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Long-term indoor-outdoor aerosol measurement in Helsinki, Finland

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Total aerosol number concentration measurements were carried out with a condensation particle counter in a Helsinki suburban area throughout the period from 1 November 1999 to 30 June 2000. The variation of the aerosol concentration was investigated in connection with the season, meteorological conditions and traffic activity, which were concluded as the main factors affecting the outdoor aerosol concentrations. In addition, the indoor-outdoor connection was investigated based on the indoor/outdoor (I/O) concentration ratio. Two daily patterns of the total aerosol number concentration were observed in each season, one for weekdays and another for weekends. On average, the submicron aerosol number concentration was at its highest during the winter and lowest during the summer. The temporal variation of the total aerosol number concentration indoors followed the outdoor variation with a small delay. Larger I/O ratios (average 0.66) were observed during the summer than during the winter and the spring (average 0.58).

Introduction

The number concentration of ultrafine aerosol particles (particles smaller than 100 nm in diameter) is usually very high in the vicinity of roads. In general, an urban aerosol consists of long-range transported particles, re-emissions from the road surface, primary/secondary aerosols produced in the air by traffic combustion emissions, and emissions from industrial activities, particurlarly energy production (Kulmala *et al.* 1986, Birmili and Wiedensohler 1997, Guasta and Marini 2000, Ristovski *et al.* 2000).

The urban aerosol characteristics depend on the geographical location of a city, meteorological conditions and traffic emissions. The temporal variability of the urban pollutant concentration is affected strongest by the traffic density and weather conditions. Also, the aerosol spatial distribution varies within a city area because of variations in the traffic density and the building size along with topographical con-

ditions that influence the surface-layer roughness characteristics (Buzorius *et al*. 1999). It has been noticed that in European cities the seasonal variation of the urban pollutant concentration is mainly caused by weather conditions, since the seasonal variation of traffic emissions is considered moderate (Buzorius *et al*. 1999, Kukkonen *et al*. 1999, Oettl *et al*. 2001). Re-emission of deposited particles from the road surface varies with the traffic density, as well as with the meteorological conditions such as temperature, wind, and/or humidity (Kulmala *et al*. 1986).

Many studies have shown that outdoor air quality (OAQ) affects the properties and characteristics of indoor aerosols, thereby influencing the indoor air quality (IAQ) (Alzona *et al*. 1978, Koponen *et al*. 2001, Vette *et al*. 2001). Outdoor-to-indoor particle transport may occur through cracks in the building shell, through crevices in windows and doors, and via the mechanical ventilation system (e.g. VanOsdell *et al*. 1990, Thatcher *et al*. 1995, Tung *et al*. 1999, Mosely *et al*. 2001, Thornburg *et al*. 2001). In buildings equipped with mechanical ventilation systems, the indoor aerosol concentration can be determined from the outdoor aerosol concentration and the filtration efficiency of the ventilation system (Asmi *et al*. 2000, Jamriska *et al*. 2000).

The need for a better IAQ is very important. Following the recommendations by the National Research Council (1998), understanding the sensitivity of some people, such as allergic individuals or elderly people with cardiopulmonary diseases, to low concentrations of specific ambient aerosols has become a high priority. For example, a correlation between particulate pollution and several health hazard indicators have been observed (e.g. Braun *et al*. 1992, Dockery and Pope 1994, Jamriska *et al*. 2000). As a result, many studies have been conducted to estimate the effect of ultrafine particles on respiratory symptoms and particle deposition in the lung and other respiratory tracts. In principle, the need for studying indoor aerosols is to estimate the risks inside resident houses and working places and to try to improve the environment inside houses and office buildings.

The main purpose of this study was to investigate the temporal variation of aerosol concentrations close to a highway in suburban Helsinki, Finland. Our attention was focused on the traffic density and meteorological conditions as the possible main factors affecting the characteristics of the outdoor aerosols in a suburban area throughout seasons. Another interest was to examine the relationship between the outdoor and indoor aerosols in an office building equipped with a mechanical ventilation system.

Measurements and experimental setup

The measurement site was located about 5 km north of downtown Helsinki (Fig. 1). The site is a typical suburban background area with minor local anthropogenic aerosol sources except for the traffic. One of the major highways leading out of the Helsinki area is located about 100 m from the building. This highway is the most important local aerosol source with high temporal variability. This is in addition to several small roads that go around the building and the new building construction in the neighborhood. The office building itself is a two-storey construction with a clean air intake about 2 m above the ground level. The room is located in the basement, and the fresh air is filtrated and led to the room. The room contains no windows. The door of the office was kept closed during the experimental period, but otherwise the office was used regularly. The office was open five days a week and typical working hours were 08:00–17:00. The ventilation system is equipped with an automatic mechanical air supply and exhaust controller, with EU3-class filters installed on the inlet air supply, and it operats continuously with constant flow rate ~93.6 m^3 h^{-1}, for which the total room ventilation rate was ~3 h^{-1} (10% variance).

The indoor and outdoor total aerosol number concentration was measured during the period 1.11.1999–30.6.2000. The aerosol measurements included measuring the total aerosol number concentration with a high temporal resolution, and it was performed with a condensation particle counter (CPC 3022, TSI, Inc.) placed in a storage room next to the office. The CPC

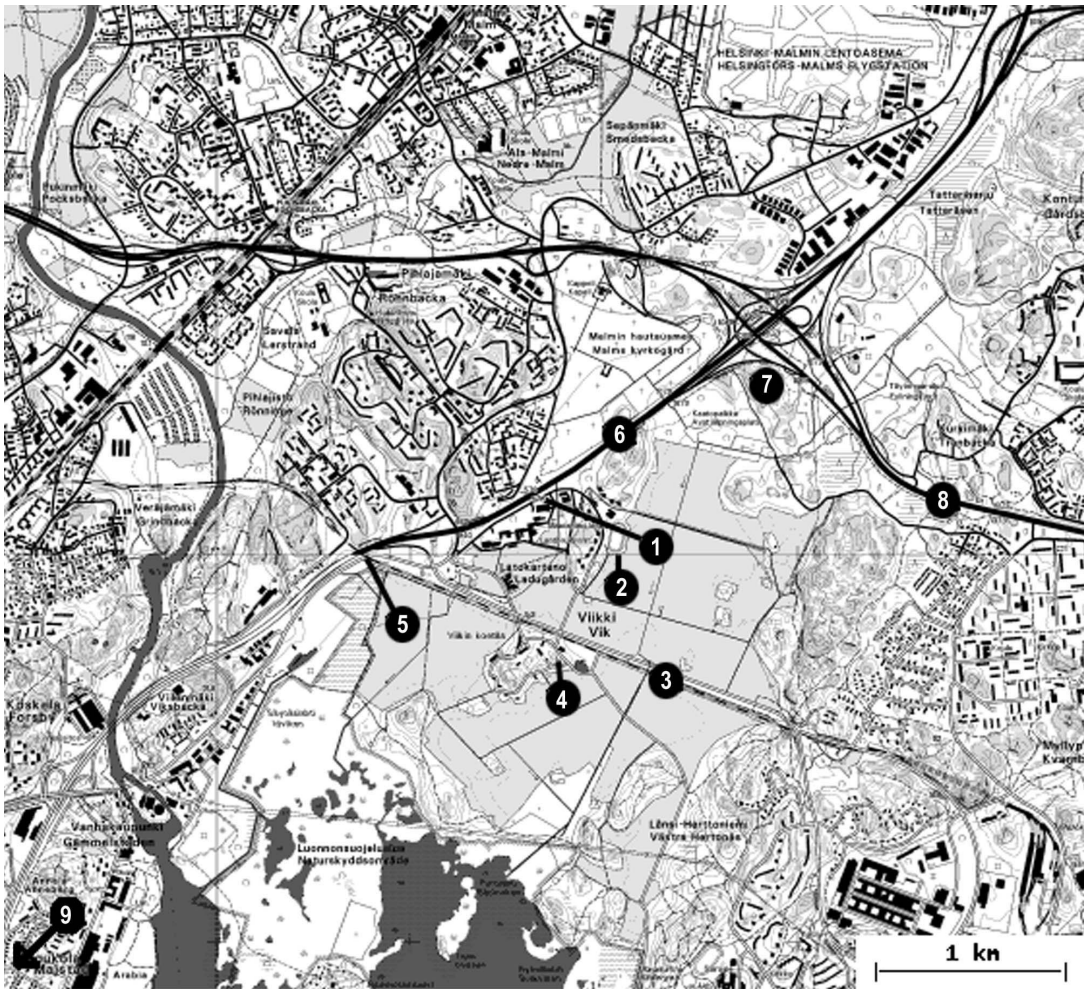

Fig. 1. Location of the measurement site in Helsinki, Finland (MAPSITE: National Land Survey of Finland. Available at http://www.kartta.nls.fi/. Accessed 2 March 2001). Numbered black spots mark: (1) the office building where the measurement was carried out, (2) the nearby building construction, (3) the closest road to the south of the measurement site, (4) other building constructions, (5) the closest crossroads and highways, (6) the main highway leading to downtown Helsinki, (7) the highways connection, (8) another main highway connecting the eastern and western sides of Helsinki and (9) to downtown Helsinki.

3022 detects particles larger than about 7 nm in diameter, the upper limit being typically a few micrometers. The sampling was performed at 1-min intervals from either the indoor or outdoor air using a computer-controlled valve system. The outdoor air sampling was performed near the fresh air intake, and even though it was performed as near as possible, the sampling line was 10 m in length. An identical sampling line was used for indoor air sampling to obtain a better comparison between the indoor and outdoor concentrations. Both sampling lines were made of copper and had an inner diameter of 8 mm. The sampling was done with flow rate of 1.5 liters per minute.

In addition to the aerosol measurements, the Finnish Meteorological Institute (FMI) in Helsinki provided meteorological information for the outdoor temperature, relative humidity, and wind speed and direction.

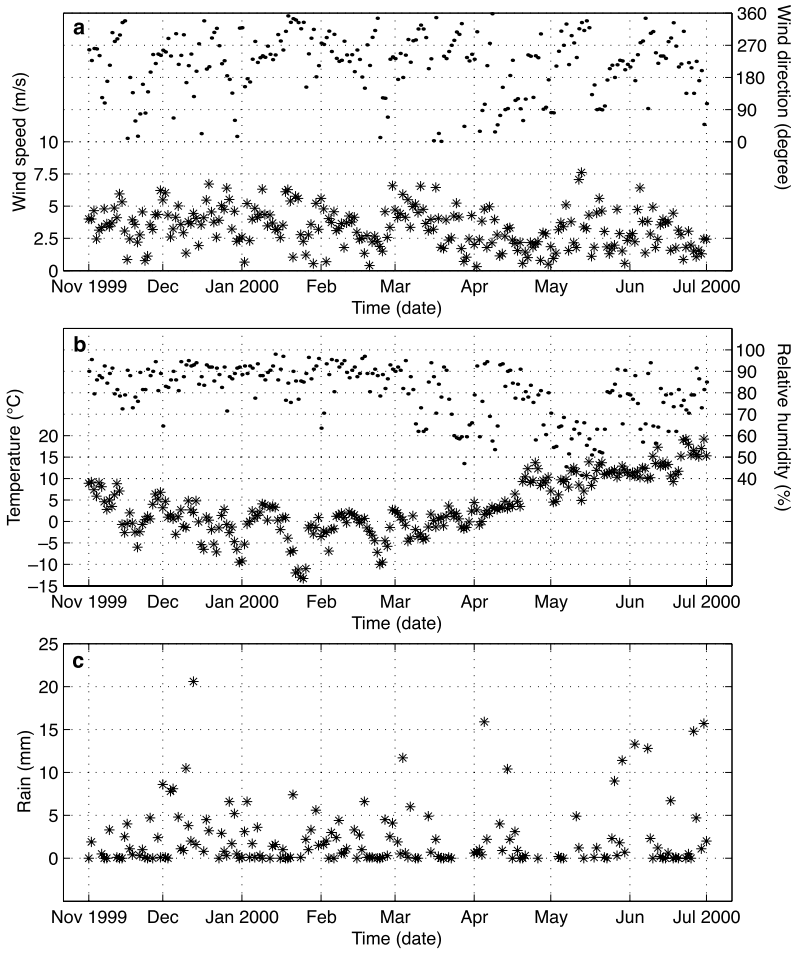

Fig. 2. Meteorological conditions throughout the entire measurement period from 1.11.1999 to 30.6.2000. — **a**: Prevailing wind direction (dots) and wind speed (stars). — **b**: ambient relative humidity (dots) and temperature (stars). — **c**: daily averaged occurring rainfall.

Results and discussion

Meteorological conditions

There are not many buildings close to the measurement site which is indeed an important factor for the meteorological conditions, especially the wind, to affect the outdoor air quality (OAQ). The wind direction was typically south-west (~240°) throughout the entire measurement period with some fluctuations between east (90°) and north (360°). The wind speed was moderate and did not exceed 8.0 m s^{-1} (Fig. 2a). In the Helsinki region cold air masses usually come from the north, while warm air masses come from the south.

The temperature was influenced by the air mass origin: northern air masses decreased the temperature, while southern air masses increased it (Fig. 2b). There were several sudden decreases in the temperature correlated with the northern wind (Fig. 2a and b). In general, the overall trend of the temperature was a decrease until the end of February 2000 when it started to increase. Throughout the measurement period, the registered minimum temperature was about –14 °C (in January 2000), and the maximum temperature was about +20 °C (in June 2000).

The relative humidity was rather constant (~90%) during the first five months of the measurement period, after which it started to fluctuate between 50% and 90%. The daily averaged occurring rainfall is shown in Fig. 2c.

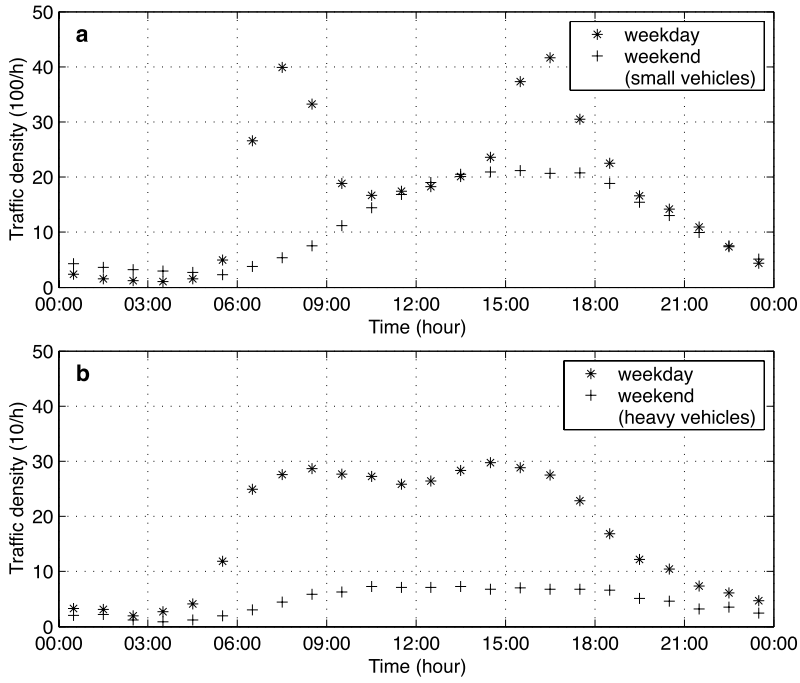

Fig. 3. Traffic density throughout the entire measurement period averaged for weekdays and weekends separately. — **a**: Small vehicles. — **b**: Heavy vehicles.

Traffic density

There were two daily patterns for each traffic type. The weekend daily pattern of the traffic density represents the background traffic density in the measurement site (Fig. 3a and b). On average, the daily patterns of the traffic density did not change throughout the entire period, while the daily total number of traveling vehicles increased by ~5% during the spring and by ~10% during the summer.

On weekdays two narrow peaks representing the morning and afternoon traffic rush hours characterized the traffic density of small vehicles, while during weekends there was one wide peak representing the daytime traffic rush hours (Fig. 3a). During the early morning hours, the traffic density of small vehicles was stronger on weekends in comparison with normal weekdays due to activities in downtown Helsinki. On a normal weekday, the morning traffic rush hours started around 05:00 and lasted until 10:00, whereas the afternoon traffic rush hours started around 14:00 and lasted until 19:00 (Fig. 3a). The traffic density of small vehicles was moderate (1500–2000 h^{-1}) during midday hours (10:00–14:00), and low (smaller than 1500 h^{-1}) at night and during the early morning hours (00:00–05:00). On weekends, the traffic activity started to increase around 07:00 and lasted until midnight, after which it continued to decrease until 04:00.

Two overlapped peaks characterized the traffic density of heavy vehicles on weekdays (Fig. 3b). The daytime rush hours started around 04:00 and ended around 22:00 with mean maximum ~300 h^{-1}. During weekends, a wide peak starting around 07:00 and lasting until 20:00 characterized the traffic density of heavy vehicles.

Total aerosol number concentration

In general, the daily averaged total aerosol number concentration had maximum values during November 1999 through March 2000 with rapid fluctuations between 2000 and 65 000 cm^{-3}. During the last four months of the measurement period, the total aerosol number concentration decreased and varied between

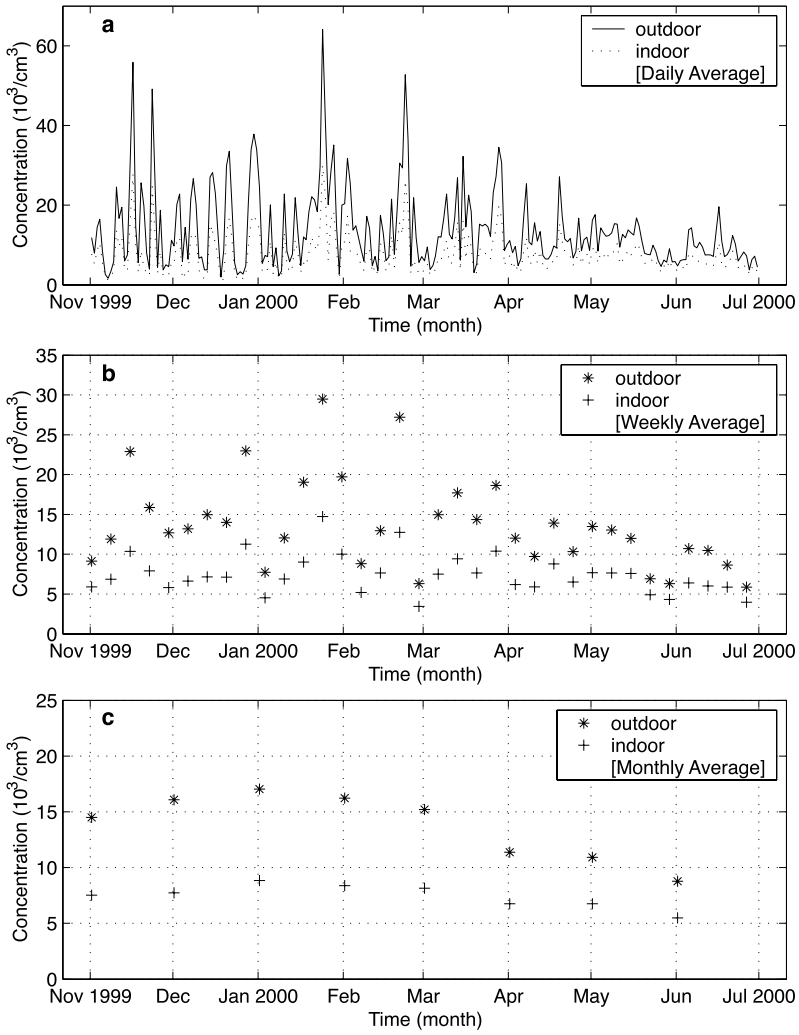

Fig. 4. Total aerosol number concentration throughout the entire measurement period. — **a**: daily average. — **b**: weekly average. — **c**: monthly average.

4000 and 25 000 cm^{-3} (Fig. 4a). The weekly averaged total aerosol number concentration displayed clearly the highest values during January 2000, and the lowest values during June 2000 (Fig. 4b). The monthly averaged total aerosol number concentration emphasizes this result (Fig. 4c, Tables 1 and 2).

Daily patterns for the total aerosol number concentration were observed. These patterns showed six characteristics during the measurement period. According to the daily pattern of the total aerosol number concentration, three periods were constructed to represent the different characteristics of the total aerosol number concentration. Two characteristics for every period were seen; a daily pattern for weekdays and another one for weekends. The first period was 1.11.1999–31.1.2000, and it was called the winter period. The second period, which was called the spring period, was 1.2.–15.4.2000. The last period was 16.4.–30.6.2000, and it represented the summer period. The daily pattern of the total aerosol number concentration during each period is shown in Fig. 5.

During the winter period, the aerosol number concentration outdoors varied between 6000 and 33 00 cm^{-3} on weekdays, and between 5000 and 14 000 cm^{-3} on weekends. The daily patterns on weekdays and weekends were clearly correlated with the traffic activity (Figs. 3 and 5a). The morning and afternoon traffic rush hour effect is clear in the patterns too. The daily averaged

outdoor total aerosol number concentration was about 18 000 and 8500 cm^{-3} for the weekdays and the weekends, respectively. The Pearson correlation between the weekday daily patterns of the outdoor total aerosol number concentration and the traffic density of all vehicles was equal to 0.93, and that of heavy vehicles equal to 0.95.

During the spring period, the outdoor daily pattern of the total aerosol number concentration for weekdays changed in shape, and varied between 9000 and 35 000 cm^{-3} (Fig. 5b). Even though the daily averaged total aerosol number concentration was about 16 000 cm^{-3}, which is smaller than that in the winter, the maximum registered value was higher. The correlation between the total aerosol number concentration and the daily pattern of the traffic density was still clear. The weekend daily pattern of the number concentration did not change completely; only the daily average increased by ~2500 cm^{-3} in comparison with the winter period. The Pearson correlation between the weekday daily patterns of the outdoor total aerosol number concentration and the traffic density of all vehicles was equal to 0.71, and that of heavy vehicles equal to 0.66.

The daily patterns of the number concentration changed clearly during the summer period (Fig. 5c). The daily average of the total aerosol number concentration on weekdays decreased to about 10 600 cm^{-3}, whereas during the weekends it was about 9100 cm^{-3} which is an intermediate between the values obtained during the winter and the spring periods. The daily pattern correlation between the number concentration and the traffic density is not clear during this period. The Pearson correlation between weekday daily patterns of the outdoor total aerosol number concentration and the traffic density of all vehicles was equal to 0.06, and that of heavy vehicles equal to 0.11.

Since there were remarkable differences between the weekdays and weekends in the daily patterns of the total aerosol number concentration, it is likely that the traffic density influenced the total aerosol number concentration. However, the meteorological conditions were the most important factor in controlling the aerosol characteristics. In other words, the aerosol number concentration (on weekdays, weekends, and at night) was clearly correlated with the traffic density during the winter. When the meteorological conditions changed during the

Table 1. Characteristics of the total aerosol number concentration indoors.

	Number Conc. (cm^{-3})		
	Minimum	Maximum	Average
Hourly: Winter (1.11.1999–31.1.200)	431.19	53718.87	8044.65
Hourly: Spring (1.2.–15.4.2000)	911.35	77846.39	7810.82
Hourly: Summer (16.4.–30.6.2000)	267.20	36747.26	6408.47
Daily	961.67	29960.02	7448.55
Weekly	3441.28	14733.18	7430.84
Monthly	5482.36	8844.89	7454.34

Table 2. Characteristics of the total aerosol number concentration outdoors.

	Number Conc. (cm^{-3})		
	Minimum	Maximum	Average
Hourly: Winter (1.11.1999–31.1.200)	547.11	116539.42	15895.80
Hourly: Spring (1.2.–15.4.2000)	1184.23	143598.73	14741.91
Hourly: Summer (16.4.–30.6.2000)	370.09	75077.02	10264.31
Daily	1675.23	64147.85	13761.12
Weekly	5867.50	29470.25	13713.40
Monthly	8764.07	17036.35	13765.44

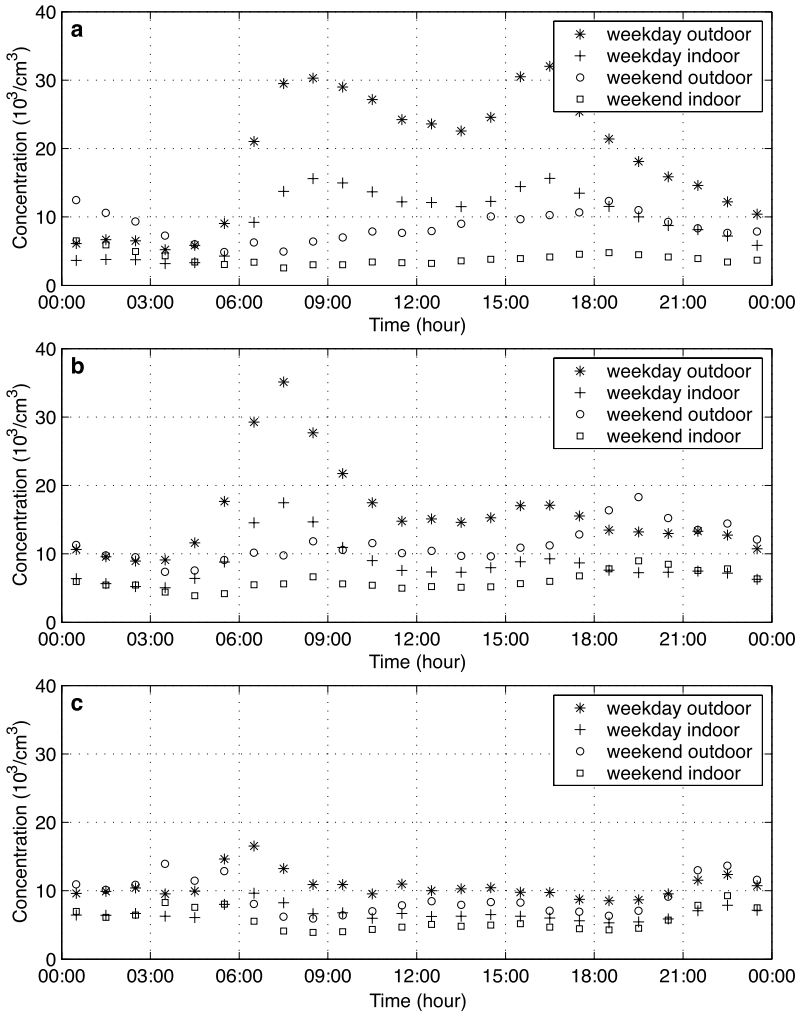

Fig. 5. Seasonal variation of the total aerosol number concentration. The average was calculated separately for weekdays and weekends. — **a**: Winter (1.11.1999–31.1.2000). — **b**: spring (1.2.–15.4.2000). — **c**: summer (16.4.–30.6.2000).

spring and summer, the daily pattern of the aerosol number concentration changed accordingly, and lower correlations were obtained during the spring and summer periods.

As demonstrated in an earlier study (Buzorius *et al.* 1999), rapid temporal variations in aerosol concentrations can be related to direct traffic emissions as well as re-emissions of deposited dust on the road surface in connection with traffic activity and meteorological conditions such as cold, warm, windy, and/or humid weather conditions. The fine particle concentrations over a reasonably large region of Helsinki follow very similar temporal patterns, with spatial differences occurring mainly in absolute concentrations which are lower at more remote areas (Buzorius *et al.* 1999, Väkevä *et al.* 1999, Koponen *et al.* 2001). Therefore, we expected that the time behavior of aerosol concentrations could be reasonably well generalized over the entire Helsinki region. Furthermore, meteorological conditions contribute the most in affecting the temporal variation of pollutant concentrations in both suburban and urban areas.

Indoor-to-outdoor aerosol relationship

Indoor and outdoor aerosol concentrations were directly correlated to each other, and the indoor aerosol number concentration followed that of outdoors with a short delay. The correlation

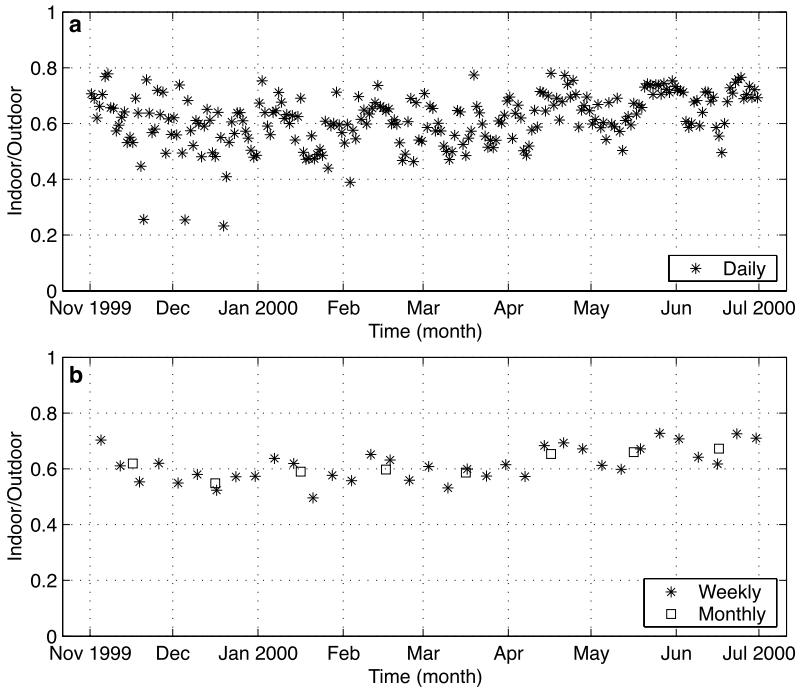

Fig. 6. Indoor/outdoor concentration ratio throughout the entire measurement period. — **a**: Daily averaged. — **b**: weekly and monthly averaged.

between indoor and outdoor aerosol number concentration was higher than 0.95. Throughout the entire measurement period, the total aerosol number concentration indoors showed minor variations, while outdoor number concentrations varied considerably. On average, the I/O ratio was equal to 0.58 during December 1999 through March 2000, and equal to 0.66 during April through June 2000 (Fig. 6).

Since the ventilation air supply was operating continuously with a relatively high ventilation rate (~3 h^{-1}), we observed a rapid response in the indoor aerosol number concentration following that outdoors with a small delay time. Since the inflow pump in the mechanical ventilation system was operating continuously to blow air indoors, a steady-state condition for the particle exchange rate between indoors and outdoors was obviously attained.

In this study we obtained larger I/O ratios than those obtained by Koponen *et al.* (2001). However, both studies showed I/O ratios smaller than unity. The larger I/O ratios found by us can partly be related to the filter class installed in the ventilation system; in this study EU3-class filter was used, while EU7-class was used by Koponen *et al.* (2001). The filtration efficiency of EU3-class filters is smaller than that of EU7-class filters.

Conclusions

Long-term indoor and outdoor total aerosol number concentrations were measured in an office building close to a main highway leading out of downtown Helsinki. The main purpose of this study was to investigate the temporal variation of the aerosol concentration close to a highway in a suburban area throughout seasons. It can be summarized that the aerosol properties were mostly influenced by meteorological conditions. The wind was the main factor in affecting the measured pollution level by transporting pollutants to the site. The traffic density was characterized by two different daily patterns according to weekdays and weekends. The measurement period covered the winter, spring and summer seasons, and accordingly the variation of the meteorological conditions affected the daily pattern of the total aerosol number concentration. According to the traffic density variation

(weekdays and weekends) and the seasonal variation (three seasons), a total of six different daily patterns for the total aerosol number concentration were observed outdoors.

Another purpose of this study was to study the indoor-to-outdoor relationship of aerosols. The indoor aerosol characterization followed the same pattern as that of outdoors, but with a short delay. The indoor/outdoor (I/O) concentration ratio analysis showed relatively constant values of smaller than unity during each season. This was related to the continuous operation of the mechanical ventilation system. Aerosols originated mainly from outdoors, as the I/O ratio was smaller than unity throughout the entire measurement period.

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