cm^{-3}, and a yearly median of 1.8×10^4 cm^{-3}. These concentrations were higher than what was reported in some cities. For example, Salma, et al. (2011) measured the particle number concentrations in the range (0.006 to 1 μm)

near central Budapest for a year, and found that the daily median number concentrations of particles varied from 3.8 × 10^3 to 2.9 ×10^3 cm^{-1} with a yearly median of 1.18 ×10^4 cm^{-3}, this is 42 % lower than the results in this study. Birmili, et al. (2009) measured the particle number concentrations that are less than 0.5 µm at sites 80m and 400m far away from a main road in Berlin, Germany, and their results were 1.1×10^4 cm^{-3}, 9 ×10^3 cm^{-3} respectively, which are, also, lower than the results of the current study. However, the results of this study are in line with many other results reported for various locations in Europe. For example, Reche, et al. (2011) reported the average particle concentrations in the urban background of Barcelona (Spain), North Kensington (UK), and Lugano (Italy) as 1.7×10^4 cm^{-3}, 1.2×10^4 cm^{-3}, and 1.5×10^4 cm^{-3}, respectively. The results of the current study are also in agreement with a similar study at an urban background site (North- Eastern Iberian Peninsula) which had a daily average of particle number concentrations in the range of 7.0×10^3 cm^{-3} - 3.1×10^4 cm^{-3} with an annual average of 2.5 ×10^4 cm^{-3} (Perez et al., 2010).

The average concentration of the submicron aerosols was the highest during winter and the lowest was during summer. The lowest monthly average (~1.3×10^4 cm^{-3}) was observed during June–August, whereas the highest concentrations (~2.6×10^4 cm^{-3}) were observed during December–February (Table 1 and Figure 1). The average number concentration in winter was two times higher than that in summer. This result could be attributed to the increased particle emissions in winter (e.g. from heating processes). Also, these high concentrations in winter are related to the boundary layer height, which is proportional to the ambient temperature. Therefore, during winter, particle number concentrations are accumulated in a smaller volume (below boundary layer) giving higher concentrations than winter.

Table 1. Monthly statistical values for the submicron particle number concentrations. The last two columns are the number of valid data points and the corresponding percentage in each month. This table was generated from the hourly averages.

Year	Month	Mean	Stdev	Min	5%	25%	Median	75%	95%	Max	N	%
2016	July	--	--	--	--	--	--	--	--	--	--	--
2016	Aug	12907	6224	3398	5436	8585	11220	15583	25517	34669	297	40
2016	Sep	16491	8013	3334	6248	10826	15475	20634	31988	47040	298	41
2016	Oct	21342	9892	3552	6794	14640	20119	26975	39831	64945	569	76
2016	Nov	23935	14491	3692	5925	12951	22163	30332	54361	82004	358	50
2016	Dec	--	--	--	--	--	--	--	--	--	--	--
2017	Jan	--	--	--	--	--	--	--	--	--	--	--
2017	Feb	26320	13303	4047	6710	16668	25453	35159	48769	82791	438	65
2017	Mar	21306	10486	3449	5835	13972	20299	27340	41091	61939	530	71
2017	Apr	19152	9867	3504	6278	13111	17918	23803	36604	88080	220	31
2017	May	--	--	--	--	--	--	--	--	--	--	--
2017	Jun	13394	7172	4173	6127	8254	11570	16105	27775	40069	229	32

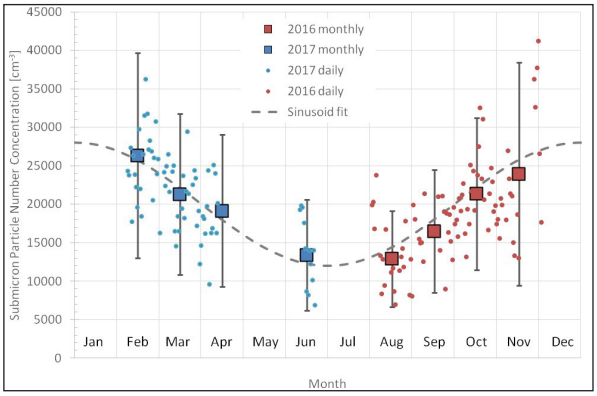

Figure 1. Seasonal variation of the submicron particle number concentrations fitted to a sinusoidal function of the form PN = 8×10^3 COS (360 t / 365) + 2×10^4, where PN is the particle number concentration [cm^{-3}], and t is the day of year starting from January 1st.

This result is consistent with several previous studies in other urban areas (e.g. Wehner and Wiedensohler, 2003; Olivares et al., 2007; Wu, et al., 2008). For example, Wehner and Wiedensohler (2003) showed the seasonal trend in the particle number concentrations at a moderately polluted site in Leipzig (Germany) with lowest average concentration (~1.1×10^4 cm^{-3}) in summer and highest average concentration (~2.1 ×10^4 cm^{-3}) in winter. However, the findings of the current study are not in line with the results of Singh, et al. (2000), who studied the variation of aerosol concentration in view of some meteorological parameters in Roorkee, north India during monsoon (June–Sep / 1996) and winter (November – Feb/1997), and found that aerosol concentrations were minimum in August, September, and November, 1996, but remained around the maximum concentrations in (June–July), 1996 and (January–February), 1997.

The annual cycle of the concentrations is revealed by looking closely at the monthly analysis (Table 1 and Figure 1). The annual cycle of the daily mean concentration can be fitted with a periodic function in the form

$$PN = 8(\cos(t/365 \cdot (" 360°) + 20 \quad \text{.....(1)}$$

where *PN* is the daily average aerosol number concentration [×10^3 cm^{-3}], and *t* is the number of days starting from January 1st (Figure 1). According to this fitting, the lowest concentrations seem to be also observed in July (summer), whereas higher concentrations are expected in January or December (winter).

Based on the monthly analysis of the submicron aerosol concentration against the relative humidity and the

temperature, the monthly mean of the concentrations was proportional to the monthly mean of the relative humidity, but was inversely proportional to the monthly mean of the temperature (with a lag of less than a month). For example, the annual cycle of the daily mean relative humidity was also fitted to a periodic function

$$RH = 23(\cos(t/365 \cdot (" 360°) + 55 \quad \text{.....(2)}$$

where *RH* is the daily average relative humidity [%], and *t* is again the number of days since January 1st (Figure 2a). This means that the annual cycle of the daily mean relative humidity is in phase with the daily mean submicron aerosol concentration.

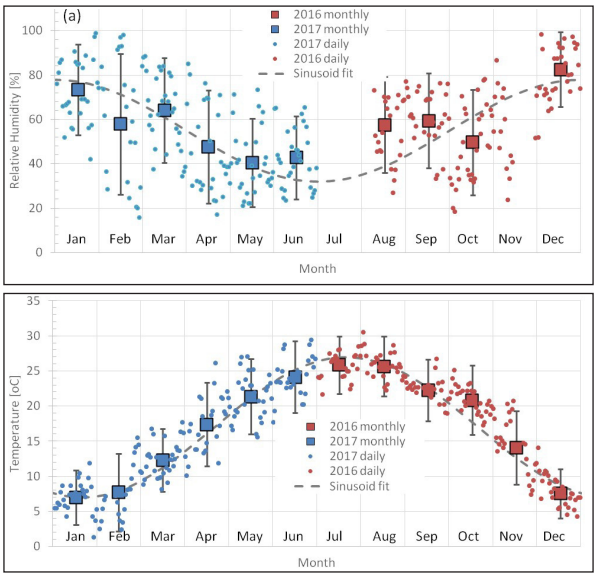

Figure 2. Seasonal variation of **(a)** relative humidity fitted to a sinusoidal function (RH = 23 COS (360 t / 365) + 55, where RH is the relative humidity [%] and t is the day of year starting from January 1st) and **(b)** temperature fitted to a sinusoidal function (T = 10 SIN (360 (t – 112)/ 365) + 17, where T is the Temperature [°C] and t is again the day of year).

Similarly, the annual cycle of the daily mean temperature was fitted to a periodic function

$$T = 10(\cos(t/365 \cdot (" 360° - 200°) + 17 \quad \text{.....(3)}$$

where *T* is the daily average temperature [°C], and *t* is again the number of days since January 1st (Figure 2b). However, this annual cycle of the temperature was shifted by about six months and twenty-two days. In other words, the annual cycle of the temperature is inversely proportional (with ~22 days lag) to both the relative humidity and the submicron aerosol concentration. So, a satisfactory relation between number concentrations and (temperature and RH) is deduced. This is not in agreement with Wu, et al. (2008) who reported that the number concentration in their study didn't show a clear dependency on ambient relative humidity and temperature, and that a complex relation connected them, although their measurements lasted for two years.

Based on the hourly means, the submicron aerosol concentration was inversely proportional to the temperature (T), relative humidity (RH), and the wind speed (WS) (Figure 3). The relationship between the concentration and these three weather parameters is best described by an exponential function, where the concentration decreases with the increase of T, RH, or WS. Interestingly, at zero T, RH, and WS, the concentration approaches 2.5×10^4 cm^{-3}, which is close to the monthly average during winter (e.g. Figure 1). On the other end of the curves; i.e. high T, RH, and WS, the concentration approaches 1.5×10^4 cm^{-3}, which is close to the monthly average during summer (e.g. Figure 1).

This dependence on some weather conditions is very close to the outcome reflected by Hussein et al. (2006). They studied the dependency of aerosol particle number concentrations on the meteorological variables in Helsinki, and showed that the particle number concentrations can be expressed as a function of temperature and wind speed only, but are not dependent on relative humidity; in fact relative humidity dependency was not clear in their study. However, the results of the present study seem to be inconsistent with Singh, et al. (2000), who found that aerosol concentrations increased with relative humidity during the winter season and decreased with temperature. Also, Olivares et al. (2007) reported that the increase in particle number concentrations with the decline of temperature is different for different particle sizes They also showed a distinct correlation between number concentration and (temperature and relative humidity) higher concentrations during periods with low temperatures or a high relative humidity.

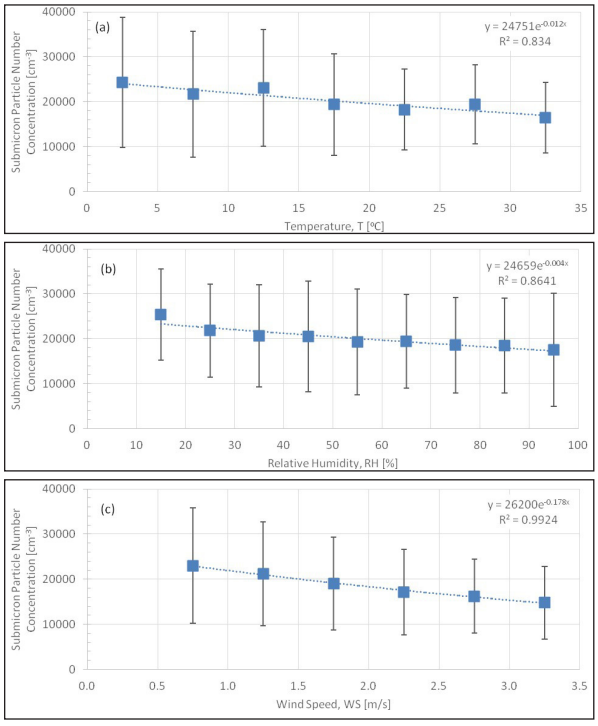

Figure 3. Submicron aerosol concentration versus the **(a)** temperature, **(b)** relative humidity, and **(c)** wind speed. These figures (average and standard deviation) were generated from the hourly average of the submicron particle number concentrations, and the trends were fitted to an exponential function.

In this research, two separate relations were deduced connecting temperature and relative humidity to number concentrations depending on monthly and hourly means. The hourly dependence relation falls under the control of the monthly dependence relation, which can be imagined as wave containing group and phase velocity.

The relationship between the submicron aerosol concentration and meteorological conditions is very important for modeling the urban air quality based on proxies

(e.g. Hussein et al., 2006). These models can help predict particle number concentrations on any day, depending on the meteorological parameters of that day. For example, a statistical forecast model was developed to predict the urban particle number concentration based on long-term aerosol database (Mølgaard et al., 2012 and 2013).

3.2. Weekly and Daily Patterns

The submicron aerosol concentration showed a clear weekly pattern with high daytime concentrations during workdays (Figure 4). Similar to many other urban environments, this reflects the combustion emissions from traffic activity, which are more during workdays (e.g. Hussein et al., 2002 and 2004). The researchers anticipated this weekly pattern previously, but the analysis was based on a short-term database limited to less than two months only (March and April 2014) (Hussein et al., 2016).

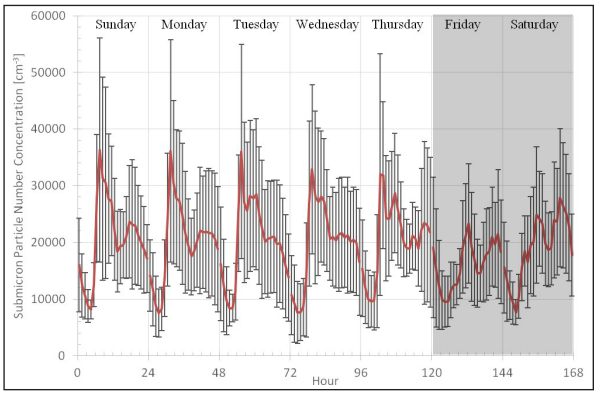

Figure 4. Weekly pattern of the submicron particle number concentrations.

In Jordan, workdays are Sunday through Thursday whereas the weekend days are Friday and Saturday. From the detailed analysis of the daily patterns of the submicron aerosol concentration, three distinguished types of daily patterns were detected (Figure 5): (1) TYPE-I for Sunday – Wednesday, (2) TYPE-II for Thursday, and (3) TYPE-III for weekend days (Friday – Saturday).

TYPE-I (i.e. Sunday – Wednesday) was characterized by the highest concentrations (in the range of 2×10^4 – 3.5×10^4 cm^{-3}) during morning traffic rush hours (06:00 – 12:00). This first peak was also observed by Hussein et al. (2016), but with a higher concentration amounting to 45000 cm^{-3}. A second peak with intermediate concentrations (2×10^4 – 2.2×10^4 cm^{-3}) was spanned between the times15:00 - 21:00. The concentration decreased after 21:00 reaching a background level of (8×10^3 cm^{-3}) between the times 03:00 - 04:00. These two peaks are relevant for the morning and afternoon traffic rush hours, which are similar to those noticed in most cities in developed countries (e.g. Wehner and Wiedensohler, 2003; Olivares et al., 2007; Wehner et al., 2004).

Since ***TYPE-II*** represents the daily pattern for Thursdays, which is a workday, it had characteristics similar to those of TYPE-I, but with a difference in the afternoon peak. The second peak of TYPE-II had slightly higher concentrations (2×10^4 – 2.4×10^4 cm^{-3}) than those observed for TYPE-I extending to after midnight. This little difference can be attributed to late night traffic activities in the city, where people spend their leisure time at coffee shops and restaurants because Thursday is the last workday. It is worth mentioning here that this pattern wasn't clear in the study of Hussein et al. (2016), because their measurements were restricted only to few months.

TYPE-III (Friday – Saturday) was different than the other two types in terms of daytime concentrations. The first peak (i.e. morning peak) started gradually around 06:00 and reached its maximum (~2.4×10^4 cm^{-3}) around midday. The concentrations decreased to ~1.7×10^4 cm^{-3} around 15:00. The second peak also had intermediate concentrations (as high as ~2.4×10^4 cm^{-3}) lasting until midnight, which is another difference between this type of pattern and the other two types. In general, the concentrations in this pattern were lower than those observed during workdays. This result agrees with what was reported by (Hussein et al., 2016). However, their short-term measurements couldn't reveal the duration differences between workdays and weekends.

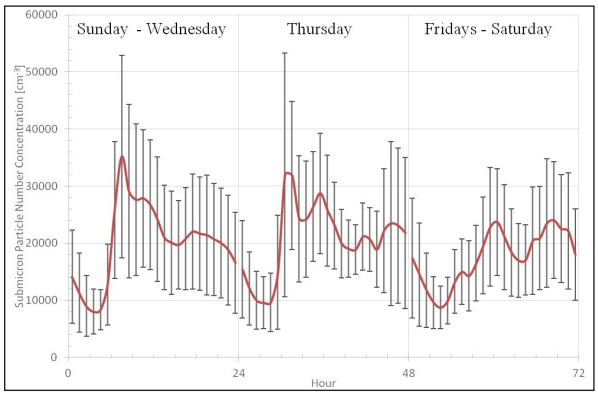

Figure 5. Daily patterns of the submicron particle number concentrations on three weekdays groups: (a) Sunday – Wednesday, (b) Thursday, and (c) Friday – Saturday.

4. Conclusions

The researchers measured the fine particle number concentrations with a condensation particle counter over the period from August 2016 to May 2017 at an urban background site in Amman, Jordan. On-site measurements for weather conditions were also conducted for this study. Both the aerosol database and the weather data-base were converted to an hourly statistical database that was used in further analysis. the main objective was to investigate the temporal variation of urban submicron particle number concentrations.

The results of this study confirmed three temporal cycles for the submicron particle number concentrations: (1) annual cycle, (2) weekly cycle, and (3) diurnal cycle. These temporal variations (annual, weekly, and daily) reflect the anthropogenic emissions, especially those emitted from combustion traffic-related activities in the city.

The annual cycle was clearly observed based on the daily mean of the fine particle number concentration with high concentrations (~2.8×10^4 cm^{-3}) during winter and low concentrations (~1.2×10^4 cm^{-3}) during summer with an annual average of about 8×10^3 cm^{-3}. This annual cycle was inversely correlated with the daily mean T cycle, but was proportional with the daily mean RH including a shift ~22 days.

The submicron particle number concentrations also showed a weekly cycle with the highest concentrations during

workdays (Sunday–Thursday). As such, the concentrations had three distinguished types of diurnal patterns: (1) the first four workdays (Sunday–Wednesday), (2) Thursday, and (3) weekend days (Friday–Saturday). The workdays had the highest concentrations during the morning rush hours. The weekend type daily pattern had the highest concentrations during midday and late night. Both pattern types had the lowest concentrations between the times 03:00 – 06:00.

The results presented in this paper are based on a long-term database, which encourages the researchers to perform more extensive measurements for a longer term and fill in the missing gaps in order to reveal more accurate temporal characteristics of the fine particle number concentrations.

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