GPS BASED DYNAMIC MONITORING OF AIR POLLUTANTS IN ZÜRICH (SWITZERLAND) AND COMPARISON WITH THE MODEL GRAL

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ABSTRACT

Despite the decrease in road traffic emissions air pollutant concentrations of nitrogen dioxide (NO_2), particulates and ozone (O_3) often exceed the limiting values at urban sites in Switzerland. The research project "GPS based dynamic monitoring of air pollutants in the city of Zürich, Switzerland" aimed at improving the understanding of the interaction between road traffic emissions and urban air quality. A tram has been equipped with air pollutant (NO/NO_2, O_3 and particulates) and satellite positioning (GPS) sensors. Two measurement campaigns were conducted in 2005–2006 in the city of Zürich, Switzerland on three different tram tracks. They represent the various characteristics of an urban environment, such as busy places and parts of the city without private road traffic.

In this paper we show the feasibility of dynamic and real-time measurements and their limitations. We present techniques developed to provide precise and reliable positioning information in an urban environment and discuss the approach used to post-process the raw measurement data. We show that a single measurement system on a dynamic platform provides ambient air concentration measurements with a high temporal and spatial resolution and coverage. Results from a photochemical smog period in summer 2005 and a smog period in winter 2006 are being presented and discussed in comparison with modelling results.

A dispersion modelling study using the NEMO, GRAMM and GRAL models of the Graz University of Technology was carried out for a $3 \cdot 3$ km^2 area in Zürich down town. NEMO was used to calculate the traffic exhaust emissions on the road network. GRAMM is a non-hydrostatic prognostic mesoscale wind field model used to calculate steady-state flow fields, which served as input to the Lagrangian dispersion model GRAL. We will present results and discuss the comparison of the measurements with the results from the dispersion simulations.

Keywords: *Dynamic monitoring, air pollution, GPS positioning, emission model, urban area*

1. INTRODUCTION

In urban areas ambient air concentrations of air pollutants depend largely on emissions of road transport (internal combustion engines), domestic heating and local industry. Cities consist of different types of urban sites, such as busy places, pedestrian areas with low to no traffic and quarters of different site density. Meteorological processes such as surface inversions, wind, precipitation and solar radiation furthermore influence the variation of ambient air concentration. Elevated ambient air concentrations have a negative effect on life on Earth in general and on human health, in particular. Even though measures were taken, such as the introduction of the catalytic converters in fuel driven vehicles (since 1988 in Switzerland) and the progress in fuel and combustion engines technologies, limit values of NO, O_3 and PM_{10} are still regularly exceeded at urban sites (Bundesamt für Umwelt, 2007). The high-resolution assessment of the temporal and spatial variability of ambient air concentration is, therefore, of great interest.

Zürich lies north of the Alps in the Limmat valley (47° 24’ N, 8° 30’ E) around the basin of lake Zürich (420m a.s.l.). It extents over an area of $15 km^2$ between and on the surrounding hills (500–650m a.s.l.). The city and the agglomeration have a population of 370’000 and 1’100’000, respectively. Light industry, a medium size airport and highways can be found in the western and northern area. Road networks are heavily used by private and commercial transport. Electric trams and trolley buses dominate public transport. However, diesel buses, which are mostly equipped with particle filters, are also in use.

The overall goal of the research project carried out in this city was to assess the feasibility of dynamic monitoring of air pollutants (Kehl, 2007). The effort for developing and operating the monitoring system should be kept low while maintaining high spatial and temporal resolution and coverage. Means for precise and reliable positioning in an urban environment had to be found and implemented. Furthermore, it was specified to monitor air quality on-line and in real-time, and to investigate the correlation between traffic and ambient air concentration.

A state-of-the art dispersion model was used to produce seasonal and yearly mean distributions of NO_X for a $3 \cdot 3 km^2$ area in Zürich downtown. Proper measurements have been carried out in this area and allow for a comparison with the simulated ambient air concentrations. The dispersion modelling involved the models NEMO (traffic and emissions), GRAMM (meteorology) and GRAL (dispersion) of the Institute of Internal Combustion Engines and Thermodynamics of the Graz University of Technology.

2. THE MONITORING SYSTEM

A tram was found to be a suitable platform for mobile air pollution measurements in Zürich for several reasons. It operates on a regular basis throughout the day, which enables measurements with a high spatial and temporal resolution and coverage. The chosen lines cross the city and represent the various urban characteristics described above.

A dedicated mobile system has been developed. The fully autonomous system was built into a box of approximately $2 \cdot 1 \cdot 0.4\ m^3$ volume. The 150 kg box was mounted on the roof of a tram and connected to the tram's internal power supply. The measurement system powered up and shut down automatically via an uninterruptible power supply, which included a fail-safe backup shutdown procedure in case the control computer would have failed. Software was developed on a Linux basis that controlled the instruments, logged the data and transmitted measurements and status information in real-time using mobile communication technology (GSM/GPRS).

GPS was chosen as a position and time reference. A suitable GPS receiver capable of providing precise positions in urban areas with pronounced street canyons of up to 20–30 m height was identified and used in the measurement system. The receiver's Kalman filter engine was tuned to the expected movement of a vehicle running on city streets. This and the receiver's optimisation for vehicle navigation provided precise measurements even under adverse condition (few satellites, unfavourable satellite constellation) most of the time. The average ratio of GPS outages, either due to no availability or due to unsatisfactory accuracy (quality filtering), was between 2.2 and 3.5%. Outage ratios of 5–10% (and rarely above 20%)

were observed at few sites. A projective map-matching technique was developed to transform the measured position to the most likely position of the tram on the track. 95% of the positions obtained from the GPS receiver were 6.7-7.4 or less metres off the used geometry of the tram track. A technique was developed to generate accurate positions during periods of GPS outages, which in general lasted a few seconds up to a few dozens of seconds. The method relies on the track geometry and the characteristics of the movement of the tram. The combination of the GPS measurements and the interpolation of missing positions enabled for a precise and reliable referencing of the environmental measurements in space and time.

Table 1 shows an overview over the used sensors. A detailed report on the measurement system, the campaigns and data analysis is given in Kehl (2007).

Table 1: Overview over the measured parameters, the measurement principle involved, the used sampling rate (averaging time) and the sensors used

Parameter	Meas. principle	S. rate	Unit	Vendor and sensor
NO / NO_2	chemiluminescence	0.1 Hz	ppb(v)	TEI Model 42TL
O_3	UV absorption	0.1 Hz	ppb(v)	2b Tech. Ozone Monitor 202
particles	diffusion charging	0.5 Hz	$\mu m^2 \cdot cm^{-2}$	Matter Engineering LQ-1DC
abs. pressure	piezo-resistive	0.5 Hz	hPa	Keller Absolute press. sensor
temperature, rel. humidity	resistive and capacitive semiconductors	0.5 Hz	°C, %RH	Rotronic Hygroclip S3
position, time	GPS	1.0 Hz	m, s	uBlox ANTARIS SBR-LS

3. MEASUREMENT RESULTS

Two measurement campaigns were carried out: 16 weeks from March to June 2005 and 23 weeks from December 2005 to May 2006. Data post-processing procedures have been developed which produced raw time series in a quasi two-dimensional way. The ambient air concentrations of the pollutants (the “sensor readings”) have been referenced by an along-track position (first dimension) and by the absolute time (second dimension). High spatial and temporal resolution of the measurements has been achieved and it has been shown that a single mobile measurement system adds a spatial component to ambient air concentration time series. The post-processed data has been analysed in various ways.

Figure 1 shows an example of the analysis of a photochemical smog period (5 days) in June 2005 measured on tram line 11 (compare figure 2 for the tram track). The tram usually operated from early morning to late night. The data has been interpolated to a grid with 50m·30min resolution using the collocation method (see Kehl, 2007 for details). NO_X, as a primary pollutant directly emitted by road transport, correlates with the amount of traffic at specific places. Two notoriously busy places in Zürich downtown are clearly visible in the measurements. The area around Hauptbahnhof (A, main railway station) is busy throughout the day. The area from “Bürkliplatz” to “Bellevue” place (B) is an intersection of two major streets connecting to each side of the lake and high capacity lanes connecting down town and near quarters (compare figure 2 for the location of the places). Besides the effect of road traffic exhaust emission strength chemical and meteorological processes influence pollutant concentrations. In the morning NO_X concentrations are rather high all along the track. They generally decrease except at busy places as the inversion dissolves during the later morning. The ozone concentrations increase because of the break-up of the inversion and mixing down of ozone from the residual layer. The third effect, best visible at the busy places, shows the titration of O_3 by NO below the inversion layer.

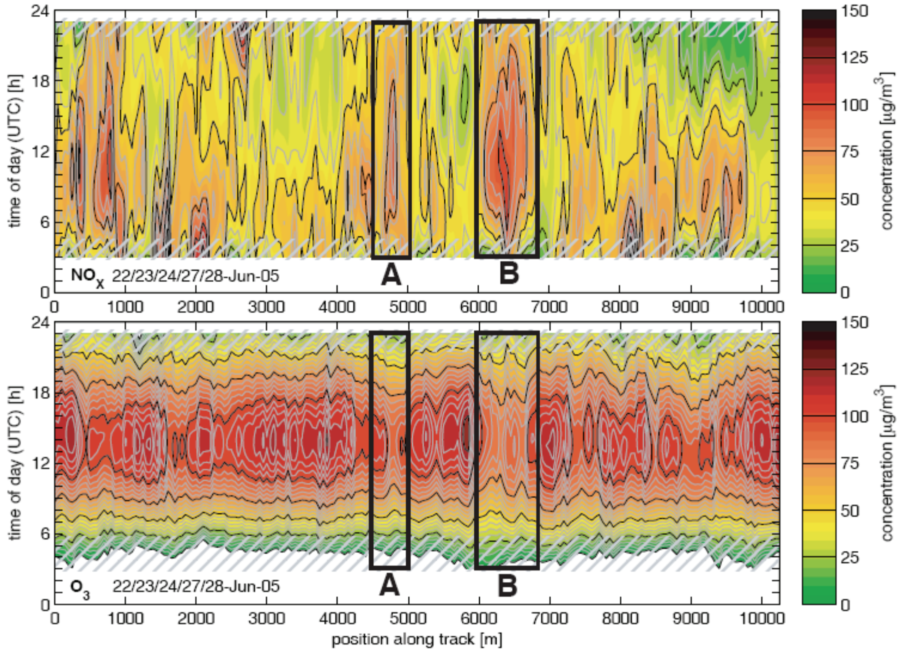


Figure 1: The plots show the average diurnal change of air pollutant concentration along tram track 11 averaged for five days in June 2005 with exceeded ozone limit values ("summer smog" days). The tram track runs North–South through the city (see figure 2). The data has been interpolated and averaged using the collocation technique. **A** and **B** represent two busy places (the area around central station and the section from "Bürklipatz" to "Bellevue" place, respectively). The section between A and B corresponds to "Bahnhofstrasse", which is a pedestrian area with very low traffic.

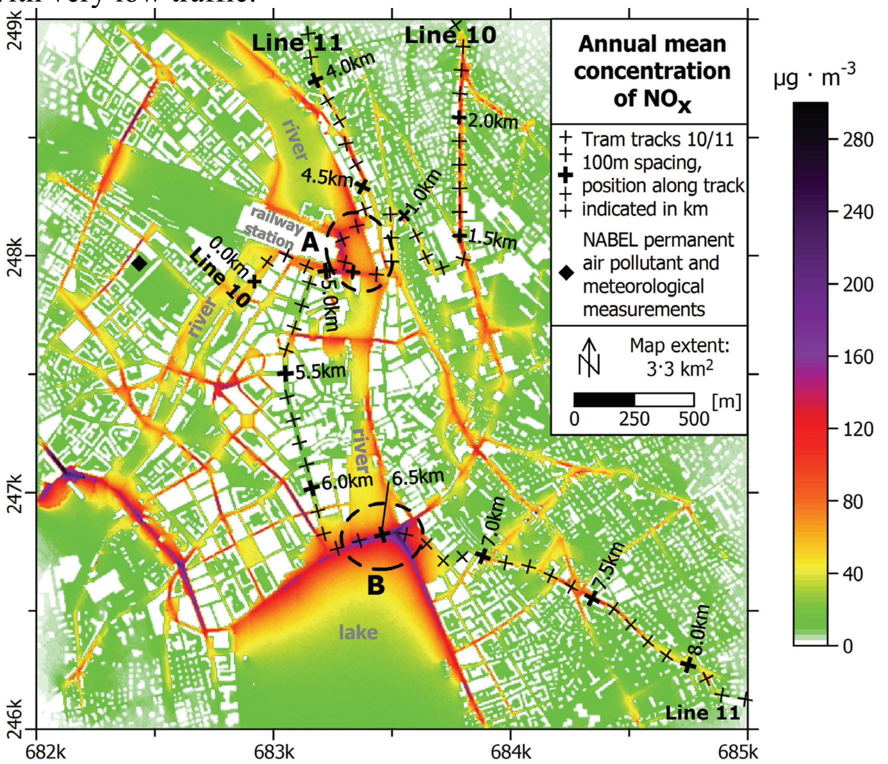


Figure 2: Annual mean concentration of NOX derived from GRAL. The tram tracks along which measurements were conducted are indicated with crosses every 100m and the along track position is labelled in km. White areas correspond to buildings. The circled areas A ("Bahnhofplatz") and B ("Bürkliplatz/-Bellevue") correspond to the respective positions in figure 1. See also text.

4. MODELLING / SIMULATIONS

Most of the pollutants at ground level in a city originate from road traffic. The emission sources are mainly internal combustion engines used in cars, trucks, busses, motorbikes and scooters. They together build line sources along the road network. The pollutants then disperse into the city. Depending on meteorological processes (wind, radiation, precipitation, inversions) they accumulate, degrade or react to other compounds. Urban areas are complex terrains with a rough surface where wind induces strong turbulences in the street canyons. This influences the dispersion of the emissions. To determine the spatial distribution of the mean concentration of a pollutant in a city numerous parameters have to be taken into account.

The study area extents over 3·3 km^2 in the inner city of Zürich. It was chosen with respect to available measurement data, both from the tram measurements and an established reference station, as well as its urban character covering busy places and streets without private road traffic and computational limits. The dispersion calculations were carried out for a period of one year (June 1, 2005 until May 31, 2006).

The modelling approach involves three models. These are:

NEMO The road traffic emission model (*Network Emission Model*) which allows the calculation of traffic emissions on road networks. It relies on the *Passenger car and Heavy duty Emission Model* (PHEM), which is compatible with the HBEFA 2.1 to a large extent (Rexeis et al., 2007).

GRAMM The 3d wind field model (*Graz Mesoscale Model*) (Oettl et al, 2008).

GRAL The dispersion model (*Graz Lagrangian Model*) (Oettl et al, 2008).

Figure 3 provides a general overview over the complete modelling and calculation process. Meteorological, geometrical and emission data is needed to carry out the final dispersion calculations.

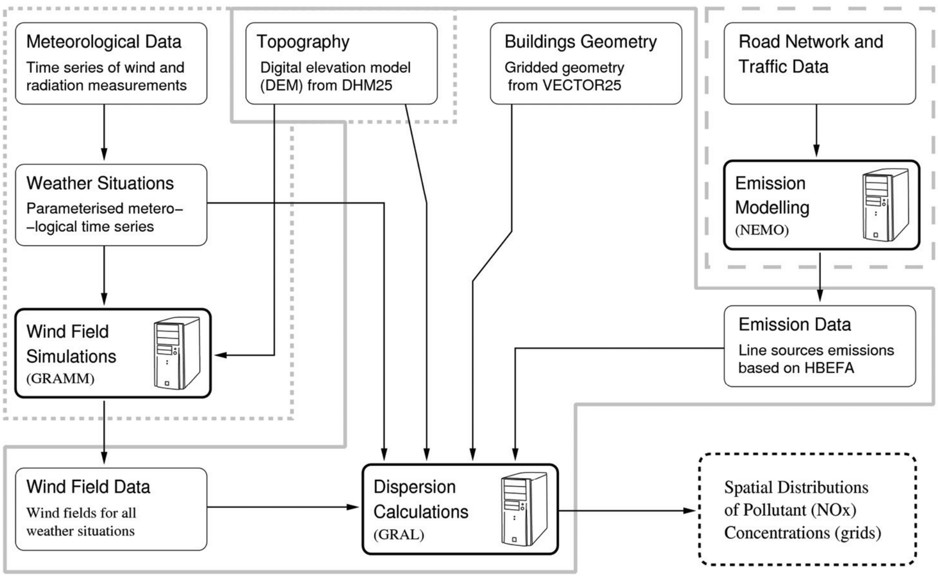


Figure 3: General flow chart of the dispersion modelling. The four boxes at the top correspond to the input data. The three bold framed boxes represent the modelling-/simulation programmes. The other framed boxes correspond to pre and post processing. The box at bottom right represents the results. The grey polygons group the boxes according to the three models used: GRAMM (dotted, left), NEMO (dashed, right) and GRAL (stroke-through, centre). See text for details.

Input to the NEMO model consists of a road network geometry, street classifications and other attributes, such as the average slope on a line segment and the yearly average daily traffic. It outputs emissions per road segment in $kg \cdot km^{-1} \cdot h^{-1}$, based on emission factors and fleet models.

The wind field modelling programme GRAMM simulates steady-state 3d wind fields for parameterised meteorological situations. These were obtained from meteorological measurements at a point within the area of investigation (see figure 2). The 1h average time series was classified into 36 wind direction classes, 5 wind speed classes ($v_1 < 0.5 < v_2 < 1.0 < v_3 < 2.0 < v_4 < 3.0 < v_5$ [$m \cdot s^{-1}$]) and seven classes which, based on wind speed and net radiation, describe the atmospheric stability or the amount of atmospheric turbulence (ÖNORM, 1996, p.29). Of the 1260 possible combinations, 696 were observed in the one-year time series (June 1, 2005–May 31, 2006) used. The percentiles are as follows: 50% = 107, 90% = 386, 95% = 478, 99% = 611. Wind fields were calculated for a $7 \cdot 7$ km^2 area.

The input to the dispersion calculation programme GRAL consists of the road network with emission data, the parameterised meteorological time series, the wind fields, geometrical data of the terrain and the buildings and configuration files. The results are grids, in this case with a 5m horizontal resolution, of annual, seasonal and daytime/night-time averages of NO_X.

Figure 2 shows the annual mean concentrations of NO_X derived from the modelling and simulation process outlined above.

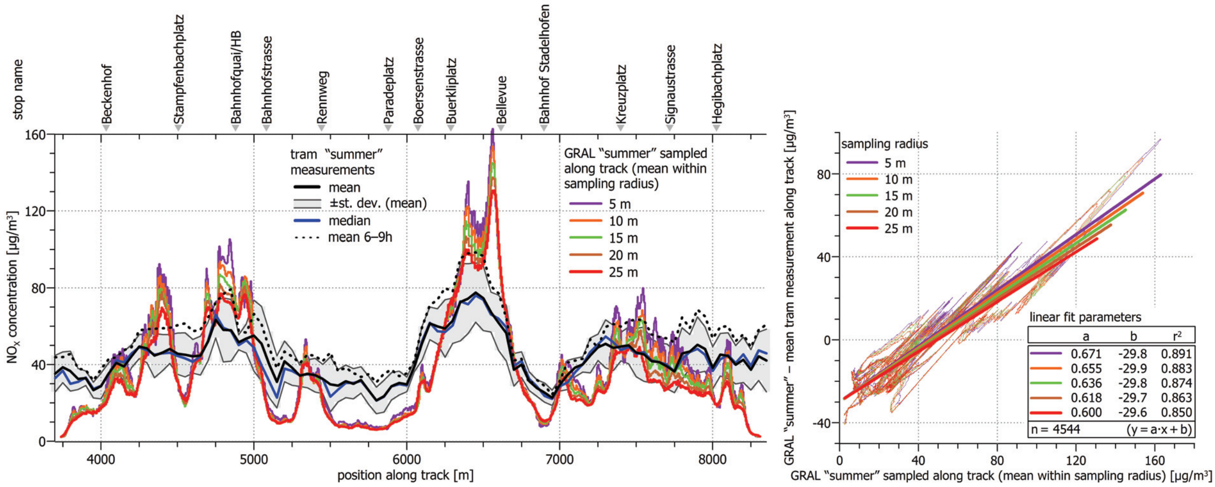
5. COMPARISON OF MEASUREMENTS AND MODEL RESULTS

Figure 4a shows the comparison of the GRAL results for the summer season (June–August) with the tram “summer” measurements. The latter are the interpolated summer measurements for fair and adverse weather (because of technical problems, the summer data includes NO_X measurements of 17 days). The combination of fair and adverse weather days should represent average “summer” days sufficiently well. The plotted curves are: the mean (black line) ±standard deviation (grey area), the median (blue line) and the early morning (6-9 h UTC) mean. The GRAL results were sampled along a cross-section which corresponds to the tram track 11 (compare figure 2). Several sampling radii were used (5–25 m) and the mean value of all grid points within the radius (excluding buildings) was calculated yielding somewhat different results. The difference is marginal at low concentrations and increases with the concentration. The smaller the sampling radius, the larger the peaks in the resulting curve turn out. The maximum difference can be seen at the section from Bürkliplatz to Bellevue place (approx. position 6300–6600 m).

The concentrations sampled from the GRAL grid follow the same pattern as the tram measurements. The qualitative agreement of the simulation and the measurements seem to be reasonable. Significant differences seem to exist where GRAL shows low concentrations. In this study only traffic emissions were used as input into the dispersion calculation, which are expected to be the main emission source in the city in summer (no domestic heating, which would be another main contributor in winter).

The results of a correlation analysis of the mean tram measurements along the track and the GRAL cross-sections of different sampling radii is shown in figure 4b. It shows significant to good correlation coefficients (>0.85). It quantifies the offset of the GRAL simulation results from the measurements (at places where GRAL shows very low values) at approximately 30 $\mu g \cdot m^{-3}$. The GRAL simulation results agree best with the measurements at busy places (main railway station) and between “Bürkliplatz” and “Bellevue” (compare section 3 and figure 2).

The differences at low concentrations probably are due to unmodelled emissions, the dominance of air pollution that originates from traffic and ignored regional NO_X background.



a) **b)**

Figure 4: Comparison of measured average NO_X concentrations along tram line 11 in summer 2005 with the GRAL results for the summer season (a) and a statistical analysis of the correlation between the two data sets (b).

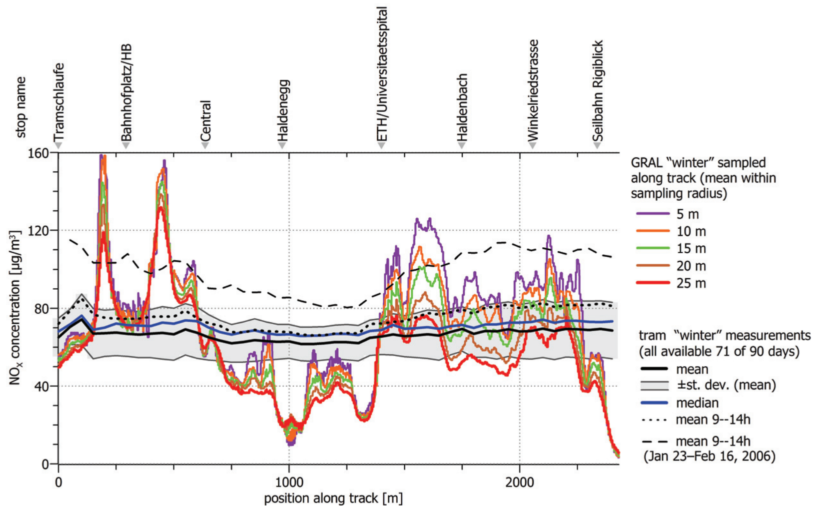


Figure 5: Comparison of measured average NO_X concentrations along tram line 10 in winter 2005/06 with the GRAL results for the winter season (left) and a statistical analysis of the correlation between the two data sets (right).

Further reasons might be inaccuracies in the input data, which includes traffic densities, street network geometry, emission factors, buildings geometry and meteorological data. The comparisons (figure 4) show higher concentrations at the polluted sites, suggesting an underestimation of dispersion in the model.

Figure 5 shows the comparison of the GRAL results for the winter season (December–February) with measurements conducted in winter 2005/06. The plot is analogous to figure 4 (left, see above). In winter 2005/06 tram measurements are available on 71 of 90 days. In the interpolated average of all measurements (black line and grey area) very little variation along the track can be seen. GRAL, however, shows distinct variations along the track with steep gradients. The offset to the measurements at the lowest GRAL values is larger than in the summer results.

The following problems add to the discrepancies between GRAL and the tram measurements: emission from domestic heating and two pronounced and long-lasting exceptional winter smog periods in January and February, which caused a very high regional background level (Bundesamt für Umwelt, 2007). The dashed black line is the 9-14h average of the measurements during a smog period. It features more pronounced variations along the track than the total winter average. It does not correlate with the GRAL curves (correlation factor of approximately 0.1).

6. CONCLUSIONS

This research project has proved the feasibility of dynamic monitoring of air pollutants in a city and its limitations have been identified. Suitable data preparation and interpretation methods have been developed to analyse the dynamic measurements.

A single measurement system has provided measurements with high temporal and spatial resolution. Techniques based on GPS measurements and post-processing routines to provide a reliable and precise position and time reference for the environmental measurements have been developed and demonstrated. The analysis of spatio-temporal distribution of air quality and its modelling have clearly revealed that the research conducted provides a solid basis for advanced interpretation of air quality.

Model simulations with GRAL for the summer season show good agreement with the measurements. The offset results from missing background concentrations and emission sources. Because of unfavourable dispersion situations, the simulated concentration values in the winter season are higher than in summer.

Nevertheless, the unmodelled emission sources and regional background concentrations seem not to be the sole explanation of the discrepancies between simulation and measurement. Further investigations are necessary to elucidate these open questions.

7. ACKNOWLEDGEMENTS

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