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ASPECTS OF RANS MODEL VALIDATION FOR UNSTEADY URBAN FLOWS

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Abstract: Urban flow fields computed by two models based on the Reynolds-averaged Navier Stokes (RANS) equations are compared to validation data measured in a boundary-layer wind tunnel. The numerical simulations were performed with the research code ADREA and the commercial code STAR-CD. Turbulent flow within and above a 1:225-scale wind-tunnel model of a semi-idealized urban complexity represents the test case. In a systematic study the quality of the numerical predictions of mean wind fields is evaluated with a focus on the identification of model strengths and limitations. State-of-the-art validation metrics for numerical models were used to quantify the agreement between the data sets. Based on the spatial identification of locations of good or bad comparison the study showed that unsteady flow effects deep within street canyons are a major cause for discrepancies between numerical and experimental results.

Key words: *Model validation; RANS simulation; boundary-layer wind tunnel; urban flow characteristics*

INTRODUCTION

The validation of numerical simulations against reference data is an essential step in creating confidence in the predictions. However, in many fields of applications this task is still a stumbling block due to the complexity of the simulated problem, the availability of suitable validation data from field or laboratory measurements and/or the applicability of statistical measures that allow for a quantitative assessment of the model performance. In connection with the quality assurance and improvement of micro-scale meteorological models the COST Action 732 (see Schatzmann et al., 2010) compiled a set of state-of-the-art validation metrics that can be applied to predictions from CFD-RANS codes. This model class allows fast computations of mean flow and dispersion pattern even in very complex urban and industrial environments. For this reason they are standard tools for applied studies in the fields of urban ventilation and planning, wind comfort or pollutant dispersion. In the present validation study urban flow fields computed by two RANS codes are systematically compared to validation data from boundary-layer wind-tunnel measurements. The quality of the numerical predictions is evaluated in order to identify model strengths and limitations based on the COST 732 standards. In addition, point-by-point comparisons are conducted to evaluate the model performance for typical urban flow scenarios. The study is part of the bilateral research project "MODEX – Modeling individual exposure from airborne hazardous releases" (cp. also Bartzis et al., 2011).

EXPERIMENTAL & NUMERICAL METHODOLOGY

Wind-tunnel measurements

Flow and dispersion experiments were conducted in the boundary-layer wind tunnel 'WOTAN' at Hamburg University. The 18m long and 4m wide test section of the tunnel is equipped with an adjustable ceiling that allows the modeling of zero-pressure gradient atmospheric boundary layers and flows within and above urban geometries. Turbulent flow in a 1:225-scale model of semi-idealized urban complexity was chosen as a test case for the validation study. The data is published in the CEDVAL-LES (2011) online validation data base (see Fischer et al., 2010; Bastigkeit et al., 2010). Figure 1a shows the wind tunnel model, whose design was chosen to be heterogeneous in consistency with typical central European city structures. With sharp building corners, open courtyards, plazas and complex intersections the model was designed to pose a challenge to numerical models while still being an approximation of a realistic city structure. Whereas the street canyon width was kept constant, the building heights varied between 15, 18, and 24m full-scale. The turbulent flow was modeled under neutral atmospheric stability conditions. The inflow featured characteristics of very rough surface layer conditions given a roughness length of z_0 = 1.53m together with a power-law exponent of α = 0.27. Turbulence intensities, integral length scales, and energy spectra of the inflow were verified to agree with the VDI (2000) benchmarks. Flow measurements were carried out by the use of non-intrusive laser Doppler velocimetry (LDV) as depicted in Figure 1b. Information about the urban wind field is available in terms of vertical velocity profiles distributed all across the urban model and from five horizontal flow layers. Three of the measurement planes are located within the street canyon (z = 2, 9, 18m full-scale) and two well-above roof top (z = 27, 30m). The area of these densely-spaced horizontal layer measurements is indicated by the rectangle in Figure 1a.

a) b)

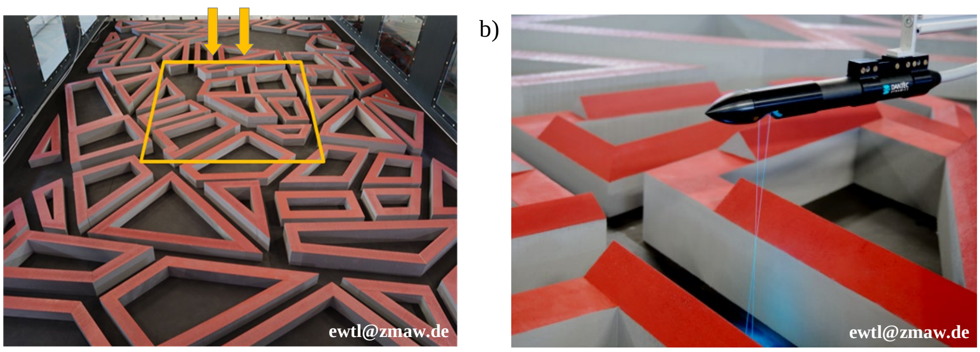

Figure 1. (a) Wind-tunnel model of semi-idealized complexity. The rectangle encompasses the model region of densely spaced flow measurements. The arrows indicate the inflow direction. (b) Optical flow sensing inside a street canyon with an LDV probe.

RANS simulations

The numerical simulations have been performed using the research code ADREA (Bartzis et al., 1991) and the commercial code STAR-CD (version 4.06). The codes solve RANS equations for mass and momentum of a fully turbulent and isothermal flow. The turbulence closure is obtained using the eddy-viscosity concept. In ADREA the two equation k-ζ turbulence closure model (Bartzis, 2005) is used, where ζ is the wave number scale, while for STAR-CD the widely-used standard k-ε model is implemented. Simulations were performed in full scale. For the ADREA predictions hexahedral cells have been used with a discretization of 191 x 118 x 41 in X, Y, and Z, respectively. The minimum/maximum sizes of the discretization cells along X, Y, and Z directions were 7.8/27m, 8.3/16.7m and 3.2/3.5m. The computational grid was uniform and dense in the area between the buildings and had a logarithmically increasing distance in the lateral areas. In STAR-CD, unstructured tetrahedral cells were used with a total number of 7,085,470 cells. Minimum and maximum cell sizes were 2.4m and 12m.

The simulations were performed in two steps. First, the experimental approach flow was simulated and tested against the wind-tunnel measurements. In case of ADREA this was achieved by solving 1D equations for the streamwise velocity U, the turbulent kinetic energy k, and the wave number ζ in the vertical direction for flow over a very rough surface (experimental z_0) and prescribing constant experimental values at the top of the domain (z = 144m). The vertical computational grid was the same as for the 3D simulations. For STAR-CD, the 3D solution of the approach flow was obtained using the computational domain of the 3D simulations without buildings and hexahedral cells with a discretization of 418 x 285 x 36 in X, Y and Z. The ground surface was treated as a rough wall using standard wall functions and the experimentally defined roughness length. At the top of the domain constant experimental values were set for U, k and the dissipation rate ε. At the lateral planes of the 3D domain symmetry boundary conditions were used. At the inlet the vertical profiles for U, k and ε were used as they have been estimated from the experiment in the approach flow boundary layer. Details on the inflow simulation and comparisons with the experimental inflow data are discussed in Efthimiou et al. (2011).

The second computational step consisted of performing the full-3D calculations of the flow field within and above the urban canopy. The inlet boundary conditions were given by the results from the first computational step. At the outlet of the domain outflow boundary conditions were imposed, i.e. zero horizontal gradients, while at the lateral planes symmetry boundary conditions were implemented. Similar to the first step, constant experimental values for U, k, ζ, and ε were specified at the top of the domain. In order to be consistent with the experiment, the ground floor was divided in three regions. The ground area upwind of the buildings was treated as a fully rough wall using the experimental z_0 of 1.53m. The ground area in between and after the buildings was treated as partly rough using a very small z_0 equal to 0.0625m corresponding to z_0 = 0.3mm in wind-tunnel scale.

INITIAL FLOW VALIDATION

The numerical simulations were performed for the ‘flat-roof case’ of the wind-tunnel measurements. Here, observational data of the horizontal velocity components U and V are available. Experimental and numerical data were homogenized by referencing all velocities to a reference streamwise velocity U_{ref} measured at z = 100m in the very rough approach flow.

Qualitative comparison

The validation starts with a ‘global’ assessment of the performance of the two models by means of an exploratory data analysis. Scatter plots of observed versus predicted quantities are a preferred representation for a more qualitative data comparison. Figures 2 and 3 show these scatter plots for the streamwise and spanwise velocity components for both model predictions. The comparison is based on all available measurement locations, i.e. a total of 2,158 points of the five horizontal layers within and above the urban canopy and 16 vertical profiles.

As can be seen in Figure 2, qualitatively both codes seem to perform comparably in simulating the mean streamwise velocity component. In general, the data points group nicely about the ideal 1-to-1 line and most of the points fall well within the diagonal bounds that indicate a 1-to-2 and 2-to-1 relation, respectively. However, there are also some systematic trends. For STAR-CD (see Figure 2a) there is a systematic under-prediction recognizable for positive streamwise velocities, whereas there is a strong trend towards an over-prediction for situation in which the streamwise velocity has a negative sign. The latter feature is also seen in the predictions from ADREA (Figure 2b) while at positive velocities the data are better distributed about the ‘ideal’ relation to the measured values. Especially in the case of ADREA a larger scatter of data points is found for low magnitude velocities measured/calculated within the three street canyon flow layers. This is presumably mainly due to the coarser grid of ADREA compared to STAR-CD (1 million versus 7 million cells, respectively).

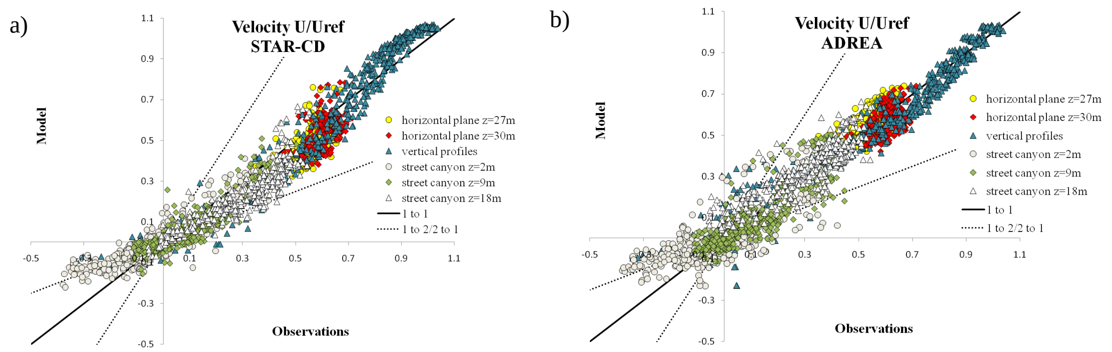

Figure 2. Scatter plots of measured versus modelled streamwise velocities from (a) STAR-CD and (b) ADREA.

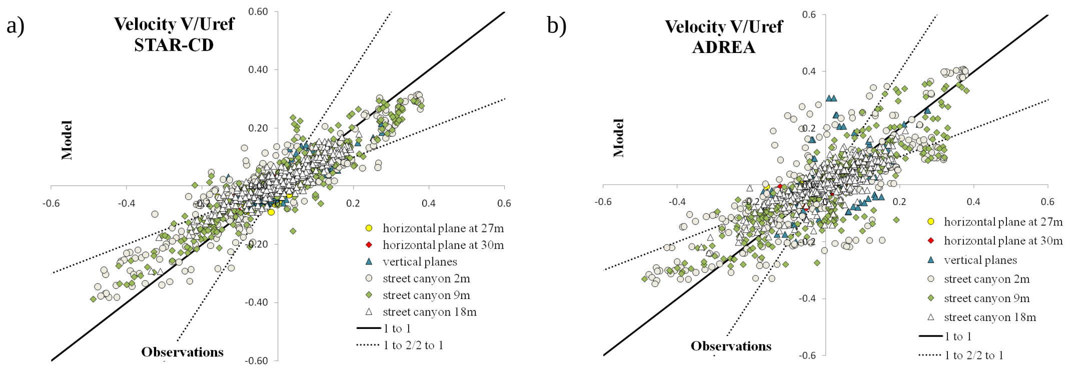

Figure 3. Scatter plots of measured versus modelled spanwise velocities from (a) STAR-CD and (b) ADREA.

Similar trends can be observed from the comparison graphs of the spanwise velocities shown in Figure 3. Here, the velocity magnitudes at street canyon level (i.e. at 2, 9 and 18m) are high due to the presence of buildings that strongly deflect the wind flow laterally. Both models have the ability to predict the magnitudes of V/U_{ref} quite well. A higher scatter of the results is again found for ADREA (see Figure 3b) and this is again likely to be caused by the coarser grid for this simulation. A linear trend is obvious around the 1-to-1 line, which is more pronounced in the case of the STAR-CD predictions (Figure 3a).

Validation metrics

Following the COST 732 recommendations so-called validation metrics are used for a quantitative assessment of the model performance. The metrics that have been selected are the factor of two of observations (FAC2) and the hit rate (HR). For the hit rate the allowed relative difference was set to 25% as suggested by VDI (2005). The allowed absolute difference was set equal to 0.033 for the quantity U/U_{ref} and 0.0576 for V/U_{ref} based on the statistical scatter of the experimental values. The quality acceptance criteria are set to FAC2 > 0.5 and HR ≥ 0.66 following VDI (2005) and Hanna et al. (2004).

The validation results for the dimensionless velocity components U/U_{ref} and V/U_{ref} for both codes are listed in Table 1. The results are presented for all measurement points (2,158) and individually for the three horizontal planes within the urban canopy at heights of z = 2, 9, and 18m, each consisting of 383 measurements. For all data points and the velocity component U/U_{ref} the FAC2 is well above the acceptance limit of 0.5 for both codes. A slightly worse performance is indicated by the HR, with the STAR-CD predictions falling below the acceptance limit. Contrary to this, the FAC2 for V/U_{ref} yields smaller values while the HR is higher. This is due to the much smaller magnitude of V/U_{ref} compared to U/U_{ref} at many positions especially at higher elevations above the urban roughness. For these situations, the FAC2 is known to be quite sensitive and the value prescribed for the allowed absolute deviations between simulation and measurements is very important. However, based on the metrics obtained from all measurement locations the predictions of both codes are ‘acceptable’. This picture changes when the metrics are purely calculated from measurements within the canopy. Here, the metrics for the individual layers show a clear dependency on the measurement height, with a general tendency of worse predictions close to the ground. Especially for the 2m and 9m height the HR is very low for both codes and also the FAC2 acceptance limit is not always reached. At the lowest elevation the influence of the prescribed wall boundary conditions is strong and most likely causing the observed deviations from the experiment. As will be discussed in the next paragraphs, unsteady flow effects triggered by the presence of buildings are a further influencing factor. At a height of 18m, which is close to roof level for most of the buildings, the FAC2 values for U/U_{ref} are quite high, indicating the readjustment of the canopy flow field to the inflow.

Table 1. Validation metrics for the horizontal velocity components as predicted by ADREA (normal font) and STAR-CD (italic font).

		all positions	street canyon 2m	street canyon 9m	street canyon 18m
U/U_{ref}	FAC2	0.76 / *0.79*	0.48 / *0.57*	0.53 / *0.53*	0.87 / *0.89*
	HR	0.67 / *0.62*	0.29 / *0.34*	0.45 / *0.50*	0.68 / *0.52*
V/U_{ref}	FAC2	0.52 / *0.60*	0.50 / *0.60*	0.56 / *0.65*	0.48 / *0.62*
	HR	0.76 / *0.82*	0.49 / *0.60*	0.63 / *0.75*	0.72 / *0.79*

POINT-BY-POINT EVALUATION

In order to evaluate how large the deviations between the predicted and observed velocities really are, horizontal velocity vectors were also compared (not shown). Both codes are able to reproduce the general flow pattern realistically. With regard to the local magnitude and direction of the wind vectors some tendencies are identified. At the lowest measurement plane, ADREA shows a tendency to under-predict wind speeds especially in streamwise oriented street canyons and on the plaza. STAR-CD, on the other hand, seems to capture the near ground wind magnitudes better while showing the same struggle in predicting wind directions at complex geometrical positions of the city. At 18m the agreement of the vectors is much better.

Local FAC2 distribution

For the investigation of the local dependence of the quality of the prediction the FAC2 metric for both velocity components was calculated at each of the measurement points individually. An example of this analysis is shown in Figure 4 for the 2m flow predictions from ADREA. Black dots mark locations at which the local FAC2 is below the acceptance limit while white

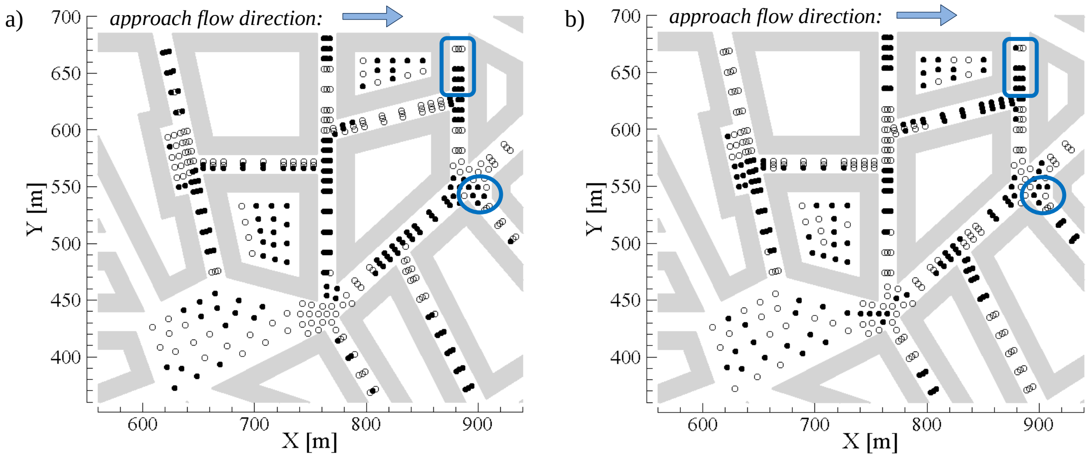

Figure 4. Local FAC2 distribution of the streamwise U (a) and spanwise V (b) velocity components as calculated from ADREA at a height of 2m. Black dots mark locations where FAC2 ≤ 0.5 and white dots where FAC2 > 0.5.

dots indicate positions at which the criterion of FAC2 > 0.5 is fulfilled. For the streamwise velocity component it can be seen that the code particularly struggles with predicting the right magnitudes in lateral street canyons, at complex intersections and in courtyards – thus, in cases where the magnitude of this velocity component is low (see Figure 4a). An analogous picture is observed for the local FAC2 of the spanwise component shown in Figure 4b. At points where there is a strong lateral deflection of the flow the component is predicted well while in streamwise oriented street canyons the metric often falls below the acceptance threshold. Similar results were obtained from the local FAC2 analysis of the STAR-CD predictions (not shown). However, there are also situations in which the FAC2 is low for both components simultaneously. Two of these locations are encircled in Figure 4 (cross-canyon and complex intersection). These are areas where strong bimodal flow behaviour was observed from an analysis of the experimental flow time series. RANS codes are known to struggle for such flow situations that are dominated by unsteady flow effects. For a detailed discussion it is referred to Efthimiou et al. (2011).

CONVERGENCE ANALYSIS

Another aspect of RANS flow validation is connected to the question how many data points are sufficient in order to appraise the performance of the model reliably. Since most reference data sets are available in terms of field measurements the number of data available for validation studies is usually rather limited. For laboratory measurements the spatial resolution of the studied problem is usually much better. More measurement locations are available and the acquainted data are characterized by well-defined and controllable inflow and boundary conditions. Thus, it becomes possible to study the statistical dependence of the value of the calculated validation metric on the number of data points that were included in its computation.

For the present problem the dependence of the FAC2 on the ensemble size for velocities at street canyon levels of 2, 9, and 18m were studied. In particular, the scatter of FAC2 values dependent on the ensemble size is an interesting indicator of the statistical robustness. All of the three horizontal layers consist of n = 383 measurement points. The FAC2 values for ADREA and STAR-CD predictions based on this largest ensemble size were presented in Table 1. Smaller ensemble sizes were defined as k = 10, 25, 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, 300, 325, 350, and 375. From basic knowledge of combinatorics it is known that there are 'n-choose-k' possibilities to extract subsets of k values from maximum ensemble given by n. However, because of the large number of available measurement locations it is computationally infeasible to calculate all possible combinations. It was therefore decided to use a random permutation algorithm to obtain the range of metric values for each of the specified ensemble sizes k. For the results shown in Figure 5 a total 10,000 permutations of data points were conducted for each ensemble size in order to obtain statistically representative values of the variance.

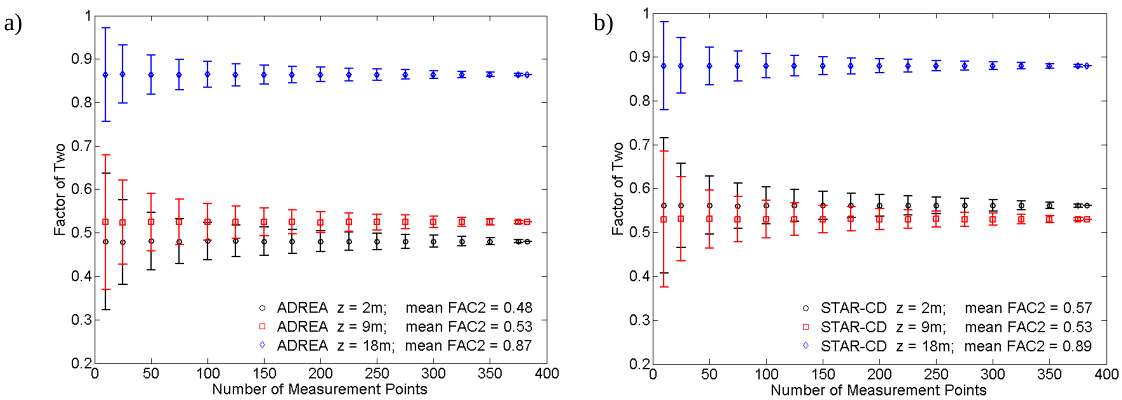

Figure 5. Dependence of the FAC2 of the streamwise velocity component U/U_{ref} at street canyon level on the number of measurement points used for its calculation: (a) for ADREA predictions and (b) for simulations with STAR-CD.

Figure 5a shows the FAC2 of the streamwise velocity component predicted by ADREA based on the number of measurement points that were included in its calculation. The scatter bars attached to the respective mean values for each ensemble size represent the standard deviation obtained from the total of 10,000 FAC2 values that were calculated from a random combination of the k measurement points. The large statistical scatter of values for small ensemble sizes is striking. For the smallest ensemble size of $k = 10$ the range of FAC2 values is very large compared to the mean values of this metric, especially for the two lowest measurement heights at 2 and 9m. Thus, based on the knowledge from only 10 measurement positions that are randomly allocated within the city the quantitative assessment of the model performance is either quite good (e.g. 0.64 at 2m) or quite bad (e.g. 0.32 at 2m). Not until an ensemble size > 200 is reached the scatter is reducing. For the most elevated street canyon measurements at $z = 18$m the overall scatter is smaller and the convergence is thus found to be faster. A similar trend can be observed through a convergence analysis based on the simulations from STAR-CD (see Figure 5b).

The analysis showed that a sufficiently high number of comparison points are crucial in order to obtain reliable validation statistics especially in complex flow situations (e.g. close to the ground) and to really assess whether the model performance is good or bad. Having regard to this, the role of field data as a reference in validation studies is accompanied by caveats since usually only a limited number of observational data are available.

DISCUSSION & OUTLOOK

The ability of two CFD-RANS models to adequately predict the wind fields within and above a semi-idealized urban structure was studied. Based on wind-tunnel validation data a systematic study of the performance of both models revealed that unsteady flow effects deep within street canyons are a major source of discrepancies between numerical and experimental results. The study showed that a point wise evaluation is crucial in order to determine such model limitations and enables to distinguish these kinds of uncertainties from numerical or modelling errors. Especially close to the ground the model performances have to be further evaluated with respect to the influence of the prescribed wall boundary conditions. From a convergence analysis the dependence of the calculated 'global' FAC2 on the number of incorporated data points was illustrated. The analysis indicated that a reference data base should offer a sufficiently high number of comparison points in order to allow for high statistical confidence levels of the calculated measures.

The next steps of the analysis will concentrate on further investigations of the experimental flow time series in terms of frequency distributions in order to determine possible systematic dependencies of the agreement or disagreement with the numerical predictions based on non-Gaussian flow behaviour. Since the flow field is the driving mechanism for the dispersion process of pollutants a 'safe' prediction of the mean velocity values is crucial.

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REFERENCES

Bartzis, J. G., Venetsanos, A., Varvayani M., Catsaros, N., Megaritou, A., 1991. ADREA-I: A three dimensional transient transport code for complex terrain and other applications. *Nuclear Technology*, **94**, 135–148.

Bartzis, J. G., 2005. New approaches in two-equation turbulence modelling for atmospheric applications. *Boundary-Layer Meteorol.*, **116**, 445-459.

Bartzis, J. G., Efthimiou, G. C., Hertwig, D., Leitl, B., Fischer, R., Harms, F., Bastigkeit, I., Mytilinou, V., 2011. Modeling individual exposure from airborne releases, in: Proceedings of HARMO14, Kos, Greece.

Bastigkeit, I., Fischer, R., Leitl, B, Schatzmann, M., 2010. Fundamental quality requirements for the generation of LES-specific validation data sets from systematic wind tunnel model experiments, in: Proceedings of CWE2010. Chapel-Hill, NC, USA.

CEDVAL-LES, 2011. Compilation of Experimental Data for Validation of Microscale Dispersion Models: *www.mi.uni-hamburg.de/CEDVAL-LES-V.6332.0.html*. Meteorological Institute, University of Hamburg, Germany.

Efthimiou G. C., Hertwig D., Fischer R., Harms F., Bastigkeit I., Koutsourakis N., Theodoridis A., Bartzis J.G., Leitl B., 2011. Wind flow validation for individual exposure studies, in: Proceedings of ICWE13, Amsterdam, The Netherlands.

Fischer, R., Bastigkeit, I., Leitl, B., Schatzmann, M., 2010. Generation of spatio-temporally high resolved datasets for the validation of LES-models simulating flow and dispersion phenomena within the lower atmospheric boundary layer, in: Proceedings of CWE2010. Chapel-Hill, NC, USA.

Hanna, S. R., Hansen, O. R., Dharmavaram, S., 2004. FLACS CFD air quality model performance evaluation with Kit Fox, MUST, Prairie Grass, and EMU observations. *Atmospheric Environment*, **38**, 4675-4687.

Schatzmann, M., Olesen, H., Franke, J., (Eds.), 2010. COST 732 model evaluation case studies: Approaches and results. University of Hamburg.

VDI Guideline 3783/12, 2000. Environmental Meteorology, Physical Modelling of Flow and Dispersion Processes in the Atmospheric Boundary Layer – Applications of Wind Tunnels. Beuth Verlag, Berlin.

VDI Guideline 3783/9, 2005. Environmental Meteorology – Prognostic microscale windfield models – Evaluation for flow around buildings and obstacles. Beuth Verlag, Berlin.