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Statistical model for assessing the portion of fine particulate matter transported regionally and long range to urban air

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Original article

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Statistical model for assessing the portion of fine particulate matter transported regionally and long range to urban air

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Objectives This study attempted to develop a simple statistical model for assessing the contribution of aerosols transported regionally and those transported long range to the concentrations of fine particulate matter ($PM_{2.5}$) in urban air in Helsinki.

Methods The construction and testing of the linear regression model was based on $PM_{2.5}$ measurement data from two locations in the City of Helsinki (Vallila & Kallio) and on ion concentration data obtained from the three nearest monitoring stations of The Co-operative Programme for Monitoring and Evaluating of the Long-range Transmission of Air Pollutants in Europe (EMEP). The "ion sum" was calculated on the basis of the following daily measured EMEP parameters in 1998–2000: (i) sulfate (SO_4^{2-}), (ii) the sum of nitrate (NO_3^-) and nitrogen acid (HNO_3), and (iii) the sum of ammonium (NH_4^+) and ammonia (NH_3). The ion sum was compared with sulfate as the proxy variable for $PM_{2.5}$ transported long range.

Results The correlation of the daily average $PM_{2.5}$ concentration with the ion sum ($R^2 = 0.59–0.61$) was higher than that with sulfate ($R^2 = 0.48–0.50$). The regression estimates showed relatively small year-to-year variation. The contribution of long-range transport to the measured $PM_{2.5}$ concentration in urban air in Helsinki was estimated to be 64–76%.

Conclusions The results showed a strong association between the ion sum interpolated from the EMEP data and the $PM_{2.5}$ concentration measured at urban sites in Helsinki. This association can be utilized in local dispersion modeling of the $PM_{2.5}$ concentration in urban air.

Key terms air quality, fine particles, ion concentration, modeling, particulate matter, secondary inorganic ions.

Particulate matter (PM) in urban air originates from local mobile and stationary emission sources, from regional and long-range transport and from traffic- or wind-induced airborne dust. Particles are also formed via gas-to-particle conversion processes during atmospheric transport, in which they are constantly transformed and depleted by various physical and chemical processes, including coagulation, condensation and evaporation, chemical transformation, and dry and wet deposition. In most major European cities, no reliable PM emission inventories are available. The formation of vehicle non-exhaust emissions that originate from brakes, tires, and the like is also poorly understood. It is, therefore, worthwhile to develop and evaluate simpler, semi-empirical and statistical methods for analyzing the contributions of different emission sources to mass-based PM concentrations in urban air.

Previous studies have shown that vehicle traffic is the most important local pollution source of both thoracic particles [ie, particulate matter with an aerodynamic diameter of <10 μm (PM_{10})] and its subfraction of fine particles [ie, particulate matter with an aerodynamic diameter of <2.5 μm ($PM_{2.5}$)] in the Helsinki metropolitan area (1, 2). The particle number concentrations in this area have been fairly uniform spatially (3), and also the measured $PM_{2.5}$ concentrations have shown only

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moderate variation both spatially and temporally (4). In contrast, the spatial distribution of PM concentrations originating from local traffic varies substantially on the microscale (ie, on a scale of tens or hundreds of meters). It can, therefore, be anticipated that regional transport and long-range transport (LRT) of aerosols are major contributors to the urban air $PM_{2.5}$ concentration.

Continuous measurements of LRT contributions to $PM_{2.5}$ are available for only a few European cities. However, the data from a measurement network of The Co-operative Programme for Monitoring and Evaluating of the Long-range Transmission of Air Pollutants in Europe (EMEP) are available throughout Europe. We have, therefore, developed a simple statistical model for estimating the LRT contribution to the $PM_{2.5}$ concentration in urban air. The modeling has been based on linear regressions of the EMEP background air ion concentrations (SO_4^{2-}, NO_3^-, NH_4^+) with the locally monitored urban air $PM_{2.5}$ concentration. The main objectives of this study were to present this model and to evaluate its accuracy against experimental data. The applicability of the model to other European regions is also discussed.

Figure 1. Location of the Helsinki Metropolitan Area and its three nearest EMEP monitoring stations in Finland. Distances from Helsinki: Virolahti 155 km, Utö 205 km and Ähtäri 260 km. (EMEP = The Co-operative Programme for Monitoring and Evaluating of the Long-range Transmissions of Air Pollutants in Europe)

Material and methods

Finnish monitoring network of The Co-operative Programme for Monitoring and Evaluating of the Long-range Transmission of Air Pollutants in Europe

The EMEP stations located nearest Helsinki are shown in figure 1: Utö (59°47'N, 21°23'E), Ähtäri (62°35'N, 24°12'E) and Virolahti (60°32'N, 27°41'E). The following background air ion concentrations are measured daily at the EMEP stations: (i) sulfate (SO_4^{2-}), (ii) the sum of nitrate (NO_3^-) and nitrogen acid (HNO_3), and (iii) the sum of ammonium (NH_4^+) and ammonia (NH_3). The sulfate, nitrate, and ammonium ions are in particulate form, while nitrogen acid and ammonia are gaseous compounds in atmospheric conditions. The 24-hour sampling and reporting period of the EMEP values starts at 0600 Coordinated Universal Time (UTC) (in accordance with meteorological conventions). A detailed description of the sampling and analysis methods used by EMEP has been published elsewhere (5, 6).

Ion sum calculations

The aforementioned (EMEP) measurements of sulfate and the sum of nitrate and nitrogen acid, together with the sum of ammonium and ammonia, are reported as equivalent masses of sulfur and nitrogen, respectively. We defined the ion sum (C_{ion}) as follows:

$$C_{ion} = 3.0\,(SO_4^{2-})_S + 4.4\,[(NO_3^- + HNO_3)]_N + 1.3\,[(NH_4^+ + NH_3)]_N, \quad \text{equation 1}$$

where the subscripts S and N denote that the mass had been given as the equivalent mass of sulfur or nitrogen. These values were converted to equivalent masses of the ions SO_4^{2-}, NO_3^- and NH_4^+, using the conversion factors 3.0, 4.4 and 1.3, respectively. This conversion was necessary to make the particulate concentration variables comparable.

The C_{ion} variable (equation 1) was assumed to be a suitable proxy variable for LRT in the model. However, it should be noted that this variable contained, in part, measurements of gaseous substances (HNO_3, NH_3) and, on the other hand, LRT was likely to contain also other compounds, such as elemental and organic carbon.

Each of the three ion terms in equation 1 could be assumed to be, even alone, a suitable proxy variable for LRT. However, it was convenient to define a combined variable that was based on all three measurements of ion concentrations. This variable represented a larger portion of the $PM_{2.5}$ mass than any of its components and therefore made it a better candidate for the prediction of temporal variations.

One of the main criteria in the selection of sites for EMEP stations has been that these sites represent regional

background concentrations and are not directly influenced by local emission sources. However, this assumption may not be strictly true in all cases, due to reasons such as changes nearby in land use and the location of major roads. In the present study, we utilized a combination of data from the three EMEP stations nearest Helsinki to smooth out any possible disturbances caused by local emission sources. This procedure also removed the difficulties that might have arisen from data missing at any individual station.

Whenever possible, we utilized an interpolated value of the ion sum, defined as follows:

$$C_{\text{ion}} = \sum_{i=1}^{n} \chi_i \, C_{\text{ion},i} \qquad \text{equation 2}$$

where the subscript i refers to the included EMEP stations, n is the total number of stations, χ_i is the weight coefficient, and $C_{\text{ion},i}$ is the ion sum of each included station. The weight coefficient was defined, on the basis of the EMEP stations with available data, as a normalized inverse value of the distance between the urban measurement location and the EMEP station. The normalization implied simply that the sum of all χ_i values was required to be 1. The purpose of using the inverse values of the distances was to give larger weight coefficients for the EMEP stations that were closer to the city in question. For instance, two EMEP stations at distances of 40 and 60 kilometers from Helsinki would have had weight coefficients of 0.6 and 0.4, respectively.

The measured urban air $PM_{2.5}$ concentrations (ie, 24-hour average values corresponding to the EMEP network sampling times starting at 0600 UTC) were associated with the ion sum values as follows:

$$PM_{2.5}\,(\text{measured}) = k_1 C_{\text{ion}} + k_0, \qquad \text{equation 3}$$

where k_1 and k_0 are regression coefficients determined experimentally. The statistical estimation of k_1 indicated the strength of the temporal association of the background C_{ion} concentration with the urban air $PM_{2.5}$ concentration, while k_0 indicated the uncorrelated portion of the $PM_{2.5}$ concentration. Consequently, the terms $k_1 C_{\text{ion}}$ and k_0 were interpreted to represent contributions from LRT and all local sources, respectively.

Monitoring data on urban air quality

We utilized the hourly time series of the $PM_{2.5}$ concentrations measured at the urban traffic station of Vallila in 1998–2000 and the urban background station of Kallio in 1999–2000 (no $PM_{2.5}$ data available from Kallio before 1999). Both of these measurement stations were located in central Helsinki and belonged to the municipal air-quality monitoring network of the Helsinki Metropolitan Area Council (YTV). The Vallila station was located in a small park, 14 meters from a street with an average traffic volume of 13 000 vehicles/day. The Kallio station was located in a small field, 60 meters from the nearest road, which had an average traffic volume of 7000 vehicles/day.

At the Vallila and Kallio stations, the $PM_{2.5}$ and PM_{10} concentrations were measured with the β-attenuation method (Eberline FH 62 I-R, Thermo Eberline, Santa Fe, New Mexico, United States). The flow rate of the PM analyzers was calibrated twice a year, and the mass measurement was calibrated once a year. The 24-hour average concentrations were calculated for PM_{10} and $PM_{2.5}$ from the hourly data and compared with the corresponding gravimetric PM concentration data obtained from daily samplings with virtual impactors (7). These comparisons were performed at the Vallila station between June 1999 and May 2000. The correlation between these two measurement series was good, as previously discussed (1).

Statistical analyses

We performed a linear regression analysis for the daily time series of the aerosol concentration parameters, using the $PM_{2.5}$ data (β-attenuation method) from the two urban monitoring stations in Helsinki and the ion sum values determined on the basis of the EMEP data from the rural stations of Utö, Virolahti, and Ähtäri. We also performed similar regression analyses using data on ion sums from only the two stations (Utö, Virolahti) nearest Helsinki or the nearest station (Virolahti). Finally, we computed the regression of the daily sulfate (SO_4^{2-}) concentrations measured at Virolahti with the measured $PM_{2.5}$ concentrations at Vallila and Kallio. These analyses were performed separately for each station on an annual basis. The statistical package SYSTAT (SPSS Inc, Chicago, Illinois, United States), version 10 for Windows, was used in the statistical analyses.

Results

The results of the linear regression analyses have been summarized in table 1 for all the different modeling options and the two urban-air monitoring stations. The relatively high correlations (R^2 = 0.48–0.65), together with a small variation in the parameter k_1, indicated that a significant portion of the urban air $PM_{2.5}$ concentration was of regional and LRT origin. The ion sum had higher correlations with $PM_{2.5}$ than with sulfate, but the number of EMEP stations (1 to 3) as sites of ion sum data was not as critical.

The LRT contribution has been estimated quantitatively in table 2, using the ratio of the term $k_1 C_{\text{ion}}$ and

Table 1. Statistical parameters of the linear regressions between the 24-hour average $PM_{2.5}$ concentration, measured at the urban Vallila and Kallio stations, and the corresponding ion sums calculated on the basis of data from one to three stations included in The Co-operative Programme for Monitoring and Evaluating of the Long-range Transmission of Air Pollutants in Europe (EMEP) in 1998–2000. ($PM_{2.5}$ = particles with an aerodynamic diameter of < 2.5 µm, N = number of observations, k_1 and k_0 = regression coefficients, 95% CI = 95% confidence interval, R^2 = correlation coefficient squared)

EMEP database	Vallila 1998–2000						Kallio 1999–2000					
	N	k_1	95% CI	k_0	95% CI	R^2	N	k_1	95% CI	k_0	95% CI	R^2
3-year ion sums												
Virolahti, Utö, Ähtäri	988	1.67	0.08	3.1	0.4	0.65	713	1.59	0.08	2.0	0.4	0.65
Virolahti, Utö	952	1.47	0.07	3.1	0.4	0.64	693	1.37	0.08	2.1	0.4	0.62
Virolahti	977	1.36	0.07	3.4	0.4	0.61	713	1.23	0.08	2.6	0.4	0.59
3-year sulfate ion												
Virolahti	987	2.11	0.13	5.2	0.4	0.50	713	1.87	0.14	4.4	0.4	0.48
1998 ion sums												
Virolahti, Utö, Ähtäri	344	1.63	0.13	3.7	0.7	0.65	..	..	..	..	..	..
1999 ion sums												
Virolahti, Utö, Ähtäri	365	1.69	0.13	3.3	0.7	0.64	348	1.60	0.13	2.3	0.7	0.64
2000 ion sums												
Virolahti, Utö, Ähtäri	277	1.61	0.14	2.3	0.6	0.64	365	1.53	0.12	1.9	0.5	0.64

Table 2. Comparison of the measured 24-hour average $PM_{2.5}$ concentrations and their estimated long-range and regionally transported portions ($k_1\ C_{ion}$) at two urban sites. These summary data cover 3 years (1998–2000, N=988) for Vallila and 2 years (1999–2000, N=713) for Kallio. ($PM_{2.5}$=particles with an aerodynamic diameter of < 2.5 µm)

	Measured mean $PM_{2.5}$ (µg/m³)		Regression $k_1\ C_{ion}$ (µg/m³)		$k_1\ C_{ion}$ / $PM_{2.5}$	
Period	Vallila	Kallio	Vallila	Kallio	Vallila	Kallio
All data	10.2	8.7	7.1	6.7	0.70	0.76
1998	10.3	..	6.6	..	0.64	..
1999	11.0	9.5	7.7	7.2	0.70	0.76
2000	8.4	7.9	6.1	6.0	0.73	0.76

the measured $PM_{2.5}$ concentration. LRT accounted for 64–73% of the urban-air $PM_{2.5}$ concentration in Vallila, while in Kallio the contribution was estimated at 76%.

Figure 2 shows the high correlation between the $PM_{2.5}$ concentrations measured in Vallila and the calculated ion sums from the three EMEP stations in 1998–2000. The correlation between the same $PM_{2.5}$ concentrations and the sulfate measurements in Virolahti was clearly lower, as shown in figure 3. In both figures, there is a fairly small number of days for which high measured $PM_{2.5}$ concentrations correlated poorly with low ion sum or sulfate values. Likely explanations for these events are higher-than-average contributions to $PM_{2.5}$ from local primary emissions (eg, due to stable meteorological conditions) or airborne dust resuspended from road and street surfaces (well-known in springtime) or both phenomena.

Figure 4 illustrates the temporal variations in the statistically estimated and measured $PM_{2.5}$ concentrations for Vallila in 1998. By fixing the regression coefficients k_0 and k_1, we could predict the daily urban-air $PM_{2.5}$ concentrations reasonably well on the basis of the calculated ion sums from the three EMEP stations. This comparison was not a validation of the model presented, as the regression coefficients were based on the same data.

Discussion

Our study describes a simple regression model for assessing the LRT contribution to the $PM_{2.5}$ concentration in the urban air of Helsinki.

The comparison of different modeling options (table 1 and figures 2 & 3) showed that the use of the distance-weighted ion sum, based on data from three EMEP stations, gave rather high and constant correlations with the urban air $PM_{2.5}$ concentration for every year and both urban stations. However, the difference between utilizing data from three or two (EMEP) stations was small. Comparison of the models using data only from one station (Virolahti) showed that the regression model based on 3-year ion sums gave better results than the model based on 3-year sulfate (SO_4^{2-}) concentrations as the proxy variable for LRT (table 1).

The variation in the slope of the regression equation (k_1 in table 1) was moderate both in terms of the year and the station. It indicated that the LRT contribution to the urban-air $PM_{2.5}$ concentrations was not particularly sensitive either to the exact location of the station or to the distribution of meteorological conditions in any study year. When the linear regression parameters for the two stations in Helsinki were compared,

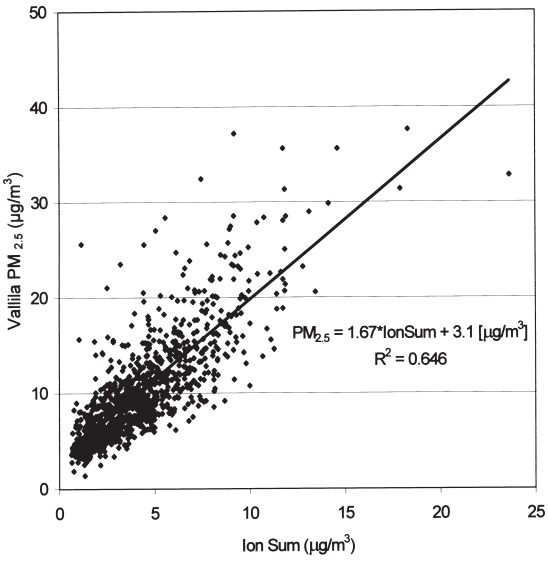

Figure 2. Correlation between the $PM_{2.5}$ concentration measured in Vallila and the ion sum calculated on the basis of data from the three nearest EMEP stations in 1998–2000. ($PM_{2.5}$ = particles with an aerodynamic diameter of <2.5 µm, EMEP = The Co-operative Programme for Monitoring and Evaluating of the Long-range Transmissions of Air Pollutants in Europe)

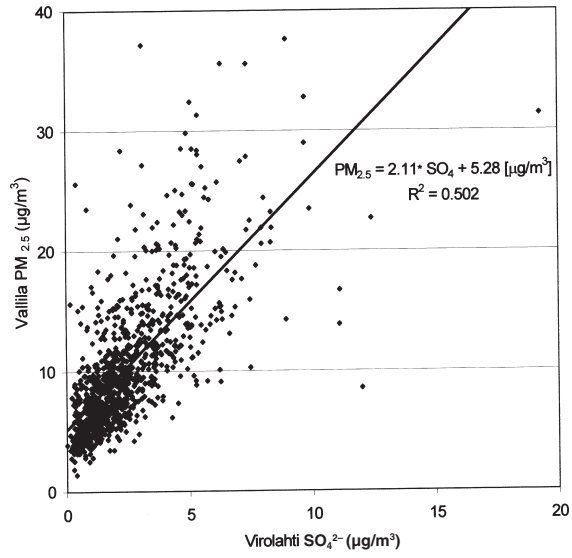

Figure 3. Correlation between the $PM_{2.5}$ concentration measured in Vallila and the sulfate ion (SO_4^{2-}) concentration calculated on the basis of data from the EMEP station of Virolahti in 1998–2000. ($PM_{2.5}$ = particles with an aerodynamic diameter of <2.5 µm, EMEP = The Co-operative Programme for Monitoring and Evaluating of the Long-range Transmissions of Air Pollutants in Europe)

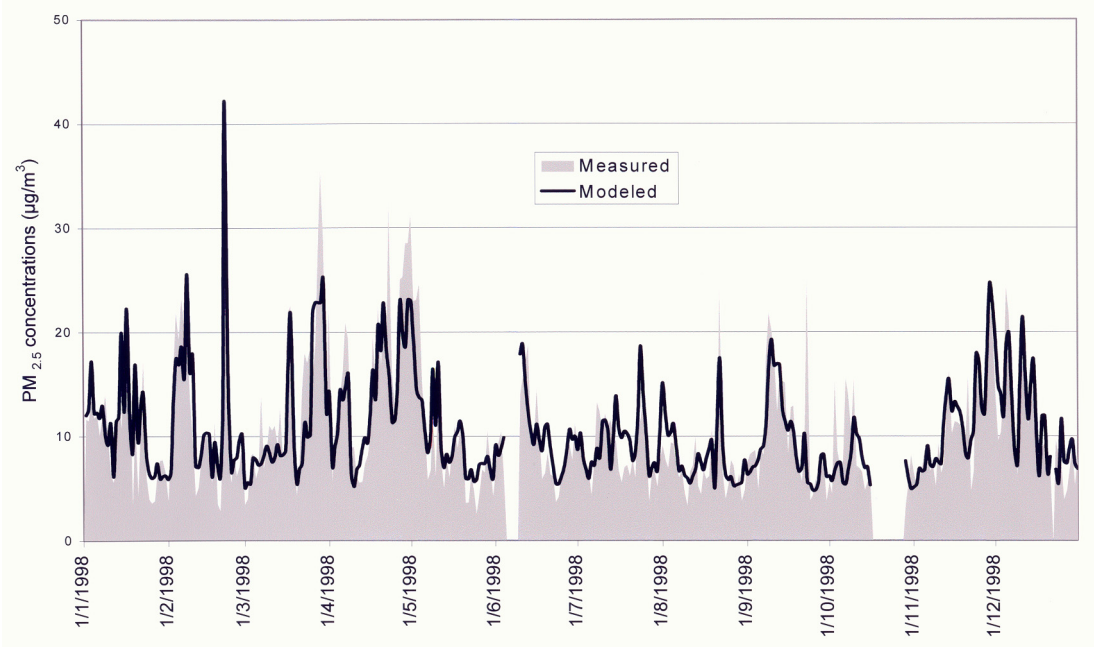

Figure 4. Time series of the measured and modeled 24-hour average $PM_{2.5}$ concentrations at the urban station of Vallila in 1998. ($PM_{2.5}$ = particles with an aerodynamic diameter of <2.5 µm, EMEP = The Co-operative Programme for Monitoring and Evaluating of the Long-range Transmissions of Air Pollutants in Europe)

there was actually more variation in the values of the intercept k_0, which represented the contribution of local emission sources and resuspension. As expected, the k_0 values for the urban background station (Kallio) were smaller than those for the urban traffic station (Vallila).

The $PM_{2.5}$ concentrations were measured during a limited period at the regional background station of Luukki, which is located near the northeastern border of the Helsinki metropolitan area. The $PM_{2.5}$ concentration averaged 8.4 µg/m^3 between October 1996 and May 1997

(8). With the use of source apportionment methods, it has been estimated (9) that less than 10% of the measured $PM_{2.5}$ concentration in Luukki originates from local sources. These estimates would produce a regional background $PM_{2.5}$ concentration of 7.6 $\mu g/m^3$ for the aforementioned period. This value is in good agreement with the corresponding computational value of 7.1 $\mu g/m^3$ for the whole period of 1998–2000 in our study (table 2).

In the study of Ojanen et al (9), the LRT contributions to the $PM_{2.5}$ concentration of Vallila were about 60–63%. These values are in reasonably good agreement with the present contributions of 64–76% for Vallila and Kallio (table 2). Our estimates are supported also by those of Koistinen et al (10), who reported a 46% contribution of secondary aerosols (which do not form total LRT) to the outdoor $PM_{2.5}$ concentration in the Helsinki metropolitan area in 1996–1997.

The regional background concentration of $PM_{2.5}$ consists mainly of ammonium nitrate, ammonium sulfate, and carbon compounds (11). Therefore, the accuracy of any model depends on the chemical composition of the $PM_{2.5}$ fraction, especially the content of carbonaceous species that are not currently measured at EMEP stations. The ion sum parameter defined in our study contains, in part, measurements of two gaseous substances (HNO_3, NH_3). If their concentrations were high, compared with the concentrations of the corresponding compounds in particulate form, there could be substantial inaccuracies in the model predictions.

A more-detailed computational method for evaluating the LRT contribution to the urban air $PM_{2.5}$ concentration could include additional factors in equation 3, which may be dependent on some relevant meteorological parameters. However, these parameters should correspond to weather conditions along the trajectories of air masses, instead of to local or regional meteorological conditions. This would drastically increase the complexity of the model.

The concentration of organic carbon in $PM_{2.5}$ varies substantially between different seasons, while the concentration of elemental carbon typically shows a pronounced spatial variation depending on the density of local traffic sources. Consequently, the ion sum concentrations used in this study may vary spatially and temporally more smoothly than the corresponding regional background $PM_{2.5}$ concentrations.

Moreover, part of the high statistical correlation between the measured $PM_{2.5}$ concentrations and the ion sum values could have been caused by local sources. This would have been possible for a local source that had partly the same temporal variation in emissions as the LRT contribution. Consequently, the simple regression model, as written in equation 3, probably slightly overestimated the LRT contribution to the urban-air $PM_{2.5}$ concentration.

The model parameter values used in this study are specific for this particular urban area, and they are valid for a limited time period even there. The model cannot be used in evaluations of future long-term scenarios, and it is not feasible to evaluate the detailed limits of its validity theoretically. In applications of the model for another urban area, it is, therefore, recommended that the model parameters (k_1 and k_0) corresponding to the area be first determined, and the model then evaluated against independent experimental data.

We have not performed an error analysis, based on inaccuracies in the EMEP and urban air $PM_{2.5}$ measurements, due to difficulties in obtaining detailed error estimates. However, if it is assumed that these well-controlled measurements did not contain any systematic bias, the model sensitivity analyses performed (eg, the results in table 1) indicate that the variability of the model coefficients (k_1 and k_0) was rather small.

Concluding remarks

Our results show a strong association between the ion sum interpolated from the EMEP data and the $PM_{2.5}$ concentration measured at urban sites in Helsinki. This association can be utilized in local dispersion modeling of urban air $PM_{2.5}$ concentrations. In future work, the performance of the model (using the coefficient values obtained in this study) should be critically evaluated against other independent data sets.

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References

1. Kukkonen J, Härkönen J, Karppinen A, Pohjola M, Pietarila H, Koskentalo T. A semi-empirical model for urban PM_{10} concentrations and its evaluation against data from an urban measurement network. Atmos Environ 2001; 35:4433–42.
2. Pakkanen TA, Kerminen V-M, Ojanen CH, Hillamo R, Aarnio P, Koskentalo T. Atmospheric black carbon in Helsinki. Atmos Environ 2000;34:1476–506.

3. Buzorius G, Hämeri K, Pekkanen J, Kulmala M. Spatial variation of aerosol number concentration in Helsinki city. Atmos Environ 1999;33:553–65.
4. Pohjola MA, Kousa A, Kukkonen J, Härkönen J, Karppinen A, Aarnio P, et al. The spatial and temporal variation of measured urban PM_{10} and $PM_{2.5}$ concentrations in the Helsinki metropolitan area. Int J Water Air Soil Pollut. In press.
5. Leinonen L, editor. Ilmanlaatumittauksia 1998 [Air quality measurements 1998]. Helsinki: Finnish Meteorological Institute,1999:254 p.
6. The Co-operative Programme for Monitoring and Evaluating of the Long-range Transmission of Air Pollutants in Europe (EMEP). Manual for sampling and chemical analysis. Kjeller (Norway): Norwegian Institute for Air Research, 2001. EMEP/CCC-Report 1/95 (revised in November 2001).
7. Loo BW & Cork CP. Development of high efficiency virtual impactors. Aerosol Sci Technol 1988;9:167–76.
8. Pakkanen T, Loukkola K, Korhonen CH, Aurela M, Mäkelä TM, Hillamo RE, et al. Sources and chemical composition of atmospheric fine and coarse particles in the Helsinki area. Atmos Environ 2001;35:5381–91.
9. Ojanen C, Pakkanen T, Aurela M, Mäkelä T, Meriläinen J, Hillamo R, et al. Hengitettävien hiukkasten kokojakauma, koostumus ja lähteet pääkaupunkiseudulla [Size distribution, chemical composition and sources of inhalable particles in Helsinki area]. Helsinki: Pääkaupunkiseudun yhteistyövaltuuskunta YTV, 1998:7. Pääkaupunkiseudun julkaisusarja C.
10. Koistinen KJ, Edwards RD, Mathys P, Ruuskanen J, Künzli N, Jantunen MJ. Sources of fine particulate matter in personal exposures and residential indoor, residential outdoor and workplace microenvironments in the Helsinki phase of the EXPOLIS study. Scand J Work Environ Health 2004;30 Suppl 2:36–46.
11. Turnbull AB, Harrison RM. Major component contributions to PM_{10} composition in the UK atmosphere. Atmos Environ 2000;34:3129–37.