THE SPATIAL AND TEMPORAL VARIATION OF MEASURED URBAN PM_{10} AND $PM_{2.5}$ IN THE HELSINKI METROPOLITAN AREA

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Abstract. We have studied particulate matter (PM) concentrations, PM_{10} and $PM_{2.5}$, measured in an urban air quality monitoring network in the Helsinki Metropolitan Area during 1997–1999. The data includes PM_{10} concentrations measured at five locations (two urban traffic, one suburban traffic, one urban background and one regional background site) and $PM_{2.5}$ concentrations measured at two locations (urban traffic and urban background sites). The concentrations of PM_{10} show a clear diurnal variation, as well as a spatial variation within the area. By contrast, both the spatial and temporal variation of the $PM_{2.5}$ concentrations was moderate. We have analysed the evolution of urban PM concentrations in terms of the relevant meteorological parameters in the course of one selected peak pollution episode during 21–31 March, 1998. The meteorological variables considered included wind speed and direction, ambient temperature, precipitation, relative humidity, atmospheric pressure at the ground level, atmospheric stability and mixing height. The elevated PM concentrations during the 1998 March episode were clearly related to conditions of high atmospheric pressure, relatively low ambient temperatures and low wind speeds in predominantly stable atmospheric conditions. The results provide indirect evidence indicating that the PM_{10} concentrations originate mainly from local vehicular traffic (direct emissions and resuspension), while the $PM_{2.5}$ concentrations are mostly of regionally and long-range transported origin.

Keywords: air pollution, episode, meteorology, particulate matter, $PM_{2.5}$, PM_{10}, resuspension, urban

1. Introduction

Particulate matter concentrations, measured as PM_{10} and particularly as $PM_{2.5}$, have been associated with hospital admissions and mortality in several studies conducted both in Europe and the U.S.A. (Katsouyanni *et al.*, 1997; Schwartz *et al.*, 1996; Dockery and Pope, 1994; Pope *et al.*, 1995). Airborne particulate matter originates not only directly from combustion processes, but also from resuspension from street surfaces. In spring, after the snow has melted and streets dry out, particles from street surfaces are resuspended by traffic induced turbulence and wind. The influence of resuspension depends on the mechanical wear of the street surfaces, on street maintenance and cleaning – particularly the winter time sanding of streets –, on traffic-induced turbulence and on meteorological conditions.

Water, Air, and Soil Pollution: Focus **2:** 189–201, 2002.

In Finland, studded tyres are in widespread use in vehicular traffic in winter, increasing street surface wear. Resuspension also commonly takes place in late autumn, probably due to the start of street salting and sanding (e.g., Kukkonen *et al*., 1999, 2000). Snow can melt several times before a permanent snow cover is obtained. In Northern and Central European cities, resuspended PM can have a substantial influence particularly on total suspended particles (TSP), but also on PM_{10} concentrations (for instance, Hämekoski and Salonen (1996) and Johansson *et al*. (1999)).

Previously, measured urban PM_{10} and $PM_{2.5}$ concentrations and their spatial and temporal variations in Europe have been discussed by, e.g. Monn *et al*. (1995), Harrison *et al*. (1997), Kingham *et al*. (2000), Johansson *et al*. (1999) and Ojanen *et al*. (1998). Buzorius *et al*. (1999) have analysed PM number concentrations (from 10 to 500 nm in particle diameter) in the city of Helsinki. However, the amount of data and the time periods considered in the above-mentioned studies have been fairly limited. In some studies carried out in North America, more extensive time periods have been addressed (Brook *et al*., 1999; Darlington *et al*., 1997). Most previous studies have not addressed systematically the influence of the relevant meteorological parameters on urban PM concentrations; Monn *et al*. (1995), however, did consider briefly the dependencies of PM_{10} concentrations on some selected meteorological parameters.

The objective of this article is to analyse and interpret $PM_{2.5}$ and PM_{10} measurements carried out in the Helsinki Metropolitan Area. We have previously analysed the PM concentrations in these years on a seasonal basis (Pohjola *et al*., 2000). We have investigated the diurnal variation of $PM_{2.5}$ and PM_{10} during 1997–1999. We also analysed a spring episode of exceptionally high PM concentrations in 1998.

2. Methodology

2.1. Monitoring sites

Figure 1 shows the location of the air quality monitoring stations in the Helsinki metropolitan area and the pollutants monitored in 1999. Many of these stations have been located for the purpose of monitoring 'hot spots' near busy traffic environments, or major local energy production sources. The network contains six permanent multicomponent stations; these are located in Helsinki city districts (Töölö, Vallila and Kallio 2), in suburban in the cities of Espoo and Vantaa centres (Leppävaara and Tikkurila), and in a rural area in Espoo (Luukki).

The stations used in this study represent urban (Töölö and Vallila) and suburban traffic environments (Leppävaara), together with the urban background (Kallio 2). Regional background concentrations were monitored in a rural environment in Luukki, approximately 20 km to the north-west of downtown Helsinki.

Two urban monitoring stations, Töölö and Vallila, are located in the Helsinki downtown area. The station of Töölö is situated in a small square in a busy cross-

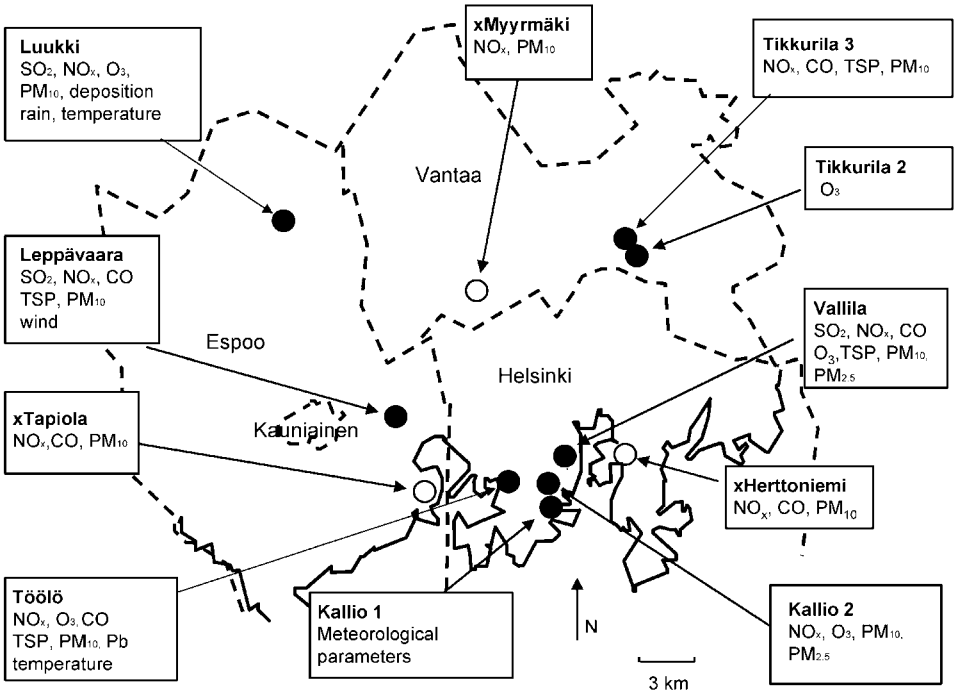

Figure 1. Urban air quality monitoring network in the Helsinki Metropolitan Area in 1999. The legends show the name of the station and the pollutants measured. X indicates a mobile station.

ing area, surrounded by several buildings. This station is situated at a distance of less than 10 m from streets with traffic volumes of approximately 50 000 vehicles per day during weekdays. The station of Vallila is situated in a small park, at the distance of about 14 m from a street with 13 000 vehicles per day during weekdays.

The suburban station of Leppävaara in Espoo is situated in a shopping and residential area. The distances of this station to three nearest roads are approximately 25, 50 and 100 m; the traffic volumes of these roads are 11 000, 29 000 and 63 000 vehicles per day during weekdays, respectively.

The monitoring height is 4.0 m at all stations, except for the regional background station at Luukki, where the probe is at a height of 7.0 m. The $PM_{2.5}$ measurements were started at the Vallila site in March 1997, and at the Kallio 2 and Luukki sites in the beginning of 1999.

2.2. Monitoring Methods

At the stations of Töölö and Leppävaara, the concentration of PM_{10} was measured with TEOM (Tapered Element Oscillating Microbalance). At the stations of Vallila, Kallio 2 and Luukki, the concentration of PM_{10} was measured with Eberline FH 62 I-R that is based on β-attenuation method. At the stations of Vallila and Kallio 2, the concentration of $PM_{2.5}$ was also measured with Eberline FH 62 I-R. The flow

rate of the PM analysers was calibrated twice a year and the mass measurement once a year.

The accuracy of continuous PM monitoring devices is dependent on the chemical composition of the PM and local meteorological conditions, due to possible evaporation of semi-volatile material. The daily average concentrations of PM_{10} and $PM_{2.5}$, determined by the Eberline FH 62 I-R analysers, were therefore compared with the corresponding results obtained by virtual impactors. These comparisons were performed at the station of Vallila during one year, from June 1999 to May 2000.

Plotting the concentrations obtained with the Eberline analyser against those obtained with the virtual impactor yields the following results. For the concentrations of PM_{10}, the slope of the regression line (k) was 1.02, the constant term (d) was – 0.31 μg m^{-3}, and the correlation coefficient squared (R^2) was 0.95. For the concentrations of $PM_{2.5}$, k = 0.98, d = +0.03 μg m^{-3}, and R^2 = 0.91. Field intercomparisons have also been conducted, in which the concentrations of PM_{10} obtained by TEOM monitors have been compared with those obtained by other corresponding methods; these have also indicated a good agreement of results (Sillanpää *et al.*, 2001).

2.3. Meteorological methods

We used the meteorological database of the Finnish Meteorological Institute, which contains weather and sounding observations. We used a combination of the data from the stations at Helsinki-Vantaa airport (about 15 km north of Helsinki town centre) and Helsinki-Isosaari (an island about 20 km south of Helsinki). The mixing height of the atmospheric boundary layer was evaluated using the meteorological pre-processor, based on the sounding observations made at Jokioinen (90 km northwest of Helsinki) and on routine meteorological observations.

The relevant meteorological parameters were evaluated using a meteorological pre-processing model, adapted specifically for urban environment (Karppinen *et al.*, 1998, 2000). The model is based mainly on the energy budget method of Van Ulden and Holtslag (1985). The model utilises meteorological synoptic and sounding observations, and its output consists of hourly time series of relevant atmospheric turbulence parameters (the Monin-Obukhov length scale, the friction velocity and the convective velocity scale) and the boundary layer height. Atmospheric stability was evaluated using a dimensionless stability parameter (Karppinen *et al.*, 1998).

3. Results and Discussion

3.1. Diurnal variation of $PM_{2.5}$ and PM_{10} concentrations

Data has been compiled on the diurnal variation of the PM_{10} and $PM_{2.5}$ concentrations at the various monitoring stations during 1997–1999. As an example, we have presented the diurnal variation of PM_{10} concentrations at the various stations in Figures 2a–c, averaged over each of the years 1997–1999, and $PM_{2.5}$ concentrations at Vallila averaged over the same years and additionally at Kallio 2 in 1999 in Figures 3a–b. Clearly, the diurnal variation of traffic-originated pollutant concentrations depends on the day of the week; for these figures we have selected data from working days (Monday–Friday) only.

The concentrations of PM_{10} show a clear diurnal variation. The concentrations increase continuously during the morning rush hours, from approximately 6 to 8 a.m.; as expected, this increase took place irrespective of the year (during the period 1997–1999) and the season of the year. Subsequently the concentrations decrease slowly during the rest of the daytime hours, also showing in some cases peak values during the afternoon rush hours, from approximately 3 to 6 p.m. The more moderate diurnal variation of the PM_{10} concentrations, compared with the traffic flows, could be caused by resuspension of PM from street surfaces. Resuspended PM increases with increasing traffic flow; however, it can reach a saturated state, in which a further increase of traffic cannot cause any more resuspension.

During working days, there is a very clear diurnal variation of local vehicular traffic. Despite this, the $PM_{2.5}$ concentrations are temporally fairly uniform during working days, except for a moderate increase during the morning rush hours. The diurnal variation of local vehicular traffic flows seems to have no substantial correlation with the $PM_{2.5}$ concentrations. In 1999, the temporal variation of $PM_{2.5}$ concentrations at both monitoring stations was also very similar. This indicates that the PM resuspended from street surfaces and other sources has only a minor effect on the $PM_{2.5}$ concentrations, and that a large fraction of the $PM_{2.5}$ concentrations most likely originates from regional or long-range scale sources. This result is qualitatively in agreement with the results by Ojanen *et al.* (1998); for the station of Vallila in 1996–1997, they evaluated that approximately 40% of the $PM_{2.5}$ concentration originated from local sources, and the rest of the $PM_{2.5}$ mass from regional or long-range transported pollution.

Both for PM_{10} and $PM_{2.5}$, the concentrations at night are higher than would be expected based on the diurnal variation of local vehicular traffic emissions. This is partly caused by commonly occurring unfavourable atmospheric diffusion conditions at night, e.g., low wind speed, stable stratification and ground-level or low-altitude inversions (Karppinen *et al.*, 2000).

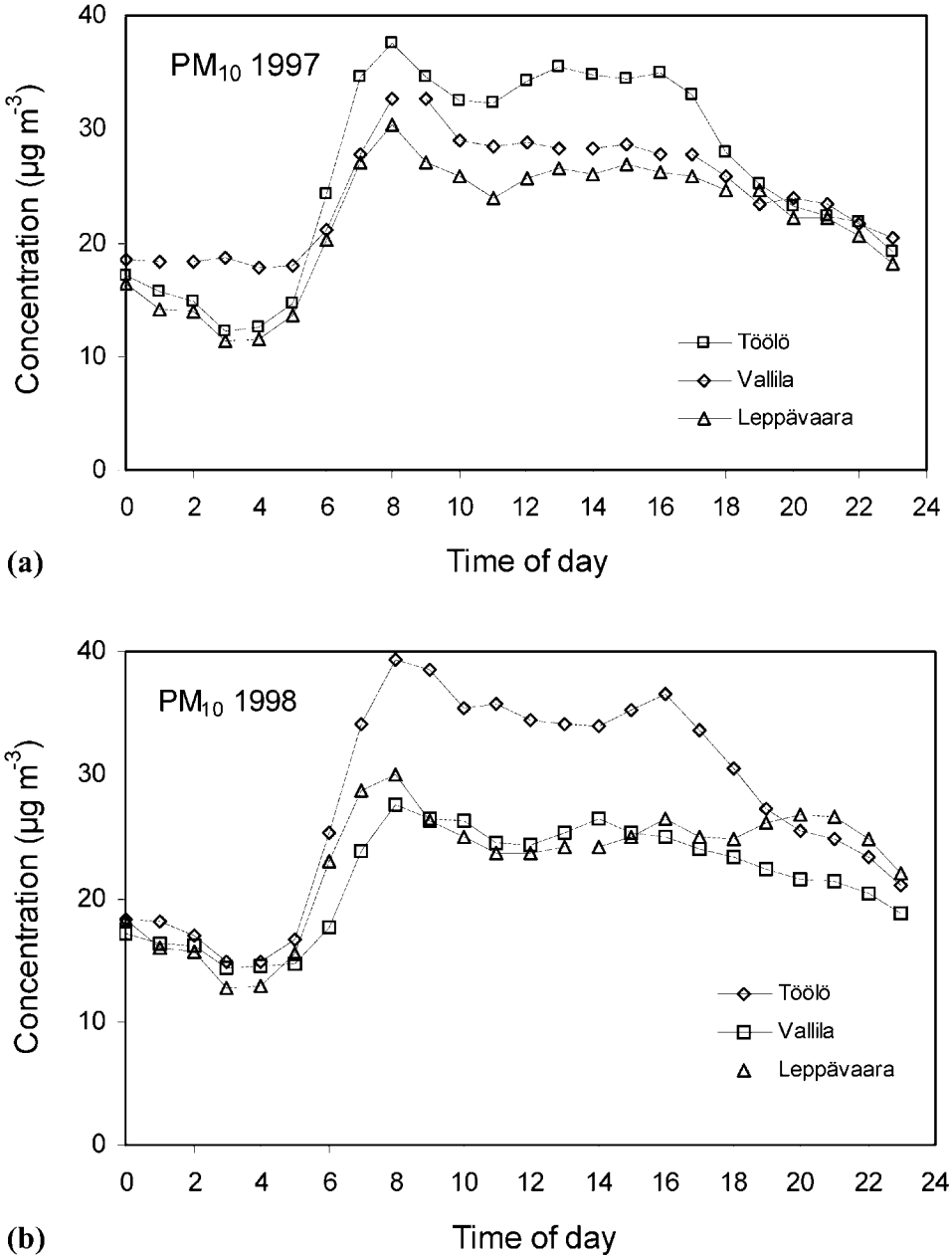

Figure 2. The diurnal variation of PM_{10} concentrations at the stations of Töölö, Vallila and Leppävaara during 1997–1999, and at the station of Luukki, during 1999. Figures include data from working days only.

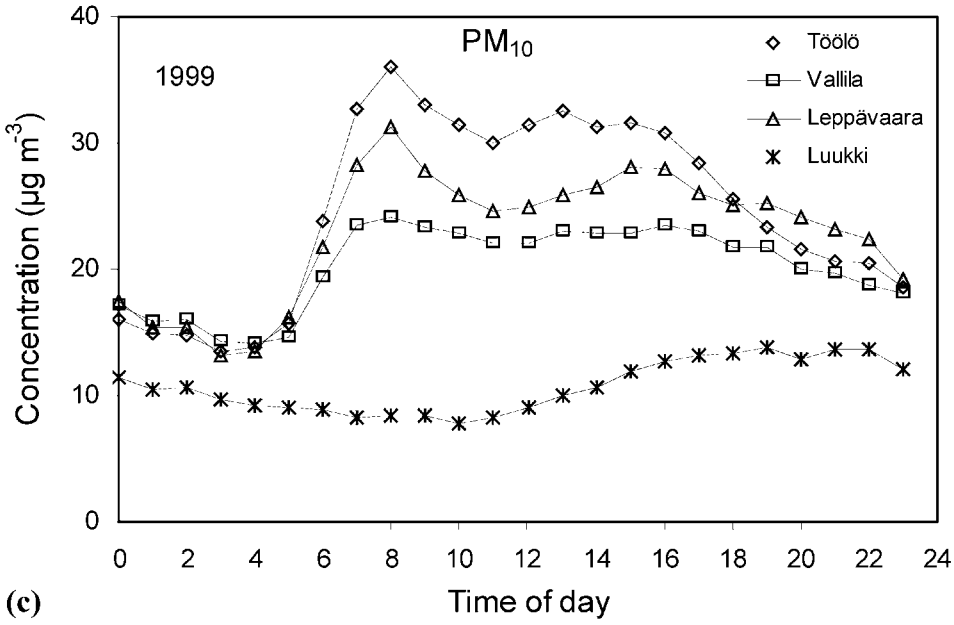

Figure 2. (continued).

3.2. THE PM EPISODE DURING 21–31 MARCH 1998

In the Helsinki Metropolitan Area as in other major Finnish cities, episodes of high PM concentrations take place particularly in spring. An example has been presented in Figure 4 of the evolution of PM concentrations in the course of such an episode. The PM_{10} concentrations were approximately at their highest level during 21–31 March 1998. The weekends are on 21–22 March and 28–29 March. During this episode, the highest hourly average PM_{10} concentration was measured at Töölö (306 μg m^{-3}) on 24 March. The second highest hourly PM_{10} concentration occurred at Töölö on 27 March (180 μg m^{-3}). The PM_{10} concentrations were at an elevated level (compared with the longer term average values) during two periods, 22–24 and 27–31 March.

We have analysed the hourly evolution of the relevant meteorological parameters during the episode. The atmospheric pressure, shown in Figure 5a, rapidly increased during 21–23 March, reaching a maximum value (approximately 1045 mbar) on 23 March. The pressure subsequently decreased during 24–27 March, and increased again to reach another local maximum value (approximately 1023 mbar) on 29 March. The ambient temperature (measured at a height of 2 m), shown in Figure 5a, had a substantial diurnal variation, during 21–25 March it varied from a minimum value of –10 °C (at night) to a maximum value of +4 °C (in the afternoon), while during the period 26–31 March the corresponding variation was from –4 to +6 °C.

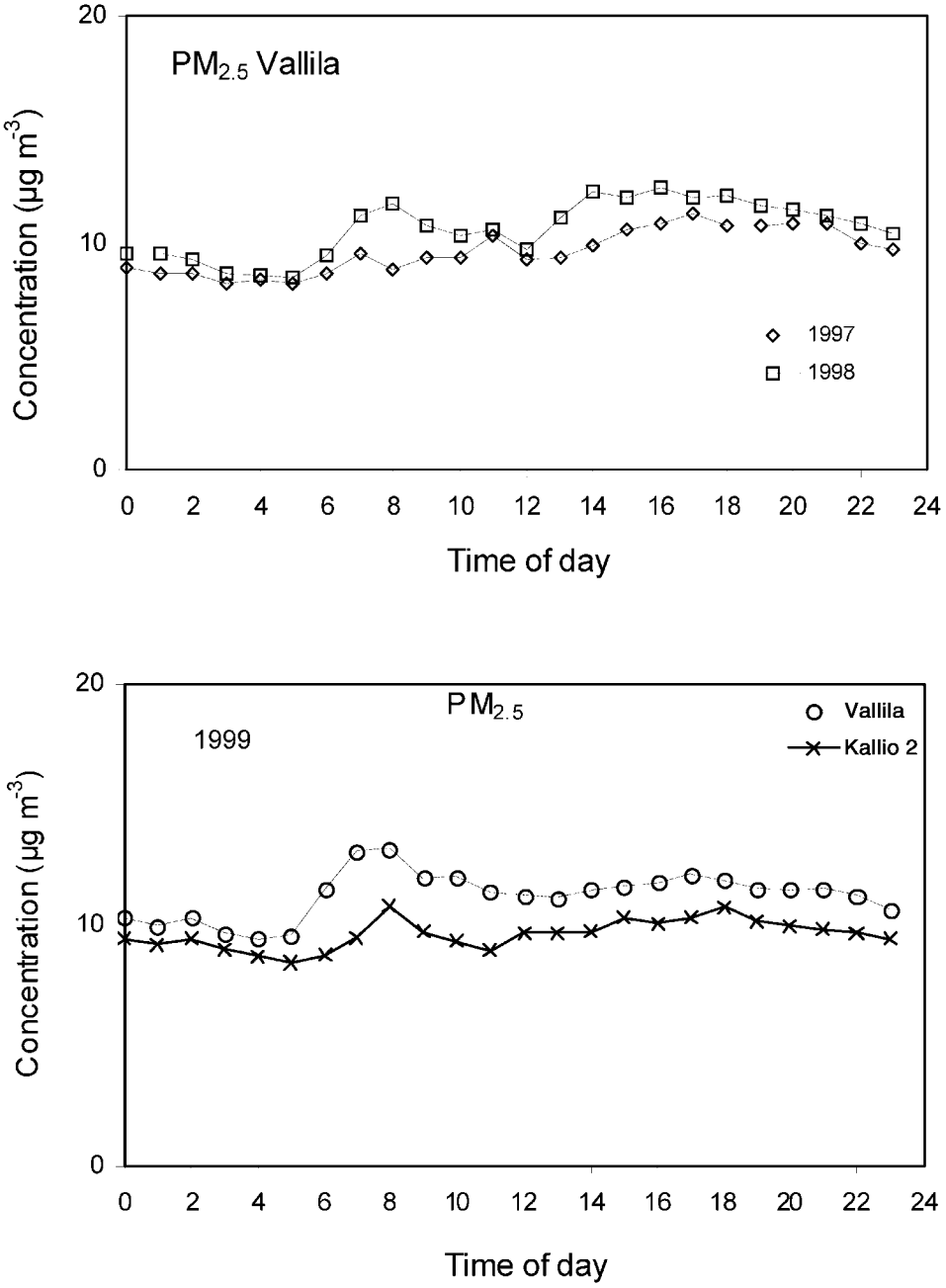

Figure 3. The diurnal variation of $PM_{2.5}$ concentrations at the station of Vallila during 1997–1998, and at the stations of Vallila and Kallio 2 during 1999. Figures include data from working days only.

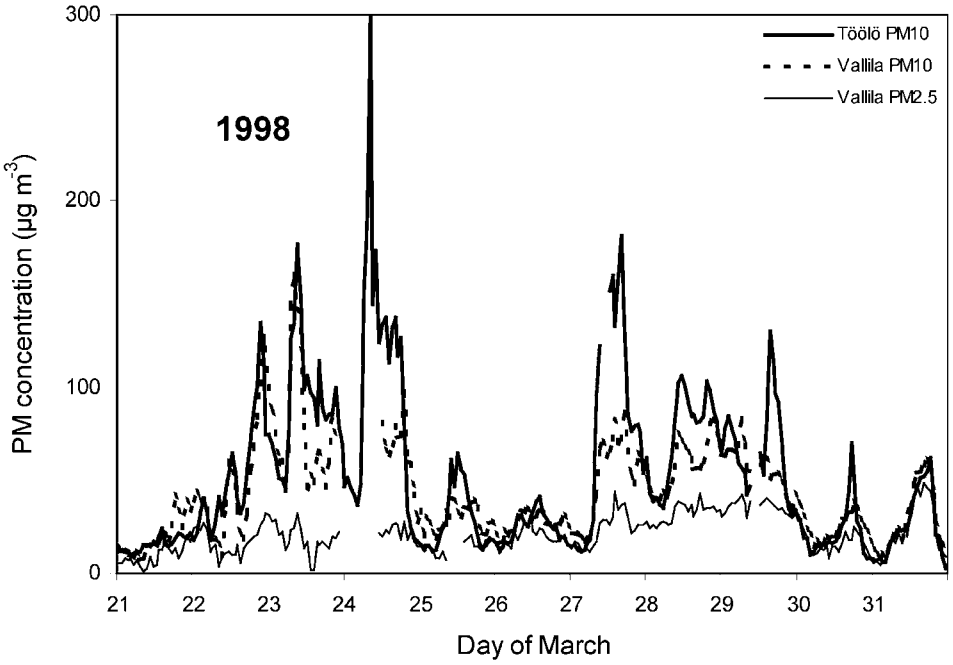

Figure 4. The evolution of the PM_{10} and $PM_{2.5}$ concentrations in the course of the air pollution episode during 21–31 March 1998, at the stations at Töölö and Vallila.

In the early stages of the episode during the period 22–24 March, the wind speed (measured at a height of 10 m), shown in Figure 5b, was very low, ranging from 1.0 to 2.5 m s^{-1}; during the latter period of 25–31 March it was occasionally higher, ranging from 1.0 to 5.0 m s^{-1}. The wind direction was initially predominantly southerly and south-westerly. The atmospheric stability was evaluated based on the dimensionless stability parameter p_q (as defined by Karppinen *et al.*, 1998). Atmospheric stratification showed a substantial diurnal variation (the parameter p_q ranged from a minimum value of –2.5 to a maximum of +2.2). Moderately or extremely stable atmospheric conditions prevailed during most of the period.

The period considered contains two shorter periods with substantially elevated PM concentrations, during 22–24 and 27–31 March (Figure 4). Both of these periods of high concentrations were clearly related to conditions of high atmospheric pressure and relatively low ambient temperatures. The elevated PM concentrations during both 22–24 and 27–31 March were caused by low wind speeds in predominantly stable atmospheric conditions. It is interesting to compare the atmospheric conditions during the two above-mentioned time periods. During the former period, the maximum value of atmospheric pressure was higher, the ambient temperatures were slightly lower and the wind speeds were on the average lower, compared with the latter period. All of these meteorological parameter values would imply a more severe episode during the former period; the maximum concentrations were indeed

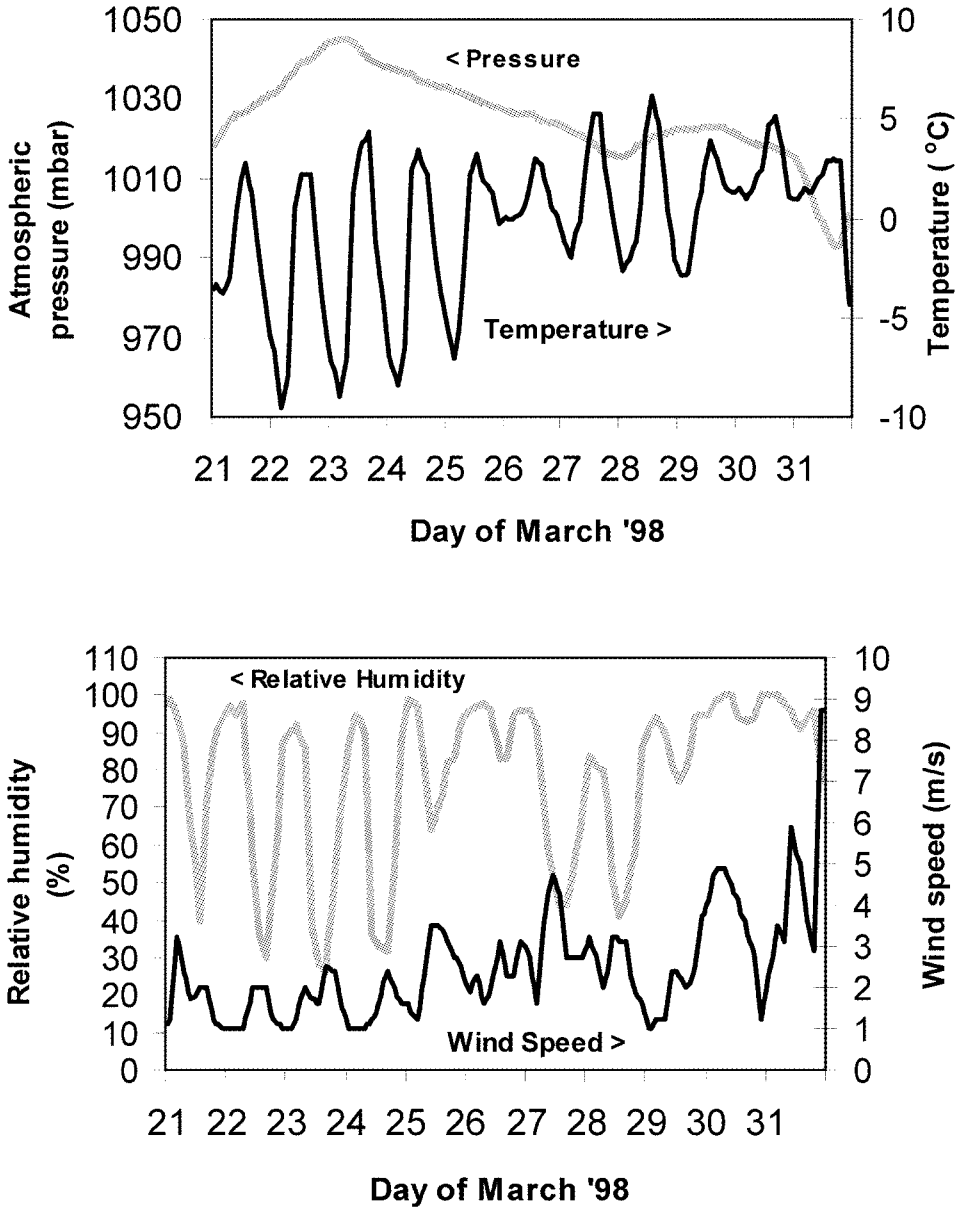

Figure 5. The evolution of atmospheric pressure and relative humidity (left-hand-side vertical axis) and temperature and wind speed (right-hand-side vertical axis) in the course of the air pollution episode during 21–31 March 1998.

higher on 24 March, compared with the corresponding maximum values during the latter period on 27 March.

The latter period of elevated PM concentrations occurred partly during the weekend on 28 and 29 March. The relatively lower concentrations during those days, compared with those on 27 March, were probably mainly caused by lower emissions of PM originated from local traffic. For instance, the annual averages of the total traffic volumes during weekends were approximately 62% of those during weekdays from Monday to Friday in central Helsinki in 2000 (Lilleberg *et al.*, 2001).

At the Vallila monitoring site, the highest hourly average $PM_{2.5}$ concentration (49 μg m^{-3}) was measured on 31 March (unfortunately, part of the $PM_{2.5}$ measurements are not available on 24 March). The $PM_{2.5}$ concentrations on this particular day were almost identical to the corresponding PM_{10} concentrations at both monitoring stations considered. This indicates that the influence of resuspension was negligible, and that the polluted air masses could have been of long-range transported origin on that particular day.

4. Conclusions

The diurnal variation of the PM_{10} concentrations was clear, irrespective of the year and the season of the year. This variation partly follows the corresponding variation of local vehicular traffic flows. On the other hand, both the spatial and temporal variation of the fine particle ($PM_{2.5}$) concentrations was moderate. The results provide indirect evidence indicating that the PM_{10} concentrations are originated mainly from local vehicular traffic (direct emissions and resuspension), while the $PM_{2.5}$ concentrations are mostly of regionally and long-range transported origin. This result is qualitatively in agreement with source apportionment studies in the same area (Ojanen *et al.*, 1998).

We have also analysed the evolution of urban PM concentrations in terms of the relevant meteorological parameters in the course of a selected peak pollution episode during 21–31 March, 1998. The episode was related to an anticyclonic high-pressure system, and the highest concentrations were connected with conditions of exceptionally high atmospheric pressure and relatively low ambient temperatures. The elevated PM concentrations were caused by low wind speeds and predominantly stable atmospheric stratification. The polluted air masses could have partly been of long-range transported origin; however, a detailed analysis would require air parcel trajectory analyses.

Acknowledgements

This study has been part of the National Research Programme on Environmental Health (SYTTY), the project 'Development of a population exposure model, using atmospheric dispersion modelling together with measured concentrations and personal exposures – EXPAND', 1998–2001, and the international research programme EUROTRAC-2, SATURN, 'Studying Atmospheric Pollution in Urban Areas', 1998–2001. The funding from the Academy of Finland for both studies is gratefully acknowledged.

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