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LES VALIDATION OF FLOW IN A DENSELY BUILT ENVIRONMENT

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Abstract: In a systematic study wind-tunnel measurements and predictions from large-eddy simulation (LES) of turbulent flow in the inner city of Hamburg, Germany, are compared. The reference laboratory measurements of velocity fields are carried out in a neutrally stratified boundary-layer wind tunnel within an urban model on a scale of 1:350. Numerical results are obtained from simulations with the implicit LES code FAST3D-CT. The numerical model is developed and operated by the U.S. Naval Research Laboratory and is based on a monotone integrated large-eddy simulation (MILES) methodology. The focus of the validation exercise is the comparison of time-series information and the characterization of turbulent flow structures within and above the urban canopy. On the basis of densely spaced measurements in vertical profiles and horizontal flow layers the developments of the turbulent boundary-layer within the city as well as typical street-canyon flow scenarios provide the framework for this analysis. Particular challenges with respect to the validation of time-resolved simulations in contrast to standard approaches are discussed with an emphasis on specific demands in the case of urban flow fields.

Key words: *Large-eddy simulation; boundary-layer wind tunnel; flow validation; time-series analysis*

INTRODUCTION

The potential to simulate the time-dependent structure of atmospheric boundary layer flows of high Reynolds numbers with eddy-resolving approaches like large-eddy simulation (LES) resulted in a great gain of information about turbulence and its spatio-temporal evolution. Within the last decades, many fundamental studies arose from these new possibilities – especially for situations that cannot be easily modeled in the laboratory or measured in the field. Apart from those more-or-less academic fields of applications for LES there is an increase in the use of time-resolved approaches in more practical fields of applications accompanied by the continuing increase of computational capacities. Prominent examples are LES calculations of flow and dispersion within the urban canopy layer. Besides wind comfort, ventilation or urban planning studies, LES is also increasingly used for emergency response activities. These are areas where the use of numerical codes based on Reynolds-averaged conservation equations (RANS) so far was the common standard. In contrast to RANS models the eddy-resolving approaches have the capability to adequately reproduce spatially complex turbulent flow regimes together with their temporal changes. Within the urban canopy layer unsteady flow effects are strongly enhanced by the presence of buildings, leading to flow situations that could formerly not be adequately described by numerical approaches (cp. recent urban LES studies by Xie and Castro, 2009; Letzel et al., 2008, or Patnaik et al., 2007).

Verification of the numerical result against suitable reference data is a crucial step in order to establish credibility of the prediction and assess its reliability for cases in which the ‘truth’ is not known *a priori*. In this context, the accuracy of the simulation in terms of expectable bounds of uncertainty should be determined – primarily by quantitative means. The thorough review by Oberkampf and Trucano (2002) addresses these points in detail. The physical character of LES adds new aspects to the validation problem. Together with the gain of information about the flow, in particular with respect to its turbulent eddy structures, there is an increasing demand on the quality and quantity of reference data. Aspects of validation data requirements for LES in contrast to RANS are for example discussed by Adrian et al. (2000) and Kempf (2008). The strategies pursued in the model validation itself have to go beyond a pure comparison of statistical moments but should additionally provide an assessment whether the simulation reproduces the spatio-temporal behavior of turbulent eddies realistically. However, so far there is no consensus about standards for such an elementary LES validation that would really give consideration to this issue. It could be demonstrated, however, that mathematical tools from the field of advanced signal analysis and pattern recognition might have the potential to establish a basis for comparisons between experiment and LES simulation (cp. Hertwig et al., 2011).

The aim of the present study is the validation of an urban LES code based on information drawn from numerical and experimental time series that were obtained in wind-tunnel measurements. Specifically it is focused on comparing time characteristics of the flow associated with the presence of energy-dominating eddy structures that should be well reproduced in an LES simulation.

EXPERIMENTAL & NUMERICAL APPROACHES

Laboratory measurements of flow and concentrations fields in specialized boundary-layer wind tunnels can provide an ideal validation data basis supplementary to information from field sites. Well definable and controllable boundary conditions together with the potential to repeat experimental runs under the same constraints as often as required result in high statistical confidence levels of the measured quantities.

Wind-tunnel measurements

The reference measurements for this study were performed in the boundary-layer wind tunnel ‘WOTAN’ at the University of Hamburg. The wind-tunnel model comprises the city center of Hamburg together with industrial harbor sites that are separated from the downtown area by the river Elbe. In total, the model domain encompasses an area of 3.7km x 1.4km in full-scale dimension (compare extent of the inner frame in Figure 1a). The physical model was built on a scale of 1:350, including terrain and a 3.5m high water front (see photograph of the wind-tunnel model shown in Figure 1b). Effects of urban greenery are not accounted for. Figure 1c shows the buildings incorporated in the wind tunnel on a model area of 42m².

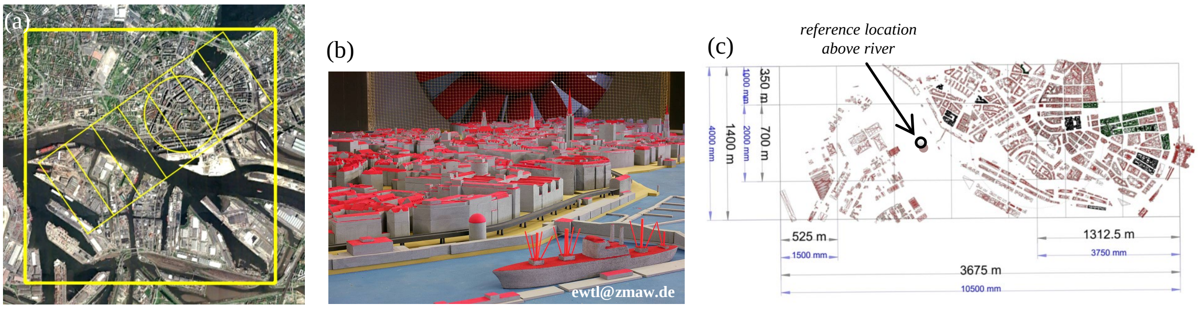

Figure 1. (a) Google Earth image showing the wind-tunnel model domain (inner frame) and the simulation region for FAST3D-CT (outer frame) of the inner city part of Hamburg. (b) Photograph of the urban wind-tunnel model. (c) Wind-tunnel model area with an indication of the reference location (framed dot) above the river.

The flow is approaching from the southwest (235°), mirroring a quite frequent meteorological condition for that area, and was physically modeled to feature urban (i.e. very rough) turbulence characteristics (α~0.29; z_0~1.5m) under neutral atmospheric stratification. All flow measurements were conducted by non-intrusive laser Doppler velocimetry. The inflow was constantly monitored and documented through Pitot tube measurements in the first section of the tunnel.

FAST3D-CT simulations

Numerical results are obtained from simulations with the urban aerodynamics LES model FAST3D-CT that handles the dynamical effects of sub-grid scales implicitly through numerical diffusion. The model is developed and operated by the U.S. Naval Research Laboratory and is based on a monotone integrated large-eddy simulation (MILES) methodology that offers high computational efficiency. Details on physics and numerics within FAST3D-CT are given in Patnaik and Boris (2010).

The 3D CFD simulation for Hamburg was performed on a 4.0km x 4.0km region of the inner city with a 2.5m grid resolution (cp. outer frame in Figure 1a). The calculation was run on 62 or 64 CPUs of a SGI Altix computer, took over three weeks for 350,000 time steps at 0.05sec/time step generating over 4 hours of real time data. The average wind direction is 235° rotated clockwise from due south. The wind speed was approximately 7.0m/s at a height of 190m. To match the FAST3D-CT conditions with the wind-tunnel experiments as closely as possible, all temperature related effects such as buoyancy and surface heating as well as drag effects of trees have been turned off. Time-dependent wind data were collected every 0.5 seconds for over 4 hours at various heights up to 130m.

Data selection & preparation

For the validation exercise 22 measurement locations within the model domain were chosen for which highly resolved time series of the horizontal wind components (and partly also for the vertical component) are available in densely spaced profiles and horizontal flow layers. The selection was made to include areas of the city that feature characteristic urban flow situations that also pose challenges to numerical models. Thus, the locations also include narrow street canyons, complex intersections, and measurement points close to the ground. Wind detectors in the numerical calculations were deployed to match the specified locations in the wind-tunnel experiment as closely as possible. The nearest neighbor extraction was chosen in order to avoid contamination of the results by interpolating data in order to have an exact spatial match. This procedure led to slight offsets of the x, y, and z positions of the comparison points that were in the range of a few centimeters up to a maximum of 1.75m. Experimental and numerical data were homogenized by referencing all velocities and their derivatives to a reference wind speed at a fixed location. This monitoring point was defined at a height of 49m above the river Elbe at approximately 1km upstream distance from the city center (see indication of that location in Figure 1c).

MEAN FLOW VALIDATION

First results of the validation study are presented in the next sections. Although the emphasis of the analyses is put on the comparison of time-series characteristics, the starting point of the study was set by the validation of the mean flow.

Figure 2 shows comparisons of vertical profiles of the streamwise velocity component from wind-tunnel measurements and FAST3D-CT simulations. The inflow is approaching from left to right. Scatter bars attached to the experimental values represent the reproducibility of the data based on repetition measurements. The profile locations differ in the arrangement of the surrounding buildings. Figure 2a shows velocity profiles above the river Elbe (the location is identical with the reference point indicated in Figure 1c). Being situated well upstream of the densely built-up city center the good agreement between experimental and numerical profiles mirrors a good match of the mean inflow conditions. A good agreement is also found for positions at which the flow is strongly influenced by the building structure.

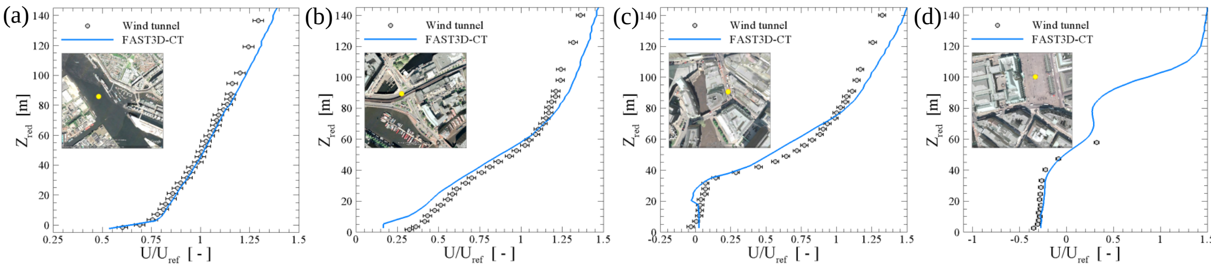

Figure 2. (a)-(d) Comparison of mean streamwise velocity profiles at various locations. Area images extracted from Google Earth.

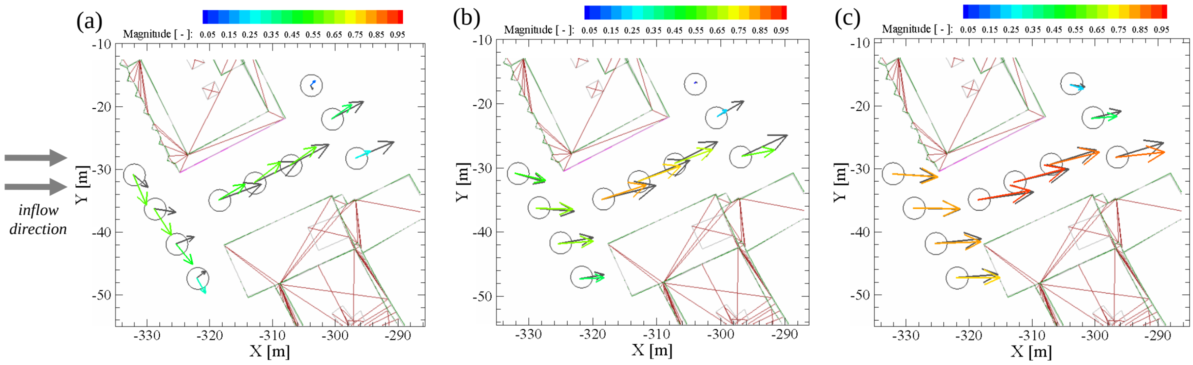

Figure 3. Mean horizontal velocity vectors of flow entering a courtyard at heights of (a) 3.5m, (b) 17m, and (c) 30m. Gray vectors represent wind-tunnel measurements. Color-coded vectors are from the numerical simulation with FAST3D-CT.

Figure 2c shows a profile measured in a very narrow street canyon. In Figure 2d the measurement position is located in an open plaza exhibiting a strong recirculation regime that is captured quite well by the code. For some of the compared locations, a slight trend towards an underprediction of velocities can be observed at elevations below the mean building height (approx. H_{mean}~35m by averaging over the city center) as seen in Figure 2b. In contrast, higher wind speeds than in the reference measurements are found at heights larger than 2.5H_{mean} (cp. Figures 2a-c). The slight offsets observed within the street canyon might be explained by the close proximity of building walls and the effect of their physical treatment inside the simulation. The stronger acceleration well above the canopy has to be investigated further and might reflect an excess of TKE in the numerical inflow prescription.

A comparison of horizontal flow fields in terms of mean horizontal wind speed vectors is presented in Figure 3 for different heights above ground. The test case is represented by the flow entering a courtyard. The large gray arrows indicate the inflow direction. The overall comparison is again quite good, although strong directional deviations at the lowest measurement plane are detected (see Figure 3a; z = 3.5m in the experiment and 2.75m for the numerical simulation). It has to be noted that this is also the lowest computational level of the simulation, which is a possible explanation for the offsets. At this first node the results are strongly influenced by the boundary constraints and the flow did not have enough time to evolve physically.

TIME-SERIES ANALYSIS

Next, experimental and numerical time series were analyzed in terms of frequency distributions, energy spectra, and joint time-frequency characteristics of the signals. It has to be noted that both signals differ in their length and their time resolution under full-scale conditions. While the 170s measurement time in the wind tunnel results in a full-scale length of 16.5h, the length of the numerical time series is 4.5h. Especially at low elevations within street canyons the full-scale temporal resolution of 2Hz of the FAST3D-CT signals is better than the scaled wind-tunnel data rate that is strongly affected by the local seeding conditions that influences the experimental data rate.

Wind-rose diagrams

First, the frequency distributions of instantaneous horizontal wind speeds and wind directions were evaluated. Figure 4a shows the location for such a test. The mean horizontal wind speeds U_h and wind directions are compared in terms of vertical profiles shown in Figures 4b and 4c, respectively. At each of the profile heights, the fluctuations about these means were investigated. Figure 5 shows wind-rose diagrams of horizontal wind speeds and directions observed (Figure 5a) and simulated (Figure 5b) at four different heights within the street canyon profile. At first view the graphs show that the model predicts the deflection of wind directions inside the canopy quite well, together with the adjustment to the wind direction of the inflow at roof-top level and well above at 57.75m (i.e. 1.65H_{mean}). The spread about the central direction is largest at roof-top height and smallest at the highest elevation in both the experiment and the simulation. However, discrepancies in velocity magnitudes are observed inside the canopy, especially for the lowermost point at 2.5m and 2.75m, respectively. As discussed earlier in connection with the mean flow validation, the lower magnitudes are most likely due to the influence of wall boundary conditions prescribed at the ground and at upright building surfaces. Despite these differences the analysis indicates that the LES code is able to reproduce the directional fluctuation levels caused by unsteady flow effects quite reliably.

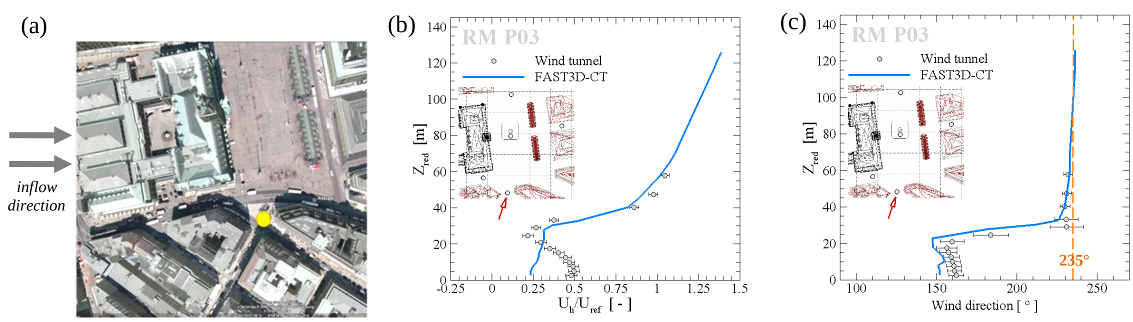

Figure 4. (a) Profile measurement location at a complex intersection; image extracted from Google Earth. (b) Mean horizontal wind speed and (c) wind direction profiles from wind-tunnel measurements and FAST3D-CT calculations.

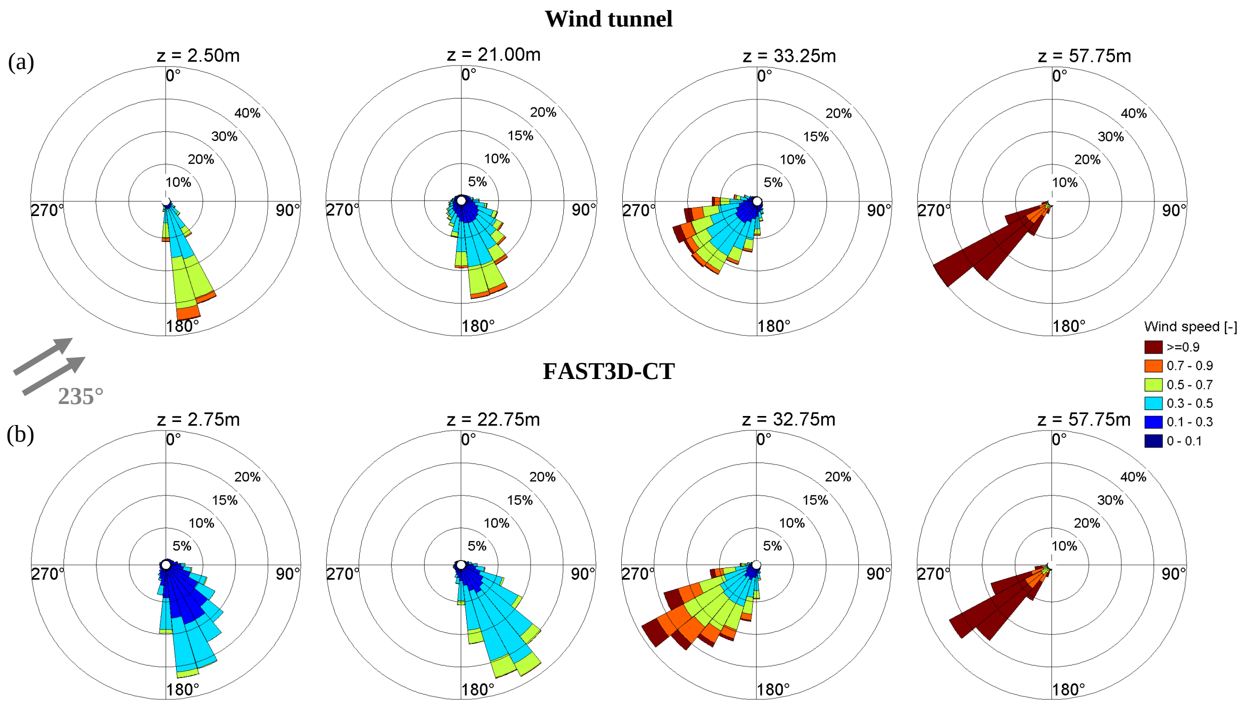

Figure 5. Wind-rose diagrams showing frequency distributions of horizontal wind speeds and wind directions for wind-tunnel measurements (a) and FAST3D-CT simulations (b) at four different heights within and above a street canyon (same location as in Figure 4a). Arrows on the left indicate the inflow direction.

Turbulence spectra

Auto-spectral energy densities of the turbulent streamwise velocity component are studied in order to analyze the spectral content associated with different eddy structures found in the flow. The spectra were obtained using an FFT algorithm. In order to make the spectra interpretable in terms of characteristic energetic ranges, two averaging techniques are used. First, the time series is separated into fragments of equal lengths and it is averaged over the spectra obtained from these sub-samples. Next, this averaged spectrum is smoothed by taking the mean over equal intervals with respect to the logarithm of frequency. Original values are only kept for the lowest frequencies that are connected to the largest structures in the flow.

Figures 6a-c show scaled frequency spectra obtained from numerical and experimental velocities at various locations at heights of 17.5m (~0.5H_{mean}) and 45.5m (~1.3H_{mean}), respectively. A very good agreement of the production and energy-containing range of the spectra is found at all positions. The energetic peaks associated with integral length scale eddies coincide very well for the measurements shown in Figures 6b and 6c, whereas at the position above the river (Figure 6a) the peak is shifted for more than a decade towards higher frequencies. This offset might have been caused by the shorter overall signal length of the numerical time series. In order to investigate this further, next analyses will concentrate on comparisons of integral length scales that can be determined from autocorrelation time scales invoking Taylor's hypothesis.

Common to all of the numerical spectra is their fast roll-off in the high frequency range that marks the onset of the influence from the dissipation scheme. At most of the investigated locations this influence becomes noticeable approximately one decade after the spectral peak was reached resulting in a shortened extent of the inertial range. In consideration of the fact that FAST3D-CT was particularly designed to simulate dispersion processes in urban areas, the very good match of the energy-containing ranges associated with eddies that play a dominant role for scalar transport confirms the model's fitness for that purpose. However, it should be studied whether an extension of the inertial range is possible in order to add to the physical character of the LES.

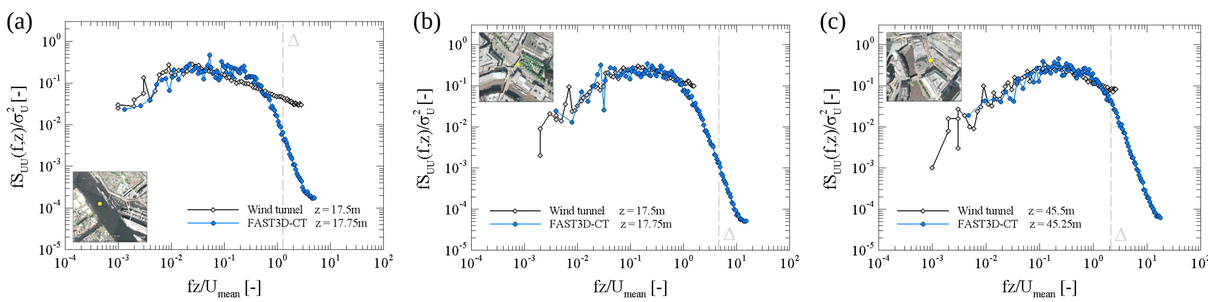

Figure 6. (a)-(c) Auto-spectral energy densities of the fluctuating streamwise velocity component from wind-tunnel measurements and simulations with FAST3D-CT at various locations within the city at heights of 17.5m (~0.5H_{mean}) and 45.5m (~1.3H_{mean}). The dashed lines separate the low frequency parts of the spectra that can be directly resolved by the numerical model given the grid resolution of Δ=2.5m and the respective mean wind speeds from the subgrid-scales affected by numerical diffusion. Area images are extracted from Google Earth.

Continuous wavelet transform

The continuous wavelet transform (CWT) is a representative of joint time-frequency analysis methods whose capabilities in the field of turbulence research and coherent structure detection were thoroughly investigated by Farge (1992). The CWT of a time-dependent, square integrable 1D function u(t) is given by the convolution of the signal and the family of so-called wavelet functions $\psi_{s,n}$. Here, n refers to the translation parameter and s > 0 is the scale parameter (Addison, 2002). Through the parameter n, the wavelet function is translated in time, covering different parts of the signal. By adjusting the scale, the wavelet function can be compressed or stretched, acting as a 'mathematical microscope' that zooms in and out of signal features to resolve components of high and low frequencies. The scale is thus inversely proportional to the frequency. The wavelet coefficients simultaneously comprehend time and frequency information of u(t).

The CWT is applied to numerical and experimental time series of the streamwise velocity component using the 'Mexican-hat' function as the mother wavelet (not shown, it is referred to Hertwig et al., 2011a). The numerical implementation follows Torrence and Compo (1998) for a computation in Fourier space. In order to make both signals comparable in the time-frequency domain, dimensionless times and sampling frequencies were adjusted. Through a representation of the coefficients in a non-dimensional time/scale framework large scale (i.e. low frequency) undulation pattern are found for both signals. These minima and maxima are associated with large eddy structures passing the sensors that could be successfully separated from high frequency 'noise'. Similar structures were found at comparable scales for both the experimental and numerical time series. Future analyses will now concentrate on determining and comparing the frequency of occurrence of these large eddies and studying their energetic contributions in terms of wavelet variances.

DISCUSSION & OUTLOOK

This study identified possible strategies concerning an in-depth LES validation. Wind-tunnel measurements of flow fields within a genuine physical model of the downtown area of Hamburg, Germany, provided the reference basis for the validation of the implicit LES model FAST3D-CT. The focus of the analysis was put on the extraction of information from numerical and experimental time series in terms of histograms, turbulent energy spectra and joint time-frequency information. Performed in terms of a 'blind test', the study documented that the code is able to capture the effects of dominant eddy structures in terms of wind fluctuation levels and associated energetic properties of the turbulent flow. First results of a wavelet analysis of the signals showed that the time evolution of turbulent structures can be tracked down, offering great potential to validate the model in terms of its time-dependent characteristics. The next steps of the study will address this topic in more detail. Other statistical measures that provide insight into turbulent eddy characteristics (e.g. autocorrelation time scales or Reynolds stress components) are subjects for further studies.

In addition to the definition of new validation standards there is also a need to agree upon quantitative measures of the model performance in order to assess whether the results are 'acceptable' for the respective purpose. Similarly to the approaches taken in the case of micro-scale atmospheric RANS models (see Schatzmann et al., 2010) a compilation of new best practice directives for LES validation should be considered in the future.

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