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Correlation between traffic density and particle size distribution in a street canyon and the dependence on wind direction

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Abstract

Combustion of fossil fuel in gasoline and diesel powered vehicles is a major source of aerosol particles in a city. In a street canyon, the number concentration of particles smaller than 300 nm in diameter, which can be inhaled and cause serious health effects, is dominated by particles originating from this source.

In this study we measured both, particle number size distribution and traffic density continuously in a characteristic street canyon in Germany for a time period of 6 months. The street canyon with multistory buildings and 4 traffic lanes is very typical for larger cities. Thus, the measurements are also representative for many other street canyons. In contrast to previous studies, we measured and analyzed the particle number size distribution with high size resolution using a Twin Differential Mobility Analyzer (TDMPS). The measured size range was from 3 to 800 nm, separated into 40 size channels.

Correlation coefficients between particle number concentration for integrated size ranges and traffic up to 0.5 counts were determined. Correlations were also calculated for each of the 40 size channels of the DMPS system, respectively. We found two maxima of the correlation coefficient for particles about 10 nm and in the size range 60–80 nm in diameter.

Furthermore, correlations between traffic and particles in dependence of meteorological data were calculated. Relevant parameters were identified by a multiple regression method. In our experiment only wind parameters have influenced the particle number concentration significantly. Very high correlation coefficients (up to 0.85) could be observed in the lee side of the street canyon as well as particles in the range between 60 and 80 nm in diameter. These values are significantly higher than correlation coefficients for other wind directions and other particle sizes. A minimum was found in the luff side of the street. These findings are in good agreement with theory of fluid dynamics in street canyons.

1 Introduction

Particles below 10 μ m in diameter can be inhaled and deposited in human airways. They may be responsible for serious long-term (e.g., cancer or cardiovascular disease, Pope et al., 2002) and acute (e.g., allergy or irritation of eyes, nose and throat, Penttinen et al., 2001; WHO, 2000) health effects. Since April 1999 the EU directive "Council directive 1999/30/EC of 22 April 1999 relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air" provides upper limits for PM_{10}. The member states are also obliged to collect data for $PM_{2.5}$.

Studies have shown (Oberdoerster, 2000; Pope et al., 1995) that per unit mass, ultrafine particles (<1 μm) are more toxic than coarse mode particles (≤1 μm). Thus, the number concentration of particles has a more significant influence on health than the particle mass, but currently there are no limit value for ultrafine particles.

In urban atmospheres, particle number concentration (dominated by ultrafine particles) and particle mass (dominated by accumulation and coarse mode particles) tend to be decoupled (Tuch et al., 1997).

In urban street canyons, traffic is a major source of aerosol particles and thus mainly influences local particle size distributions. Traffic-emitted particles are complex mixtures and consist of elemental carbon (EC), hydrocarbons (HC), sulfur compounds and other substances. Particles originating from gasoline and diesel powered engines are mainly smaller than 300 nm in diameter (Wahlin et al., 2000).

Especially diesel powered vehicles emit ultrafine soot particles below 100 nm in diameter (Morawska et al., 1998). Typical particles (from modern diesel engines) are agglomerates consisting of mainly spherical primary particles of about 15–40 nm, which is significantly smaller than from old diesel engines (Burtscher, 2005). These primary particles can be oxidized to agglomerates into the accumulation mode (60–100 nm, Karasev et al., 2004).

Larger particles (>300 nm in diameter) originate mainly from regional background. In a previous study, particle size distributions from 11 to 452 nm and traffic volume have been measured at an arterial road in central London (Marylebone Road) (Charron and Harrison, 2003). In these studies, integrated particle number concentrations in three different size ranges were investigated to confirm the relationship between traffic densities and number concentrations of fine particles and differences between passenger cars and trucks were found. Passenger cars showed a stronger correlation with particles in the range of 30 to 60 nm, while trucks showed a stronger relationship to larger accumulation mode particles.

To investigate the influence of traffic on particle size distribution in the street canyon, correlation between the two values were calculated. With no regard to meteorological and other parameters, correlations are weak. Values of about 0.5 for particles between 3 and 800 nm determined in this study are similar to other investigations (e.g., Harrison et al., 2000). After being emitted, exhaust undergoes distinct dilution stages (Zhang and Wexler, 2004). Except during the first few seconds, dilution is mainly dependent on atmospheric conditions, especially atmospheric turbulent mixing.

Several previous studies included meteorological parameters, but focussing on investigated integrated particle number concentrations (Zhu and Hinds, 2002; Charron and Harrison, 2003).

The dispersion of pollutants inside the canyon is influenced by the flow field. Many other studies focussed on investigations of circulation and mixing of pollutants inside street canyons (e.g., Kim and Baik, 2004; Kovar-Panskus et al., 2002; Cheng and Hu, 2004). When the wind flow is perpendicular to the street, a recirculation vortex developes. If the height to width ratio of the canyon is roughly unity, the street canyon is called regular (Vardoulakis et al., 2003). In deeper canyons, a weaker second (and a third) vortex can be observed and modeled (Assimakopoulos et al., 2003) and in wide canyons (height to width ratio below approx. 0.5) no recirculation vortex is observed.

When the main source is located at ground level of the canyon (high traffic volume), the circulation leads to higher concentrations in the lee side of the street and lower concentrations in the luff (Kovar-Panskus et al., 2002). Thereby, the lee side is defined as the side were the roof level wind comes from. Traffic emissions are transported with the circulation directly to the lee side of the street. At the top of the canyon, turbulent processes mix urban background air into the canyon (Baik and Kim, 2002), which causes a lower concentrations at the luff side building.

A survey of modeling air quality in street canyons has been presented by Vardoulakis et al. (2003). Within the European TRAPOS network Ketzel et al. (2002) compared different models with wind tunnel experiments and field measurements in Hannover, Germany (Goettinger Strasse). The models have shown similar results for the wind field (with differences in detail), but the calculated immissions differed by a factor of seven. Thus, an evaluation against in situ measurements is necessary when using CFD-models, especially in order to describe the pollution dispersion.

The purpose of this study was to investigate the contribution of traffic to the measured particle number size distribution in a typical street canyon. Thus, the investigations presented here were made with high size resolution. All 40 available size channels of the particle spectrometer used here were considered separately. Furthermore, influences of meteorological parameters were analyzed. Relevant parameters were identified by a multiple regression. Using the result of this analysis, the study focussed on wind data, which were both measured and modeled.

2 Methods

2.1 Site description

The data presented in this study were measured from October 2003 through March 2004 in a street canyon in Leipzig (Eisenbahnstrasse), Germany. Street canyons with multistory buildings and high traffic volume is typical for European cities. The Eisenbahnstrasse is oriented nearly from west to east (285 degree from true north). Prior to reconstruction it was one of the arterial roads in the city of Leipzig with a daily traffic volume of around 23 000 vehicles. Reconstruction began in January 2004. The road was partially closed for this purpose allowing us to investigate the effects of different traffic density.

The street canyon can be called regular, because the ratio between the height of the five story buildings and width of the street is nearly unity (Vardoulakis et al., 2003). The height of the buildings and the width of the canyon are about 18 m. In such canyons, a flow field with one large recirculation vortex is expected when wind direction is perpendicular to the street and when the wind speed is larger than a lower limit of about two meters per second. Furthermore, the street canyon can be specified as short (Vardoulakis et al., 2003), because an intersection is located about 150 m from the measurement site. This causes stop and go traffic in front of the measurement site.

2.2 Instrumentation

2.2.1 Traffic counts

Traffic was detected with an optical system (Autoscope-Rackvision Image-Sensing-Systems (ISS), St. Paul, USA, MN). Traffic on all four lanes of the street was counted using a single camera. The camera was positioned on the top of a traffic light pylon at the nearby intersection, located about 20 m from the aerosol inlet. The camera was installed in October 2003. Reconstruction of the road started January 2004. The traffic light pylon with the camera was removed in April 2004.

Automatic traffic counts were validated with several manual counts in October 2003. The inaccuracy in counting passenger cars was about 2.5%. The relatively high error of 25% for trucks was due to several reasons. First is was necessary to discriminate trucks from trams, which do not emit particles in the considered size range. This differentiation did not work exactly at all times. Another problem was differences in contrast, especially at twilight and at nighttime conditions. Furthermore, the relatively low position of the camera implicated overlapping effects between the lanes during heavy traffic. Errors also caused by abnormal use of the lanes, for example by parking cars.

2.2.2 Particle size distribution measurements

The measurement site with the aerosol inlet is located on the north side of the street at the second floor of an five storey apartment house. The height above the sidewalk is approximately 5 m.

Particle size distributions are measured using identical TDMPS systems (twin differential mobility particle sizer, TDMPS, Birmili et al., 1999) consisting of two Hauke-type DMAs (differential mobility analyzer). The first DMA is an Ultrafine DMA (UDMA) which selects particles from 3–22 nm in diameter at an aerosol/sheath-air flow rate of 2/20 l/min, and the second DMA selects particles from 22–800 nm at an aerosol/sheath-air flow rate of 0.5/5 l/min. The relative humidity of the sheath air is stabilized at less than 5%. Particles are counted downstream of the DMA using a condensation particle counter (CPC), model TSI 3010 (TSI Inc., St. Paul, MN), and downstream of the UDMA using an Ultrafine CPC, model TSI 3025 (TSI Inc., St. Paul, MN). Custom software using the measured transfer functions of the DMAs is used for the inversion of the raw mobility distributions (Stratmann and Wiedensohler, 1996). The TDMPS system measures a complete particle size distribution (40 channels, 3–800 nm) every 10 min.

2.2.3 Meteorology data

Meteorological parameters were measured at the Leibniz Institute of Tropospheric Research (IfT) at the same time, located at a distance of approx two kilometers away. These measurements were made above general roof level at a height of 16 m. In this study, wind speed and direction (Metek USA1, Elmshorn, Germany), air pressure (Vaisala PTB220, Helsinki Finnland), temperature (Thiess, model PT100, Goettingen, Germany), relative humidity (Vaisala HMP243, Helsinki, Finnland) and global radiation (Kipp and Zonen CM11, Delft, NL) were used for investigations.

Wind data were also measured with ultrasonic anemometers in the Eisenbahnstrasse (Gill R2, Gill Instruments, Hampshire, England). One anemometer was positioned on the top of the five storey apartment house with the station in the street canyon in December 2003 and another one was positioned next to the aerosol inlet in June and July 2004. Because horizontal wind measurements at the Eisenbahnstrasse started December 2003, data from the IfT were used for investigations in this study. Wind direction between the two sites was in good agreement, whereas measured wind speed slightly differed. Therefore, wind speed data were only categorized into two cases ($>1.5\,\mathrm{m\,s^{-1}}$ and $\leq 1.5\,\mathrm{m\,s^{-1}}$) for correlation analysis.

2.3 Data analysis

Measurements of vertical wind speed inside the street canyon as well as traffic were conducted at different times. Vertical wind speed was measured in June and July 2004. Traffic counts were already finished at that time, because the camera was dismounted during road restructuring. Furthermore, only one measurement site inside the canyon was used, which is not enough to characterize the whole flow field.

The data were available with different temporal resolutions. From Hourly averages were used to correlate the data.

In order to identify meteorological parameters that could have influenced the particle size distribution, a multiple regression was calculated using hourly data and integrated particle number concentration. Calculations were made using SPSS11 (SPSS base 11.0, SPSS Inc., Chicago, IL).

Because the Eisenbahnstrasse is a regular street canyon with a very typical behavior, a simplified fluid dynamics model (CFD model) was used to generalize the wind measurements calculating the flow field inside the canyon. Correlation between measurements and modeling results were about 0.95. Thus, the calculations established the connection between horizontal roof level wind and the flow field inside the canyon (Voigtlaender, 2005). The typical circulation in a regular street canyon is shown in Fig. 1. Traffic exhaust from street is directly transported to the lee side building of the street canyon.

3 Results and discussion

3.1 Traffic counts

Traffic volume measured from October 2003 to through March 2004 is shown in Fig. 2. From October through December 2003 an average of 17 000 vehicles were counted per day. On weekdays, the fraction of trucks was between 3 and 4% (Fig. 2). In November 2003 a bypass road was opened. A weak reduction of traffic volume was therefore observed.

In January 2004 a reconstruction of the Eisenbahnstrasse started along with partial closure of the road. Therefore, traffic was reduced to approximately 3000 cars per day. In April 2004, the Eisenbahnstrasse was completely closed near the measurement site and the traffic light pylon with the camera was dismounted.

On weekdays, the traffic volume was significantly higher than during weekends. The lowest traffic volume was observed on Sundays. On weekdays, two maxima were observed, which occurred during the rush hours around 08.00 h in the morning and 16.00 h in the afternoon. The daily minimum was around 03.00 h at night (Fig. 3).

3.2 Particle measurements

3.2.1 Integral number concentration

Figure 4 shows the time series of the daily means of the total particle number concentration in the size range between 3 to 800 nm during the measurement campaign from October 2003 through March 2004.

Similar to the diurnal variation of the traffic volume (Fig. 3), maxima of particle number concentrations were observed on weekdays and during the rush hours, minima on weekends and at nighttime. In Fig. 5, particle number concentration and number of passenger cars on weekdays from October to through December 2003 are compared.

The reduced traffic volume after the beginning of road reconstruction in January 2004 led to a reduced particle number concentration. From January to through March 2004 the reduction in total particle number concentration was about 50% compared with the period from October to through December 2003 (from 24 000 cm^{-3} October–December 2003 to 12 000 cm^{-3} January–March 2004).

Correlation coefficients between aerosol number concentrations and traffic were calculated on an hourly basis. Using total particle number concentration and all wind directions, a correlation coefficient less than 0.5 was obtained for the time period from October 2003 to through March 2004. This value is similar to previous studies (e.g., Harrison et al., 2000). In contrast to other studies (e.g., Charron and Harrison, 2003) no significant differences were found between passenger cars and trucks in our measurements, because passenger cars and truck traffic densities were highly correlated (>0.8) at our site on weekdays. For weekdays the fraction of trucks was only about 3%. The uncertainty of the counted trucks was relatively high compared to passenger cars and differences between the correlation coefficients were within this uncertainty.

3.2.2 Regression analysis

Correlation coefficients between total particle number concentration and traffic volume are relatively weak. A multiple regression was calculated to identify meteorological parameters that could have influenced the particle size distribution. Horizontal wind data, temperature, pressure, relative humidity and global radiation were included in the analysis. Due to its discontinuity at north (360=0), wind direction cannot be used in a linear regression directly, but has to split up with trigonometrical functions. Wind data has to be also used in form of wind vectors. In this study, the transformation of the wind data was made due to the orientation of the Eisenbahnstrasse (285 degree from true north).

The results of the analysis are represented in Table 1. Therein, the used variables, the correlation coefficient between regression model and integrated particle number concentration (R) and the variance (R^2) are shown. Traffic explained more then one third of the integrated particle number concentration in the considered size range. Next to traffic, wind parameters showed the strongest influence on particle number concentrations.

Limits of 300 $\mathrm{W\,m^{-2}}$ for solar radiation and 98% for relative humidity were used. High values of solar radiation may cause particle nucleation events, which should be excluded. Furthermore, only few valid data were available. Less then 3% of all data were above the chosen limits. Measurements above 98% of relative humidity were neglected, because measurement accuracy is weak. On the other hand, aerosol droplets size is highly dependent on small variations of RH in this range.

Our regression analysis show (Table 1), that parameters other than number of cars and wind vector have only negligible influence on correlation coefficients between cars and meteorology. We have therefore only used wind parameters for further analysis.

First, the data set was divided according to wind speed. Data were separated into cases with wind speed greater than 1.5 $\mathrm{m\,s^{-1}}$ and cases below this limit, because the typical large eddy (which is influencing dilution and dispersion) inside of a canyon does not develop below a certain synoptic wind speed. Cases with lower wind speed were associated with slightly lower correlation coefficients (of traffic and particle size distribution) than cases with higher wind speed (0.49 vs. 0.51, integrated particles number concentration). Because differences were low, the results are not presented here separately.

The data were also segregated according to different sectors of horizontal wind direction. In order to have sufficient data in each sector, a sector width of 30 degrees were used. 360 of these sectors with an increment of one degree horizontal wind direction were accumulated.

Calculated correlations strongly depend on wind direction. For luff side conditions (southerly wind) very low correlations about 0.3 were calculated, whereas lee side conditions (northerly wind) led to very high correlation coefficients of about 0.8. In a regular street canyon, traffic emissions are transported to the lee side of the street directly. These results agree well with further investigations about street canyons (e.g. Vardoulakis et al., 2003).

With regard to the flow field inside the canyon, integrated mean particle number concentrations for different wind directions are shown in Fig. 6. The data were averaged over all days of the measurement campaign. For additional information, the averaged particle number concentrations measured at the IfT are also shown in these figures, but were not included in investigations (Tuch et al., 2006). Concentrations found in the luff (Fig. 6a) where significant lower than those at the lee side building (northerly wind, Fig. 6b) and in the size range of the concentration measured at the IfT. In cases of southwind (luff side), urban air was transported to the aerosol inlet with the large vortex in the canyon. Otherwise, during northerly wind, aerosol from street was transported directly to the inlet.

3.2.3 Number size distribution

Mean particle size distribution on weekdays (Monday–Friday) and diurnal variability are shown in Figs. 8. The effect of reduced traffic densities during road reconstruction is clearly seen in both plots (Figs. 8). During road restructuring, the strongest decrease was observed for accumulation mode particles around 100 nm in diameter, which were reduced by more than 55%.

Correlation coefficients between particle size distribution and traffic volume were calculated. The results are shown in Fig. 9. The correlation coefficients are strongly size dependent. Largest coefficients were calculated for the 10 nm and the 60–80 nm size bin. The first maximum is associated with nucleation mode particles originating from gas to particles conversation of traffic exhaust. The second maximum represents soot particles directly emitted from diesel engines (January 2004: 18.5% fraction of diesel cars in passenger cars in Germany, Kraftfahrt-Bundesamt (KBA), Germany). These findings are also in good agreement with diesel exhaust measurements (Burtscher, 2005).

In Fig. 9 two extreme cases for wind perpendicular to the street are shown. Correlation coefficients up to 0.85 were calculated for northerly wind directions (aerosol inlet in the lee side of the street) in the 60–80 nm size bin. Southerly wind (luff side) yielded however lower coefficients of maximal 0.45 (Fig. 9).

Figure 10 shows a combination of vertical wind speed (measure for the large eddy in the street canyon) and size dependent correlation coefficients between traffic densities and particle number concentrations depending on horizontal wind direction. Our findings show a good agreement of measured vertical wind speed (black line) with modeled vertical wind velocities (red line). Both, measurements and modeling results show, that the transport of traffic exhaust to the measurement site depends on wind direction. Therefore, correlation coefficients between traffic volume and particle concentration in size bins can only be high, if wind directions is perpendicular to the street canyon and northerly wind directions (300 to 45 degree). Correlation coefficients are lower for wind directions parallel to the street canyon (maximal 0.7 for westerly wind directions in the 60 to 80 nm size bin). Lowest correlation coefficients were observed for southerly wind directions.

These findings are in good agreement with fluid dynamics in street canyons. Our measurements of the dependence of particle size distribution on wind direction along with the good agreement of vertical wind speed from measurements and modeling suggest that models currently calculating particle number concentrations in street canyons from traffic densities may be extended to calculate number size distributions in the future.

4 Conclusions

Atmospheric particle number size distributions in a particle size range between 3 and 800 nm were measured in a highly-trafficked street canyon in Leipzig, Germany (width: 17 m, height: ca. 18 m). The continuous measurements between October 2003 and April 2004 also included real-time traffic volume and locally measured wind parameters. Typical particle concentrations during work days were between 25 000 and 35 000 cm^{-3}, accompanied by vehicle densities between 1000 and 1300 h^{-1}.

Taking into account all occurring wind directions, only moderate correlations (<0.5) were found between particle number concentration and traffic volume. Considering northerly winds only, i.e., those under which the sampling location was downwind the stream of vehicles, these correlations increased remarkably. A maximum correlation coefficients of 0.85 were found between traffic volume and the concentration of particles between 60–80 nm. Weaker correlations, however, were found for smaller (∼0.7 for D_p<40 nm) and larger particles (∼0.4 for D_p>300 nm).

The results demonstrate that the influence of the given traffic mix (3% trucks and busses, about 20% fraction of diesel cars in passenger cars) on the urban particle size distribution is highly size selective. Notably, the particle size range of maximum correlation to traffic corresponds to the size distribution maximum in passenger car diesel exhaust in dynamometer tests. We observed no conclusive effects of solar radiation, air pressure, ambient temperature and relative humidity on the measured particle concentrations.

The linear correlation analysis suggested that about 70% of the particles between 60 and 80 nm at the street canyon sampling site originated from traffic under downwind conditions, but less than 20% under upwind conditions. This illustrates the importance of the local flow circulation on point measurements in a street canyon, and was verified for the geometry of the given street canyon using a fluid dynamics model.

We therefore confirm previous findings that the local flow conditions need to be carefully characterized and considered when establishing representative particle number size distributions in a strongly inhomogeneous urban terrain, such as a street canyon.

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Table 1. Conclusion of the multiple regression using **(a)** wind direction (split up) and velocity, **(b)** wind vectors, **(c)** like (b) but excluding high values of global radiation (greater than 300 Wm^{-2}, **(d)** like (b) but excluding high values of relative humidity (greater than 98%). The short cuts mean: cars – number of cars, V – wind vector perpendicular to street, R – global radiation, RH – relative humidity, p – air pressure, T - temperature.

multiple regression				
	model	R	R^2	ΔR^2
(b)	cars	0.601	0.361	0.361
	cars, V	0.640	0.409	0.048
	cars, V, R	0.648	0.419	0.010
	cars, V, R, RH	0.660	0.435	0.016
	cars, V, R, RH, T	0.666	0.443	0.008
	cars, V, R, RH, T, p	0.671	0.449	0.006
(c)	cars	0.613	0.375	0.375
	cars, V	0.655	0.429	0.054
	cars, V, RH	0.667	0.445	0.016
	cars, V, RH, T	0.673	0.453	0.008
	cars, V, RH, T, p	0.678	0.459	0.006
	cars, V, RH, T, p, R	0.681	0.463	0.004
(d)	cars	0.592	0.350	0.350
	cars, V	0.631	0.397	0.047
	cars, V, T	0.639	0.408	0.011
	cars, V, T, p	0.646	0.417	0.009
	cars, V, T, p, RH	0.647	0.418	0.001

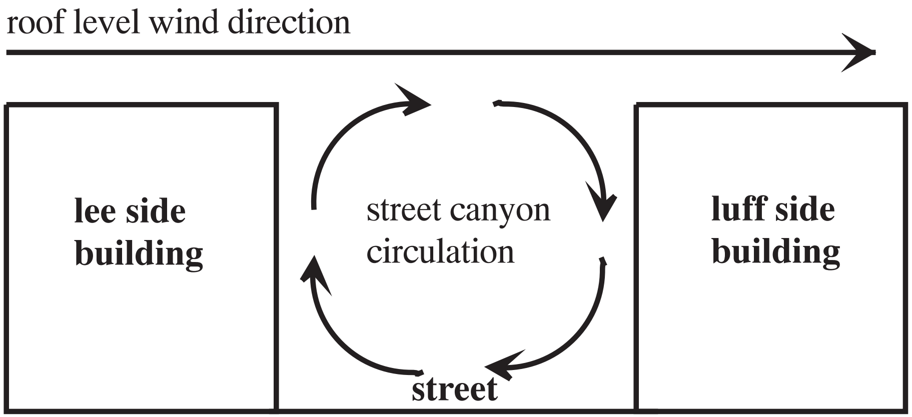

Fig. 1. Typical circulation in a regular street canyon for a wind direction perpendicular to the street.

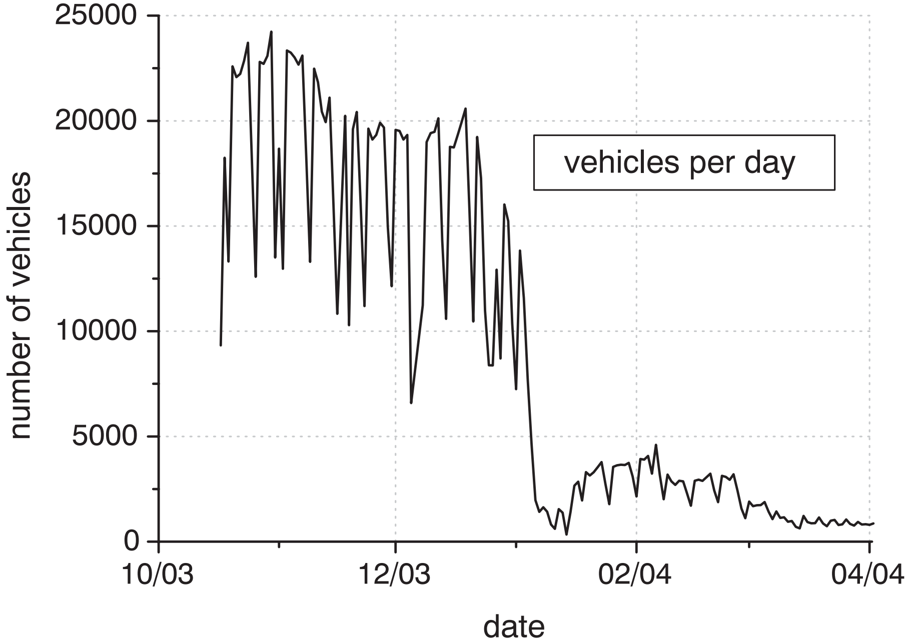

Fig. 2. Time series of the traffic volume **(a)** and the fraction of trucks **(b)** during the measurement campaign from October 2003 through March 2004.

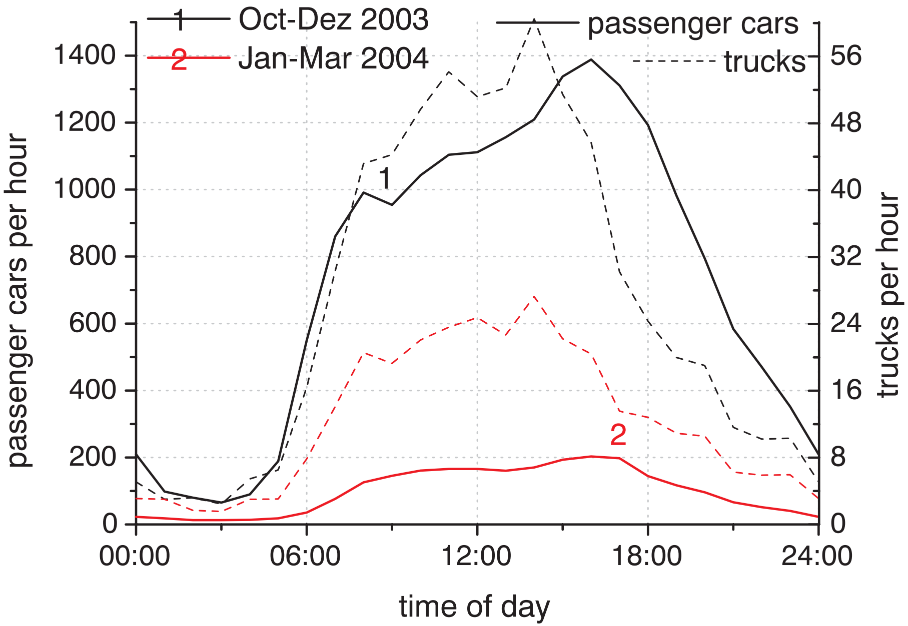

Fig. 3. Mean daily time series of traffic volume for passenger cars and trucks on weekdays.

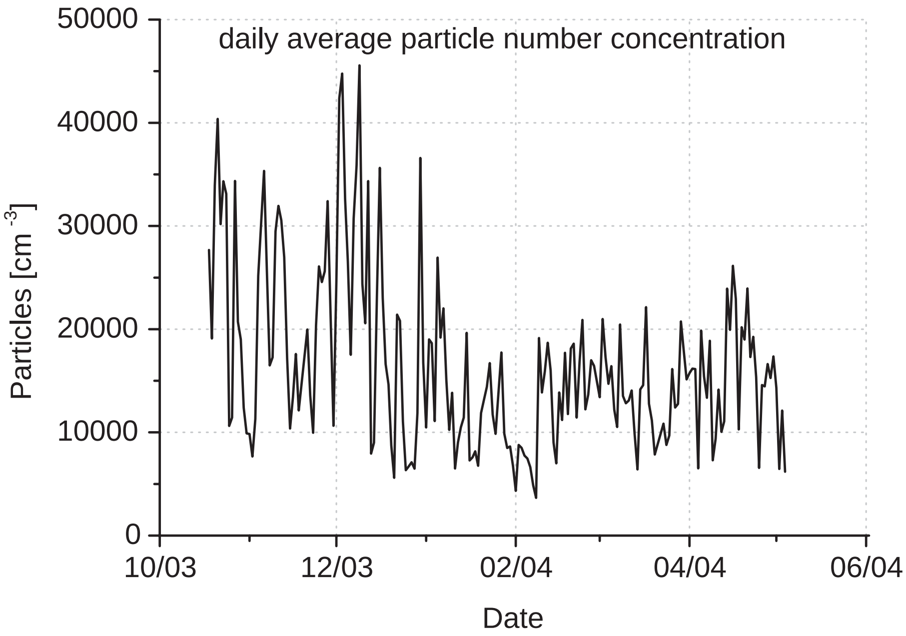

Fig. 4. Time series of daily means integrated article number concentration in the range from 3 to 800 nm from October 2003 through March 2004.

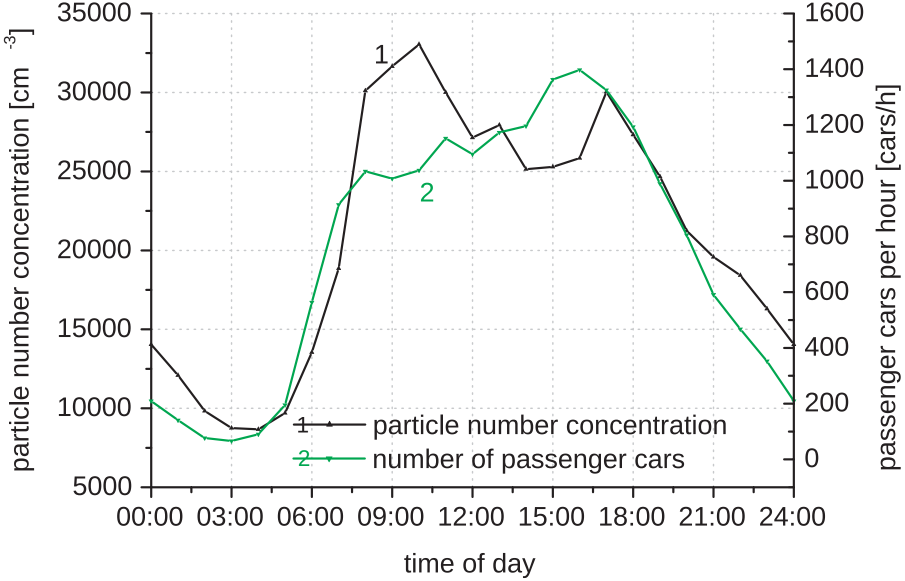

Fig. 5. Total particle number concentration and traffic volume at weekdays from October through December 2003.

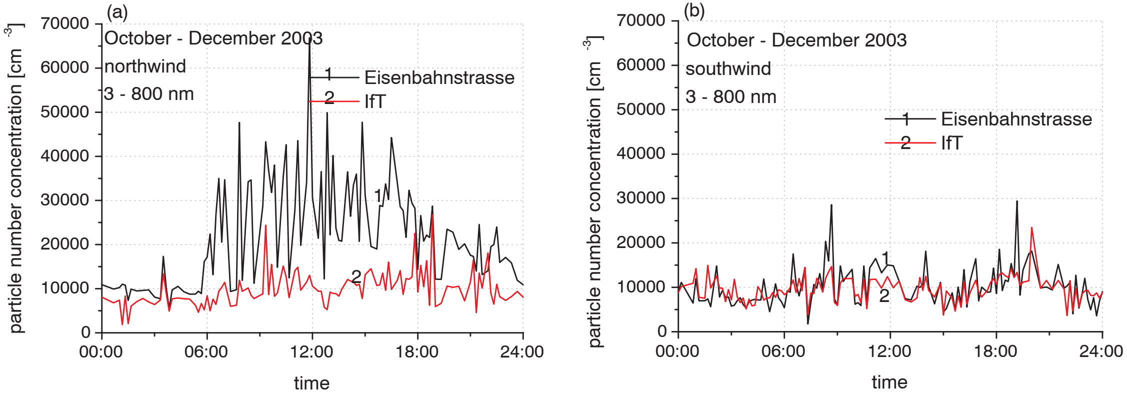

Fig. 6. Mean diurnal variability of the integrated particle number concentration in the Eisenbahnstrasse in the range between 3 to 800 nm from October through December 2003. The data set was separated into cases with northerly wind (perpendicular to the street, with the measuring site in the lee **(a)**) and south wind (perpendicular to the street, with the measuring site in the luff **(b)**). For additional information we included measurements from the IfT. Note that IfT data should not be subtracted from Eisenbahnstrasse, because IfT is not a regional background site (Tuch et al., 2006).

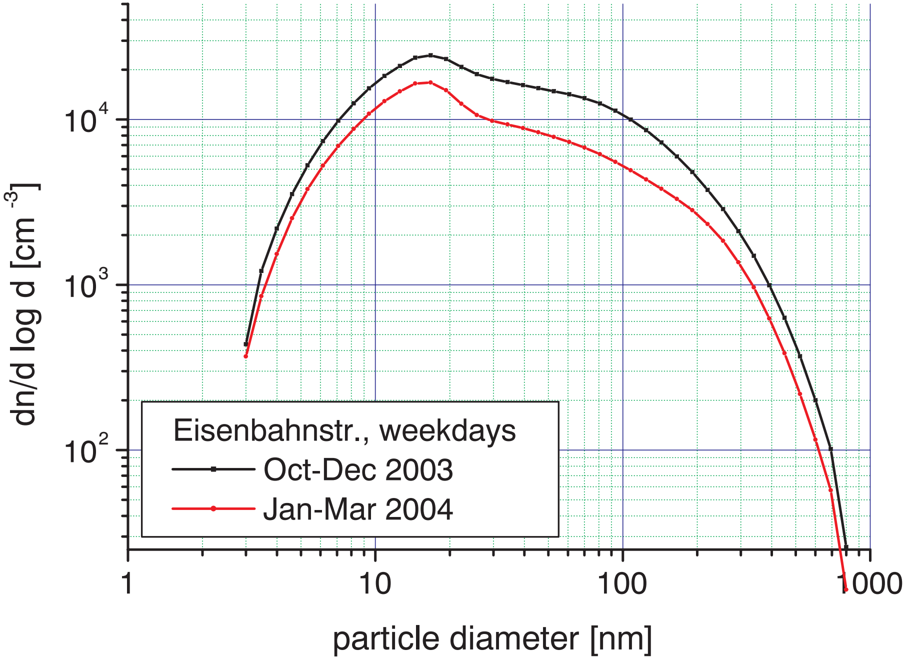

Fig. 7. Mean particle size distribution at weekdays in the Eisenbahnstrasse in the range between 3 to 800 nm.

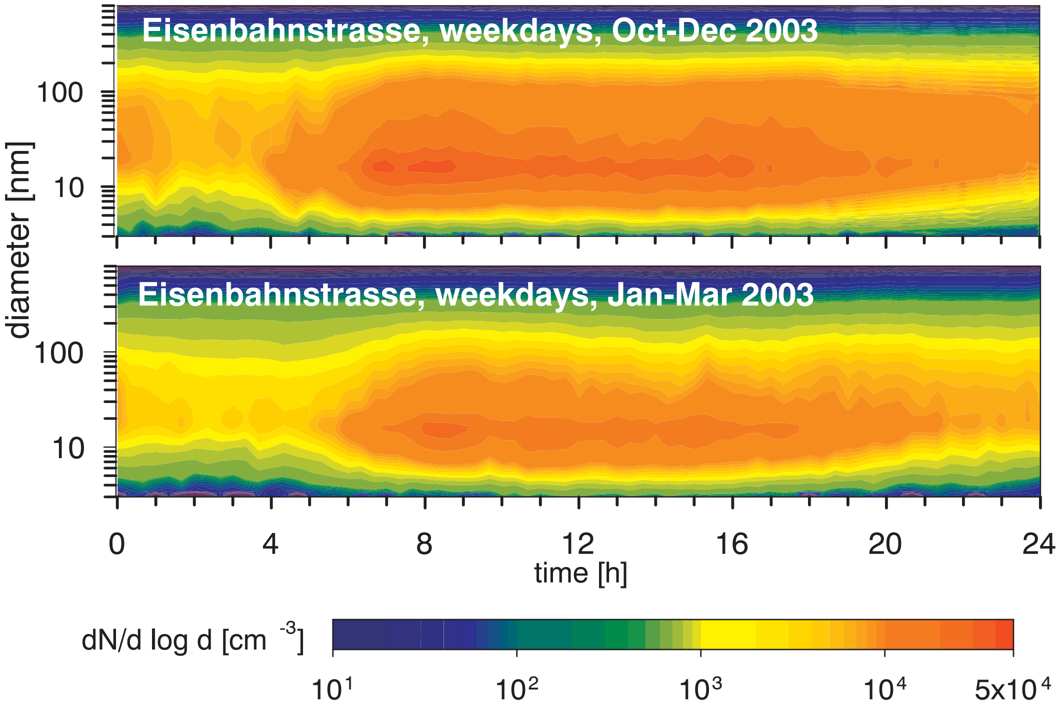

Fig. 8. Diurnal variability of the mean particle size distribution at weekdays in the Eisenbahnstrasse in the range between 3 to 800 nm.

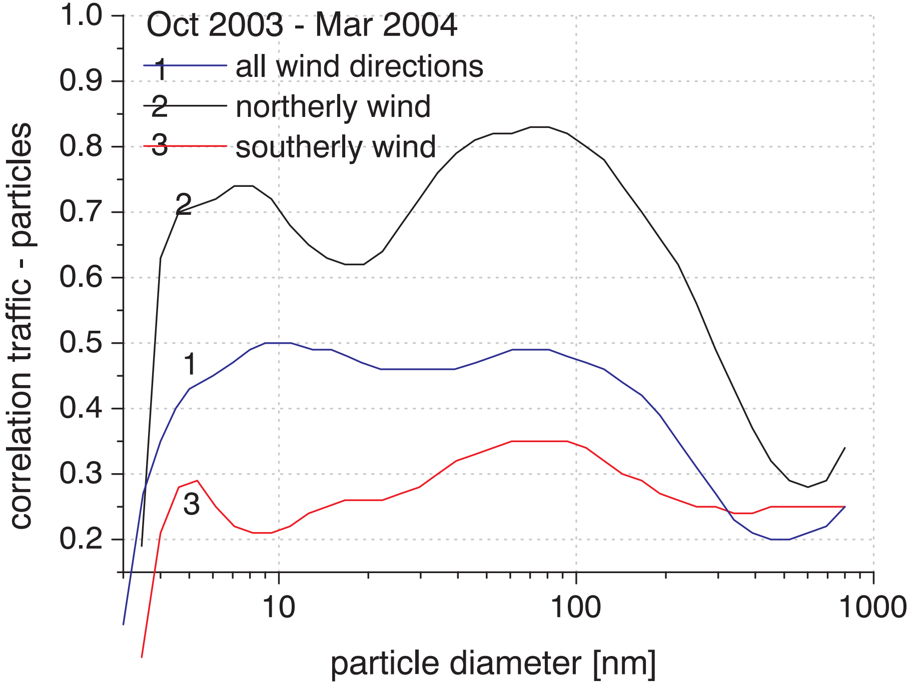

Fig. 9. Correlation between passenger cars and particle number size distribution for all days during the measurement campaign from October 2003 to through March 2004. The results are plotted for different wind directions due to the orientation of the Eisenbahnstrasse and with no regard to wind velocity. For northerly wind data with 0 to 30 degree horizontal wind direction were used, for southerly wind data with 180 to 210 degree.

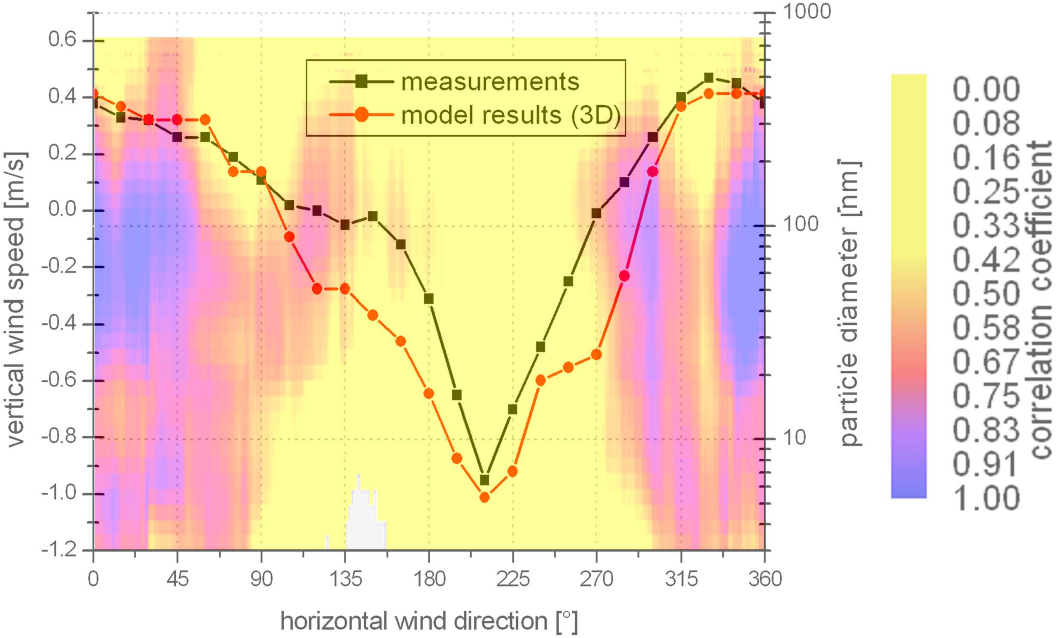

Fig. 10. Comparison of measured and modeled vertical wind speed with correlations between traffic volume and particle number size distribution dependent on the horizontally wind direction. The given wind direction is valid for the Eisenbahnstrasse, but the results are valid for similar street canyons by transforming the axis. In the figure, directions of 105 and 285 degree means a wind direction longitudinal to the street.