Large-eddy simulations to characterize the role of turbulent and dispersive production, transport and dissipation of TKE over and within a realistic urban canopy

Abstract – A characterization of the vertical structure of turbulent kinetic energy (TKE) and of its budget terms over a realistic urban geometry in the city of Basel, Switzerland, is here performed via large-eddy simulation. We consider fully developed flow over a 512x512m subset of the city, centered at a location where extensive tower-measurements are available from the Basel Urban Boundary Layer Experiment (2001-02). In agreement to measurements, TKE in the roughness sublayer (RSL) is found to be primarily produced at roof-level. Here, turbulent production overcomes dissipation by SGS stresses and the excess in TKE is dislocated down into the cavities of the urban canopy layer (UCL), and upwards into higher parts of the RSL by turbulent transport and dispersive transport terms. Turbulent and dispersive transport terms are comparable in magnitude and act as a sink of TKE in the upper RSL and as a source term in the lower RSL and UCL. The spatial heterogeneity of mean velocities and Reynolds stresses in the lower RSL and in the UCL results in a significant wake production rate of TKE. Moreover, pressure transport is found to be a significant source of TKE in the lower UCL, whereas transport by SGS stresses is negligible throughout the RSL.

Introduction

Accurate modeling of flow and turbulence in the urban roughness sublayer (RSL) is essential to properly predict weather, air quality, and dispersion of gases in urban environments. Within the RSL flow and turbulence exhibit strong spatial variations in both the vertical and the horizontal directions and hence Monin-Obukhov similarity (MOST) is not applicable. Nevertheless, one dimensional urban canopy parameterizations (UCPs), used to represent the effects of urban surfaces in mesoscale weather forecasting and air pollution dispersion models, are still relying on MOST relationships to compute vertical fluxes of momentum and scalars such as heat, humidity or pollutants between the urban facets and the atmosphere. Proper techniques to reintroduce a 1D approach in a truly three-dimensional RSL should account for the inherently variable canopy morphology, and its hierarchical structure of scales, as discussed in Britter and Hanna (2003). The increased availability of high resolution digital datasets on urban morphology is recently promoting the use of real topographies in CFD studies (see for instance Kanda et al., 2013). Further, advances in computational power now allow for representation of the three-dimensional processes of interest at the neighborhood scale. Output from numerical models, such as large-eddy simulations (LES), can therefore be used to understand the physics of the flow and quantify the most relevant terms and processes that occur in realistic urban RSLs. This is the goal of the current study, where LES are used to resolve the airflow over and within a detailed urban geometry and to characterize the vertical structure of the turbulent kinetic energy (TKE) and the role of TKE budget terms in the RSL. Such information can then guide and/or validate approaches used in one-dimensional UCPs.

Throughout the study *H* will denote the top of the boundary layer, a given height in the domain will be denoted as z_{label}, where the subscript "label" will refer to various specific heights. Further, $\bar{(\cdot)}$ is used to denote a spatially filtered variable (the spatial filtering that is implicitly understood in LES), $\overline{(\cdot)}$ denotes time-averaging, <·> denotes horizontal (x, y) intrinsic averaging (fluid domain only), time fluctuations are written as (·)′ and departures of time-averaged terms with respect to their horizontal mean are denoted as (·)″. We will use (·)* to denote a normalized variable.

Numerical algorithm and setup of simulations

The isothermal filtered Navier-Stokes equations are solved on a 512 × 512 × 160 m regular domain, where a subset of the city of Basel, Switzerland is used as lower interface (see Fig. 1). The LES algorithm was developed in Albertson and Parlange (1999) whereas the immersed boundary method (IBM) algorithm is a minor modification of Chester et al. (2007). Equations are solved on a regular domain $L_x \times L_y \times H$, imposing a free-lid boundary condition at $z = H$, using the IBM algorithm to account for the lower interface, and where periodic boundary conditions are applied in the horizontal directions. The flow is forced through an imposed pressure gradient, resulting in a friction velocity $u_* \approx 1$ m s^{-1} (fully rough regime). Two hydrodynamic roughness lengths, $z_0 = 0.15$ and $z_0 = 0.3$, and two LES closure models are considered: the classical static Smagorinsky model (Smagorinsky, 1963), and the scale-dependent model with Lagrangian averaging of the coefficient (LASD) (Bou-Zeid et al., 2005).

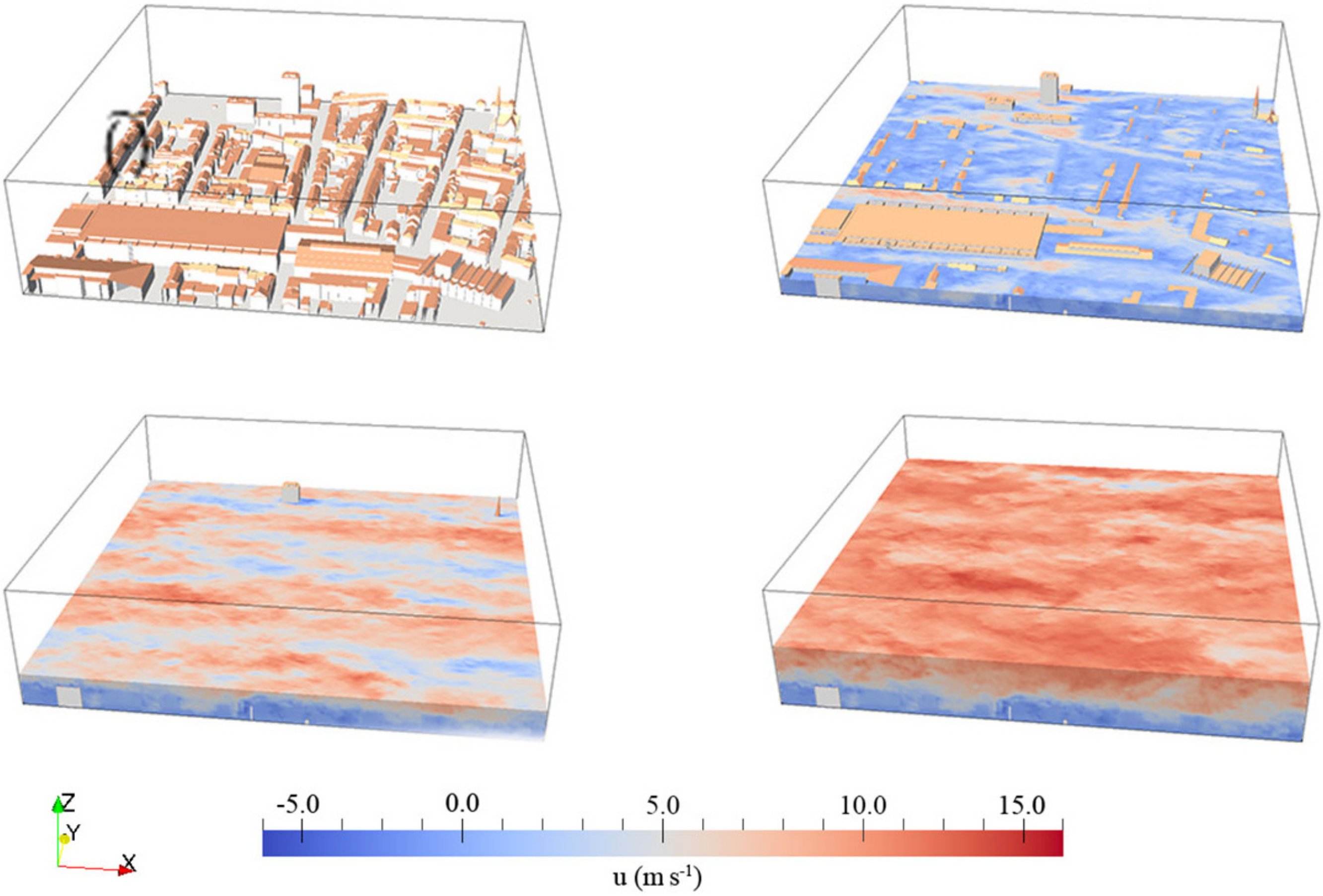

Figure 1. Reference surface and color contour of the dimensional stream-wise wind velocity at the planes $z/z_h = 1$, $z/z_h = 2$, $z/z_h = 4$ for the across-canyon wind direction (SMAG model, $z_0 = 0.15$).

During BUBBLE, a 32 m high tower was deployed inside the 13 m wide Sperrstrasse street canyon in Basel, Switzerland (Rotach et al., 2005). The computational domain is centered at the tower location where wind components u, v, w and virtual acoustic temperature θ were continuously recorded at six levels. The orientation of the street canyon is along the axis 066° - 246° (ENE to WSW). Data acquisition systems and quality control procedures including wind-tunnel calibrations of the instruments are described and documented in Christen (2005). We consider two directions of the incoming wind, $\alpha = 66°$ and $\alpha = 156°$, which correspond to an along-canyon (Sperrstrasse) and an across-canyon wind regime. Equations are integrated in time for 480 non-dimensional time units $T = z_h/u_\tau$ (≈ 2 hours in dimensional time) in the coarser grid, before being used as initial condition for the finer grid, where they are further integrated for 250T.

Results and discussion

A color contour of the stream-wise velocity field for wind approaching from SSE (across-canyon regime) is displayed in Fig. 1. The flow is characterized by a broad spectrum of explicitly resolved length scales, as typical of LES approaches, which are heterogeneous in space and strongly depend on the actual configuration of the buildings. Double averaged (DA) numerical profiles are made dimensionless using the friction velocity and the mean building height ($z_h = 15.3$ m) as repeating variables. Tower profiles are first rescaled with the ratio between measured and simulated quantity at the tower top location and then normalized as DA profiles. Throughout the study z_γ will denote the height where the stream-wise velocity profile shows an inflection point. Normalized profiles of TKE and wake kinetic energy (WKE) are shown in Fig. 2. Locally sampled time-averaged LES data show relatively good agreement with measured data for both wind directions. LES slightly under-predicts TKE in the urban canopy layer (UCL), when compared against measured values. This might be partly due to boundary conditions we could not include in the model, or to lack of resolution in these delicate regions of the flow. TKE peaks at z_γ for the across-canyon wind regime and slightly above z_γ in the along-canyon wind regime, to then decrease linearly with height, consistent with tower measurements for the across-canyon wind regime and

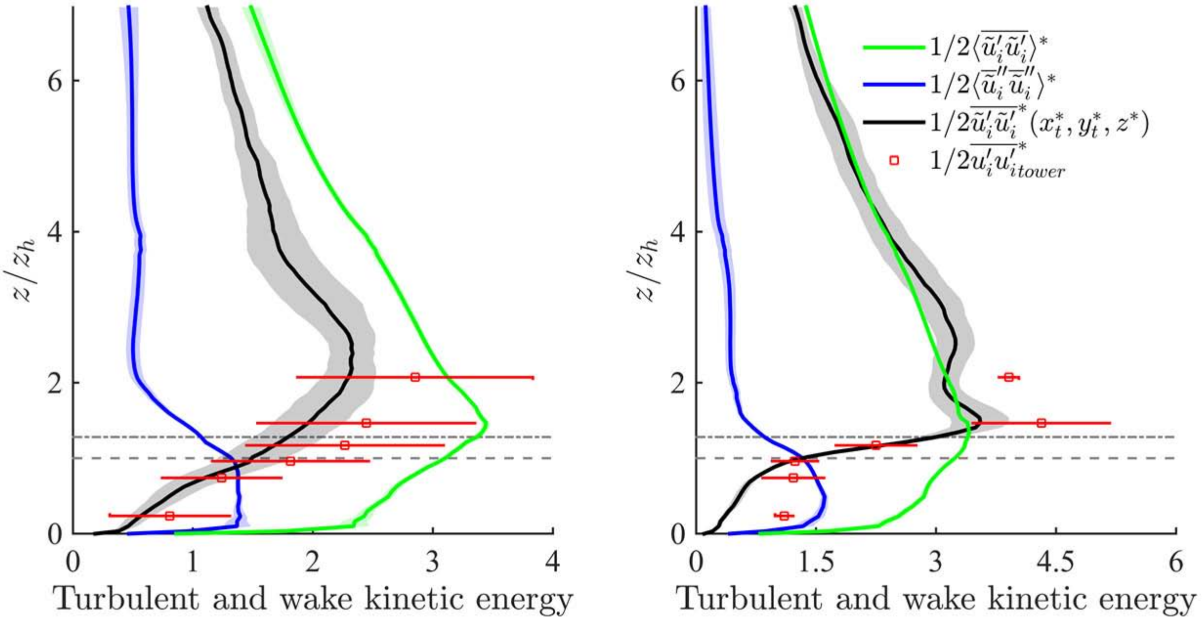

Figure 2. Comparison of TKE and WKE against tower-measured data for wind approaching from ENE (top) and SSE (bottom). Notation: DA TKE, green; dispersive TKE, blue; time-averaged locally-sampled TKE, black; tower data, red circles. Horizontal dashed and dot-dashed (grey) lines denote z_h and z_γ respectively.

in agreement with results from flow over random height cubes (Xie et al., 2008). A peculiar feature of the current study is the remarkable strength of TKE in the UCL, when compared against results from flow over gravel beds (Mignot et al., 2009) or flow over regular/random arrays of cubes (Coceal et al., 2006; Xie et al., 2008). This might be induced by the presence of organized street canyons, which allow the flow to develop significant MKE that then cascades into WKE and TKE due to surface drag and due to the energy cascade process. Further, for both wind directions, WKE is approximately constant within the UCL and shows a rapid decay in the lower RSL. The relatively large WKE in the RSL for the along-canyon wind regime is due to locking of streaks in between high-rise structures in the RSL. From Fig. 3 it is apparent that, for both approaching wind angles, DA turbulent shear production $<P_s>$ peaks exactly at the inflection point $z_\gamma = 1.28z_h$. This location is connected with the presence of thin shear layers that separate from the highest buildings, and are advected downstream. A second maximum is found in the $<P_s>$ profile, which can be regarded as a very specific feature of the current setup, linked to the shear layers separating from a relatively tall building in the considered canopy. <Pw> is the production rate of TKE in the wakes of roughness elements by the interaction of local turbulent stresses and time-averaged strains; in the lower UCL it is approximately constant, positive (WKE converts to TKE) of magnitude $<Pw>^* \approx u_\tau^3/z_h$. <Pw> accounts for over 50% the total production rate of TKE in the UCL, and is therefore non-negligible. Our results suggest that in flows over realistic urban canopies the presence of street canyons aligned with the mean flow and of variable building geometry tends to increase <Pw> in the lower UCL, when compared to results of flow over strip canopies (Raupach et al., 1991). The additional form-induced production term $<P_m>$ is non-zero only in the vicinity of the inflection layer z_γ, where it accounts for 16% the magnitude of $<P_s>$.

DA transport terms are found to be non-negligible throughout the roughness sublayer. From Fig. 3 it is apparent how DA production terms ($<P_s> + <P_w> + <P_m>$) overcome dissipation in the RSL down to z_h, and DA transport terms are responsible to remove TKE from this layer of high production, and transport it towards the wall to balance dissipation. In the upper RSL transport terms are thus negative, and contribute about 12% to the total sink rate of TKE. They change sign in the UCL, where they are of highest significance, contributing about 40% to the total rate of TKE. $<T_d>$ appears as a modulation of $<T_t>$, whereas $<T_p>$ is significant at z_γ (where it is a sink of TKE) and in the very near wall regions, where it peaks at $<T_p>^* = 0.8u_\tau^3/z_h$. Furthermore, we note the modest standard deviation in the computed $<T_t>$ terms for both approaching wind directions. This is indicative of the poor sensitivity of the solution with respect to the specific SGS model and to the z_0 parameter, when the roughness is explicitly resolved through an IBM method.

DA dissipation $<\varepsilon>$ peaks at z_γ, as displayed in Fig. 3. This is another peculiar feature of the current study, and is in contrast with results of flow over gravel beds

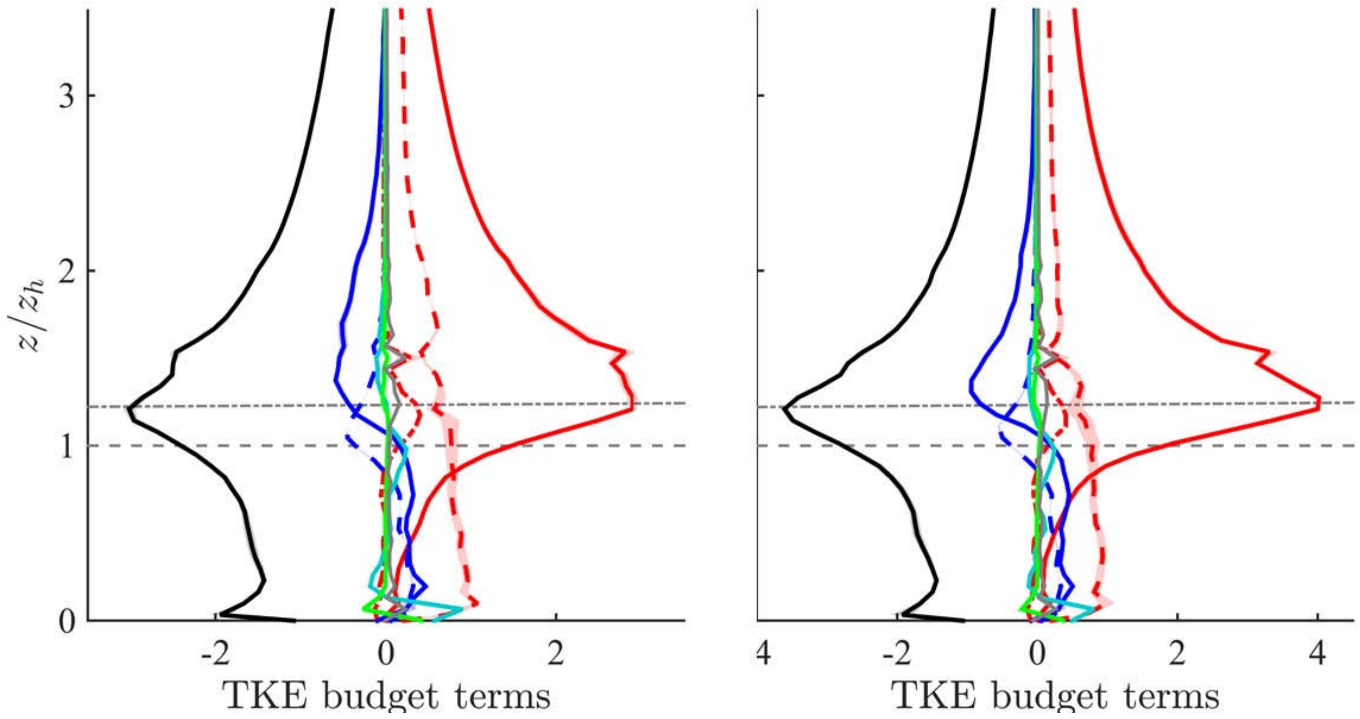

Figure 3. DA TKE budget terms for the across-canyon α = 156° wind direction. Notation: turbulent shear production <P_s>*, solid red line; wake production <P_w>*, dashed red line; form- induced production <P_m>*, dot-dashed red line; dissipation <ε>*, black; turbulent transport <T_t>*, solid blue line; dispersive transport <T_d>*, dashed blue line; pressure transport ⟨T_p⟩*, light blue; subgrid transport ⟨D⟩, green; residual, grey. Horizontal dashed and dot-dashed (grey) lines denote zh and zγ respectively. Only the lower 33% of the domain is shown.

(Mignot et al., 2009; Yuan and Piomelli, 2014), where the peak in dissipation was found to be shifted toward the wall, with respect to the peak in the shear production rate. Further, a strong rate of dissipation characterizes the near-wall regions. This peak is required in order to balance pressure transport of TKE from aloft, again confirming the important role of pressure transport in the vicinity of walls, in flows over directly resolved building interfaces. The small residual is likely due to interpolation of variables in the near interface regions (which are required to compute certain TKE budget terms), and leads to numerical truncation errors affecting the quality of the computed terms.

Conclusions

A characterization of TKE and of its budget terms has been performed via LES over a realistic urban canopy, representing a subset of the city of Basel. TKE profiles have been compared to direct tower measurements from a field campaign and found to be in good agreement, certifying the quality of the computations. DA TKE peaks above $z_γ$, in agreement with results from studies of flow over synthetic urban-like surfaces. TKE is significant in the UCL, when compared against results of flow over gravel beds and over regular / random arrays of cubes. Further, dispersive TKE is found to be non-negligible in the UCL, and of the same order of magnitude of its turbulent counterparts. Turbulent kinetic energy (TKE) in the UCL is primarily produced at $z_γ$ by shear, and is transported down into the cavities of the UCL (street canyons, backyards) by turbulent and dispersive transport terms, which share similar magnitudes. Transport terms are non-negligible throughout the RSL. They are of negative sign and contribute about 12% to the total variation rate of TKE in the RSL, whereas they are of highest significance in the UCL. Here, they are of positive sign and contribute about 40% to the local variation rate of TKE. Wake production is roughly constant up to $z_γ$ and of non-negligible magnitude, contributing up to 50% of the total TKE production rate in the UCL. Further, pressure transport is found to be a significant source of TKE in the near wall regions, in agreement with previous findings in flow over vegetation canopies and flow over gravel beds.

From our results it is also apparent that tower measurements cannot be used to quantify all terms in a horizontally-averaged view, because the non-measurable dispersive terms and pressure terms are important in a real canopy and should therefore be considered in future UCPs.

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