EXPERIMENTAL INVESTIGATION OF URBAN CANOPY LAYER FLOW AND DISPERSION

Schatzmann, M.[1]*, Bächlin, W.*[2]*,Emeis, S.*[3]*, Kühlwein, J.*[4]*, Leitl, B.*[1]*, Müller, W.J.*[5]*, Schäfer, K.*[3]
[1] University of Hamburg, Centre for Marine and Atmospheric Research, Meteorological Institute, Bundesstrasse 55, 20146 Hamburg, Germany
[2] Ingenieurbüro Dr. A. Lohmeyer, Karlsruhe
[3]Forschungszentrum Karlsruhe, IMK-IFU, Garmisch-Partenkirchen
[4]University of Stuttgart, IER
[5]Lower Saxony State Agency for Ecology, Hanover

INTRODUCTION

In the framework of the German Atmospheric Research Program AFO-2000, a research consortium with the acronym VALIUM was formed, which consisted of German research institutes, environmental consultancies and an environmental agency. A substantial part of the VALIUM program was devoted to the generation of a set of high quality data for the validation of obstacle resolving numerical models. The validation data generated are based on a combination of field experiments and corresponding wind tunnel experiments. An intelligent data base VALIDATA was generated that provides most of the measurement results in convenient form.

EXPERIMENTS

The field measurements were carried out at the test site 'Goettinger Strasse' in Hanover/Germany (Fig. 1). This side includes a busy street canyon with approximately 30000 vehicles per day, a large percentage of them being trucks. Since about two decades

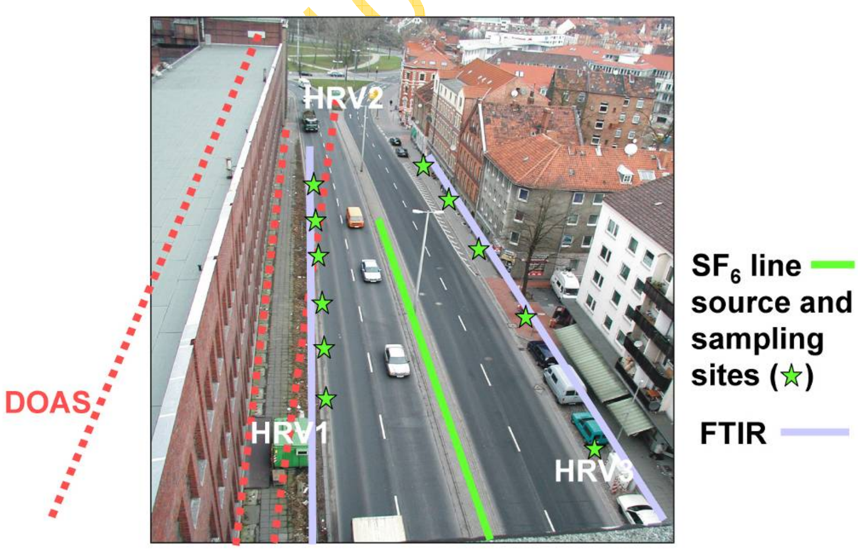

Fig.1: Street Canyon 'Goettinger Strasse with instrumentation. The picture shows the continuous monitoring stations HRV1 to HRV3 in white and the SF6-line-source at the median strip plus the sampling bag locations in green colour. The path-averaged measurements are indicated by the blue solid (FTIR) and red dotted (DOAS) lines.

the Lower Saxony State Agency for Ecology (NLÖ) operates a monitoring station at this site. Long time series of data are available which offer the opportunity to approach the urban air pollution problem also by statistical methods.

Continuous measurements of air pollutants inside the street canyon and in the surrounding area of 1 km x 1 km (Goettinger Strasse in Hanover) were performed in addition to the routine NLÖ monitoring from early 2001 until the end of 2003. Both air pollutants and meteorological parameters were measured by in-situ instruments at four locations inside the street canyon and at three locations in the surroundings of the canyon (one of those being a roof-top station at the highest building in that area). Path-averaging optical measurement techniques (two, some times three DOAS systems) were used continuously at the ground and at building roof level. The meteorological background (vertical profiles of wind and turbulence plus mixing layer height) came from a SODAR system that was positioned about 500 m apart from the street canyon.

Three intensive observation periods (IOPs) in different seasons were successfully executed. Path-averaged concentrations of air pollutants were measured at both sides of the street using FTIR spectrometry. In addition, vertical gradients of air pollutants in the street canyon were determined applying a DOAS-system. During selected periods, the standard meteorological parameters measured continuously at the roof top station and by the SODAR system were complemented by (1) a ceilometer (operated by Vaisala) that was located at the roof of a building, and (2) a Wind-Temperature-RADAR (WTR, operated by IMK-ASF). The ceilometer (aerosol backscatter profile) and WTR data (temperature profile) were used for comparisons with the SODAR data. All measurement systems were carefully calibrated. Simultaneous operation of the different instruments carried out at one site before or after each IOP showed only differences in the order of the specified accuracy of the instruments.

Most of the previous field experiments carried out in urban areas suffer from the fact that the source term is not properly known. There is the choice between several emission models that link the traffic flow to the source strength. Since the concentration fields predicted in dispersion calculations are directly proportional to the source strength, the results of numerical models may to a large degree depend on the particular choice of the emission model. In order to circumvent this problem, the meteorological and pollutant measurements in the Goettinger Strasse were complemented by some tracer experiments. An artificial line source was installed on the median strip dividing the four traffic lanes, and controlled amounts of SF_6 were released. The line source had a length of 96 meters. Air probes were collected at 15 sampling points within the street canyon and at roof level. The SF_6 content of the probes was subsequently analysed in the laboratory. For altogether 8 days within the period 2001 to 2003, 100 half-hourly averaged concentration values were determined at each monitoring position. Additionally path averaged concentrations of tracer SF_6 were measured at both sides of the street using FTIR spectrometry. Prevailing wind directions during the experiments were westerly for five days and northerly, easterly and southerly, respectively, for the remaining 3 days.

The tracer experiments provided the opportunity to validate not only dispersion models but emission models as well. During the intensive observation periods, manual traffic counts were carried out together with traffic speed measurements. In addition, the vehicles were subject to an automated plate number registration. The subsequent consultation of the German vehicle register allowed the exact determination of the vehicle engines and, by means of emission factors, the best possible quantification of the traffic emission rate.

Field measurements cannot properly be controlled. During the measurement campaigns one has to cope with the weather as it is, the boundary conditions for the experiments are only partly known and, even worse, they change continuously due to the diurnal cycle. Therefore, VALIUM comprised also a wind tunnel sub-project that was tasked to support the field measurement campaigns with corresponding flow visualization experiments and with some systematic sensitivity studies which help to analyse and to understand the data. In addition complete fields of velocity and concentration were measured within the street canyon with a spatial resolution which corresponds to that of micro-scale numerical models. A detailed aerodynamic wind tunnel model of the urban site was built, the complete model covering an area of about 1 km x 1 km (Fig. 2). A wind tunnel boundary layer corresponding to the model scale (1: 250) was generated utilizing a combination of vortex generators and floor roughness elements. The complete mean and turbulent boundary layer properties were determined. Subsequently numerous and until now unique experiments have been carried out from which only a few examples can be presented in the results chapter.

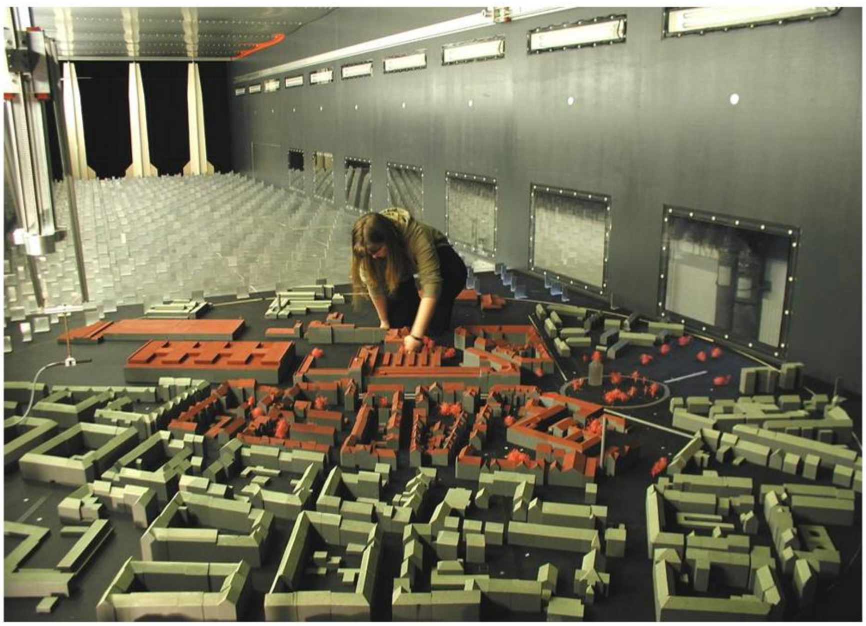

Fig. 2: Physical model of the site in the Boundary Layer Wind Tunnel of Hamburg University

RESULTS

The VALIUM experiments are up to now the probably worldwide largest and most detailed of its kind. In order to make the data generally accessible, the 'intelligent' database VALIDATA was created that comprises all the measurements in a well-documented and easily understandable form. Before the data entered the database they have carefully been checked for plausibility and consistency. Part of the examination was the comparison of the spot concentrations at the monitoring positions with the line-averaged measurements along the Goettinger Strasse. Furthermore the dilution of the tracer gas SF_6 was compared with that of NO_x. It was checked whether the pattern of path-averaged air pollutant concentrations at both sides of the Goettinger Strasse shows the rotor-like circulation inside the street canyon. Whenever possible the data were compared with the results of the wind tunnel that were obtained under carefully controlled and steady boundary conditions. In all cases the data agreed reasonably well with each other and showed the expected qualitative and quantitative behaviour.

From the numerous results obtained only a few can be mentioned here. The analysis of NO_x concentrations measured at the roof top station revealed that about one third of the variance of NO_x concentrations was caused by regional transport and depends on the mixing layer height. At ground-level stations this dependence has not been found. The correlation between mixing layer height and PM_{10} is much weaker and not different for ground and roof top level data, but the PM_{10} concentrations at ground level inside the street canyon are about twice as high as those at roof level. That confirms the expectation that the concentrations measured at roof top are representative for the urban quarter surrounding the street canyon. In contrast to that, the concentration measurements at ground level are dominated by traffic emissions inside the canyon.

The comparison of wind vectors determined by the SODAR system with those from the roof top station (10 m above roof level) showed that for this quantity the roof station measurements are not fully representative for the site. The velocity data are influenced by the building itself and by the building structure surrounding the site. This finding is confirmed by the wind tunnel measurements that allowed quantifying the wind vector modification.

The traffic measurements in the street canyon Goettinger Strasse in Hanover showed, that the driving behaviour and the driving patterns are subject to strong temporal variations. The common procedure to assign a rigid “traffic situation” to a given road segment results in considerable errors and should not be applied in numerical simulations with high temporal resolution. The quality of currently published emission factors (including systematic errors) has been assessed by comparisons between the emission rates, modelled on the basis of the extended traffic measurements, measured pollutant concentrations and the data from the tracer gas experiment.

Air pollution in the Goettinger Strasse is predominantly caused by traffic emissions. As is typical for so-called hot spots in cities, the sources and the receptor points are close together. The values measured at the pedestrian walkway must depend on the source location. The VALIUM tracer experiment was carried out with an artificial SF_6 line source, which was located at the median strip at the centre of the street canyon, whereas the vehicles emit along the four traffic lanes. To study how the values measured depend on the source conditions, in the wind tunnel the following scenarios were carried out, (a) all traffic lanes emitted equally, (b) the lanes emitted according to their traffic density and (c) each lane emitted separately. Since in the field experiments the line source was only 96 m long, the effect of the finite length of the source was also studied. Additional laboratory experiments investigated the influence of different averaging times on mean concentration values.

CONCLUSIONS

The combination of field studies, wind tunnel experiments and numerical model simulations within one project proved to be a very successful strategy to investigate the complex flow and transport processes that occur in urban environments. One major objectives of VALIUM, the generation of a high quality data set based on a combination of field measurements and wind tunnel simulations in a city district, was reached.

Project VALIUM can give answers to a number of questions that are of particular importance for urban air pollution studies:

- How accurate are present emission models for micro-scale applications?

- What are the chances of ground-based remote sensing techniques for the determination of vertical profiles of atmospheric variables in urban areas?
- What is the influence of surrounding buildings on roof-top measurements at urban sites?
- How much dependent are air pollution levels in urban environments on the height of the mixing layer?
- How representative are concentrations measured at positions within the canopy layer with respect to time and space?
- Is the commonly used non-dimensional concentration c* a suitable parameter for the generalisation of street canyon concentrations from one situation to the other?
- To which extent depend numerical or physical model results on the choice of the domain size?
- How sensitive are street canyon measurements to the particular source pattern?

Answers to these questions are given in the subsequent references and in the talk. However, there are also open questions for which final answers have not yet been found. These comprise the contribution of vehicle-induced turbulence to pollutant dispersion in street canyons, the representativeness of episodic measurements within the urban canopy layer and the concepts for a unified presentation of concentration data.

REFERENCES

Emeis, S., 2004: Vertical wind profiles over an urban area. Meteorol. Z., 13, 353-359.

Emeis, S., M. Türk, 2004: Frequency distributions of the mixing height over an urban area from SODAR data. Meteorol. Z., **13**, 361-367.

Emeis, S., Chr. Münkel, S. Vogt, W.J. Müller, K. Schäfer, 2004: Atmospheric boundary-layer structure from simultaneous SODAR, RASS, and ceilometer measurements. Atmos. Environ., **38**, 273-286.

Kühlwein, J. 2004: Unsicherheiten bei der rechnerischen Ermittlung von Schadstoff-emissionen des Straßenverkehrs und Anforderungen an zukünftige Modelle. PhD-thesis, Fakultät Maschinenbau, University of Stuttgart (in German).

Pascheke, F., Leitl, B., Schatzmann, M., 2005: Dispersion of traffic pollutants in street canyons – a systematic wind tunnel study to evaluate a field tracer experiment
Proceedings, 5th Int. Conf. On Urban Air Quality, Valencia, March 29-31.

Pascheke, F., 2005: Systematische Untersuchung von mikroskaligen Strömungs- und Transportprozessen in städtischer Bebauung. PhD thesis, Dep. of Earth Sciences, University of Hamburg (in German, under preparation).

Schatzmann, M., and Leitl, B. 2002: Validation and application of obstacle resolving urban dispersion models. Atmospheric Environment,Vol.**36**, pp. 4811-4821.

Acknowledgement: The authors are grateful for financial support from the German Ministry for Education and Research (BMBF) through the Atmospheric Research Programme AFO2000.