J5.2 Modeling of flow and dispersion characteristics in typical urban building configurations with the fast-response model QUIC

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1. INTRODUCTION:

Many studies have shown that an increase in urbanization has been observed worldwide, and this trend can be expected to continue in the future. As a consequence, the environmental impact of urban areas is of growing concern and one of the major problems in urban areas is atmospheric pollution. An excellent overview of the urban effects on air quality was recently presented by Britter and Hanna (2003). They discuss the different spatial scales that are of importance for particular pollution problems.

In particular, modeling of small-scale flow and dispersion inside urban areas is challenging, and the National Research Council recently concluded that no model system exists that fulfills all critical requirements for emergency response (NRC, 2003). Such types of applications are especially difficult since fast, but reliable and accurate predictions are necessary to minimize the risk for emergency response personnel and to guarantee successful evacuation strategies in critical areas. With presently available computational resources it is still impossible to use complex codes, like computational fluid dynamics (CFD) models, as fast response tools. The computational time for each simulation is still of the order of hours or days. Previous fast response modeling efforts have therefore often focused on incorporating urban flow parameterizations in Gaussian-type dispersion models (see e.g. Hall et al., 2000). The challenges of urban dispersion modeling and fast response modeling in particular are also discussed in Brown et al. (2004).

More recently, a diagnostic wind field model (QUIC-URB) has been coupled with a Lagrangian dispersion model (QUIC-PLUME) in the fast response modeling system QUIC (see e.g. Pardyjak and Brown, 2002 and Williams et al., 2002). Brown et al. (2004) provide also information about the development and evaluation of QUIC. The method currently used in QUIC (Pardyjak et al., 2001) is based on the work of Röckle (1990). It requires an initial wind field that is computed using simple urban flow parameterizations that were derived from empirical data. The basic procedure involves minimizing the functional shown in Eq. 1 that forces the final velocity field to be mass consistent subject to the weak constraint that the difference between initial and final velocity fields be minimized (Sherman, 1978):

$$E(u,v,w,\lambda) = \int_V \begin{bmatrix} \alpha_1^2\left(u-u^o\right)^2+\alpha_1^2\left(v-v^o\right)^2+\alpha_2^2\left(w-w^o\right)^2 \\ +\lambda\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial x}+\frac{\partial w}{\partial x}\right) \end{bmatrix} dxdydz \quad (1)$$

In Eq. 1, the initial wind field is given by the components u_o,v_o,w_o in the x,y and z directions and the final wind field by u,v and w. The term λ is a spatially varying Lagrange multiplier function and α_i positive weighting functions called Gaussian precision moduli (GPM). This approach provides computational times of the order of minutes and is thus a rather promising tool for emergency response. However, further evaluations and improvements of these types of models are necessary to ensure reliable predictions of dispersion in a complex urban setting.

The current paper presents a comparison of QUIC-URB predictions with wind-tunnel data for an idealized street-canyon, and discusses improvements of street-canyon parameterizations used in QUIC-URB. Furthermore, a concept to implement parameterizations of traffic-produced turbulence (TPT) into QUIC-PLUME is outlined and first results from simulations with and without TPT are shown.

2. STREET-CANYON FLOW FIELDS

2.1. Wind-tunnel data

Kastner-Klein et al. (2004) recently presented wind-tunnel data from flow field measurements for idealized street canyons. For the same street-canyon configurations, the influence of TPT was

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also studied in the wind tunnel (Kastner-Klein et al. 2003). All experiments were performed in the atmospheric boundary layer wind tunnel of the University of Karlsruhe (UKA), Germany. Details about this facility and the characteristics of the neutrally stratified boundary-layer simulated in the wind tunnel are given in Kastner-Klein (1999). Further information about the UKA street-canyon studies can also be found in Kastner-Klein and Plate (1999) and Kastner-Klein et al. (2001).

In the study chosen for the inter-comparison of wind-tunnel and QUIC results, isolated street canyons consisting of two bar-type buildings were investigated. The base height of the buildings forming the canyon is 0.12m, their length is either 1.20m or 0.60m, and the distance between the buildings is 0.12m. This provides the canyon-aspect ratio $S/H = 1$ and the length-to-height ratios $L/H = 10$ and 5. The upwind flow is perpendicular to the axis of the street, and the x-axis is oriented along the direction of external wind. The reference velocity u_0 measured at the level $z_{ref} = 4H = 0.48$m was $7ms^{-1}$.

Wind velocity time series were measured with a laser Doppler anemometer in the central vertical plane of the canyon and in a horizontal plane at $z_{ref} = 0.25H = 0.03$m. In the latter case, only the along-wind velocity component, u, and the lateral velocity component, v, were recorded. In the central vertical plane all three velocity components were measured for most of the sampling locations inside the canyon and above it. However, due to technical constraints the vertical velocity component, w, could not be sampled at all locations. From the time series obtained, the mean flow parameters and one-point, second-order turbulence statistics have been computed.

The mean flow field in the central vertical plane for the street canyon with $L/H = 10$ is shown in Fig. 2a in form of vector plots. The length of the vectors is proportional to the wind speed. A flow separation can be noted at the upwind edge of the upwind building and a vortex forms within the canyon. The location of the vortex centre inside the canyon varies with the L/H – ratio, whereby the vortex centre is shifted closer to the downwind wall in the case of the shorter canyon (not shown here). The results from the measurements in a horizontal plane in the lower part of the canyon (Fig. 3a) indicate that vortex zones develop near the lateral building edges. These lateral vortex zones cover a distance of about 2-3 H inside the canyon. As a consequence, a distinct area with quasi two-dimensional flow does not exist in the case of the shorter canyon (not shown here), but the lateral vortex zones converge in the canyon centre which explains the stronger vertical motions observed for this configuration.

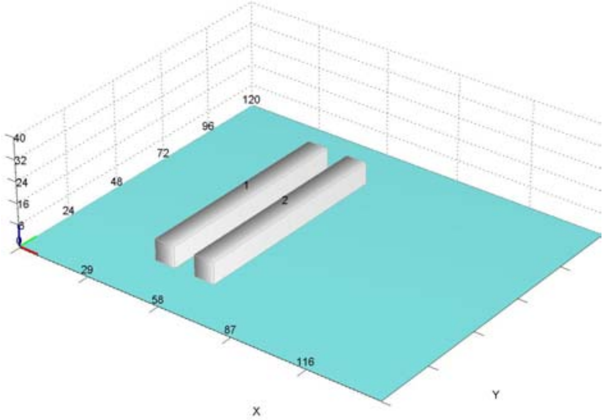

Figure 1: QUIC-URB domain for simulations of street canyon with $L/H = 10$

2.2. Street-Canyon Parameterizations and QUIC-URB results

For comparison with the wind-tunnel data QUIC-URB simulations were performed using the domain shown in Fig. 1. For simulating the canyon with $L/H = 10$, the buildings were 8 cells high, 8 cells wide and 80 cells long. The width of the street was also 8 cells. The shorter canyon was simulated using the same configurations except that the buildings were only 40 cells long. The upwind wind profile was modeled by a power-law profile according to

$$u_0(z) = 7ms^{-1}\left(\frac{z}{4H}\right)^{0.23} . \qquad (2)$$

The wind direction (270 °) was perpendicular to the orientation of the street.

At first simulations were done with the original version of QUIC that applied the street-canyon parameterization (Org-Par) proposed by Roeckle (1990):

$$\begin{aligned} \frac{u(x,y,z)}{U(H)} &= -\left(\frac{x}{0.5S}\right)\left(\frac{S-x}{0.5S}\right) \\ \frac{w(x,y,z)}{U(H)} &= -\left|0.5\left(1-\frac{x}{0.5S}\right)\right|\left(1-\frac{S-x}{0.5S}\right) \end{aligned} \qquad (3)$$

In this parameterizations scheme the across canyon, u, and vertical, w, wind velocity components are both only a function of the distance x from the upwind canyon wall, but independent of the height z, and the across canyon component, *u*, is negative over the whole depth of the canyon. As it can be seen in Fig. 2b, this initialization of the street-canyon vortex results in unrealistic predictions of the street-canyon flow field. The final, mass-consistent flow shows still negative values for the *u*-component up to the building tops while in the wind tunnel the centre of the vortex was found approximately at half canyon depth, and in the upper part of the canyon the values of *u* are positive. Such discrepancies in the flow field will have a strong impact on the accuracy of the dispersion predictions. Pollutant concentrations inside the canyon crucially depend on the street canyon ventilation which is governed by the vortex dynamics.

In order to improve the street-canyon predictions it was tested to use the street-canyon parameterization scheme (CPB-Par) applied in the canyon-plume-box model (Hotchkiss and Harlow, 1973):

$$\begin{aligned}
&\frac{u(x,y,z)}{u_0} = (1-\beta)^{-1}\left[\alpha(1+ky) - \beta/\alpha\,(1-ky)\right]\sin(kx)\\
&\frac{w(x,y,z)}{u_0} = -ky(1-\beta)^{-1}\left[\alpha - \beta/\alpha\right]\cos(kx) \qquad (4)\\
&k = \pi/S,\ \ \beta = \exp(-2kH)\\
&\alpha = \exp(ky),\ \ y = z - H
\end{aligned}$$

Both velocity components are then a function of the distance from the upwind canyon wall, *x*, and the height *z*. Implementation of Eq. (4) into QUIC-URB results in a significant improvement of the street-canyon flow predictions (Fig. 2c).

However, the above parameterization scheme is based on potential flow theory and is already mass consistent. As a consequence, the mass-consistency solver of QUIC leaves the initial, parameterized velocity field almost unchanged and the model, without further modifications of the street-canyon initialization scheme, predicts no notable horizontal exchange between the in-canyon region and undisturbed flow at the lateral edges of the buildings (not shown). The lateral vortex zones seen in the wind-tunnel data (Fig. 3a) could only be simulated (Fig. 3c) by modifying the initialization near the lateral canyon edges (Fig. 3d), while in the case of the Org-Par scheme lateral vortex zones are predicted (Fig. 3b) without such modifications. However, the size of the lateral vortex zones is underpredicted. For the CPB-Par simulations, acceptable predictions for both *L/H* – ratios were achieved using the following very simple initialization scheme for the lateral vortex zones: Their size *d* is a function of a reference length L_{ref}, which is currently the smallest value of building height *H*, street width *S* and half building length *L/2:*

$$d = L_{ref}/2 \ \text{ with } \ L_{ref} = \min(H, S, L/2) \qquad (5)$$

In the zones $L/2 - d < \pm y < L/2$ (origin of along canyon axis *y* is located in the central plane of the canyon) the horizontal velocity components are initialized as follows:

$$\begin{aligned}
&\text{for } x < S/4:\ \ u(x,y,z) = v(x,y,z) = 0\\
&\text{for } L/2 \le y \le L/2 + d \text{ and } x \ge S/4: \begin{cases} u(x,y,z) = v_0(z) \\ v(x,y,z) = u_0(z) \end{cases} \qquad (6)\\
&\text{for } L/2 - d \le y \le L/2 \text{ and } x \ge S/4: \begin{cases} u(x,y,z) = v_0(z) \\ v(x,y,z) = -u_0(z) \end{cases}
\end{aligned}$$

Eq. (5) guarantees that the lateral vortex zones do not overlap in the case of short canyons. Eq. (6) accounts for the along-canyon component in the upwind profile (v_0) in the case of wind directions that are oblique to the orientation of the street. We are currently performing further tests and comparisons with additional data sets to verify that Eqs. (5) and (6) result in satisfactory results for street-canyon configurations of variable geometries.

Finally, an experimental street-canyon parameterization (Exp-Par) that is based on the wind-tunnel data sets of Kastner-Klein et al. (2004) was tested. As can be seen in Fig. 4, in which wind-tunnel profiles (dashed lines) are plotted for the *u*- and *w*-velocity component measured at different distances *x* from the upwind canyon wall, the across canyon component *u* varies only slightly with *x*. Accordingly, in the Exp-Par street-canyon scheme, *u* is expressed only as a function of *z* while *w* depends both on *x* and *z*:

$$\begin{aligned}
&\frac{u(x,y,z)}{u(4H)} = 0.3\sinh\left(0.4\pi(z/H - 0.6)\right)\\
&\frac{w(x,y,z)}{u(4H)} = 0.2(1 - 2\,x/S)\sin(\pi\,z/H)
\end{aligned} \qquad (7)$$

The solid lines in Fig. 4 correspond to the initial velocity profiles calculated by Eq. (7). The final velocity fields calculated with QUIC-URB applying Eq. (7) in the initialization of the street-canyon region are shown in Fig. 2d, and Fig. 5 shows a comparison of *u*- and *w*-profiles at two different distances from the upwind canyon wall. Eqs. (5) and (6) were again used to initialize lateral vortex zones near the building edges. The results from the Exp-Par simulations agree best with the wind-tunnel data, which is not surprising since the Exp-Par parameterization was based on this particular wind-tunnel data set (*L/H*=10). However, as can be seen in Fig. 6, the Exp-Par scheme gives also the best results for the shorter canyon with *L/H*=5, for which different vortex dynamics were observed in the wind tunnel. Although larger differences than in the case of the longer canyon can be noted particularly close to the downwind wall, the agreement between wind-tunnel data and calculated velocity profiles inside the canyon is still acceptable.

All three parameterization schemes have deficiencies in predicting the shear-layer zone developing above the building tops. It must be noted that Eq. (7) was only applied to initialize the velocity fields inside the canyons. Future tests will focus on improving the shear-zone predictions by applying the Exp-Par formulas (Eq. 7) also above the building tops or by adding special shear-layer parameterization schemes.

3. SIMULATION OF TRAFFIC-PRODUCED TURBULENCE

Kastner-Klein et al. (2003) have shown that traffic-produced turbulence (TPT) can have a strong influence on dispersion in street canyons and that applications of simple TPT parameterization schemes discussed in Di Sabatino et al. (2003) significantly improve predictions of street-canyon pollution levels. It was thus concluded to implement a TPT parameterization scheme into the Lagrangian dispersion model QUIC-PLUME. As a first approach, the parameterization of Di Sabatino et al. (2003) for intermediate traffic densities

$$\sigma_t^2 = c\left(\frac{n_v C_D h^3}{S_c}\right)^{2/3} v^2 \qquad (8)$$

is applied. For first tests, the dimensionless proportionality constant, *c*, was set equal to one, the number of vehicles per unit length, n_v, was 20 m^{-1}, the drag coefficient, C_D, was 0.3, and the vehicle speed, *v*, was 12 ms^{-1}. The average vehicle length scale, *h*, is calculated by $h = \sqrt{A}$ whereby the frontal vehicle area, *A*, was estimated as 2 m^2. The latter value and the C_D-value that was used can be considered to be typical for passenger cars, and the simulations performed so far thus resemble conditions without significant heavy traffic. The street canyon region, S_c, in which TPT is of importance was set equal to the lower half of the street canyon ($S_c = 0.5HS$).

Using Eq. (8) the turbulent kinetic energy due to TPT is calculated assuming that TPT is isotropic, and the total turbulent kinetic energy is determined as sum of the wind and TPT contributions:

$$\begin{aligned} &TKE_{tot} = TKE_{wind} + TKE_{TPT} \Leftrightarrow \\ &\sigma_{tot}^2 = \sigma_{wind}^2 + \sigma_{TPTt}^2 \end{aligned} \qquad (9)$$

First results from QUIC simulations with and without TPT parameterizations are shown in Fig. 7. The street-canyon configuration corresponds to the longer street canyon with *L/H*=10 that is described in the previous section. The Exp-Par street-canyon scheme was applied in the QUIC-URB runs. The QUIC-PLUME simulations were done with a line source placed in the lowest grid cell at half canyon width whereby 100000 particles were released. The results shown in Fig. 6 correspond to half-hour mean values by an emission rate of 10 g/h. It can be seen that application of the TPT parameterization scheme results in stronger mixing and lower concentrations close to the source. This result is qualitatively similar to the wind-tunnel results presented in Kastner-Klein et al. (2003 and 2001). The chosen approach to implement TPT into QUIC is thus rather promising in terms of improving the predictions of street-canyon pollution levels. A number of additional tests are currently performed to verify the value of the proportionality constant, *c*, to study the influence of heavy traffic, and to prove the practical applicability of the scheme for realistic, rather complex building and traffic arrangements. A quantitative comparison of QUIC-PLUME predictions with wind-tunnel concentration profiles for situations with and without TPT is also undertaken to carefully evaluate the scheme.

4. CONCLUSIONS

The paper presents an evaluation of QUICURB predictions against high resolution wind-tunnel flow data sets in street canyons. It is shown, that simple modifications of the street–canyon initialization scheme result in significant improvements of the flow field predictions. Additionally, the implementation of a TPT scheme into QUIC is outlined and first results of QUIC simulations accounting for TPT have qualitatively shown similar results as observed in the wind-tunnel studies of Kastner-Klein et al. (2003).

5. ACKNOWLEDGEMENTS

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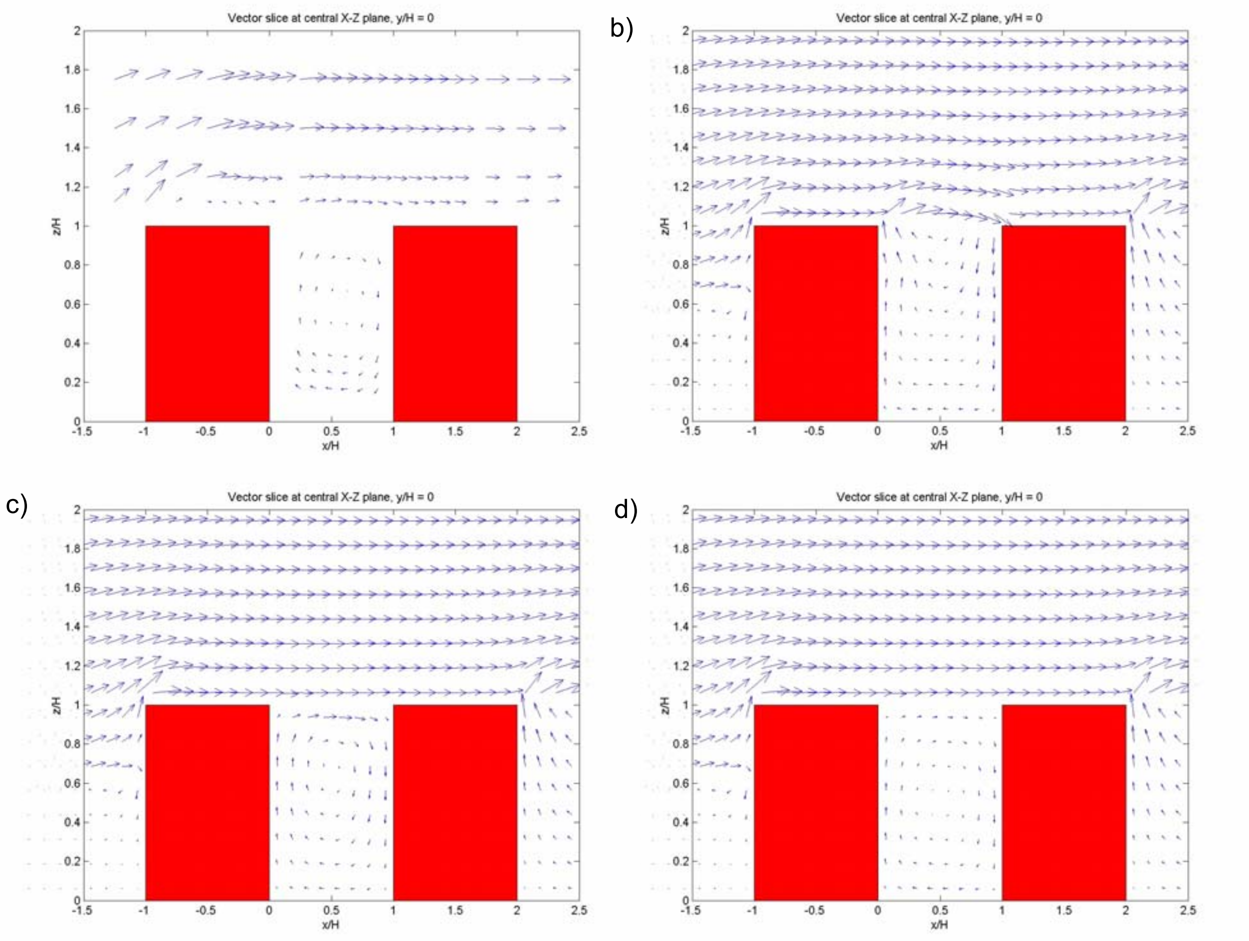

Figure 2: Street-canyon vortex in the central plane of an idealized street canyon with *L/H* = 10: a) measured in the wind tunnel by Kastner-Klein et al. (2004), b) QUIC-URB flow field based on the Org-Par street canyon initialization, c) QUIC-URB flow field based on the CPB-Par street canyon initialization, and d) QUIC-URB flow field based on the Exp-Par street canyon initialization.

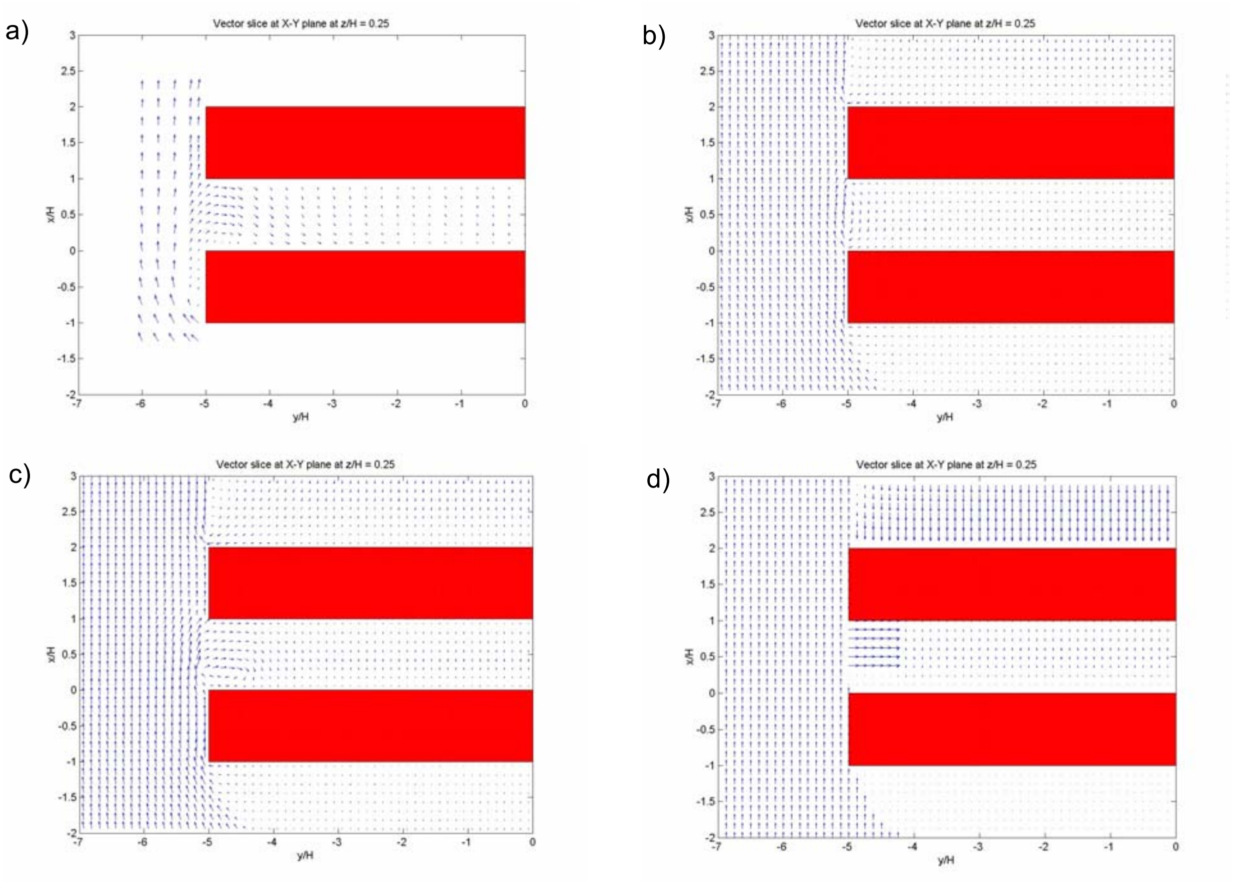

Figure 3: Lateral vortex zones for an idealized street canyon with *L/H* = 10: a) measured in the wind tunnel by Kastner-Klein et al. (2004), b) QUIC-URB flow field based on the Org-Par street canyon initialization, c) QUIC-URB flow field based on the CPB-Par street canyon initialization and the initialization of lateral vortex zones shown in d).

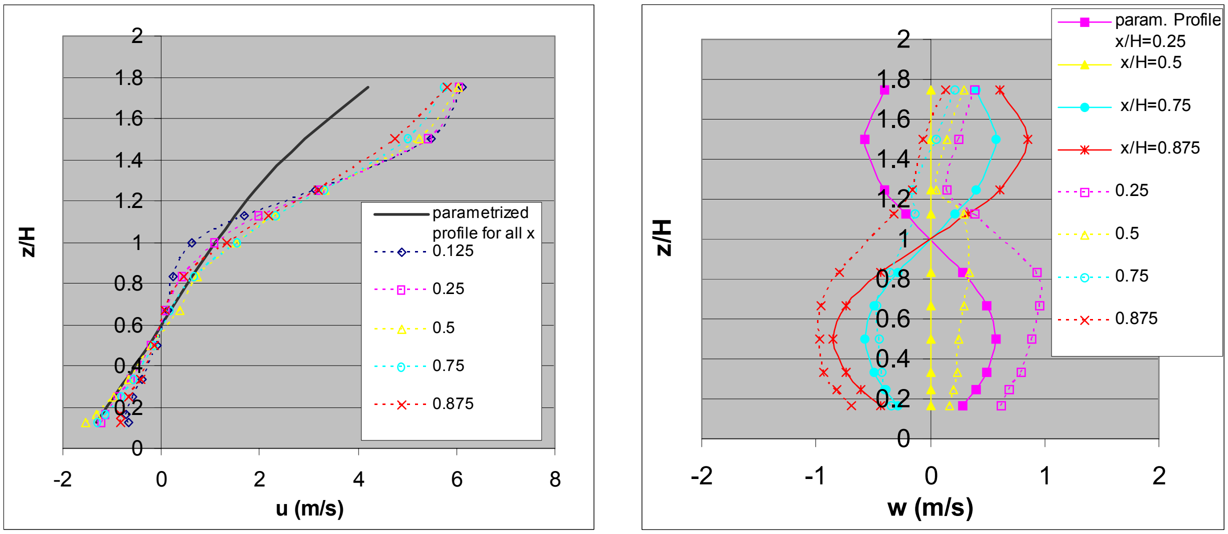

Figure 4: Vertical profiles of the across-canyon (u) and vertical (w) velocity components measured at different distances from the upwind canyon wall for an idealized street canyon with *L/H* = 10. The dashed lines correspond to the wind-tunnel data of Kastner-Klein et al. (2004), and the solid lines to the Exp-Par initialization implemented in QUIC-URB.

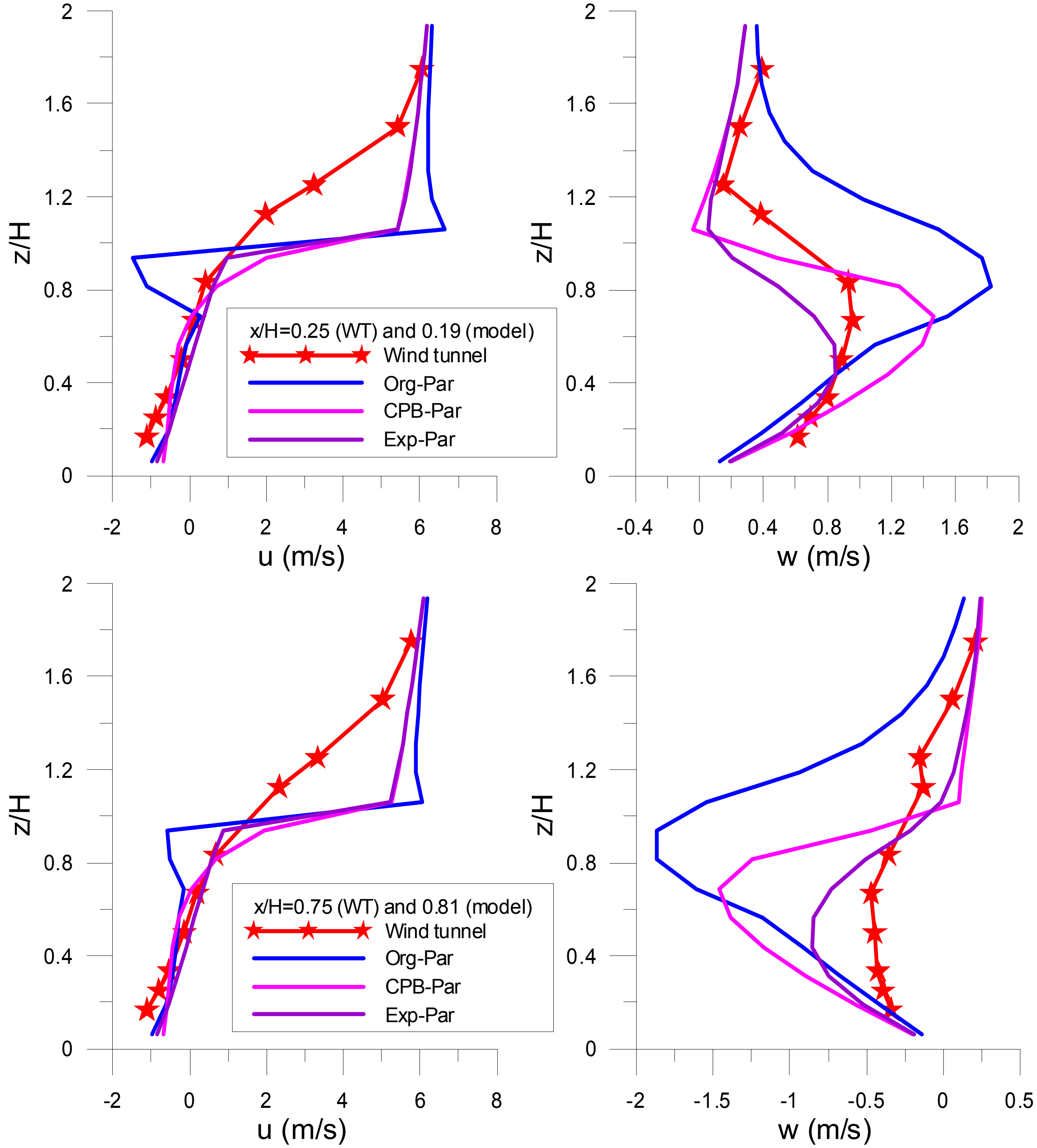

Figure 5: Vertical profiles of the across-canyon (u) and vertical (w) velocity components close to the upwind (top) and downwind (bottom) canyon wall for an idealized street canyon with *L/H* = 10 (see text for more details).

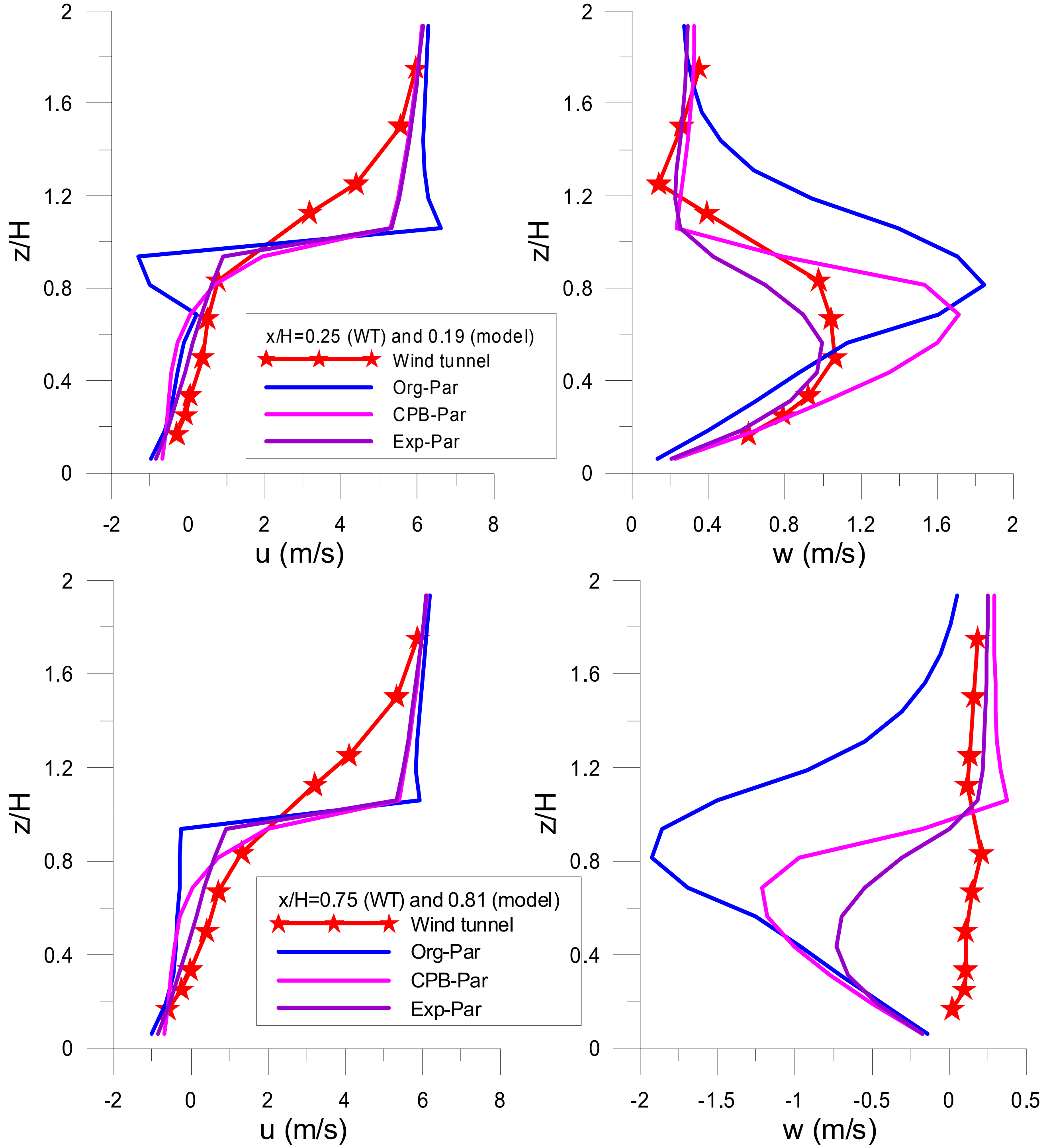

Figure 6: Vertical profiles of the across-canyon (u) and vertical (w) velocity components close to the upwind (top) and downwind (bottom) canyon wall for an idealized street canyon with *L/H* = 5 (see text for more details).

Without TPT:

with TPT:

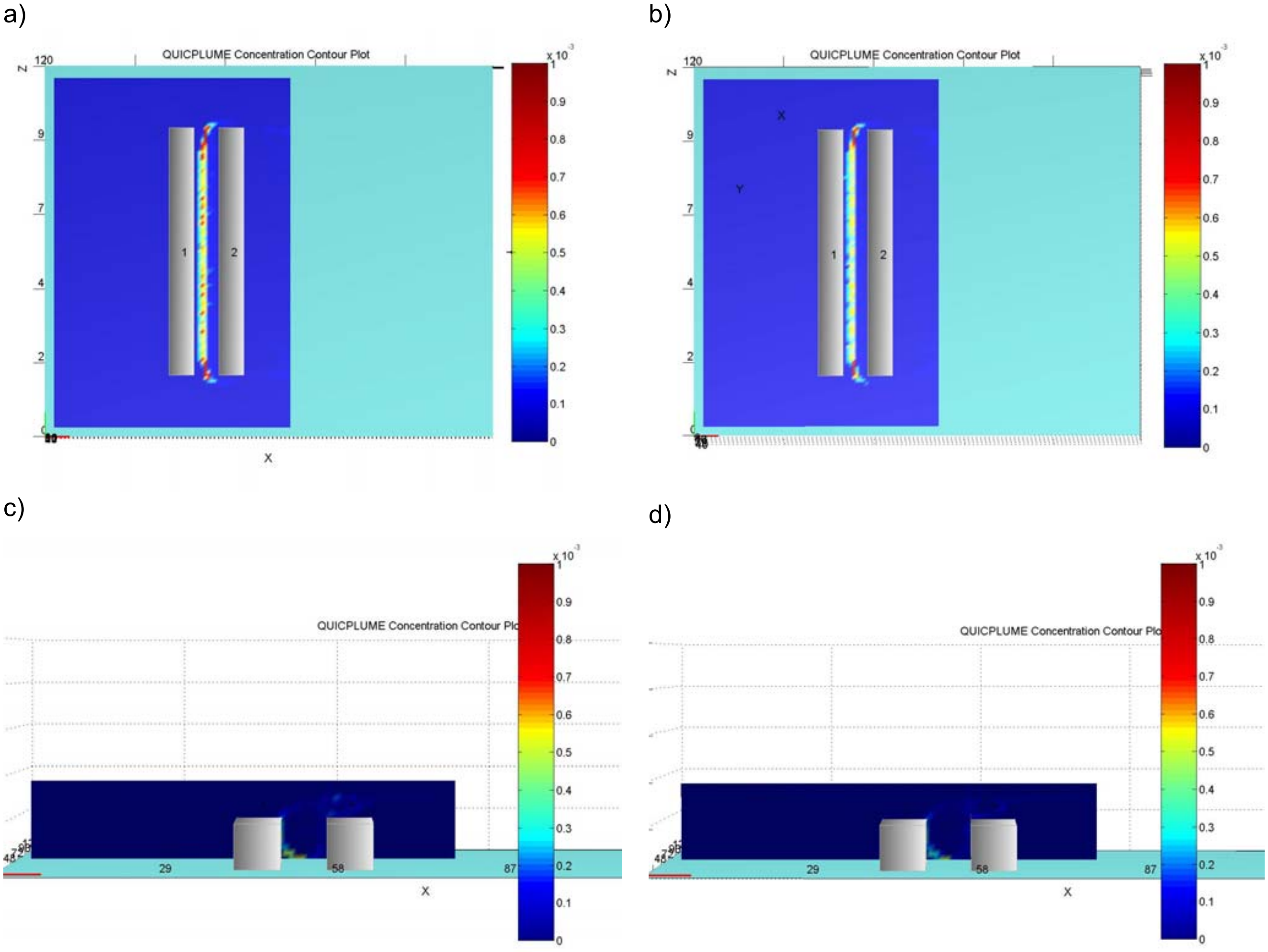

Figure 7: Line-source concentration distributions in a horizontal plane close to the ground, a) and b), and in the central vertical plane of the canyon, c) and d), for QUIC-Plume simulations with and without TPT. The line source is located in the lowest grid cell in the centre of the street of an idealized street canyon with *L/H* = 10 and aspect ratio *S/H* = 1.