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SMALL SCALE PARTICULATE MATTER MEASUREMENTS AND DISPERSION MODELLING IN THE INNER CITY OF LIEGE, BELGIUM

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Abstract: Due to the costs of monitoring networks, geostatistical and physical models are often used as substitutes for particulate matter (PM) measurements. However, quality and uncertainty of urban and regional-scale models still need to be evaluated by comparative field measurements.

The Interreg IV "PMLab" project aims at harmonizing PM measurement and modelling procedures between monitoring networks of the Netherlands, Germany and Belgium, hence providing consistent information on the spatial distribution of PM concentrations within the densely populated Euregio Meuse-Rhine.
Within the frame of this project, an observational campaign at local scale is set up in the inner city of Liège, Belgium (pop. 190,000). The city is situated within the river Meuse valley with altitude differences of up to 200 m. The dominant wind directions are southwest and northeast, which corresponds to the orientation of the valley. Industrial activities located in the upwind direction have an impact on ambient air quality in the city centre.

Within the monitoring area, traffic is the most important source for air pollutants, and as such, has been chosen as focus of this study. The dominating sources of emissions are two segments of a boulevard with high traffic densities. For PM measurements using optical devices 16 monitoring sites were selected: 5 sites are located within both boulevards surrounded by tall buildings and 11 sites along transects in two smaller streets oriented perpendicular to the boulevards. Spatial variation of particle concentration in the vicinity of this inner city major axis is determined by mobile measurements and compared to simulation results. The Lagrangian dispersion model AUSTAL2000, provided by the German Environmental Agency, is run to simulate PM concentrations, considering topography, buildings, meteorological conditions and road emissions. Differences between modelled and measured values are analyzed along with other parameters.

This study is part of a series of investigations in three major cities of the Euregio Meuse-Rhine (Aachen, Maastricht, Liège). In the scope of the "PM Lab" project, results are used to determine hotspots of intra-urban traffic effects and their range in urban surroundings. Hereby, a regional statistical air quality model is supplemented by verified high resolution data from a dispersion model.

Key words: particulate matter, dispersion modelling, urban air pollution

1 INTRODUCTION

Air pollution remains one of the biggest challenges with regard to the health of urban residents. Especially particulate matter (PM) causes severe respiratory diseases leading to an increase in mortality and morbidity. Hot spots of particulate air pollution within urban areas appear mainly near roads with high traffic intensities, especially in inner city areas with a high building density (Merbitz et al. 2011). However, PM concentrations are strongly dependent not only on emission intensities but also on meteorological conditions influencing dispersion and diffusion of airborne particles (Demuzere et al. 2009, Merbitz 2009, Wolf-Benning et al. 2009). In urban surroundings air pollution is commonly simulated by numerical models in order to predict concentrations in time and space. However, the quality of air pollution models needs to be assessed by comparative measurement campaigns. Mobile measurements in the city of Liège were carried out in order to test the performance of the dispersion model AUSTAL2000, which until now has been mainly applied for industrial point sources (Langner and Klemm 2011). The applicability of the model is investigated for traffic emissions within a complex urban environment examining the influence of meteorological conditions as well as to detect small scale air pollution hot spots under these circumstances.

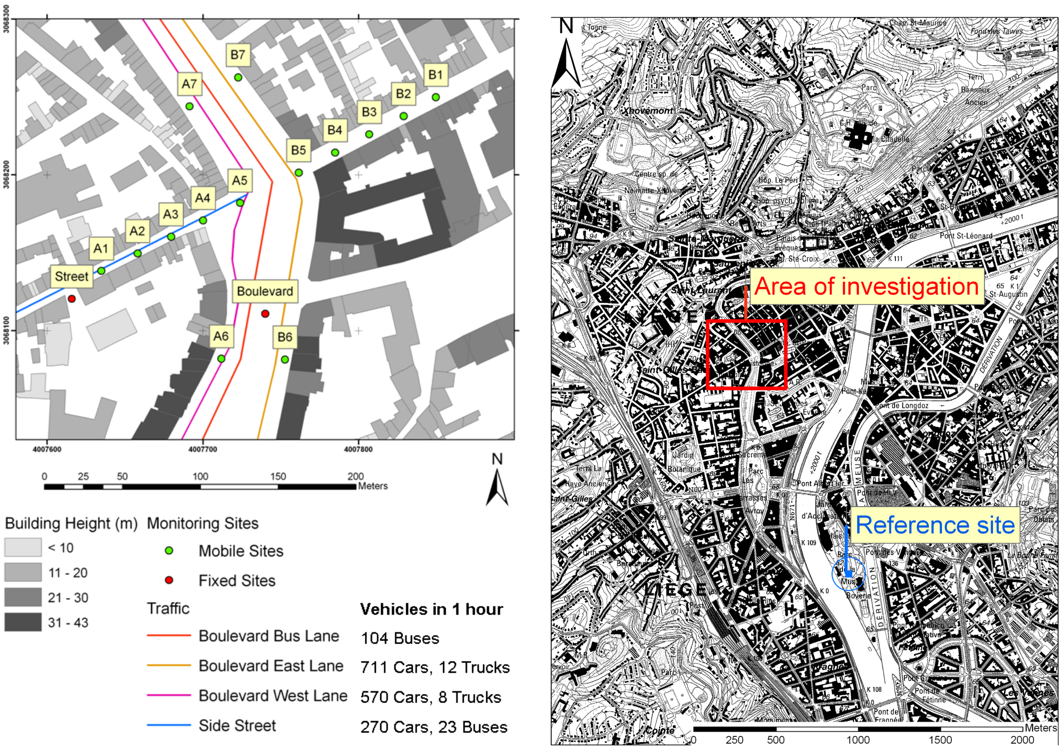
2 MEASUREMENT SETTING AND AREA OF INVESTIGATION

Within a measurement campaign in May and June 2011 PM10, PM2.5 and PM1 concentrations were measured with 4 mobile optical devices (type GRIMM EDM 107), where of 2 were operated continuously at fixed locations in a narrow and a wide street segment ("Street", "Boulevard") and 2 at different locations on 4 non consecutive days. Additionally the permanent station R201 of the ISSeP air quality network could be used as reference site. The mobile measuring points are situated along transects in order to analyze the decay of concentration with increasing distance from a large traffic source within typical inner city side streets. Furthermore, the effect of local traffic within a side street is investigated.
The mobile measurements took place on the sidewalks of a 45-70 m wide boulevard with 3 double-lanes and an average traffic intensity of >1,000 vehicles per hour during the day, and along two transects (A/B) within side streets of the boulevard (Fig. 1a). One of the side streets has a width of 8-9 m and a daytime traffic volume of approximately 300 vehicles per hour while the other street is 12-13 m wide and nearly free of car traffic. The distance between the measurement sites along the transects is approximately 25 m which leads to a total length of 100 m for each transect.
Altogether 14 locations were selected for the mobile measurements which took place on 4 days (2011-05-24, 2011-05-25, 2011-05-30 and 2011-06-09) over periods between 3 and 8 hours during daytime between 8 a.m. and 6 p.m. On 2011-05-30 and 2011-06-09 additional mobile meteorological measurements were made simultaneously to the mobile PM measurements.
One of the 2 continuously operated mobile stations was situated in the middle of the boulevard (3 m height) and the other within a doorway in the traffic influenced side street (1.5 m height).
At each of the mobile measuring sites 10 PM-measurements were carried out, the concentrations were measured as 1-minute averages and further averaged over the 10 minute measuring period. Measurements took place on both sides (A/B) simultaneously using two mobile devices. The measurement height was 1 to 1.5 m.

For normalization of measured PM concentrations and for meteorological model input a reference site without local traffic influences was selected. The site is situated within a park, about 1.2 km southeast of the area of investigation (Fig. 1b).
From the measured PM concentrations (mobile and stationary measurements) the half-hourly PM concentration at the reference site was subtracted in order to remove the influence of highly variable background concentrations, allowing for a comparison with model results which represent the traffic induced offset ("additional concentrations").
The mobile PM measurements were complemented by meteorological measurements (wind speed, wind direction, temperature, relative humidity) on two days. According to equation (1) wind speed was normalized by simultaneously recorded values at the reference site in order to compensate for temporal variability:

$$V_{rel} = \frac{1}{n} * \sum_{i=1}^{n} \frac{v_{x\,i}}{v_{ref\;i}} \,, \tag{1}$$

where V_{rel} is the normalized average wind speed coefficient, v_x is the wind speed measured at the mobile site (2 m height) for time i and v_{ref} is the wind speed at the reference site (30 m height) for the same time.



a) b)

Fig. 1a/b: Area of investigation with mobile (A1-A7, B1-B7) and permanent sites ("Boulevard", "Street") (left), location of the area of investigation within the city of Liège including the reference site for meteorological parameters and PM background concentrations (right).

3 MEASUREMENT RESULTS

3.1 PM levels and meteorology during the campaign

The average concentrations (PM10, PM2.5) at the permanent sites are shown in Table 1. Table 2 shows average values of selected meteorological parameters (see also Fig. 3 for wind direction and wind speed distribution). Table 3 shows wind speeds relative to the reference station at the mobile sites, calculated according to equation (1).

Table 1: Daily average PM10/PM2.5 concentrations (µg/m³) during the campaign at the 2 permanent sites and the reference site.

	Averages during measurement periods (daytime)						24 hour averages					
	Site "Boulevard"		Site "Street"		Reference Site		Site "Boulevard"		Site "Street"		Reference Site	
Date	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5
2011-05-24	32.46	13.21	34.45	13.12	15.77	7.38	27.90	13.41	30.86	12.96	17.96	8.40
2011-05-25	31.51	10.31	37.05	10.24	14.23	4.77	27.57	11.53	30.59	10.54	16.27	6.02
2011-05-30	15.55	5.57	19.85	5.88	12.57	4	22.16	9.38	24.14	8.67	13.02	6.35
2011-06-09	19.81	9.24	25.61	10.37	15.88	6.82	21.66	11.33	22.87	10.80	18.69	9.56

Table 2: Average wind speed, wind direction, air temperature, relative humidity during the measurement periods at the reference site.

Date	Wind speed (ms^{-1}) in 30 m height	Wind direction (°) in 30 m	Air temperature (°C)	Relative humidity (%)
2011-05-24	3.11	276	15.1	47.8
2011-05-25	1.48	137	16.7	40
2011-05-30	2.38	186	21.6	49.9
2011-06-09	2.22	254	15.6	52.5

Table 3: Wind speed coefficients relative to the reference site at the 14 mobile measurement sites.

A1	0.28	**B1**	0.26
A2	0.18	**B2**	0.33
A3	0.24	**B3**	0.18
A4	0.28	**B4**	0.63
A5	0.39	**B5**	0.59
A6	0.25	**B6**	0.59
A7	0.38	**B7**	0.38

3.2 Temporal and spatial variability of PM levels

The permanent site "Street" shows higher additional concentrations than the site "Boulevard" during all 4 days (Fig. 2 b). Average additional PM10 concentrations on the 4 days are 9.1 µg/m³ at site "Boulevard" and 11.3 µg/m³ at site "Street", and 10.2 and 15.1 µg/m³ during the mobile measurement periods, respectively. The higher concentrations during the mobile campaigns in relation to the averages over 24 h periods can be related to higher traffic emissions during daytime. The average additional PM concentrations range between 10.2 and 41.2 µg/m³ for all 16 sites. The highest absolute and additional PM level was measured within the relatively narrow side street west of the boulevard at site A3 (Fig. 2 c).

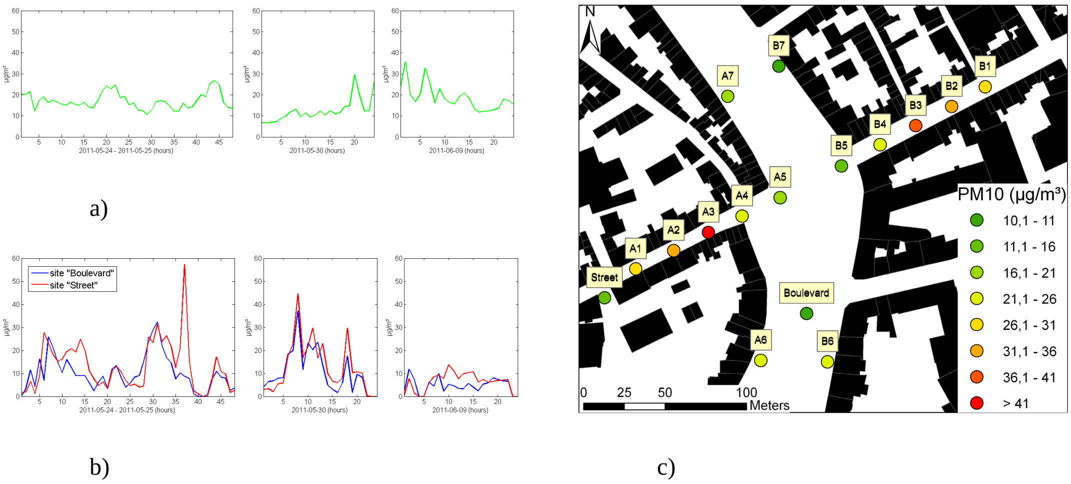


Fig. 2: a) Temporal variability of PM10 concentrations (µg/m³) during the 4 measurement days at the reference site, b) Temporal variability of additional PM10 concentrations (µg/m³) during the 4 measurement days at the two permanent sites, c) Mean additional PM10 concentrations (µg/m³) during the mobile campaign at all measurement sites.

4 MODEL RESULTS

4.1 PM10 average concentrations

The dispersion modelling was performed with the Lagrangian dispersion model AUSTAL2000 which is the German state-of-the-art model for simulation of atmospheric pollutant dispersion. It is the reference model for short range dispersion, developed for the German Federal Environmental Agency for emission approval procedures (Langner and Klemm 2011). The model was run with a spatial resolution of 4 m. Transport and diffusion of particles along trajectories are modelled based on three-dimensional wind fields simulated for 36 wind direction sectors of 10° width. Point, area, line and volume sources can be defined. Meteorological input parameters are wind speed, wind direction and dispersion category according to Klug-Manier. Klug-Manier classes represent the German standard stability classification for the atmosphere, similar to the Pasquill stability classes, reaching over 6 classes from very stable (1) to very unstable (6) (Langner and Klemm 2011, VDI 2000). As no measurement data on atmospheric stability was available, wind fields and pollutant dispersion were modelled for 4 stability classes reaching from neutral (classes 3 and 4) to unstable (5 and 6) daytime conditions, representing the range of atmospheric stability conditions. Classes 1 and 2 were excluded as they represent stable conditions at nighttime situations only. In order to compare modelling results with measured concentrations, PM10 additional concentrations were considered, after the background PM10 levels were removed from the measured values.
Average concentrations predicted by the model are highest in the narrow side street west of the boulevard (A1-A5), which is in good accordance with the measurement results (Fig. 3). Even for very unstable, favourable dispersion conditions (dispersion class 6, Fig. 3 b) extraordinary high additional PM concentrations are simulated within the narrow western side street. Sharp decreases of concentrations can be indicated along the eastern side street without local traffic influences.
Fig. 4 shows PM10 model results in comparison to measured concentrations for all 4 dispersion categories (disp. cat. 3 to 6). For sites B1, B2, B3, B4 the model clearly underestimates PM10 concentrations (<0.5 of measured values). Possible reasons are the absence of traffic within that street and an underestimation of transport of polluted air from the boulevard in connection with an overestimation of local diffusion.

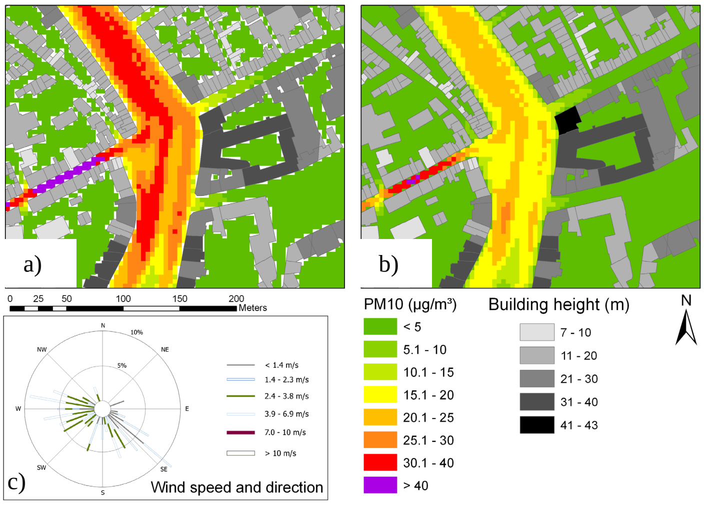


Fig. 3: Modelled average PM10 concentrations (µg/m³) for stability class 3 (slightly stable, a) and 6 (very unstable, b). The relative distribution of wind direction and wind speed is shown in the lower left corner (c).

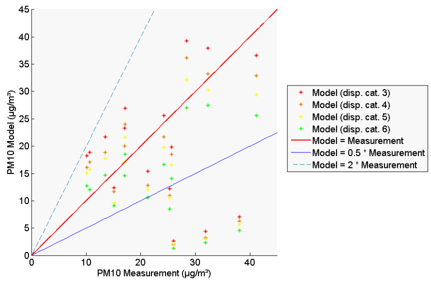


Fig. 4: Average modelled and measured PM10 concentrations at all 16 sites (µg/m³).

4.2 Wind fields

AUSTAL2000 creates diagnostic wind fields and turbulence fields on the basis of a meteorological time series, considering the influence of buildings. Meteorological input parameters are roughness length (z_0), wind measurement height, wind direction and speed and dispersion category (Langner and Klemm 2011). Wind fields have been modelled for 36 wind directions (10° range each). Fig. 5 a-c shows wind fields for wind directions 140°, 190° and 260°, according to the prevailing wind directions on the 4 measurement days. For all wind directions very low wind speeds are simulated within the western side street, even for wind directions close to the street axis (260°, Fig. 5 b). This can be identified as main reason for the very high modelled PM concentrations. Mobile wind measurements within this street are in accordance with these results (sites A1 to A4, see Table 3). For the opposite side street with a larger width (transect B), the model simulates relatively high wind speeds for southerly to westerly wind directions, which serves as explanation for the sharp decrease of modelled PM levels with distance to the boulevard (Fig. 3 a/b). This is in contrast to the relatively low measured wind speed (sites B1, B2, B3, Table 3) and the high PM concentrations measured at those 3 sites (Fig. 2 c).

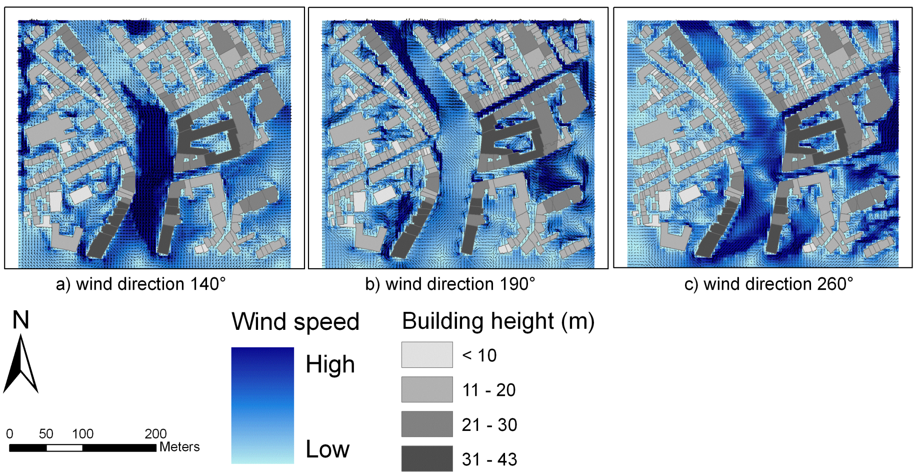


Fig. 5 a-c: Modelled wind fields for stability class 4 and wind direction 140° (a), 190° (b) and 260° (c).

4.3 PM time series

The PM10 time series for the permanent site "Street" over the 4 measurement days are shown in Fig. 6 both for measured PM10 concentrations and for concentrations modelled for dispersion classes 3 (neutral/slightly stable) and 6 (very unstable). Only daytime values (7 a.m. to 7 p.m.) were chosen for comparison, because traffic counts took place within these time intervals only, so that realistic emissions could only be modelled for daytime situations.

The time series show varying quality of modelled concentrations in comparison to the measured PM10 levels at the permanent site. On the first day (Fig. 6 a) with the highest average wind speed the model underestimates concentrations in the side street, both for neutral and unstable atmospheric conditions. On day 2 (Fig. 6 b) in connection with low wind speeds and south-easterly wind directions the extraordinary high peak at the site in the early afternoon is well reproduced by the model both in magnitude and timing, showing almost no concentration differences between dispersion category 3 and 6. On day 3 measured concentrations are underestimated by the model before 2 p.m. During this period, the results of the mobile meteorological measurements in the street canyon show frequently changing wind directions from lateral to upwards and to downwards along the road, which makes complex PM transport along the road as a reason for model underestimation very likely. The lower PM levels in the afternoon which can be explained by an increase in wind speed, are better reproduced, except for the peak around 6 p.m. On day 4 the modelled and measured concentrations are in good accordance again.

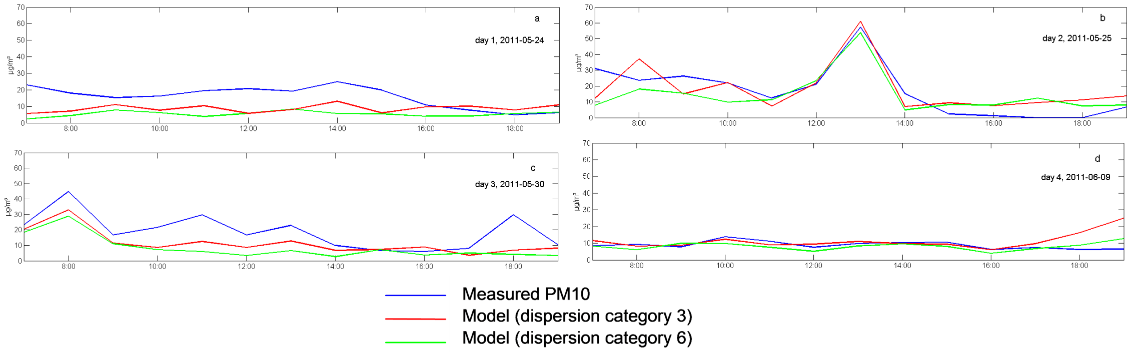


Fig. 6 a-d: Time series of measured and modelled PM10 concentrations at permanent site "Street" over the 4 measurement days.

5 CONCLUSION

Mobile short-term PM measurements were carried out in connection with small-scale dispersion modelling in order to test the applicability and quality of the model in traffic influenced urban settings. One main result of the study is that the model was able to locate hot spots of high PM concentrations, if traffic intensity, street geometry and meteorological conditions are given as input parameters. However, for the no-traffic side street the model underestimates pollution levels. Possible reasons are unrealistic wind fields that underestimate transport of particles from the boulevard. Furthermore, additional sources within that street, which are not related to traffic and could not be quantified were neglected in the model runs. For the prediction of concentration levels at a given time, the model performance depends on the meteorological situation and the site characteristics. In some cases simulated PM concentrations were in very good agreement with observed ones, e.g. the peak concentration within a side street was well reproduced both in magnitude and timing, proving the capability of the model to predict extraordinary high concentrations in space and time. The results of the study will be further compared with mobile measurements in the cities of Aachen (Germany) and Maastricht (The Netherlands) within the scope of the "PMlab" project.

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