9th Asia-Pacific Conference on Wind Engineering
Auckland, New Zealand
3-7 December 2017

Field Data versus Wind Tunnel Data: The Art of Validating Urban Flow and Dispersion Models

Leitl, Bernd, Harms, Frank, Hertwig, Denise, Schatzmann, Michael[1]
([1] presenting author)
Meteorological Institute, University of Hamburg, Germany

Abstract

When a numerical model has the potential to simulate flow and dispersion episodes in complex urban terrain, it does not mean that the model is actually able to do this in a proper way. Whether the model output is in agreement with observation has to be proven in model validation exercises.

The backbone of any validation work is the existence of data which have sufficient quality and detail that they can be regarded as a standard. Due to the variability of the atmosphere it seems to be hardly feasible to obtain such data in urban field experiments. This shifts the focus to wind tunnel modelling. In the talk it will be reported how such data can be generated in the laboratory and how wind tunnel data compare with those from corresponding field tests.

Validation of Numerical Models

Validating models is not a trivial task. In urban environments it is much more difficult to generate reliable validation data than for many technical applications. The urban geometry is heterogeneous and so are the properties of the urban boundary layer flow. Due to the generally complex geometrical structure of urban sites a variety of time and space scales are involved.

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 urban canopy layer (UCL). Here the flow is sort of channeled 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 [4].

The lack of spatial representativeness is accompanied by a lack of representativeness with respect to time. As will be subsequently shown, even within more or less regular arrays of obstacles and under steady ambient conditions, flow and dispersion properties measured within the UCL are difficult to interpret. Averages over 10 min or even 30 min are usually not ergodic, i.e. repeating an 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 atmospheric flow which make the plume meander. Results from single measurements are highly uncertain and usually not representative. The degree of uncertainty can be large and must be known before the data can be used for model validation purposes.

As meteorologists would prefer to use full-scale field data for model validation, Schatzmann and Leitl [8] raised the question whether field data do represent the truth, particularly in urban flow and air quality modelling. In order to decide how close models should get to measured field data, the representativeness of them needs to be evaluated carefully. Often it must be stated that a perfect match of reference data from field experiments and simulation results is not proving a successful model validation rather than providing an example for successfully tuning simulation results. The variability inherently present in field data sets results in a large degree of freedom with respect to interpretation of measured values and assumed boundary conditions. Obviously, there is a gap between what can be observed and measured at full scale and the well-defined world of a numerical model.

Field Experiments

In recent years, Hamburg University participated in a number of field experiments in urban or industrial landscapes. With VALIUM in Hanover [7], BUBBLE in Basel [5], JOINT URBAN 2003 in Oklahoma City [1], the Mock Urban Setting Tests (MUST) at Dugway Proving Ground (Utah) [2] or the CT_ANALYST flow and dispersion experiments in the city of Hamburg [3] only the most important are mentioned here. All these field experiments were either prepared or replicated in Hamburg University's boundary layer wind tunnel facility, so that data sets from both, the field and laboratory are available and can be compared with each other.

The Hamburg field experiment

To perform measurements in a vibrant metropolitan area is subject to many restrictions, above all when dispersion experiments are on the agenda. Although we were tasked by the Hamburg State government and had full support from police and fire fighters, permission for carrying out such experiments was granted only for a few early Sunday morning hours at 2 weekends. In order to gain flexibility we planned to position the source on a boat on river Elbe and to select wind directions from the river to the inner city area. This strategy proved to be reasonably successful. As tracer gas SF_6 was chosen, but despite the fact that this is a nearly inert gas, we were allowed to release only a few g/s. In consequence, since the expected concentrations were very small, we had to use bag samplers and to analyse the probes subsequently by using gas chromatography. About 20 automated bag samplers (Fig 1) were distributed over the inner city area (Fig. 2). This was done in cooperation with scientists from the Forschungszentrum Jülich.

Fig.1: Picture of an automated bag sampler rig in front of the Hamburg town hall.

Fig 2: Measurement positions during the field experiments.

Early morning observations are always somewhat problematic. During the first observational period at April 16, 2011, there was high pressure over Hamburg with clear skies and large radiative cooling of the surface. Such weather situations are subject to stratification and inversion layers, and this was indeed the case as the measurements at the 300m Hamburg TV-Mast approximately 10 km apart from the site clearly indicated. As becomes evident from Fig 3, there was a strong inversion above the 110 m measurement platform although the wind speed at higher altitudes was quite strong (Fig 4). As smoke experiments carried out at the end of the intensive operation period evidenced, there were even more inversions near to the ground. None of the altogether 8 ultra-sonic-anemometers which were operated simultaneously at different locations and heights around the test site provided a wind speed and direction which matched the movement of the cloud.

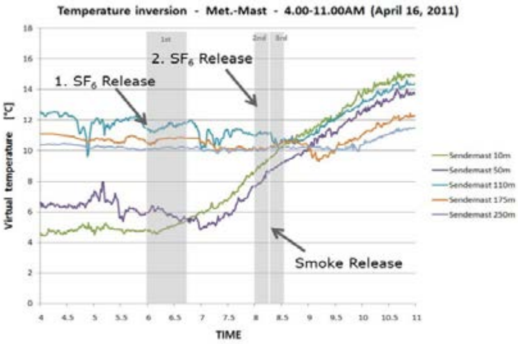

Fig. 3: Virtual potential temperatures measured during the first experimental period at 5 different height levels at a TV mast located about 10 km apart from the test site at the eastern edge of Hamburg.

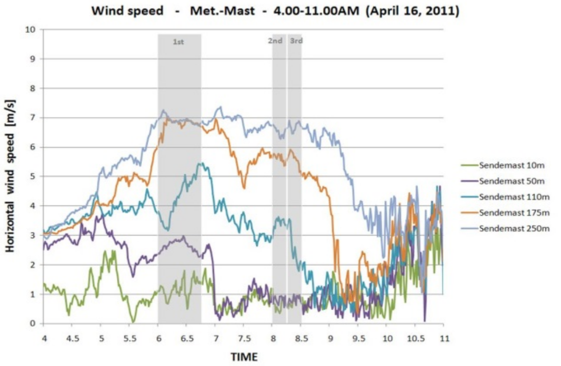

Fig. 4: Wind velocities measured during the first experimental period at 5 different height levels at a TV mast located about 10 km apart from the test site at the eastern edge of Hamburg.

With the second field experiment we waited until a weekend with sufficient wind from the favored directional sector arrived. Although highly fluctuating with time, wind speed and direction were much more uniform compared to the first campaign (Fig 5). This finding was fully corroborated by the measurements performed at different height levels at the Hamburg TV mast. In contrast to Fig. 3, in the second phase the boundary layer was well mixed. The wind directions in the lowest 250 m above ground were always around 220°, independent of height and time, and the velocity profile only slightly increased with height.

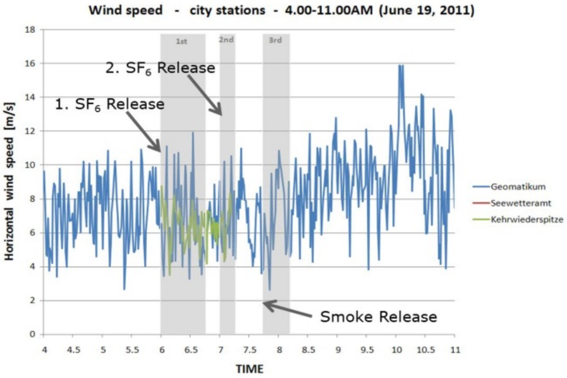

Fig. 5: Wind velocity versus time trace measured simultaneously at 2 different stations during the intensive operation period.

The automated samplers were spread over an area much wider than the expected cloud width in order to identify not only polluted but unpolluted areas as well. Fig. 6 (a and b) shows a few results. Shown are estimated cloud contours together with arrival times and time averaged cloud concentrations. All care was taken to secure the quality of the data. However it must be clear that the time resolution of the measurements was insufficient. Since the bag samplers average over an intermittently fluctuating contaminant supply rate, large variability bars would have to be added to the measured values since it is to be expected that repeats of the experiments under seemingly identical ambient conditions would show largely different results. The magnitude of these bars indicating the natural variability of the atmosphere (and not the error of the instruments!) remains unknown since short-time experiments do not provide the information necessary for statistical analyses of the data (see Schatzmann and Leitl [8]). Such analyses, however, would be necessary in order to quantify the representativeness of the data which is of utmost importance for any validation data set.

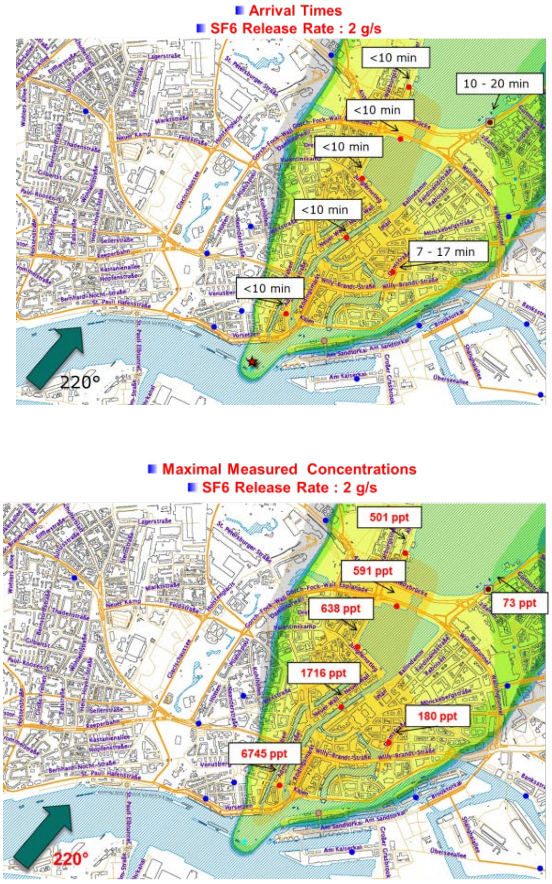

Fig. 6: Second campaign at June 19, 2011. Bag sampler positions are shown with red dots polluted and blue dots unpolluted. The bag-samplers operated time-staggered with suction intervals of 10 min. Shown are arrival times (a) and concentration averages of the cloud (b).

The Hamburg wind tunnel experiment

In order to enhance the data, wind tunnel experiments were carried out in the large boundary layer wind tunnel ‘Wotan’ of Hamburg University. This tunnel has a total length of 25 m with a test section which is 4 m wide and 2.75 m high and contains a flow establishment section of about 18 m length. The wind tunnel is equipped with an adjustable ceiling allowing 0.5 m height extension of the test section. An approach flow boundary layer matching the scale of the Hamburg model (1:350) was generated. The size of the test section allowed the reproduction of turbulence with length scales of more than 1 km in full scale.

The boundary layer properties were controlled and documented similarly as described in Schatzmann and Leitl [8] for another wind tunnel investigation. Non-intrusive flow measurements were carried out with an optical LDA fibre probe with a focal length of 800 mm. To measure high resolution concentration time series a fast flame ionisation detector was used.

Fig. 7 shows a sector of the (in full scale) 3700m long and 1400m wide physical model in the wind tunnel. Under steady-state mean flow conditions numerous instantaneous and continuous clouds were released at multiple positions, and time series of the resulting velocity and concentration fields were monitored. Only a few details of the results can be given here due to space limitations. So it is mentioned that the time and space variability of concentration measurements found in the wind tunnel experiments was very pronounced (Fig. 8). This corroborates the expectation that only long-time averages can provide representative mean concentrations as they are needed, e.g., for the validation of RANS-models.

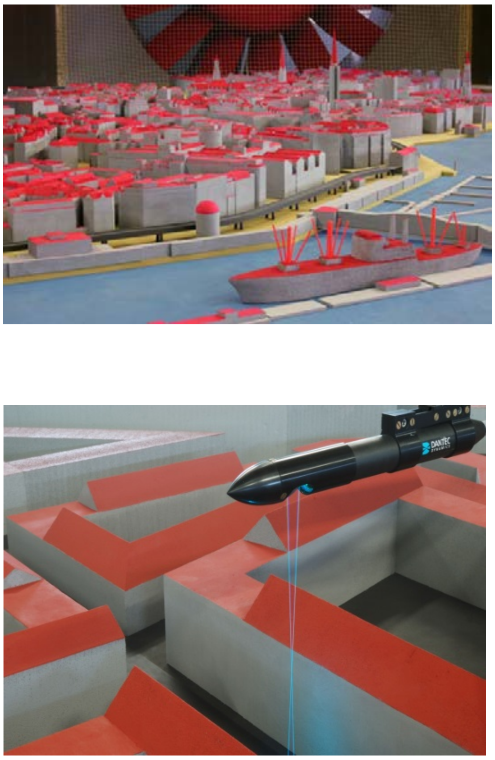

Fig. 7: Physical model of the site in Hamburg University’s large boundary layer wind tunnel (a) and non-intrusive flow measurements with Laser-Doppler-Anemometry (b).

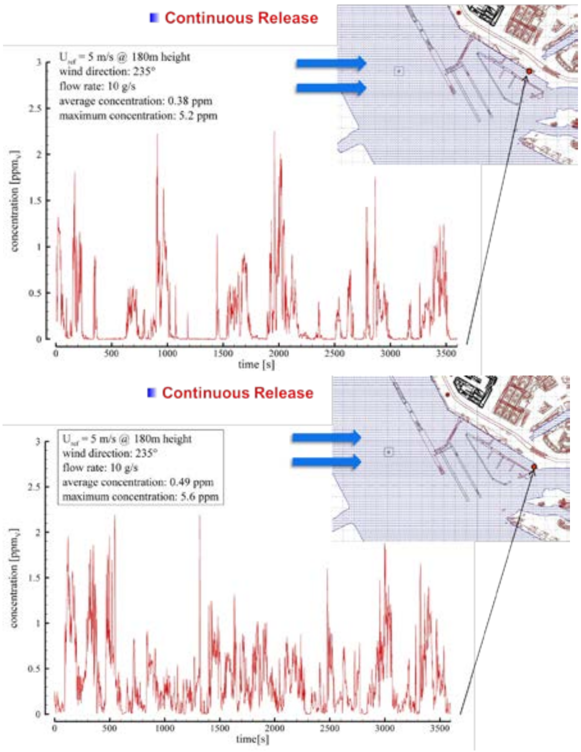

Fig. 8: Time series of concentration measured at two neighboring positions under identical mean wind and source conditions in the wind tunnel.

The wind tunnel data set was mainly used to test the validity of a high-resolution large eddy simulation model (FAST3D-CT developed by the US Naval Research Laboratory in Washington DC). Although the wind tunnel experiments and LES simulations were done at the same time in different locations, and neither side knew the results of the other side beforehand, the agreement was very satisfying. This is demonstrated in Fig. 9 at the example of a vertical wind profile at a geometrically complex intersection

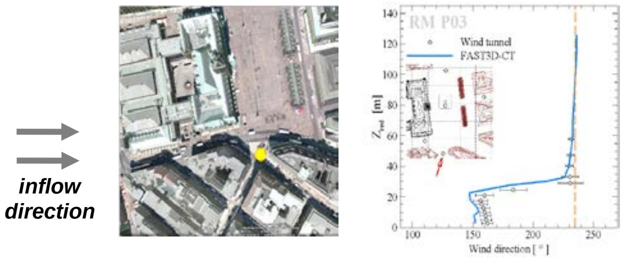

Figure 9: (a) Profile measurement location at a complex intersection; (b) Mean horizontal wind direction profiles from wind-tunnel measurements (with error bars) and FAST3D-CT calculations (blue line).

Conclusions

Validation data for numerical models are not just any experimental data; they must fulfill certain requirements with respect to completeness, spatial and temporal resolution, accuracy, representativeness and documentation of the measured results [8]. If these requirements are not met, too many degrees of freedom remain to set-up numerical model runs. A wide variety of numerical results can be generated with reasonable assumptions for the input data, with the consequence that a solid conclusion concerning the model quality cannot be reached. Hence validation datasets that match the complexity of specific groups of models are needed.

In order to validate urban RANS or LES models, validation data are required that contain flow and concentration fields measured with high resolution in space and time. Field measurements usually do not fulfil these high validation requirements. Under certain limiting conditions, such datasets can be generated under carefully controlled conditions in well-equipped boundary layer wind tunnels.

In the present example two short field campaigns were carried out in addition to wind tunnel experiments. Such field tests are always limited in scope. As was described in more detail in Schatzmann and Leitl [8] for another combined data set, it is nearly impossible gaining reliable test data for complex CFD models in field experiments. The atmosphere is intrinsically time dependent and never steady state. The commonly assumed 15 min or 30 min quasi-steady episodes exhibit a large inherent variability. Data obtained over such short periods of time are not representative for the assumed mean wind velocity and direction. And even worse, in urban canopy layers it occurs to be nearly impossible to determine positions at which a wind vector representative for the dispersion of the cloud could be measured. Nevertheless comparisons with field data are vital for building confidence in the quality of numerical and physical model predictions; whenever possible they should be carried out.

The dispersion process in complex geometries is driven by complex wind flows and turbulent diffusion. From a strict physical point of view, the source sizes, release rates or (mostly short time) durations of release events often restrict the use of conventional tools which are based on mean flow and dispersion modelling because in the atmosphere the assumed mean conditions do not exist for relevant time periods less than many hours of constant weather.

Therefore it is necessary to move forward to advanced modelling technics which have the potential to deal with the unsteady behavior of local scale dispersion in complex geometries in a more consistent way.

Acknowledgments

Financial support by the German Federal Office of Civil Protection and Disaster Assistance as well as by the Parliament of the Free and Hanseatic City of Hamburg is gratefully acknowledged.

References

[1] Allwine, K.J., Leach, M.J., Stockham, L.W., Shinn, J.S., Hosker, R.P., Bowers, J.F., Pace, J.C. (2004) Overview of JOINT URBAN 2003-An atmospheric dispersion study in Oklahoma City. Symposium on Planning, Nowcasting, and Forecasting in the Urban Zone, January 11-15, WA. Amer. Meteor. Soc. J7.1, Seattle.

[2] Biltoft, C.A. (2001): Customer report For Mock Urban Setting Test, DTC Project no. 8-CO-160-000-052, DPG Document No. WDTC-FR-01-121

[3] Leitl, B., Hertwig, D., Harms, F., Schatzmann, M., Patnaik, G., Boris, J., Obenschain, K., Fischer, F., and Rechenbach, P. (2013) Large Eddy Simulation of Accidental Releases. In: Talamelli, A.; Oberlack, M.; Peinke, J.; (Eds.): Progress in Turbulence V. Springer Proceedings in Physics 149, 2013, pp. 133-147. ISBN: 978-3-319-01859-

[4] Repschies, D., Schatzmann, M., Leitl , B. (2007) How dense is dense enough? – Systematic evaluation of the spatial representativeness of flow measurements in urban areas. *Proceedings International Workshop on Physical Modelling of Flow and Dispersion Phenomena*, Orleans, France, Aug. 28-31.

[5] Rotach, M., Vogt, R., Bernhofer, C., Batchvarova, E., Christen, A., Clappier, A., Feddersen, B., Gryning, S.E., Martucci, G, Mayer, H., Mitev, V., Oke, T.R., Parlow, E., Richner, H., Roth, M., Roulet, Y.A., Ruffieux, D., Salmond, J.A., Schatzmann, M., Voogt, J.A. (2005) BUBBLE- An urban boundary layer meteorology project. *Theoretical and Applied Climatology*, 81, pp. 231-261.

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

[7] Schatzmann, M., Bächlin, W., Emeis, S., Kühlwein, J., Leitl, B., Müller, W.J., Schäfer, K., Schlünzen, H. (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.

[8] Schatzmann, M. and Leitl, B. (2011) Issues with validation of urban flow and dispersion CFD models. *Journal of Wind Engineering and Industrial Aerodynamics*, 99, pp. 169-186.

[9] Patnaik, G., Boris, J. P. Grinstein, F. F. and Iselin, J., 2005: “Large Scale Urban Simulations with FCT”, High-Resolution Schemes for Convection-Dominated Flows: 30 Years of FCT, D. Kuzmin, R. Löhner, and S. Turek, Eds., Springer, 105-130.