Supplement

Scand J Work Environ Health 2004;30(2):28-35

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The following articles refer to this text: 2004;30 suppl 2:36-46; 2004;30 suppl 2:73-79; 2004;30 suppl 2:80-90

Key terms: air pollution; air quality; black carbon; dust; elemental composition; particle size distribution; particulate matter; resuspension; subarctic region; urban air quality

This article in PubMed: www.ncbi.nlm.nih.gov/pubmed/15487683

Original article

Scand J Work Environ Health 2004;30 suppl 2:28–35

Resuspended dust episodes as an urban air-quality problem in subarctic regions

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Hosiokangas J, Vallius M, Ruuskanen J, Mirme A, Pekkanen J. Resuspended dust episodes as an urban air-quality problem in subarctic regions. Scand J Work Environ Health 2004;30 suppl 2:28–35.

Objectives This paper describes the resuspension of road dust in an urban subarctic environment and focuses especially on the effect of wind speed on the formation of resuspended dust episodes.

Methods The study was conducted in Kuopio, Finland, in the spring of 1995. There were 36 daily measurements of mass concentrations of fine particulate matter ($PM_{2.5}$), thoracic particulate matter (PM_{10}), total suspended particulate matter, black carbon and carbon monoxide; size-segregated number concentrations of particles (diameter range 0.01–10 μm); and meteorological parameters. Total elemental compositions of $PM_{2.5}$ and PM_{10} samples were analyzed with inductively coupled plasma mass spectrometry.

Results The mass and number concentrations of particles in all the size ranges and the concentrations of soil-derived (iron) and combustion-derived (vanadium and lead) elements in the $PM_{2.5}$ and PM_{10} increased during the dust episodes. The daily average wind speed dually affected the episodes. The pollutant concentrations increased at wind speeds of <4 m/s and >5 m/s. The former was related to inversion-type conditions characterized by low wind speeds, while the latter was likely to be due to wind-blown resuspended dust. Resuspended lead accounted for an average of 27% of the total lead, and resuspended vanadium for 46% of the total vanadium in $PM_{2.5}$.

Conclusions Resuspended dust episodes were related to both low and high wind speeds, and the relationship suggests that factors other than wind speed, such as turbulence induced by traffic, affect the emergence of such episodes. The contribution of elevated levels of crustal material and toxic metals in resuspended $PM_{2.5}$ to human adverse health effects should be investigated.

Key terms air pollution, black carbon, elemental composition, particle size distribution, particulate matter, resuspension.

The term "resuspension" refers to an emission of previously deposited materials into the atmosphere, whereas the term suspension is used if the material has not previously been deposited by an atmospheric process (1). As suspension and resuspension usually take place at the same time, it is not easy to distinguish between the two. There are several inducers of resuspension, such as wind, traffic and agricultural processes (1). These inducers vary in importance from place to place, and no universal order of importance can be defined. Wind tunnel experiments have suggested that an increased resuspension rate is associated with increased wind speed and particle size (2). Moreover, coarse particles have been more easily resuspended than fine particles from road surfaces due to the passage of vehicles (3).

Resuspended dust episodes are a common problem in many subarctic cities every spring. Usually the concentrations of particulate matter in the ambient air of these towns and cities are relatively low, but resuspended dust episodes can raise the levels to exceed the national air quality guidelines, for example, the Finnish guidelines for total suspended particulate matter (TSP) (120 μg/m^3, 98th percentile of annual daily averages) and for particulate matter with an aerodynamic diameter of <10 μm (PM_{10}) (70 μg/m^3, second highest daily average concentration in a month) (4). In subarctic regions, resuspended dust episodes usually occur in March-April, when the snow and ice have melted and the streets have dried to reveal the sand that has been spread during the winter to prevent slipperiness. Studded

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tires, which are commonly used on vehicles in Finland, grind the sand particles smaller and erode the road surface. A similar effect has been reported for soil-derived particles also during late autumn (5), probably because of studded tires being put on vehicles for the coming winter.

It has been assumed that the high concentrations of particulate matter during resuspended dust episodes are caused mainly by coarse particles derived from soil and road surfaces. Only few measurements of elemental concentrations or particle-size distributions have been carried out during these episodes, although this information would be important in the assessment of possible health risks posed by anthropogenic resuspended dust. It has been suggested that the large number of ultrafine particles (0.01–0.1 μm in diameter) in urban air (6) or the chemical composition of particles (7, 8) would be the main causative factors for adverse health effects. In a Finnish study (9), crustal PM_{10} had no effect on the respiratory health of adult asthmatic subjects, and in a study carried out in the United States (US) high coarse particle concentrations were not associated with increased mortality (10). However, in another US study (11), rather low ambient-air concentrations of coarse crustal material were associated with an increase in daily outpatient visits for asthma and upper respiratory illness. Laden et al (12) found that particulate matter with an aerodynamic diameter of <2.5 μm ($PM_{2.5}$) from mobile and coal combustion sources, but not crustal fine particles, were associated with increased daily mortality.

Our aim was to study the effect of wind speed on the formation of resuspended dust episodes in a subarctic urban setting. The dust episodes were characterized by measurements of mass concentrations of particulate fractions, size-segregated particle number concentrations, and the elemental composition of particulate fractions during the study period.

Material and methods

This study was carried out in Kuopio, a town of approximately 85 000 inhabitants in eastern Finland. The town center is located on a peninsula that extends into Lake Kallavesi, and its main stationary air pollution sources are a peat-fired power station connected to a municipal district heating system, a chipboard factory, and a few oil-fired industrial power plants, as presented in figure 1. The air quality measurements were conducted near the town center, at a monitoring station belonging to the environmental office of the municipality. The measurement site was located next to a park area alongside a 2-story office building, and about 40 meters from the nearest busy street, on which the average traffic density was about 14 000 cars per 24 hours on weekdays, 11 000 cars on Saturdays, and 9000 cars on Sundays. The sampling height was 4 meters from the ground.

The following measurements were carried out for 36 days between 19 March and 23 April 1995: mass concentrations of TSP, PM_{10}, $PM_{2.5}$, carbon monoxide (CO) and black carbon (BC); size-segregated number concentrations of particles ranging from 0.01 μm to 10 μm in diameter; and meteorological parameters, including temperature, wind speed, and wind direction. All the measurement data were calculated to represent 24-hour average concentrations from noon to noon, labeled with the date of commencement of the measurements.

TSP matter was measured with a high-volume sampler based on standard NAAQS 40 CFR 50 of the US Environmental Protection Agency, and PM_{10} and $PM_{2.5}$ were measured with single-stage impactors at an airflow rate of 10 l/min (Air Diagnostic & Engineering Inc, Naples, ME, USA), similar to the instrument described by Marple et al (13). The particles were collected on a 37-mm teflon filter with a 2-μm pore size. The sampling flow was controlled with a critical orifice and measured both before and after the measurement period with a calibrated flowmeter. The filters were weighed on a microbalance before and after the sampling. Because the humidity control in the weighing room was unreliable, the effect of humidity on the filter weights was eliminated by means of a correction factor corresponding to the change in weight of a set of control filters, stored permanently in the weighing room and weighed every time sample filters were weighed. Their weight change

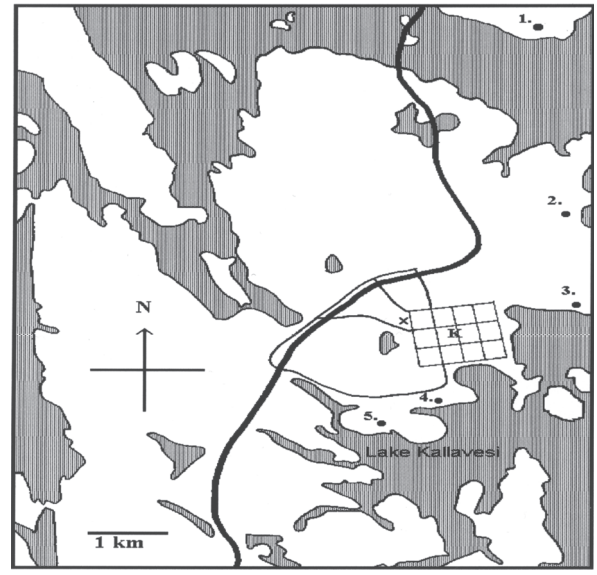

Figure 1. Major stationary sources of atmospheric particles and the busiest highway and streets representing the location of major mobile sources in the Kuopio area (1 = pulp mill, 2 = industrial power plant, 3 = chipboard factory, 4 = peat-fired power station, 5 = industrial power plant, X = measurement site, K = town center)

was observed to be linearly dependent on the relative humidity of the weighing room.

The aerosol number concentrations were measured by electrical aerosol spectrometry employing the principle of electrical charging and mobility analysis (14–16). The aerosol size distribution was derived from continuous measurements of particle number concentrations in 12 size fractions covering the overall particle diameter range from 0.01 to 10 µm. The data were converted later to noon-to-noon results for the combined size classes of 0.01–0.1, 0.1–1.0, 1–3.6, and 3.6–10 µm, encompassing the different modes of atmospheric aerosols (nucleation mode, accumulation mode, coarse mode). Later in the text, tables and figures, the size-segregated number concentrations (NC) of particles are referred to as $NC_{0.01–0.1}$, $NC_{0.1–1}$, $NC_{1–3.6}$, and $NC_{3.6–10}$, the size range in question (µm) being given in the subscript.

CO was measured with a nondispersive infrared spectrometer (Thermo Environmental Instruments Inc, USA, model 48), and for sulfur dioxide a fluorescence analyzer (Monitor Labs Inc, USA, model 8850) was used. The 24-hour average concentrations were calculated from 1-minute samples. The analyzers were part of the ambient-air quality-monitoring network of Kuopio. BC concentrations were measured with a computer-controlled aethalometer (Magee Scientific Company, Berkley, CA, USA, model AE-9) (17) on the basis of a continuous measurement of optical attenuation resulting from the deposit accumulating on a filter. Weather data were obtained from a meteorological station located 1 kilometer south of the measuring site at a height of 50 meters from the ground. The elevation difference between the meteorological station and the air quality monitoring station was approximately 25 meters.

The total elemental composition of the PM_{10} and $PM_{2.5}$ samples was analyzed by Geological Survey of Finland using a PerkinElmer 8 SCIEX ELAN-500 ICP-MS instrument (PerkinElmer, Shelton, CT, USA). The procedure used for the inductively coupled plasma mass spectrometry has been described elsewhere (18). The results of the elemental analyses were used to study the role of resuspension as a source of soil- and combustion-derived particulate matter during episodes of high dust concentrations. On the assumption of two dominant sources of vanadium (V) and lead (Pb), namely, combustion processes and resuspension from surfaces, it was possible to separate these two sources by regression analysis. Since iron (Fe) is a unique tracer for soil dust in the Kuopio airshed (19), the regression of the daily concentrations of vanadium and lead against those of iron in the PM_{10} and $PM_{2.5}$ ranges enabled an estimation of the resuspended portions of vanadium and lead. This estimation was made by multiplying the daily concentrations of iron by the respective regression coefficients obtained from the regression models. The statistical software package Statistica for Windows 5 [STATISTICA for Windows 5.0 program manual by StatSoft Inc (1996) (http://www.statsoft.com)] was used for the statistical calculations.

Table 1. Descriptive statistics of the data.

Variable class [a]	Unit	Mean	Range
Particle mass			
$PM_{2.5}$	µg/m³	17.7	3.2–54.6
PM_{10}	µg/m³	32.5	4.5–122
TSP	µg/m³	69.5	6.1–234
BC	ng/m³	914	287–2250
Particle counts			
$NC_{0.01-0.1}$	1/cm³	17600	6970–40400
$NC_{0.1-1}$	1/cm³	451	145–907
$NC_{1-3.6}$	1/cm³	0.55	0.23–1.22
$NC_{3.6-10}$	1/cm³	0.08	0.02–0.23
Elements			
Pb_{10}	ng/m³	5.1	1.0–12.1
V_{10}	ng/m³	5.2	0.4–18.2
Fe_{10}	ng/m³	1450	2.7–7280
$Pb_{2.5}$	ng/m³	3.7	0.6–8.5
$V_{2.5}$	ng/m³	2.8	0.1–8.5
$Fe_{2.5}$	ng/m³	586	2.7–2750
Gases			
CO	mg/m³	0.39	0.08–1.02
Meteorology			
Wind speed	m/s	4.0	1.8–6.6
Temperature	°C	0.7	-6.1–7.4

[a] See the text for an explanation of the abbreviations.

Results

The descriptive statistics of the air quality data are presented in table 1. There were 6 days on which the mass concentrations of TSP and PM_{10} exceeded 100 µg/m³ and 50 µg/m³, respectively (figure 2). With the use of the preceding concentration limits, 30 March could be identified as the day of the first major resuspended dust episode.

Particle number concentrations in all four size fractions often showed similar variations (figure 3). The highest particle number concentrations of both the nucleation mode ($NC_{0.01–0.1}$) and coarse mode ($NC_{3.6–10}$) particles occurred on 30 March and 6 April. On 20 and 22 April, the number concentrations of particles were again high for the accumulation and coarse mode ($NC_{0.1–1}$, $NC_{1–3.6}$, $NC_{3.6–10}$) particles, but not for the nucleation mode particles.

The number concentrations ($NC_{0.01–0.1}$, $NC_{0.1–1}$, $NC_{1–3.6}$, and $NC_{3.6–10}$) and mass concentrations ($PM_{2.5}$, PM_{10}, TSP, and BC) of particles depended on the wind speed (figures 4 and 5). This dependence was twofold; the concentrations tended to increase both when the daily average wind speed decreased to below 4 m/s and when it increased to above 5 m/s. The association of the highest par-

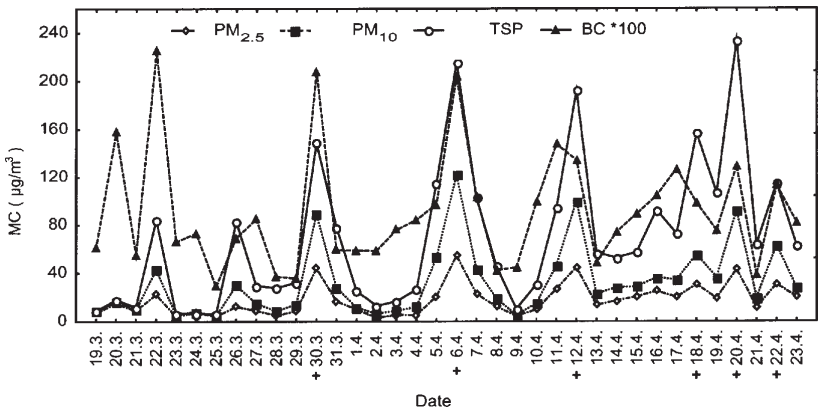

Figure 2. The 24-hour average mass concentrations (MC) of particles during the study period. The six strongest dust episode days are marked with a + sign. See the text for an explanation of the abbreviations.

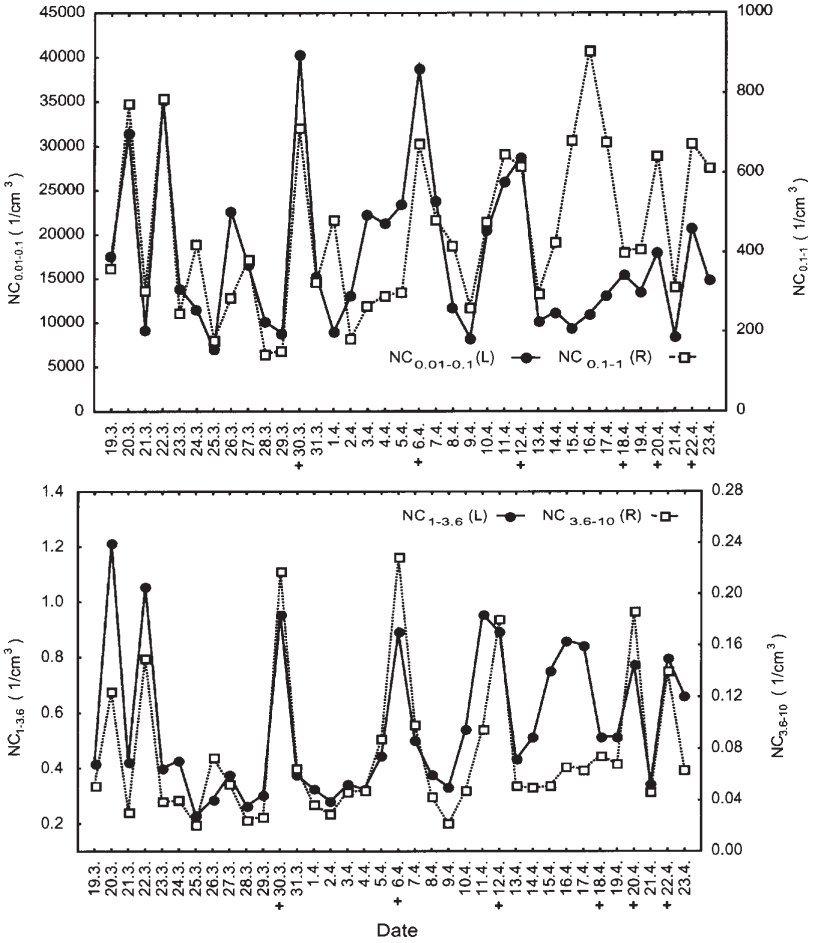

Figure 3. The 24-hour average number concentrations of particles in four size classes during the study period. See the text for an explanation of the abbreviations.

ticle concentrations with wind speed was clearer for low average wind speeds (eg, on 30 March and 6, 12 and 22 April) than for high average wind speeds (eg, 20 April).

The BC concentration followed a pattern similar to that of the other measured particle parameters, as shown in figure 5. The Spearman correlation coefficients (r) of BC and CO with the particle number concentrations in different size classes are shown in table 2. The correlation coefficient of BC with CO was 0.60.

The mass concentrations of iron, lead, and vanadium in the $PM_{2.5}$ and PM_{10} fractions are shown in figure 6. When these data were compared with the data in figure 2, it was obvious that the variations in the iron concentrations followed closely the variations in the total mass concentrations of these particulate fractions. The Spearman correlation coefficient of $Fe_{2.5}$ (mass concentration of iron in $PM_{2.5}$) with $PM_{2.5}$ was 0.96.

The concurrence of the high $Pb_{2.5}$ (mass concentration of lead in $PM_{2.5}$) and $V_{2.5}$ (mass concentration of vanadium in $PM_{2.5}$) concentrations with the high $Fe_{2.5}$ concentrations was confirmed by the relatively high correlation coefficients of their mass concentrations with iron

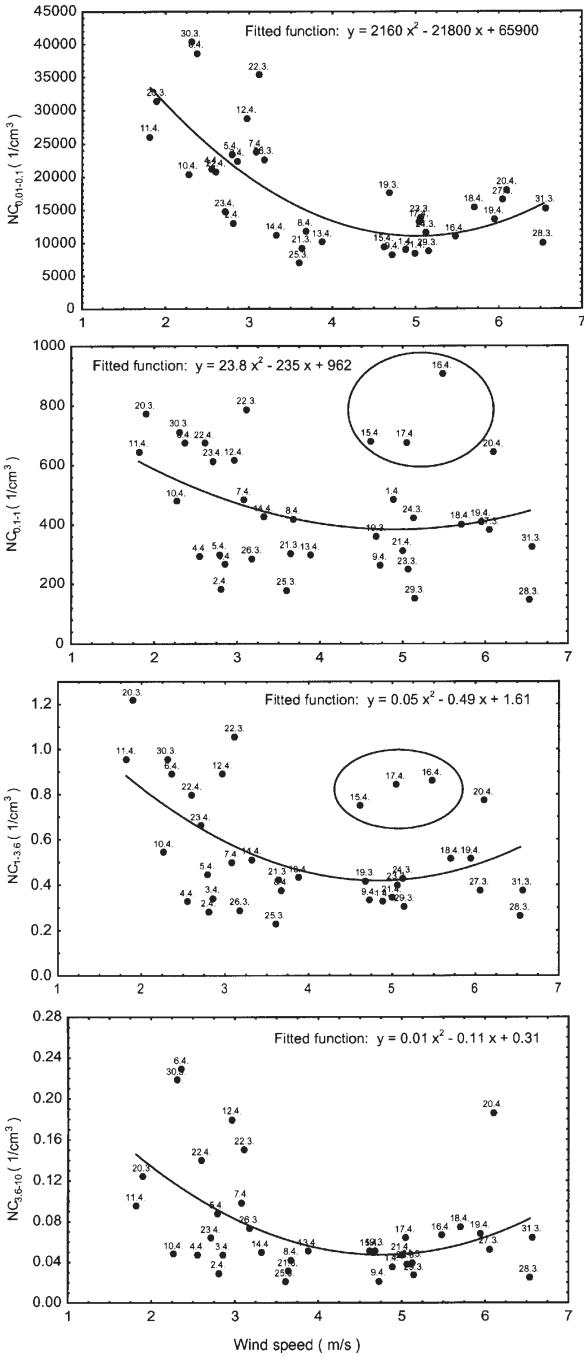

Figure 4. The 24-hour average number concentrations of particles as functions of the average wind speed. The episode of accumulation mode particles between 14 and 18 April is circled in the two middle-size fractions. See the text for an explanation of the abbreviations.

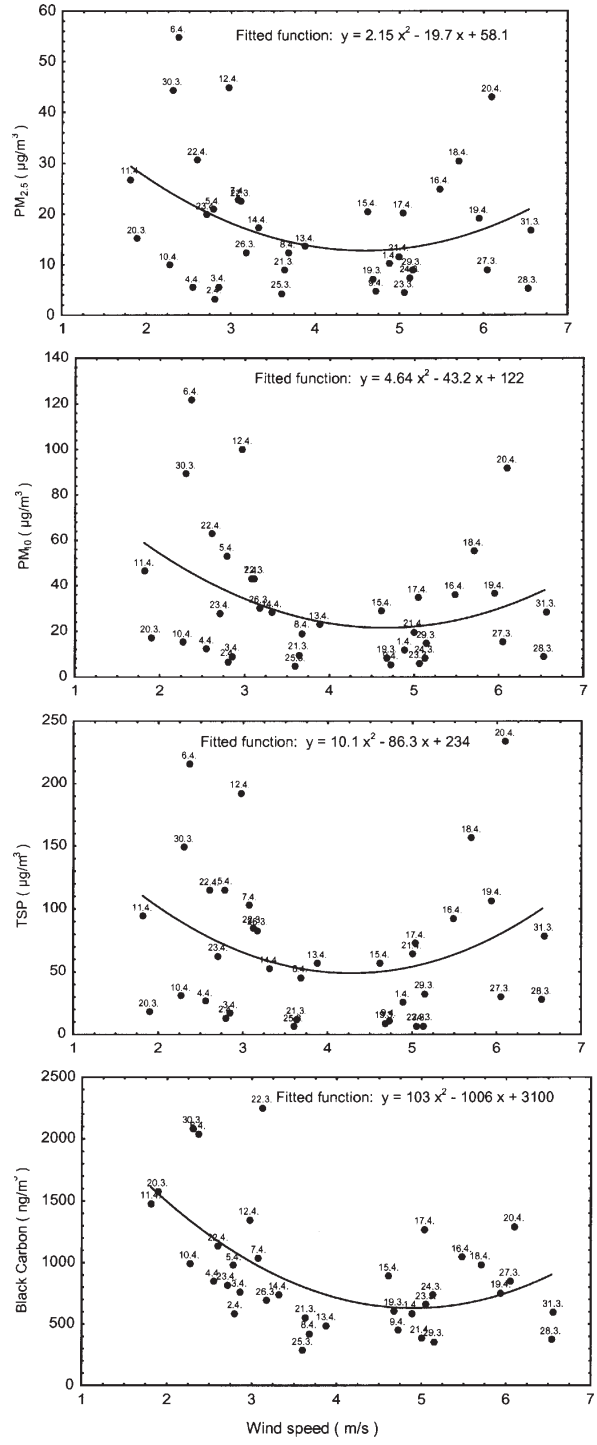

Figure 5. The 24-hour average mass concentrations of particles as functions of the average wind speed. The text shows the abbreviations.

(vanadium 0.81, lead 0.57). A comparison of the daily resuspended portions of vanadium and lead in the $PM_{2.5}$ fraction, as calculated from regression equations [4], showed that the $V_{2.5\ res}$ and $Pb_{2.5\ res}$ were high on the strongest resuspension days. Resuspended lead accounted for an average of 27% of the total lead, and resuspended vanadium represented 46% of the total vanadium in the $PM_{2.5}$ fraction (figure 6).

4 $Pb_{2.5} = 0.001875 \times Fe_{2.5} + 0.002600$; $Pb_{2.5res} = 0.001875 \times Fe_{2.5}$;
$V_{2.5} = 0.002654 \times Fe_{2.5} + 0.001228$; $V_{2.5res} = 0.002654 \times Fe_{2.5}$

An interesting episode of accumulation mode particles occurred between 14 and 18 April. The particle number concentrations in the two size classes, representing accumulation mode ($NC_{0.1–1}$ and $NC_{1–3.6}$) particles, started to increase on 14 April and reached a maximum on 16 April, while the concentrations of the nucleation ($NC_{0.01–0.1}$) and coarse ($NC_{3.6–10}$) modes were almost at their lowest at that time (figure 3 and circled days in figure 4). In addition, the mass concentrations of BC, lead, and, to some extent, vanadium had the same patterns as the particle numbers in the accumulation mode (figures 2 and 6), but those of $PM_{2.5}$, PM_{10}, and TSP were only slightly affected during this episode.

Discussion

In this study, resuspended dust episodes were shown to emerge in two ways. First, episodes were found to occur when the daily average wind speed was below 4 m/s, permitting a low mixing height and possibly inversion conditions. Under these circumstances, traffic-induced resuspended particles were accumulated in urban air rather than diluted in larger air masses. These episodes were also characterized by high concentrations of gaseous pollutants, black carbon and nucleation mode particles (< 0.1 μm), due to poor air mixing.

Table 2. Spearman correlation coefficients of black carbon and carbon monoxide with the continuously measured particle numbers in different size classes (15-minute average concentrations). See the text for an explanation of the abbreviations.

PM size class [a]	BC	CO
$NC_{0.01-0.1}$	0.74	0.52
$NC_{0.1-1}$	0.56	0.36
$NC_{1-3.6}$	0.69	0.48
$NC_{3.6-10}$	0.77	0.53

[a] The size range is given in micrometers in the subscript.

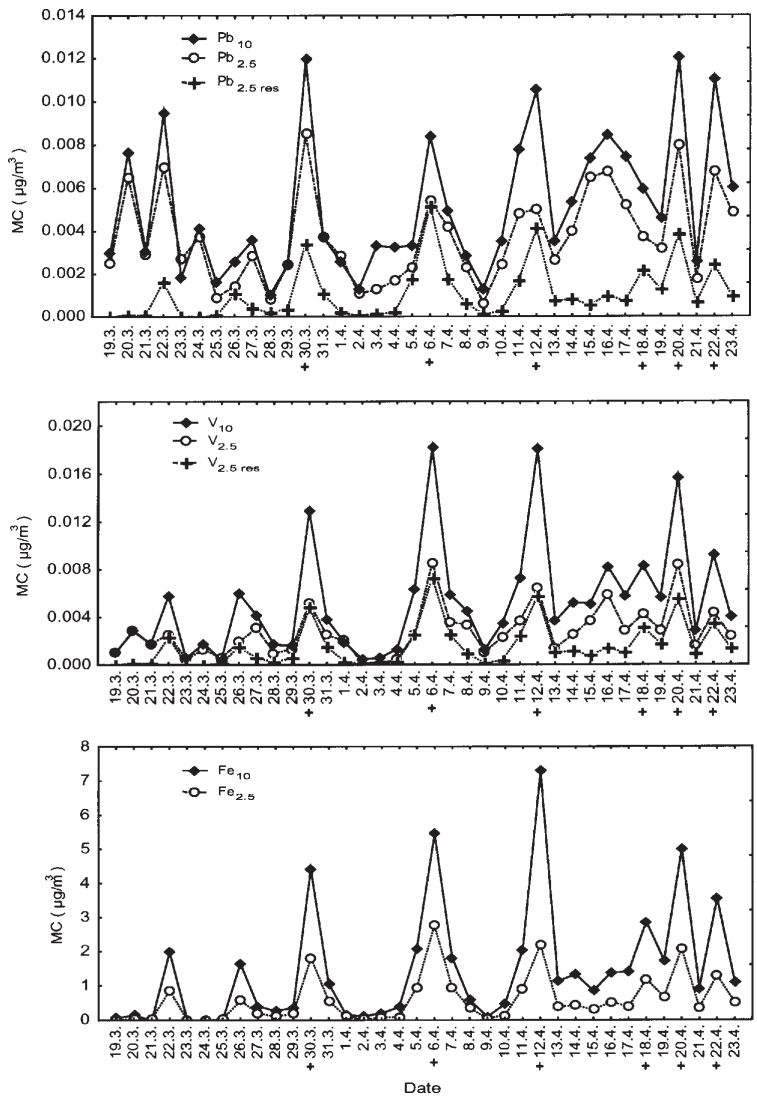

Figure 6. The 24-hour average mass concentrations (MC) of lead, vanadium, and iron in the PM_{10} and $PM_{2.5}$. The $V_{2.5\ res}$ and $Pb_{2.5\ res}$ fractions represent the elemental concentrations in the estimated resuspended portion of $PM_{2.5}$. See the text for an explanation of the abbreviations.

The second type of dust episodes occurred when the wind speed was above 5 m/s, as high wind speed alone can induce the resuspension of dust from road surfaces and the ground. In our data, 20 April represented a day when the measured parameters of particulate matter were the most clearly affected by wind-blown resuspended dust. The effect of resuspension was not restricted to the number concentration of coarse particles; instead it was also noted in the number concentrations of accumulation mode particles and mass-based measures of particulate matter. The increased concentration of the accumulation mode particles could be explained by the "co-resuspension" of smaller particles on the surfaces of coarse ones. In co-resuspension, coarse particles could serve as vehicles for smaller particles during the resuspension event. Horvath et al (20) examined the effect of average wind speed on ambient-air particle mass concentrations in Vienna, Austria, and found increased concentrations at wind speeds exceeding 5.5 m/s. However, wind tunnel experiments (2) have not supported the existence of a threshold for the induction of resuspension due to wind speed. Our analyses suggest a threshold wind speed of about 5 m/s, but the results are not conclusive due to only a slight increase in the particle concentrations above this speed, and also to the relatively small database.

The number concentrations of accumulation mode particles ($NC_{0.1–1}$ and $NC_{1–3.6}$) were high on the days of resuspended dust episodes, but they were also increased during special episodes of long-range transported particles. The analysis of wind direction showed that, during the period of high-accumulation particle concentrations from 14 to 18 April (circled in figure 4) the wind blew constantly from the southeast sector, that is, over southeast Finland and St Petersburg, located about 500 kilometers from the measurement site. Several large industrial facilities are located in both of these areas. Therefore, it is likely that the episode of accumulation-mode particles on 14–18 April was caused by long-range transported particles originating from one or more combustion processes in those industrial areas. It is known that air masses can be transported from the St Petersburg area to Kuopio in less than 1 day. Relatively high average wind speeds during the episode on 14–18 April supported the assumption that the episode was caused by something other than local pollution sources, since high wind speeds usually prevent the in situ growth of locally emitted nucleation mode particles into accumulation mode particles.

The mass concentration of BC correlated best with the number concentrations of nucleation mode ($NC_{0.01–0.1}$) and coarse mode ($NC_{3.6–10}$) particles and, therefore, indicated that it was closely connected to the local emission processes. Traffic was probably the common source of both the primary combustion-derived emissions and the resuspension of deposited dust. This assumption was strengthened by the fact that the CO concentration, indicating vehicle exhaust emissions, had its highest correlations with the particle number concentrations in the same size classes as BC (table 2). However, on 14–18 April, the mass concentration of BC followed the number concentrations of accumulation mode particles; this finding suggests that these pollutants were then derived from common distant combustion sources specific for that period.

The high BC concentrations occurred mostly on the days that the other mass measures of particles were high. However, the overall trend for the BC concentrations was decreasing towards the end of the study period, whereas the trends of the other particle mass concentrations were increasing (figure 2). The six highest BC concentrations occurred before 12 April and were related to daily average wind speeds lower than 3 m/s (figure 5); this finding suggests that they were caused by an impaired dilution of emissions from vehicles and other local combustion sources, such as domestic wood burning. The correlation coefficient between the BC concentration and temperature was negative (–0.12), while that between the $PM_{2.5}$ mass concentration and temperature was positive (0.20). A similar finding was reported for the black smoke index of Kuopio in the winter of 1994 (21). Thus the BC concentrations seem to be more dependent on direct emissions and atmospheric stability than on the resuspension of deposited dust.

Iron has been shown to be a good marker for ground crustal particles of soil dust from the street surfaces of Kuopio (19), where no other significant local sources of iron, such as fly ash from coal combustion or emissions from metal industries, contribute to its atmospheric concentration. However, small amounts of iron can be emitted from traffic, mainly through the wearing and rusting of cars (22, 23). Vanadium is often used as an indicator of heavy fuel oil combustion and lead as a marker of leaded gasoline. The selling of leaded gasoline was discontinued in Finland in the autumn of 1994, that is, well before the present measurements were made. Therefore, most of the detected $Pb_{2.5}$ and Pb_{10} was probably attributable to other forms of combustion and, to a smaller degree, to residues of traffic-related lead originating from long-lasting past use of leaded gasoline. However, the peaks in the $Pb_{2.5}$ and $V_{2.5}$ concentrations and their relatively high Spearman correlation coefficients with the corresponding $Fe_{2.5}$ concentration (0.81 for vanadium and 0.57 for lead) indicated that the soil dust contained considerable amounts of vanadium and lead. The most plausible explanation is that particles emitted from combustion processes were deposited on the ground during the winter and released back into the air during resuspended dust episodes. This possibility was further supported by the finding that the highest

mass concentrations of the soil-derived element (iron) and the combustion-derived elements (vanadium and lead) coincided on the strongest dust episode days (figure 6). During the episode between 14 and 18 April the elevated concentrations of vanadium and lead in the PM_{10} and $PM_{2.5}$ fractions, but not in the estimated resuspended portion of the $PM_{2.5}$ fraction, suggested that the accumulation mode particles came from distant sources, including industrial plant(s) using oil contaminated with lead, or less likely, foreign vehicles using leaded gasoline.

In conclusion, resuspended dust episodes were related to both low and high wind speeds and therefore suggested that factors other than wind speed, such as turbulence induced by traffic, affect the emergence of these episodes. The resuspended dust episodes not only increased the atmospheric concentration of the coarse fraction of PM_{10}, but also those of fine particles and trace elements originally emitted from combustion processes and subsequently deposited on the ground. The contribution of elevated levels of crustal material and toxic metals in resuspended $PM_{2.5}$ to human adverse health effects should be investigated.

Acknowledgments

We wish to thank the Academy of Finland, Finnish Research Programme on Environmental Health (SYTTY); the Centre of Excellence Programmes 2002–2007 of the Academy of Finland; and the National Technology Fund (TEKES) for funding.

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