EXPERIENCES WITH URBAN CANOPY LAYER DATA

Michael Schatzmann, Bernd Leitl

Meteorological Institute (ZMAW), Univ. of Hamburg, Germany

Abstract: It is common believe that field data are best be suited for the purpose of model calibration and validation since they represent the 'truth'. At the example of field data from several urban measurement campaigns, it will be demonstrated that this believe is rather a fiction. As will be pointed out, data sampled within the urban canopy layer exhibit a large inherent variability. They are very distinct from those a numerical model produces. This makes comparisons of model results with data a challenging task.

Key words: *Urban flow and dispersion, model validation, field data, natural variability.*

1. INTRODUCTION

Flow and Dispersion within and above the urban canopy layer (UCL) has been subject to numerous experimental investigations but is still not well understood. Due to the generally complex geometrical structure of urban sites a variety of time and space scales are involved. The weather is continuously changing and so are the properties of the urban boundary layer flow.

Above the buildings, but still within the roughness layer, the flow is continuously adjusting to the ever changing surface conditions, never reaching equilibrium. Consequently, the laws known from established flows over homogeneous roughness elements (constant fluxes, logarithmic profiles etc) are not applicable here. The situation is even worse within the canopy layer. Here the flow is sort of channelled by the street canyons which, at least in Europe, have many different orientations with respect to the wind direction.

It is trivial to note that measured values heavily depend on where the probes are located. Since the gradients of flow properties are considerable within the UCL, measurements taken a few meter apart from each other might show largely different results. Less known is the fact that the lack of spatial representativeness is accompanied by a lack of representativeness with respect to time. Averages over 10 min or even 30 min are usually not ergodic, i.e. a repeat of the experiment under identical conditions would not lead to the same result. As smoke experiments within the UCL reveal, this is caused by low frequency turbulent variations of the flow which make the plumes meander. Consequently, data taken in urban environments need to be interpreted with care. Measurements from short campaigns are highly variable and usually not representative. The degree of variability can be large. Usually it is impossible to determine the potential error from the information contained in the field data itself. Data with unknown error band, however, are useless for model validation purposes.

2. ANALYSIS OF DATA FROM AN URBAN MONITORING STATION

It is common believe that field data are best suited for the purpose of model calibration and validation since they represent the 'truth'. Using the example of data from an urban monitoring station, it will be demonstrated that this belief can well be a fiction. As will be shown, data sampled within the urban canopy exhibit a large inherent variability, which makes direct comparisons of data with model results a bold venture.

The data used for comparisons are mostly post-processed data. The special way in which the raw data were treated is usually unknown to the modeller. It will be demonstrated that many 'degrees of freedom' exist in transforming raw data into processed data as needed for model validation purposes. Likewise reasonable procedures employed in processing the data lead to differences in the final data set. These differences will be quantified and discussed.

Concept for data presentation

One of the most pertinent pollutant sources within the urban canopy layer is traffic. Since the vehicles are moving it is usually assumed that their emissions can be represented by a line source since it is not yet feasible to simulate a large number of individually moving cars.

For momentum-free line sources and under conditions as subsequently specified, it is to be expected that the concentration C [g m^{-3}] (in excess above background) at any point in the vicinity of the source is proportional to the source strength Q/L [gs^{-1}m^{-1})] and inversely proportional to the wind velocity u [ms^{-1}] measured at a reference height well above the buildings. Dimensional reasoning suggests the introduction of a normalized concentration c^* [-] which depends on the following non-dimensional variables

$$c^* = \frac{C \cdot u \cdot H}{(Q/L)} = f\left(DD, \frac{1_i}{H}, \mathrm{Re}, \frac{L_M}{H}, TIT\right) \qquad (1)$$

with the additional parameters:

H = characteristic building height (in m),

DD = wind direction (in degree),

l_i/H = multiple length scales (normalized by H) describing all details of the urban geometry,

Re = Reynolds number ($Re = H\,u/\nu$),

L_M/H = Monin-Obukhov length (normalized by H) which characterizes the density stratification of the wind flow,

TIT = an appropriately defined dimensionless parameter describing the traffic induced turbulence.

Chemical reactions are excluded from the analysis, i.e. only passive tracer dispersion is considered here. If the wind speed is sufficiently high, the Reynolds number takes on an above-critical value and the turbulence within the canopy layer is dominated by shear turbulence. This means that effects of stratification or traffic induced turbulence should be of minor importance for pollutant transport within the UCL. Then, for a given urban landscape (H and all l_i/H-values are fixed), c^* is a function of the wind direction alone

$$c^* = \frac{C \cdot u \cdot H}{(Q/L)} = f\,(DD) \qquad (2)$$

Practitioners seldom care for the limiting conditions mentioned so far. Those who carry out the field measurements either provide the raw data or group the excess concentration mean values from a particular measurement campaign according to Equation (2). Numerical modellers use the processed data, believing that they represent the "truth" and tune their models accordingly. Using the example of field data from an urban monitoring station it will be demonstrated how dangerous this practice can be.

Description of the monitoring station

For more than a decade, the Lower Saxony State Agency for Ecology (NLÖ) has operated a monitoring station at the pedestrian walkway in an urban street canyon (Goettinger Strasse in Hanover, Germany). The Goettinger Strasse is a busy inner-city street with four traffic lanes (Fig. 1). The traffic load is about 30 000 vehicles/day, about 15% of which are trucks. Automated traffic counts provide the vehicle flow rate for each lane separately. In combination with general information on the composition of the German vehicle fleet, reasonable estimates of pollutant emission rates can be obtained. The width of the street and the height of the buildings alongside the street are both approximately 25m. Most of the buildings are joined, thereby forming a street canyon with an aspect ratio (height to width) of approx. 1. The orientation of the street canyon is virtually perpendicular to the prevailing westerly wind directions (Fig. 1).

The meteorological measurements cover wind direction and wind velocity within the canyon and above roof (10m above street level or 10m above roof level of the highest building, respectively). The measurements are made with Ultra-Sonic-Anemometers that provide the 3 components of the mean wind and the turbulent wind velocity fluctuations. Pressure, temperature, global radiation and precipitation (amount and duration) are also measured (only at the above roof station).

In addition to the meteorological parameters, the Goettinger Strasse monitoring station is also tasked to collect air quality data. The pollutants measured at street level comprise NO, NO_2, CO, Benzene, Toluene, Xylene and Soot. The above roof station provides the corresponding background measurements plus SO_2, O_3 and PM10 values. At the street monitoring station samples are routinely taken at "nose height" (1.5 m above ground), but provisions are available to collect samples at other heights (up to 10 m) as well. More information on the site can be found in NLÖ (1995) and Mueller et al. (2002).

Figure 1. Experimental site and orientation of the street canyon towards the wind.

Data acquisition and data processing

The subsequent discussion is based on the assumption that all data is collected with state of the art equipment, and that all possible care has been taken to assure the quality of the measurements. In case of the Goettinger Strasse data this condition should be fulfilled.

A permanent monitoring station as that operated by NLÖ in Hanover provides the opportunity to analyse data collected over long periods of time. This creates the possibility that particular dispersion situations are met several times and that the statistical significance of measured results can be assessed.

Fig. 2 (left) shows *c**-concentrations of NO_x for a whole year (1994), presented acc. to Equation (2) as a function of wind direction alone. NO_x calculated from measured NO and NO_2, can be regarded as a passive tracer for the short dispersion time periods of interest here. Each of the approximately 12500 dots in Figure 2 represents a half-hourly mean value, and the curve the ensemble average over the 30 min values of the whole year grouped according to the wind direction.

The scatter of data points in Figure 2 (left) is striking. In order to decrease the spread, the data points are subsequently re-analysed and all those points are eliminated which do not properly meet the conditions underlying Equation (2). The elimination process will be done in a step-by-step procedure by scrutinizing the individual parameters that enter Equation (2).

Determination of *C*

In the definition of *c**, *C* is the concentration excess above ambient, which means the background concentration C_b needs to be subtracted from the value C_m measured at the monitoring station. In a city environment with numerous sources and large local concentration differences it is not easy to determine a meaningful background. In case of the Goettinger Strasse the background C_b is measured on top of the highest (NLÖ-) building (left hand side in Fig. 1) about 30 m above street level. Although for certain wind directions the background is likely to be increased by pollutants flushed out of the street canyon, this can not be quantified. Thus, C_b as measured is assumed to be correct.

Determination of wind direction and wind velocity

The wind vector is also measured on top of the NLÖ-building at a mast 10 m above the highest elevation of the building complex and 42 m above street level. The wind directions used in Figure 2 are those which were directly measured. From the velocity u_{42} a sort of representative free-stream reference wind speed u_{100} (100 m above ground) was calculated assuming the existence of a power law wind profile above the urban canopy with an exponent of $n = 0.3$. Wind directional changes between 42 m and 100 m height were neglected. The present practice is similar to that frequently applied in CFD modelling. The velocity u $(= u_{100})$ might correspond to the wind speed at the top of the numerical domain. Although the velocity is measured 10 m above roof level, free stream conditions are certainly not yet met. It remains unknown to what degree the flow is disturbed by surrounding obstacles or the NLÖ-building itself. If such disturbances occur, they are surely different for different wind directions.

Line source approximation

The *c**-equations (1) and (2) are valid only for line sources. The question arises of what traffic rate must be exceeded before the line source approximation holds. To find an answer, all data were grouped according to the traffic rate and plotted according to Equation (2). A large scatter between the different curves became visible. However, with the exception of the lowest traffic category (< 60 vehicles/30 min), all curves had a similar shape which indicates a certain consistency of source conditions. In the subsequent analysis not only the lowest but also the second lowest traffic rate class will be neglected, i.e. only half hourly values with 120 or more vehicles/min will be taken into account. The elimination of low traffic data points corresponds to the elimination of most of the night time measurements.

Determination of the source strenght

The determination of the emission rate per unit length *Q/L* is usually somewhat of a problem. To obtain an estimate as reliable as possible, automated traffic counters are used at the Hanover site. These counters register not only the number of vehicles per time interval and per lane, they also discriminate between passenger cars and light and heavy trucks. In combination with knowledge of the composition of the German vehicle fleet in the year 1994, the prevailing driving pattern alongside the monitoring station and emission factors for specific vehicle types, *Q/L*-values were estimated. In the present study the emission model MOBILEV was used which is recommended by the German Environmental Agency. It should be noted, however, that there are several other sets of emission factors presently in use. Depending on which one is chosen, the whole ensemble of measured points in Figure 2 moves up or down by about 50%, the degree of scatter is not affected.

Minimum wind velocity

In the derivation of Equation (1) it was made clear that the *c**-concept is not applicable to low wind situations. Only if the wind speed rises above a certain minimum value it can be assumed that

- the critical Reynolds number is exceeded,
- stability effects inside the canopy layer are negligible, and
- the dispersion is governed by wind generated rather than by traffic induced turbulence.

In order to determine the minimum wind speed, the data were split into 9 velocity classes. As will be shown in the talk, at very low wind speeds *c** appears to be rather independent of the wind direction. This suggests that traffic induced turbulence is the major mixing mechanism since there is no preferred direction for pollutant transport perpendicular to the traffic lanes. With increasing wind velocity, the situation changes. The wind seems to form a secondary flow inside the canyon with the consequence of higher concentrations for westerly than for easterly winds. The street canyon has an approximate north-south orientation. Winds from 77° or 257° would be exactly perpendicular to the canyon. The monitoring station is positioned at the walkway west of the traffic lanes. The c*-

values show a maximum for westerly winds which is in line with expectation. It appears that the curves take on a similar form for wind velocities $u_{100} > 3.9$ ms^{-1} which corresponds to wind speeds in unobstructed terrain upstream of the city and at standard anemometer height of $u_{10} \approx$ 2-3 ms^{-1}.

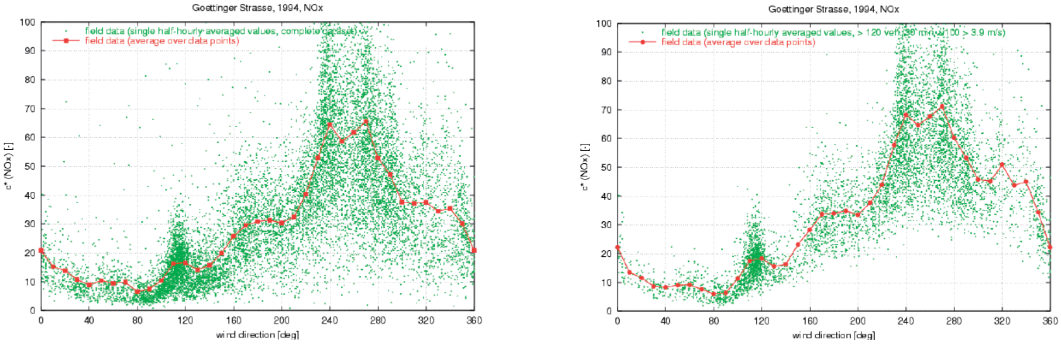

Figure 2. Normalized half-hourly mean concentration values as a function of wind direction measured over a period of one year at the street monitoring station ‘Goettinger Strasse’ in Hanover/Germany. Unfiltered (left hand side) and filtered (right hand side) data, see text.

Analysis of filtered data

Figure 2 (right hand side) replicates the data presentation of Figure 2 (left hand side) but comprises, from the original 12424 values, only those 6562 values that survived the filtering process explained before. The ensemble averaged values change by only about 10% (different for different wind directions). This is small compared to data sets from other monitoring stations for which a similar analysis was made (Schatzmann et al., 2001).

The spread of filtered data points is somewhat reduced but still significant. Disturbing is the fact that in spite of the filtering the data not only scatters but shows a trend. As will be shown in the talk, the c*-values increase with increasing wind velocity. This is contrary to expectation and seems to undermine the c*-concept with its underlying assumption that C and u are inversely proportional to each other. It has been speculated that C might have a more complex relationship to u or that traffic-induced turbulence might be important even under strong wind conditions (Kastner-Klein et al.(2001), Ketzel et al.(2002)). But if that would be the case, the strong dependence of c* on wind direction (for higher wind speeds) could not be explained.

The real explanation is probably much simpler and has to do with the unsteady behaviour of plumes dispersing inside urban canopy layers. As can be made visible in smoke experiments, plumes meander inside street canyons and city quarters. Even for rather steady above-roof winds, instantaneous pictures show a plume that moves to one canyon wall, remains there for a while and then, in a random manner, flaps to the opposite wall and back again before the material moves into one or the other neighbouring street or is flushed out of the canopy. The presence of an organized secondary flow inside the canyon, an assumption on which many simple models are based, is only observable in long-time averages of the velocity or concentration fields. It appears logic to assume that high-resolution concentration measurements at receptor points located at the pedestrian walk way would reveal a highly intermittent signal, i.e. periods of low or even zero concentrations (in excess above ambient) are interspersed with high, fluctuating concentrations.

The field concentrations sampled at the Goettinger Strasse monitoring station are mean values based on 30 min averaging intervals. However, absolute averaging times are not entirely meaningful in physical contexts (Schatzmann and Leitl, 2002). Dimensionless averaging or sampling times $t^* = t/(L_{ref}/u_{ref})$ should be used, with t the absolute averaging time, L_{ref} a properly chosen length scale (e.g. the reference height) and u_{ref} again the reference wind speed. Strictly, mean values are only comparable with each other if averaged over the same dimensionless sampling (averaging) interval t^*. That would require adjusting the absolute sampling time to the actual above-roof wind velocity. Practitioners tend to neglect such theoretical worries. They use automated systems that always sample over the same time interval. For two cases with above-critical Reynolds numbers that differ in wind speed by a factor of 2 and are otherwise identical, the eddy velocities would be twice as fast for the strong wind case. The concentration versus time trace in Figure 2 would contain roughly twice as many ‘events’ within 30 min. Although not yet entirely clear, it might be speculated that the increase of c^* with u in the higher velocity range might have something to do with the averaging procedure.

Another notable point is that concentrations cannot get negative and that at most receptor points mean concentrations are small compared to concentration fluctuations. The probability density function of concentration fluctuations is skewed. A “mean” value obtained under those conditions is distinct from that of a normal Gaussian distribution. The experimentalist who samples probes over fixed periods of time or arithmetically averages over time series measured online with low frequency response instrumentation is often not familiar with those problems. He produces numbers and is unaware of the fact that those numbers may to some degree be dodgy.

When these results were presented to experts in the field it was frequently argued that the scatter observed in the data would reflect the many uncertainties in connection with the assumption of a traffic-generated ‘line source’ rather than the urban dispersion conditions. A few years later the chance arose to confute this hypothesis (Bächlin et al, 2004, Schatzmann et al, 2006). An artificial line source of about 100 m length was positioned at the median strip between the four traffic lanes of the Goettinger Strasse (Fig. 3). A carefully controlled flux of a real passive tracer (SF_6) was continuously released and during several campaigns half-hourly SF_6 mean concentrations were measured next to the monitoring station. The result shown in Figure 3 (left) exhibits a similar scatter as was found before.

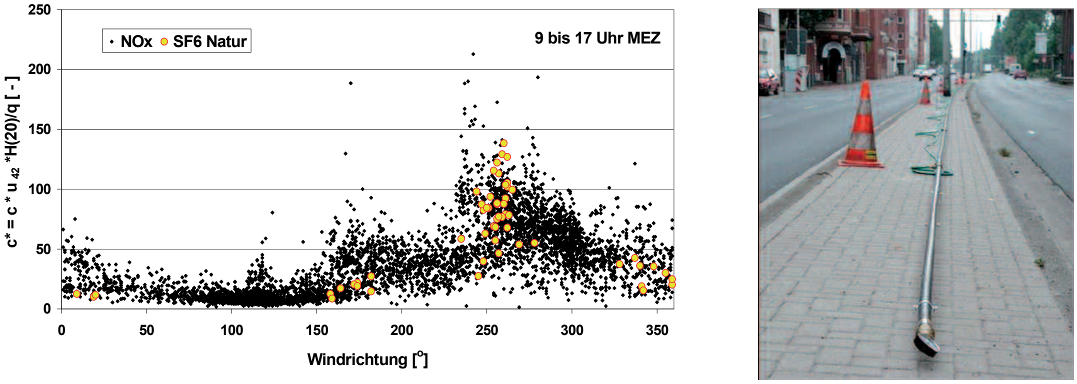

Figure 3. Normalized half-hourly mean concentration as a function of wind direction (left hand side). Black data points represent measurements of traffic generated NO_x immissions, yellow data points represent corresponding SF_6 immissions originating from the artificial line source shown in the right hand side figure.

3. CONCLUSIONS

The wide scatter of data points (Figs. 2 and 3) makes it clear that the ‘period’ of concentration fluctuations measured within the urban canopy is not small compared to sampling time. Therefore, the common 30 min mean concentrations measured inside the urban canopy have the character of random samples only. Depending on the wind direction, the variability between seemingly identical cases can be large. To simply increase the sampling time would not solve but worsen the problem since over periods longer than 30 min a systematic trend in meteorological conditions due to the diurnal cycle has to be expected.

The scatter shown in the Figs. furthermore indicates that single measurements cannot be representative for locations exposed to highly fluctuating and intermittent concentrations. Each individual data point in this figure is likewise justifiable. The instrumental error is small.

Our findings undermine the value of data generated in episodic field campaigns for model validation purposes. Such data cannot safely be regarded as the reliable standard a numerical model should meet. It must be concluded that only long duration measurement campaigns within which similar dispersion episodes occur several times are meaningful. Such experiments allow representative ensemble mean values to be determined (curve in Fig. 2 rhs). But even if such long-term data is available, it must be handled with care. There are numerous and most times somewhat arbitrary decisions to be made when processing the raw data. If these decisions are not documented and communicated to the user of such data, he will be mislead with respect to data reliability. Our example shows that, although reasons were given for the elimination of parts of the measurements or for the selection of a particular set of emission factors, other similarly plausible choices could have been made, with the consequence of different values for the processed data.

The widespread belief that the uncertainty of field data sets is solely related to the inaccuracy of the instruments is surely fiction.

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

REFERENCES

Bächlin, W., W. Theurer, W.J. Müller, H. Frantz, H., 2004: Tracermessungen in einer Straßenschlucht – neue Daten zur Validierung mikroskaliger Modelle. *Gefahrstoffe – Reinhaltung der Luft*, **64,** 393-398 (in German).

Kastner-Klein, P., R. Berkowicz, E. Fedorovich, 2001: Evaluation of scaling concepts for traffic produced turbulence based on laboratory and full scale concentration measurements in street canyons. *Proceedings, 3rd Int. Conf. On Urban Air Quality*, Loutraki, Greece, March 19-23.

Ketzel, M., R. Berkowicz, W.J. Müller, A. Lohmeyer, 2002: Dependence of street canyon concentrations on above roof wind speed - implications for numerical modelling. *Intern. J. of Env. and Pollution,* **17**, 356-366.

Müller, W.J., B. Heits, M. Schatzmann, 2002: A prototype station for the collection of urban meteorological data. *Proceedings, 8th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes,* Sofia, Bulgaria, October 14-17.

NLÖ, 1995: Lufthygienisches Überwachungssystem Niedersachsen – Standortbeschreibung der NLÖ-Stationen. Bericht, Niedersächsisches Landesamt für Ökologie, Göttinger Str. 14, 30449 Hannover (in German).

Schatzmann, M., H. Frantz, D. Grawe, B. Leitl, W.J. Müller, 2001: Do field data represent the truth? *Proceedings, 3rd Int. Conf. On Urban Air Quality,* Loutraki, Greece, March 19-23.

Schatzmann, M., B. Leitl, 2002: Validation and application of obstacle resolving dispersion models. *Atm. Env.,* **36**, 4811-4821.

Schatzmann, M., W. Bächlin, S. Emeis, J. Kühlwein, B. Leitl, W.J. Müller, K. Schäfer, H. Schlünzen, 2006: Development and Validation of Tools for the Implementation of European Air Quality Policy in Germany (Project VALIUM). *Atmospheric Chemistry and Physics,* **6**, 3077-3083.