

Analysis of unsteady concentration and flow statistics around an isolated building by Large-Eddy Simulation

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ABSTRACT: Large-Eddy Simulation is used to simulate wind-induced pollutant dispersion from a vent on the roof of a cubical building. The profiles of the computed mean value and standard deviation of the concentration in the wake of the building are compared to wind-tunnel measurements and good agreement is found. The velocity and concentration values at two monitoring points located in the shear layer developing above the roof have been sampled at each time step of the simulation. The statistics are presented and analyzed to provide insight into the dispersion process. In particular, the fact that the turbulent mass flux in the streamwise direction is directed from the low to high levels of mean concentration (counter-gradient mechanism) is explained.

KEYWORDS: Urban wind flow; scalar transport; turbulent mass flux; counter-gradient diffusion; turbulent Schmidt number.

1 INTRODUCTION

Computational Fluid Dynamics (CFD) is increasingly used to predict pollutant dispersion around buildings and in cities (e.g. Tominaga et al., 1997; Blocken et al., 2008; Gromke et al., 2008; Tominaga and Stathopoulos, 2010; Gousseau et al., 2011a; Gousseau et al., 2011b; Tominaga and Stathopoulos, 2011). Overall, it has been confirmed that Large Eddy Simulation (LES) is inherently more accurate than the Reynolds-Averaged Navier-Stokes (RANS) turbulence modeling approach for modeling wind flow and dispersion in urban environments (e.g. Tominaga and Stathopoulos, 2010; Gousseau et al., 2011a; Gousseau et al., 2011b; Tominaga and Stathopoulos, 2011).

Most of the two-equation RANS turbulence models like the standard or realizable $k-\varepsilon$ models compute the turbulence-induced transport of concentration – and more generally, of scalars – based on the gradient of the mean value, with the so-called gradient-diffusion (GD) hypothesis, also called first-order closure:

$$\overrightarrow{Q_{a,t}} = -D_{a,t} \nabla A \quad (1)$$

where $\overrightarrow{Q_{a,t}}$ is the turbulent flux of a , $D_{a,t}$ is the turbulent diffusivity and $A = \langle a \rangle$ is the mean value of a . However, some recent studies (Rossi et al., 2010; Gousseau et al., 2011b) have shown that this hypothesis is not valid in the streamwise direction for dispersion around an isolated building. In this case, above roof level, the turbulent mass flux is directed backwards, i.e. from the low to high levels of mean concentration, in contradiction with Equation 1. This so-called counter-gradient (CG) mechanism of turbulent transport has also been reported in the literature for various cases such as a ground-level line source in a street canyon (Simoëns and Wallace,

2008), a line source in a turbulent boundary layer (Raupach and Legg, 1983; Lavertu and Mydlarski, 2005), or a stratified shear flow (Meroney, 1976).

The CG mechanism cannot be reproduced by RANS models which use Equation 1 to model the turbulent mass transport. Therefore, more elaborate models are needed. To support the choice of the existing appropriate model or to develop a new one, a more complete understanding of the physical mechanism of dispersion around bluff bodies is needed. The present study aims at exploring this mechanism with LES. Since the turbulent mass flux in a given direction is equal to the covariance of velocity and concentration, the observation of the statistics of these variables allows providing insight into the dispersion process and in particular to aid in explaining the CG mechanism in the streamwise direction.

The case under study corresponds to a wind-tunnel experiment which is briefly described in the next section together with the numerical model used. The experimental results are used to validate the CFD results in section 3. Next, the CFD simulations are used to monitor velocity and concentration statistics in two points located in the shear layer developing above the roof of the building, and the results are analyzed in the framework of turbulent mass transport.

2 NUMERICAL MODEL

2.1 Domain, grid and boundary conditions

The wind-tunnel experiment by Li and Meroney (Li and Meroney, 1983a; Li and Meroney, 1983b) has been reproduced with the Ansys 12.1 CFD code. It involves a cubical building model (height $H=0.05\text{m}$) immersed in a turbulent atmospheric boundary layer (ABL) with a mean velocity profile corresponding to a power law with an exponent equal to 0.19 and an aerodynamic roughness length $z_0=7.5\times 10^{-5}\text{m}$. Wind direction is perpendicular to the windward façade. At the center of the roof, helium is emitted by a 5mm diameter circular exhaust with a low velocity ratio $M=0.19$ ($M=W_e/U_H$ where W_e is the vertical exhaust velocity and U_H is the mean velocity in the approaching ABL at building height). The Reynolds number based on H and U_H is equal to 1.1×10^4 .

The computational domain is shown in Figure 1a. Its dimensions are $26H\times 11H\times 6H$ in the streamwise (x), lateral (y) and vertical (z) direction, respectively, following the COST Action 732 (Franke et al., 2007) and AIJ (Tominaga et al., 2008) guidelines. The ground and building walls are defined as no-slip walls. At the top and sides of the domain, symmetry boundary conditions are set. Zero static pressure is imposed at the outlet face of the domain. At the inlet, unsteady perturbations are super-imposed on the prescribed mean velocity profile by the vortex method (Mathey et al., 2006) with a number of vortices equal to 190. This technique also requires the vertical profiles of turbulent kinetic energy and dissipation rate, which are prescribed based on the experiments.

The computational grid has been created with the surface grid-extrusion technique (van Hooff and Blocken, 2010). It counts 1,480,754 cells in total and the building is discretized into 32 cells in the vertical direction and 25 cells in the lateral and streamwise directions (Fig. 1b). The monitoring points P1 and P2 are also shown in Figure 1b. P1 is located at $x/H=1$; $y/H=0$; $z/H=1.24$ and P2 at $x/H=2$; $y/H=0.25$; $z/H=1.24$.

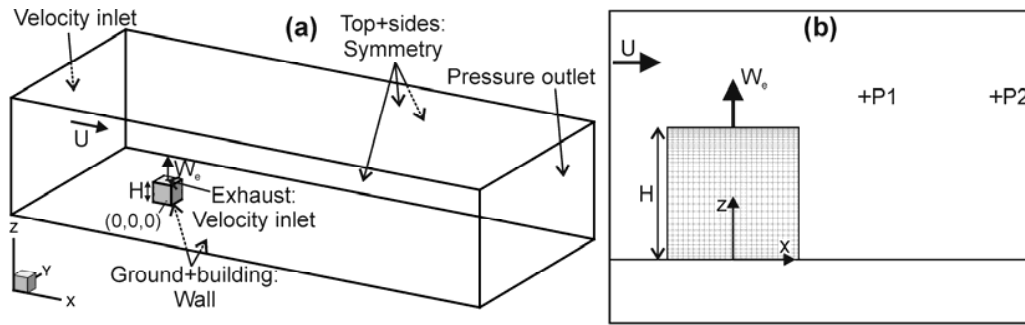


Figure 1. (a) Computational domain and boundary conditions. (b) Side view: grid on the building surface (total number of cells: 1,480,754) and location of the two monitoring points P1 and P2.

2.2 LES and dispersion modeling

In the remainder of the paper, the Reynolds decomposition is used for all variables; for example a is decomposed into its time-average component $A = \langle a \rangle$ and its fluctuation a' such that $a = A + a'$. Furthermore, in what follows, the overbar is used to symbolize the spatial-filtering operator. Note that it will be used only in this section and will be omitted in the remaining of the paper.

LES has been used with the dynamic Smagorinsky subgrid-scale (SGS) model (Smagorinsky, 1963; Germano et al., 1991; Lilly, 1992): the Smagorinsky coefficient C_s which allows computing the SGS turbulent viscosity is evaluated at each time step, based on the smallest resolved scales of motion.

The Eulerian approach has been adopted to compute the transport of the tracer gas concentration (c). In the filtered dispersion equation, the SGS mass flux $\overline{q_{SGS}}$ stands for the effects of the smallest scales of motion on the dispersion process. It is assumed to be proportional to the gradient of resolved concentration:

$$q_{SGS,i} = \overline{u_i c} - \overline{u_i} \overline{c} = -D_{SGS} \frac{\partial \overline{c}}{\partial x_i} \quad (2)$$

where D_{SGS} is the SGS diffusivity, computed with a dynamic procedure in the similar way as C_s (Moin et al., 1991).

The turbulent mass flux $\overline{Q_t}$ is the combined effect of the concentration and velocity fluctuations, plus the mean SGS mass flux:

$$Q_{t,i} = \langle \overline{u_i' c'} \rangle + \langle q_{SGS,i} \rangle \quad (3)$$

Reference concentration (C_0) and flux (Q_0) are used to make the variables non-dimensional. These quantities are defined by:

$$C_0 = \frac{Q_e}{H^2 U_H} \quad (4)$$

$$Q_0 = C_0 \times U_H \quad (5)$$

where Q_e is the pollutant exhaust rate.

Discretization of the filtered momentum equation is performed with a second-order accurate bounded central-differencing scheme. A second-order scheme is used for the spatial derivatives of the other equations (energy, concentration). Pressure interpolation is second order. The non-iterative time advancement scheme is used for the unsteady solver, with the fractional step meth-

od for pressure-velocity coupling (Kim and Moin, 1985). One single outer iteration is performed per time step, allowing reduction of the computational time needed for the simulation. A fixed time step $\Delta t^*=0.066$ in non-dimensional time units ($\Delta t^* = \Delta t \times U_H/H$, where Δt is the physical time step) has been set. After an initialization period, which allows losing the dependence on the non-physical initial state, averaging is performed during $t^*=1,584$. The data at the monitoring points are stored at each of these 24,000 time steps.

3 MEAN CONCENTRATION AND TURBULENT MASS FLUX

The profiles of the non-dimensional concentration coefficient ($K=C/C_0$) and the non-dimensional standard deviation of concentration ($c_{rms}/C_{IG}=(\langle c'^2 \rangle)^{1/2}/C_{IG}$) obtained with LES along three vertical lines ($x/H=1; 3; 5$) in the vertical mid-plane are compared to the wind-tunnel measurements in Figure 2. The standard deviation of concentration is normalized by the mean ground concentration value at $x/H=1$ and $y/H=0$ (C_{IG}). Along these three lines, a good agreement is obtained for K (Fig. 2a). Close to the building, at $x/H=1$, the LES results over-estimate the concentration fluctuations (Fig. 2b). Along the two other lines, there is a very close agreement.

Contours of the different turbulent mass flux components are depicted in Figure 3. In this figure, the isolines $\partial C/\partial x_i=0$ in the corresponding directions are also shown (dashed lines) and, in circles, the sign of $\partial C/\partial x_i$ for each zone delimited by the dashed line. As far as the vertical and lateral components of the turbulent flux ($Q_{t,z}$ and $Q_{t,y}$) are concerned, the contours in Figures 3c and 3d show that turbulent mass transport operates as a diffusion mechanism directed from the high towards the low concentration values, i.e. from the centerline of the plume to its outer edges. In the streamwise direction, however, the mechanism is different. In the horizontal plane $z/H=1.25$ for example, and more generally in the large region above the roof level colored in light gray in Figure 3a, the streamwise turbulent mass flux is negative, i.e. directed towards the high levels of K . In this region where the turbulent mass flux and the mean concentration gradient are of the same sign, the CG mechanism of turbulent mass transport is present. Another CG zone is present in the near-wake of the building where both $Q_{t,x}$ and $\partial C/\partial x$ are positive.

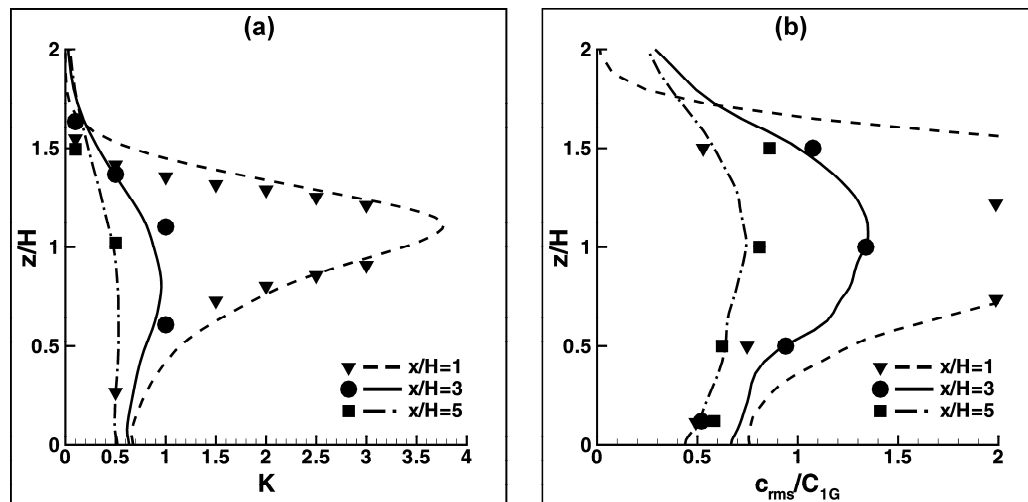


Figure 2. CFD validation: profiles of (a) non-dimensional concentration coefficient $K=C/C_0$ and (b) standard deviation of concentration normalized by C_{IG} along three vertical lines in the plane $y/H=0$. Symbols: wind-tunnel measurements (Li and Meroney, 1983a; Li and Meroney, 1983b); lines: LES of this study.

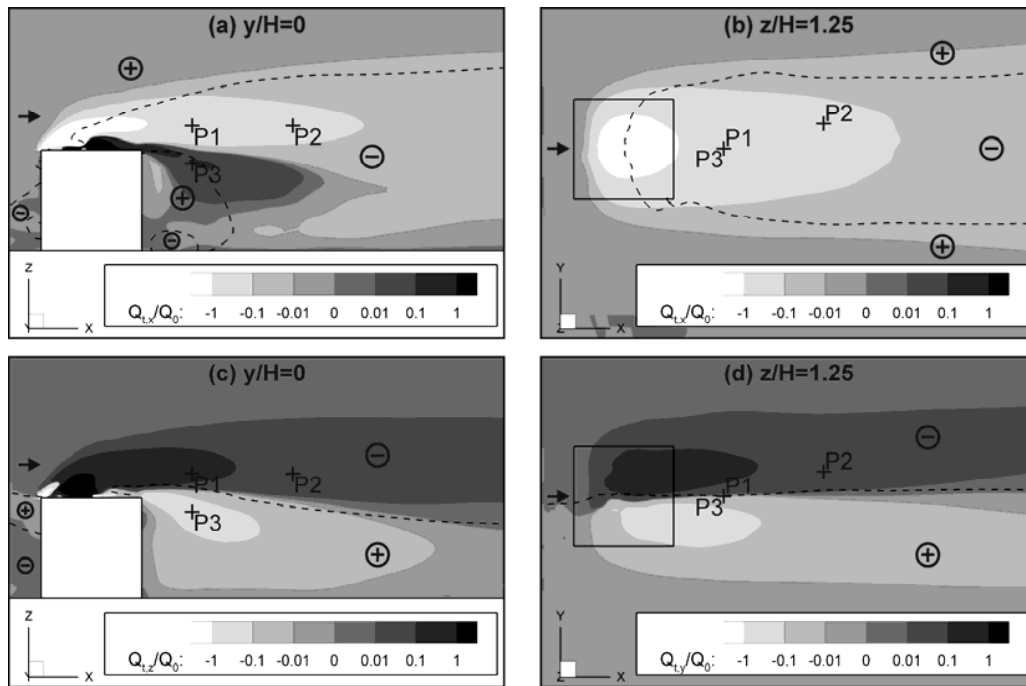


Figure 3. Contours of the (a,b) streamwise, (c) vertical, and (d) lateral components of the turbulent mass flux vector. The dashed lines represent the isolines $\partial C/\partial x_i=0$ in the corresponding direction: (a,b) $x_i=x$, (c) $x_i=z$, (d) $x_i=y$. On each side of the isoline, the sign of $\partial C/\partial x_i$ is indicated in circles (+: positive; -: negative). The CG mechanism of turbulent mass transport is characterized by $Q_{t,i}$ and $\partial C/\partial x_i$ of the same sign for a given direction

4 CONCENTRATION AND VELOCITY STATISTICS AT THE TWO MONITORING POINTS

The resolved concentration (c) and velocity components (u, v, w) have been recorded at the two monitoring points at each of the 24,000 time steps of the simulation. For the four variables of interest, the range of the non-dimensional fluctuations (a'_k/a_{rms} , where k is the sample number and the subscript rms indicates the standard deviation,) has been divided into 50 equal intervals I_i ($i=1, \dots, 50$) and the frequency f_i of occurrence of a'_k/a_{rms} belongs to I_i has been calculated to build the histogram of frequency distribution:

$$f_i = \frac{n_i}{N} \quad (i=1, \dots, 50) \quad (6)$$

where n_i is the number of samples such as a'_k/a_{rms} belongs to I_i and N is the total number of samples.

The histograms for point P1 are shown in Figure 4. The histogram of concentration fluctuations (Fig. 4a) has an exponential-like shape, which indicates that P1 is most of the time characterized by a low background concentration level and the occurrence of rare but extremely high peaks of concentration (the kurtosis of the frequency distribution is high). Approximately 60% of the samples are of negative fluctuation and the average is raised by peaks of c' reaching up to 13 times the standard deviation. This asymmetry around the mean is quantified by the high skewness value. This shape of frequency distribution corresponds to measurements by Fackrell and Robins (Fackrell and Robins, 1982) far from the ground in the case of an elevated point source and was attributed to the meandering motion of the plume caused by large turbulent eddies.

Here, the largest turbulence scales are of the order of the cube size, larger than the size of the plume at P1, and tend to move the plume as a block, resulting in the high intermittency observed at this monitoring point.

The frequency distribution of u'/u_{rms} shows negative skewness (Fig. 4b): among the samples, the majority is of positive fluctuation but some of them are characterized by a large negative u' . The opposite holds for the vertical velocity fluctuations, whose frequency distribution is right-tailed (Fig. 4d). Considering that P1 lies in the vertical symmetry plane of the computational domain, it is logical that the frequency distribution of v'/v_{rms} is symmetric with respect to its zero mean (Fig. 4c).

A similar approach can be used to analyze the statistics of the variables two by two. The bivariate histograms have been built for the three couples of variables (c'/c_{rms} ; $u_i'/u_{i,rms}$). For example, for two variables a and b , the range of the non-dimensional fluctuations has been divided into an arbitrary number of intervals (here: 20), say I_i for a'_k/a_{rms} and J_j for b'_k/b_{rms} . For given i and j , the frequency $f_{i,j}=f(I_i,J_j)$ is the ratio of the number of samples n_{ij} for which a'_k/a_{rms} belongs to I_i and simultaneously b'_k/b_{rms} belongs to J_j to the total number of samples N :

$$f_{i,j} = \frac{n_{i,j}}{N} \quad (i, j = 1, \dots, 20) \quad (7)$$

Each of the four combinations of signs of (c'/c_{rms} ; $u_i'/u_{i,rms}$) is associated with a specific event of pollutant transport. Observing the bivariate histograms gives therefore an indication of which events are the most frequent among the samples and/or contribute most to the turbulent flux. This so-called quadrant analysis was first introduced for momentum transfer (Shaw et al., 1983) but is also widely used in the case of scalar dispersion (Chen, 1990; Cheng and Liu, 2011). The definitions of the quadrants are shown in Table 1, together with the name given to the corresponding event in the vertical direction, for which quadrant analysis is often used. Note that this nomenclature can also be used here for the lateral direction, considering the symmetry of our problem. The frequency of occurrence of a given quadrant Q_m is equal to the sum of the frequencies of the intervals which compose Q_m . This frequency multiplied by the average of $u_i'c'$ on Q_m ($\langle u_i'c' \rangle_{Q_m}$) gives the contribution of the quadrant Q_m to the turbulent flux in the direction i .

Table 1. Numbering and definitions of the quadrants. The names of the corresponding events hold for the vertical direction, following (Chen, 1990).

Quadrant	u_i'	c'	Name (z-direction)
Q1	>0	>0	Ejection
Q2	<0	>0	Inward interaction
Q3	<0	<0	Sweep
Q4	>0	<0	Outward interaction

The contours of $f_{i,j}$ in the planes (c'/c_{rms} ; $u_i'/u_{i,rms}$) for P1 are shown in Figure 5. In the streamwise direction (Fig. 5a), the most frequent situation among the samples is simultaneously $u'>0$ and $c'<0$ (Q4): 46% of the samples are in this zone. Nevertheless, the most important contribution to the total turbulent flux is due to Q2, for which the frequency (27%) is lower than for Q4 but for which the individual contributions $u'c'$ are on average higher in magnitude. The contributions of Q1 and Q3 are minor in this case, both in terms of frequency and magnitude. The dominant contributions of Q2 and Q4, where u' and c' are of opposite signs, result on average in a negative turbulent flux $\langle u'c' \rangle$. Concerning the lateral direction, the frequency distribution of (c'/c_{rms} ; v'/v_{rms}) is approximately symmetrical with respect to the axis $v'=0$, leading to a zero turbulent mass flux in the lateral direction (Fig. 5b). Concerning the vertical direction, sweeps (Q3)

are the most frequent events of vertical mass transfer at P1 (Fig. 5c); they correspond to downward motions of fresh air. However, the calculation of the contribution of each quadrant to $Q_{t,z}$ shows that the dominant contribution is made by ejections (Q1), which occur less often but are more intense.

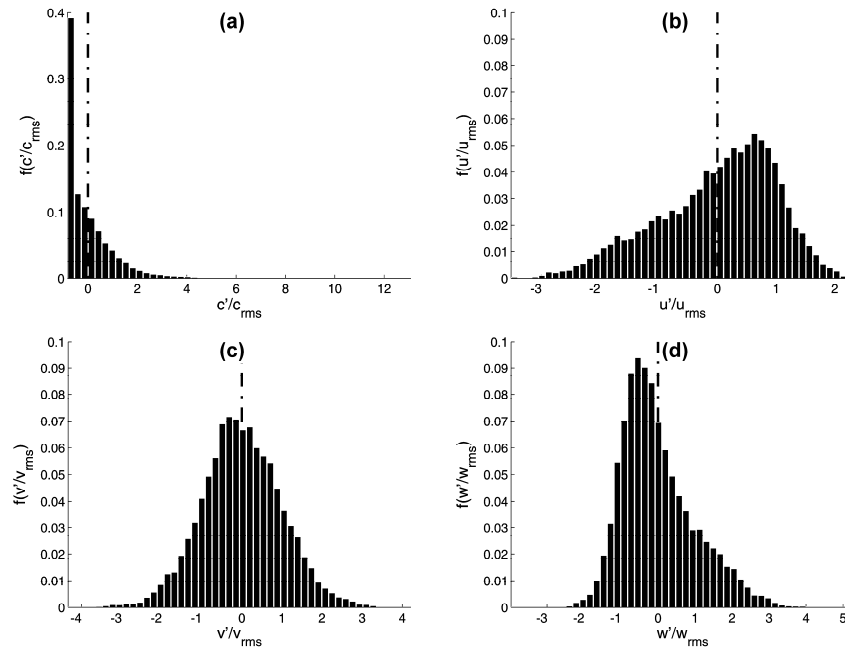


Figure 4. Point P1: frequency distribution histograms of (a) c'/c_{rms} , (b) u'/u_{rms} , (c) v'/v_{rms} , and (d) w'/w_{rms} . For each variable, the x-axis limits correspond to the minimum and maximum sample values. The dashed line indicates the mean (zero) values of the fluctuations. Mean values: $K=3.00$; $U/U_H=0.84$; $V/U_H=0.01$; $W/U_H=-0.11$.

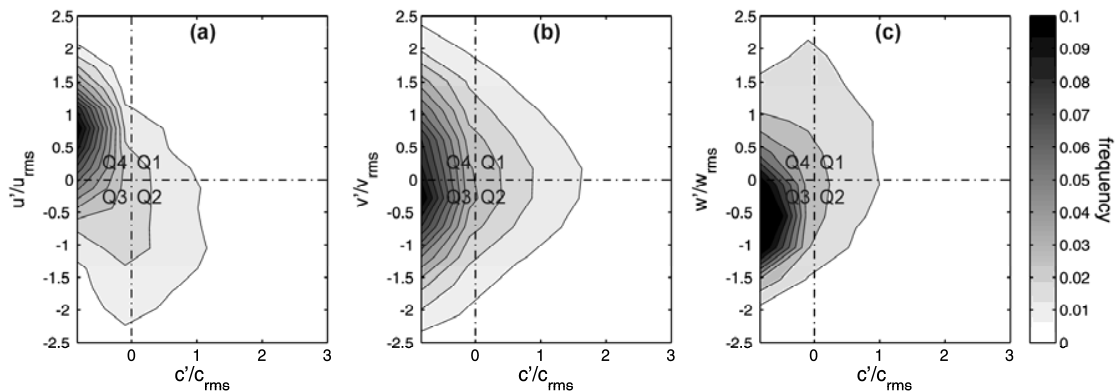


Figure 5. Point P1: bivariate histogram of frequency distribution for (a) $(c'/c_{rms}; u'/u_{rms})$, (b) $(c'/c_{rms}; v'/v_{rms})$, and (c) $(c'/c_{rms}; w'/w_{rms})$.

Figure 6a shows the frequency distribution of c'/c_{rms} for P2. The trend is similar as for P1, with even higher values of skewness and kurtosis, because of the off-center position of the sampling point at which the plume intermittency is higher (Fackrell and Robins, 1982). Approximately 65% of the samples have concentration values between zero and one third of the mean concentration value at this point. The velocity fluctuations in the x- and z-directions also have similar frequency distributions as those at P1, with a negative and positive skewness, respective-

ly. The main difference with point P1 is the asymmetry of the histogram of v'/v_{rms} , quantified by the non-zero skewness. This feature is due to the position of P2 out of the symmetry plane of the geometry.

The bivariate histogram of $(c'/c_{rms}; v'/v_{rms})$ is similar in shape to the one of $(c'/c_{rms}; w'/w_{rms})$ (Figs. 7b,c): a large majority of the samples belongs to Q3 and the main contribution to the mass flux is due to intense ejections corresponding to quadrant Q1. Hence, both $Q_{t,y}$ and $Q_{t,z}$ are positive at P2. Concerning the streamwise direction, the bivariate histogram (Fig. 7a) is similar in shape to the one at P1. Note that the intense Q2 events in the x-direction coincide with Q1 events in the y- and z-directions (not shown here).

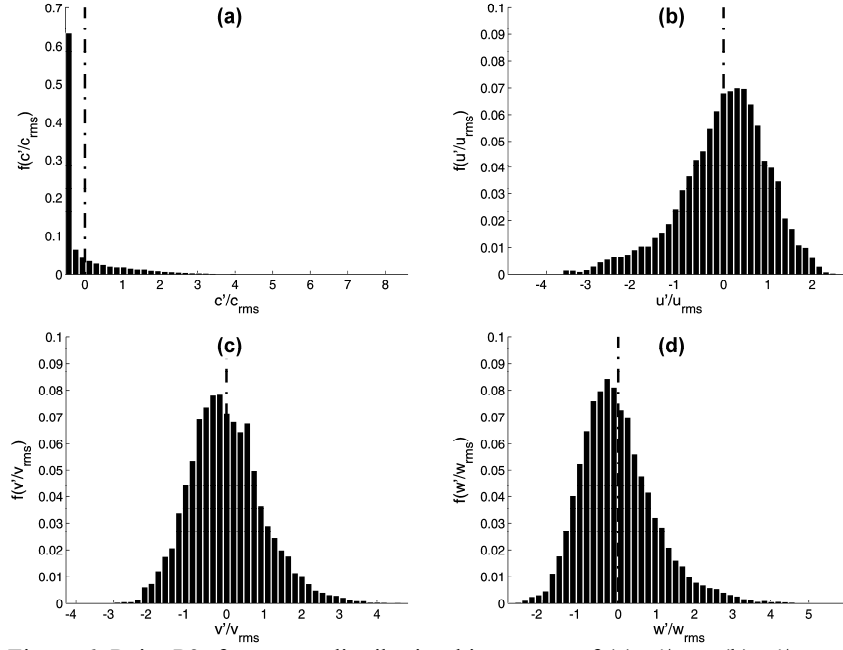


Figure 6. Point P2: frequency distribution histograms of (a) c'/c_{rms} , (b) u'/u_{rms} , (c) v'/v_{rms} , and (d) w'/w_{rms} . For each variable, the x-axis limits correspond to the minimum and maximum sample values. The dashed line indicates the mean (zero) values of the fluctuations. Mean values: $K=0.50$; $U/U_H=0.94$; $V/U_H=-0.04$; $W/U_H=-0.08$.

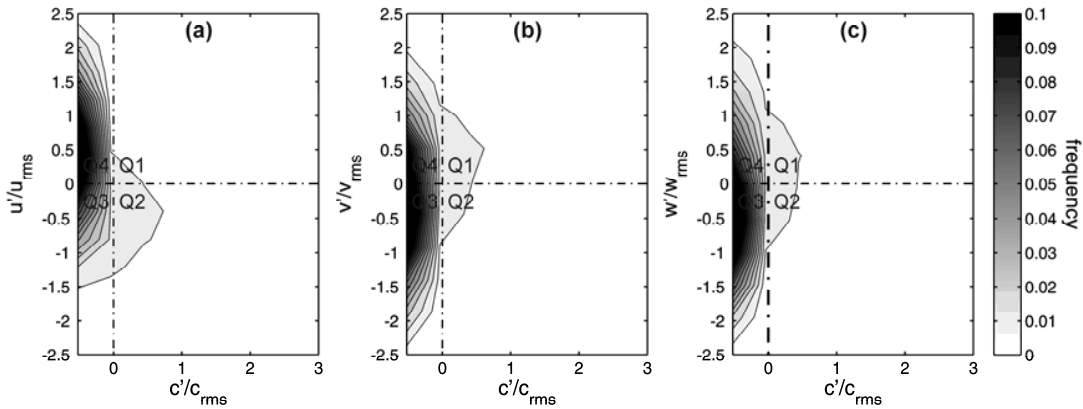


Figure 7. Point P2: bivariate histogram of frequency distribution for (a) $(c'/c_{rms}; u'/u_{rms})$, (b) $(c'/c_{rms}; v'/v_{rms})$, and (c) $(c'/c_{rms}; w'/w_{rms})$.

5 DISCUSSION AND CONCLUSIONS

Large-Eddy Simulation of pollutant dispersion around an isolated cubical building has been performed. The results have been compared with wind-tunnel measurements in terms of mean and standard deviation of concentration in the wake of the building and a fairly good agreement has been found between numerical and experimental values.

The velocity and concentration statistics have been reported for two points located in the shear layer developing above roof level. At this location, vortical structures generated at the front corner of the building and which are transported downstream are responsible for the meandering motion of the plume (see (Gousseau et al., 2012) for a further analysis of the flowfield). This could be observed in the histogram of frequency distribution of the concentration fluctuations at these two points: the exponential shape traduces the low background concentration and the occurrence of rare but intense peaks of concentration. The vortical structures also affect the frequency distributions of the velocity components by creating non-zero skewness. This holds also in the shear layers developing on the sides of the building (point P2). The bivariate analysis showed that for a given sign of c' there is a preferred sign of u_i' which is more likely to occur. In the streamwise direction, it was shown at P1 and P2 that c' and u' most of the time have opposite signs, leading on average to a negative turbulent mass flux $Q_{t,x}$ and explaining the CG mechanism in this zone.

It has been shown that specific unsteady events govern turbulent mass transport, which explains the failure of the first-order closure model (Eq. 1). If used, this model should be adapted to reproduce the CG mechanism of turbulent mass transport – for example by taking out the minus sign from the right-hand side of Equation 1 – and to take into account the flow anisotropy, by use of a diffusivity vector.

6 REFERENCES

- B. Blocken, T. Sathopoulos, P. Saathoff and X. Wang, Numerical evaluation of pollutant dispersion in the built environment: Comparisons between models and experiments, *Journal of Wind Engineering and Industrial Aerodynamics*, 96 (2008) 1817-1831.
- F. Chen, Turbulent characteristics over a rough natural surface. Part I: Turbulent structures, *Boundary-Layer Meteorology*, 52 (1990) 151-175.
- W.C. Cheng and C.H. Liu, Large-Eddy Simulation of flow and pollutant transports in and above two-dimensional idealized street canyons, *Boundary-Layer Meteorology*, 139 (2011) 411-437.
- J.E. Fackrell and A.G. Robins, Concentration fluctuations and fluxes in plumes from point sources in a turbulent boundary layer, *Journal of Fluid Mechanics*, 117 (1982) 1-26.
- J. Franke, A. Hellsten, H. Schlünzen and B. Carissimo, Best practice guideline for the CFD simulation of flows in the urban environment, *COST Action 732*, 2007.
- M. Germano, U. Piomelli, P. Moin and W.H. Cabot, A dynamic subgrid-scale eddy viscosity model, *Physics of Fluids*, A 3 (1991) 1760-1765.
- P. Gousseau, B. Blocken, T. Sathopoulos and G.J.F. van Heijst, CFD simulation of near-field pollutant dispersion on a high-resolution grid: a case study by LES and RANS for a building group in downtown Montreal, *Atmospheric Environment*, 45 (2011a) 428-438.
- P. Gousseau, B. Blocken and G.J.F. van Heijst, CFD simulation of pollutant dispersion around isolated buildings: On the role of convective and turbulent mass fluxes in the prediction accuracy, *Journal of Hazardous Materials*, 194 (2011b) 422-434.

- P. Gousseau, B. Blocken and G.J.F. van Heijst, Large-Eddy Simulation of pollutant dispersion around a cubical building: Analysis of the turbulent mass transport mechanism by unsteady concentration and velocity statistics, *Environmental Pollution* (2012), doi: 10.1016/j.envpol.2012.03.021.
- C. Gromke, R. Buccolieri, S.D. Sabatino and B. Ruck, Dispersion study in a street canyon with tree planting by means of wind tunnel and numerical investigations - Evaluation of CFD data with experimental data, *Atmospheric Environment*, 42 (37) (2008) 8640-8650.
- J. Kim and P. Moin, Application of a fractional step method to incompressible Navier-Stokes equations, *Journal of Computational Physics*, 59 (1985) 308-323.
- R.A. Lavertu and L. Mydlarski, Scalar mixing from a concentrated source in turbulent channel flow, *Journal of Fluid Mechanics*, 528 (2005) 135-172.
- W.W. Li and R.N. Meroney, Gas dispersion near a cubical model building – Part I. Mean concentration measurements, *Journal of Wind Engineering and Industrial Aerodynamics*, 12 (1983a) 15-33.
- W.W. Li and R.N. Meroney, Gas dispersion near a cubical model building – Part II. Concentration fluctuation measurements, *Journal of Wind Engineering and Industrial Aerodynamics*, 12 (1983b) 35-47.
- D.K. Lilly, A proposed modification of the Germano subgrid-scale closure method, *Physics of Fluids, A* 4 (1992) 633-635.
- F. Mathey, D. Cokljat, J.P. Bertoglio and E. Sergent, Assessment of the vortex method for large eddy simulation inlet conditions, *Progress in Computational Fluid Dynamics*, 6 (2006) 58-67.
- R.N. Meroney, An algebraic stress model for stratified turbulent shear flows, *Computer and Fluids*, 4 (1976) 93-107.
- P. Moin, K. Squires, W. Cabot and S. Lee, A dynamic subgrid-scale model for compressible turbulence and scalar transport, *Physics of Fluids*, A3-11 (1991) 2746-2757.
- M.R. Raupach and B.J. Legg, Turbulent dispersion from an elevated line source: measurements of wind-concentration moments and budgets, *Journal of Fluid Mechanics*, 136 (1983) 111-137.
- R. Rossi, D.A. Philips and G. Iaccarino, A numerical study of scalar dispersion downstream of a wall-mounted cube using direct simulations and algebraic flux models, *International Journal of Heat and Fluid Flow*, 31 (2010) 805-819.
- R.H. Shaw, J. Tavangar and D.P. Ward, Structure of the Reynolds stress in a canopy layer, *Journal of Climate and Applied Meteorology*, 22 (1983) 1922-1931.
- S. Simoëns and J.M. Wallace, The flow across a street canyon of variable width—Part 2: Scalar dispersion from a street level line source, *Atmospheric Environment*, 42 (2008) 2489-2503.
- J. Smagorinsky, General circulation experiments with the primitive equations. I. The basic experiment, *Monthly Weather Review*, 91 (1963) 99-164.
- Y. Tominaga, S. Murakami and A. Mochida, CFD prediction of gaseous diffusion around a cubic model using a dynamic mixed SGS model based on composite grid technique, *Journal of Wind Engineering and Industrial Aerodynamics*, 67 & 68 (1997) 827-841.
- Y. Tominaga, A. Mochida, R. Yoshie, H. Kataoka, T. Nozu, M. Yoshikawa and T. Shirasawa, AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings, *Journal of Wind Engineering and Industrial Aerodynamics*, 96 (2008) 1749-1761.
- Y. Tominaga and T. Stathopoulos, Numerical simulation of dispersion around an isolated cubic building: model evaluation of RANS and LES, *Building and Environment*, 45 (10) (2010) 2231-2239.
- Y. Tominaga and T. Stathopoulos, CFD modeling of pollution dispersion in a street canyon: Comparison between LES and RANS, *Journal of Wind Engineering and Industrial Aerodynamics*, 99 (2011) 340-348.
- T. van Hooff and B. Blocken, Coupled urban wind flow and indoor natural ventilation modelling on a high-resolution grid: A case study for the Amsterdam ArenA stadium, *Environmental Modelling & Software*, 25 (2010) 51-65.