Modelling concentration fluctuations for operational purposes

François-Xavier Cierco*, Lionel Soulhac, Pietro Salizzoni, Patrick Méjean and Guillevic Lamaison

Laboratoire de Mécanique des Fluides et d'Acoustique,
Université de Lyon CNRS,
Ecole Centrale de Lyon, INSA Lyon

and

Université Claude Bernard Lyon I,
36 avenue Guy de Collongue,
69134 Ecully, France
E-mail: francois-xavier.cierco@ec-lyon.fr
E-mail: lionel.soulhac@ec-lyon.fr
E-mail: pietro.salizzoni@ec-lyon.fr
E-mail: patrick.mejean@ec-lyon.fr
E-mail: guillevic.lamaison@ec-lyon.fr
Corresponding author

Patrick Armand

Commissariat à l'Energie Atomique et aux énergies alternatives,
CEA-DAM, DIF Bruyères le Châtel,
France
E-mail: patrick.armand@cea.fr

Abstract: We investigated the two first moments of the concentration distribution from a point source release thanks to wind tunnel measurements. The results were analysed with the statistical model from Yee et al. (1994). This model requires two parameters related to the larger scale velocity fluctuations and to the concentration variability due to smaller scale fluctuations respectively. A robust semi-empirical relation for the intensity of the concentration fluctuations was derived. Such a relation can be combined with the mean concentration estimates provided by a Gaussian puff model to compute the standard deviation of pollutant concentration.

Keywords: concentration fluctuations; fluctuation intensity; operational dispersion model; Wind tunnel experiment.

Reference to this paper should be made as follows: Cierco, F-X., Soulhac, L., Salizzoni, P., Méjean, P., Lamaison, G. and Armand, P. (2012) 'Modelling concentration fluctuations for operational purposes', *Int. J. Environment and Pollution*, Vol. 48, Nos. 1/2/3/4, pp.78–86.

Francois–Xavier Cierco obtained his PhD at Cemagref, Grenoble. Currently he is a research engineer at the Ecole Centrale de Lyon. He mainly investigated the fluctuations of passive scalar transported by turbulent flows by means of wind tunnel and field experiments.

Lionel Soulhac is Maître de Conférences at the Ecole Centrale de Lyon. His research activity mainly concerns pollutant dispersion modelling in urban areas. He led different projects in the field as the development of the two models SIRANE and SIRANERISK dedicated to air quality assessment after stationary or non-stationary releases respectively.

Pietro Salizzoni is Maître de Conferences at the Ecole Centrale de Lyon. His research deals with pollutant dispersion and turbulent buoyant flows. He is responsible for many experimental developments in these two fields.

Patrick Méjean is a research engineer at the Ecole Centrale de Lyon. He developed the experimental setup described in this publication. He is also a specialist in the field of instrumentation for wind and concentration measurements.

Guillevic Lamaison is a research engineer at the Ecole Centrale de Lyon. He contributed to the development of the model SIRANERISK.

Patrick Armand is a researcher at CEA in the field of atmospheric dispersion and environmental impact. He contributed to the development of the model SIRANERISK.

1 Introduction

The prediction of concentration fluctuations is essential to assess the impact of odours or accidental releases of toxic and flammable gases. Furthermore, the most serious consequences of such releases are likely to occur in densely populated city centres, where building geometry influences the flow in complicated ways.

Operational dispersion models meet some difficulties in assessing such situations for two reasons: few of them take into account the geometric complexity of the urban canopy, and many are limited to the prediction of the first order moment of the concentration distribution.

In the literature, concentration fluctuations were addressed thanks to three different strategies: by coupling a Large Eddy Simulation with a Lagrangian stochastic model (Wei et al., 2006; Xie et al., 2004); by coupling a Reynolds Averaged Navier Stokes model with an equation of the concentration variance (Mavroidis et al., 2007) or with a Lagrangian stochastic model integrating a macro-mixing and a micro-mixing scheme (Cassiani et al., 2005); by defining the functional form of the concentration probability density function as a function of space and time (Gifford, 1959, Yee et al., 1994).

In this paper, we present preliminary studies for an operational dispersion model for risk management in urban areas. The model, named SIRANERISK, is conceived to provide estimates of the mean concentration of a passive scalar ejected during an accidental release within an urban district. To compute mean concentrations, SIRANERISK embodies a specific mass-consistent model for pollutant dispersion within the urban canopy (Soulhac et al., 2011), coupled with a Gaussian puff model for the outer atmosphere. Estimations of the concentration standard deviation are also needed. They can be provided by semi-empirical models giving the spatial evolution of the intensity of the concentration fluctuation $i_c(x,y) = \sigma_c / \overline{C}$.

One model for i_c can be derived from the approach developed by Gifford (1959) and generalised by Yee et al. (1994), who proposed theoretical relations to compute higher order moments of the concentration distribution. Equations for these moments can be given the general form:

$$\frac{\overline{C^n}(x,y)}{C_0^n(x)} = F(M, i_r), \tag{1}$$

where C_0 denotes the concentration on the plume axis (respectively at puff centre), M is the meandering ratio and i_r is the ratio of the concentration standard deviation to the averaged concentration in the instantaneous plume or puff. It is worth noting that M and i_r depend on the distance from the source and on the dynamical condition of the flow field within which the dispersion process occurs.

An extensive experimental data set of M and i_r for a large variety of flows is still lacking, and therefore, there is no available empirical law to describe their spatial evolution.

For this reason, we performed specific wind tunnel experiments to investigate the two first moments of the concentration distribution, as well as M and i_r, over urban-like roughness.

2 Statistical modelling of the concentration distribution

To describe the spread of a pollutant plume or puff, different relations were proposed to model the concentration Probability Density Function (PDF): log-normal distributions (Csanady, 1973), exponential distributions (Sawford, 1987), combination of exponential and generalised Pareto distributions (Lewis and Chatwin, 1995), clipped Gamma functions (Yee et al., 1994; Yee and Chan, 1997) and clipped Gaussian distributions (Lewellen and Sykes, 1986; Mylne and Mason, 1991; Reynolds, 2007).

The advantages of the different functions are not clear enough to lead to general agreement. However, the two parameters involved in the clipped Gamma function, namely M and i_r, admit simple physical interpretation, and can be inferred by experimental measurements (Yee et al., 1994). In what follows, we will focus on the crosswind distribution of concentration without regard to the changes in the vertical direction z. The distribution of the averaged concentration $\overline{C}$ is assumed to be given by a Gaussian law:

$$\overline{C}(x,y) = C_0(x)\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2(x)}\right). \tag{2}$$

Given this assumption, following Yee et al. (1994), any moment of the concentration distribution $\overline{C^n}$ can also be described by a Gaussian law:

$$\frac{\overline{C^n}(x,y)}{C_0^n} = f_n(i_r)\frac{(1+M)^{n/2}}{(1+nM)^{1/2}}\exp\left(-\frac{1}{2}\frac{n(M+1)}{(1+2M)}\frac{y^2}{\sigma_y^2}\right) \tag{3}$$

where M, i_r and σ_y depend on the stream-wise coordinate x. f_n is an algebraic function of i_r which reduced to $f_2(i_r) = 1 + i_r^2$ for $n = 2$. The equivalent equation from Gifford (1959) can be easily obtained from equation (3), setting $i_r = 0$. M is also related to the spread of the different moments of the concentration distribution C^n denoted by σ_n through the relation (Yee at al., 1994):

$$M = \frac{1 - nR_n}{n(R_n - 1)}, \tag{4}$$

where $R_n = \sigma_n^2 / \sigma_y^2$.

For n = 2, since $\sigma_c^2 = \overline{C^2} - \overline{C}^2$, the combination of equations (2) and (3) provides an additional relation for the distribution of the concentration standard deviation, which was tested against experimental results.

3 Measurements of concentration fluctuations in plumes and puffs

The experimental campaign consisted in measurements of the time evolution of the concentration C(t) at fixed locations after either instantaneous or continuous releases in a turbulent boundary layer flow. To that purpose, a tracer gas was released over different rough surfaces, simulating either a rough terrain or an urban–like geometry. The roughness elements and the source location were different in the two configurations.

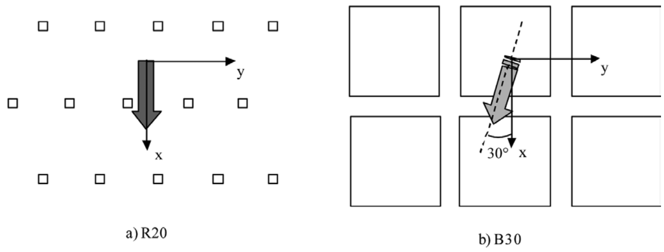
The experiments were performed in the atmospheric wind tunnel of the Ecole Centrale de Lyon, whose test channel is 14.0 m long, 3.8 m wide and 2.0 m high. Passive scalar concentrations were measured with a frequency of 1 kHz by means of a Fast Ionisation Detector (FID) probe.

3.1 Experimental configurations

Two configurations were tested by varying the height H, the form and the spacing of the obstacles placed over the wind tunnel floor. In the R20 configuration (Figure 1(a)) the flow developed over a rough surface made of 20 mm cubic roughness elements (H = 20 mm). The B30 configuration was made up of an idealised urban canopy constituted by a network of perpendicular streets, each 250 mm long (Figure 1(b)). The street cross-section was 50 × 50 mm (H = 50 mm). Nuts were spread over the building roofs to play the role of roughness elements. An angle of 30° was set between the street axis and the main direction of the flow.

The source was located at $h_s = 5H/4$ in configuration R20 and at $h_s = H/2$ in configuration B30. The measurements were performed at $z = h_s = 5H/4$ in R20 and at $z = 6H/5$ in B30. In that second case, the pollutant was released within the canopy, whereas the concentration measurements were performed in the outer flow.

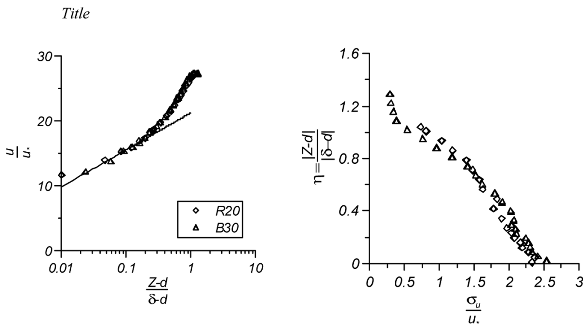
Figure 1 Experimental configurations: a) rough surface made of 20 mm cubic roughness elements (R20) and b) idealised urban area. The grey arrows indicate the wind direction



3.2 *Flow dynamics*

In both configurations, the flow developing over the roughness elements behaves as a classical turbulent boundary layer. In the lower part of the boundary layer, the mean longitudinal velocity u is well fitted by a logarithmic profile. The vertical profiles of non-dimensional flow variables can, therefore, be described by means of similarity relations (Figure 2). Therefore, the flows developing in the two configurations (R20 and B30) are similar.

Figure 2 Non-dimensional velocity profiles for the different configurations: rough surface (R20) and idealised urban canopy (B30). u and σ_u are the mean and the standard deviation of the longitudinal velocity, and δ is the boundary layer thickness and *d*, the displacement height. The solid line represents the logarithmic profile that fits the data in the lower part of the boundary layer



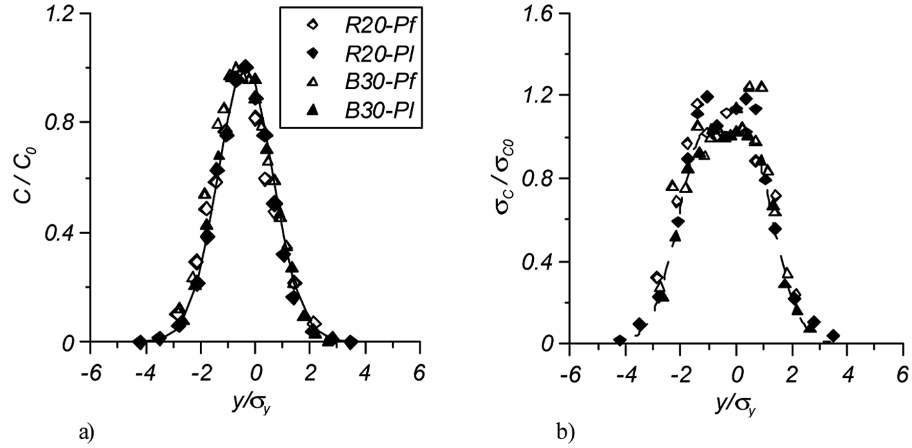
4 Results and discussion

4.1 *Plume and puff behaviour*

Different statistics were derived from the experimental results, namely the mean, variance, standard deviation and fluctuation intensity of the concentration. Statistics were obtained by means of time averages in case of continuous releases and by means of ensemble averages over 100 to 150 releases for 'instantaneous' puffs. The normalised distributions of concentration obtained with plumes and puffs at a given location are compared in Figure 3(a). The results show that the crosswind profiles of concentration are sensitive neither to the duration of the pollutant release nor to the source location. At a given height *z* above the ground and at a given distance *x* from the source, the concentration distribution is also well fitted by a Gaussian law. This feature allows us to apply the model given by equations (2) and (3).

Similarly, the crosswind profiles of the concentration standard deviation do not depend on the release duration or the source location, although some important scatter is observed close to the plume or puff centre (See Figure 3(b)).

Figure 3 Crosswind profiles of ensemble and time-averaged statistical indicators (a) non-dimensional mean concentration and (b) non-dimensional standard deviation of the concentration for short releases (white ticks) or continuous releases (black ticks) in configurations R20 (lozenges) or B30 (triangles). Experimental data obtained with plume in B30 were fitted with equation (2) (a), or with the Yee et al. model (b). The subscript 0 to any variable denote the value taken on plume axis or at puff centre. The suffixes *Pl* and *Pf* distinguish, respectively, plumes and puffs



It should be noted that the main changes between the two configurations R20 and B30 consist in the source location. As shown on Figure 2, the dynamic features of the flow – and therefore of the dispersion – are identical in both configurations.

The crosswind profile of $\overline{C^2}$ can be derived from the measurements of C and σ_C presented in Figure 3, so that estimations of both σ_y^2 and σ_2^2 are available. M can, therefore, be computed thanks to equation (4) for $n = 2$. Data have been fitted with the Yee et al. model. These fits (plotted in Figure 3(b)) allow us to estimate the value of i_r. Results for M and i_r are given in Table 1.

Table 1 Values of M computed thanks to equation (4) and values of i_r obtained by fitting the experimental data with equation (3)

		R20		*B30*		
		$x = 2$ m	$x = 4$ m	$x = 2$ m	$x = 3$ m	$x = 4$ m
Plume	M	0.508	0.356	0.089	0.106	0.215
	i_r	0.302	0.282	0.282	0.235	0.303
Puff	M	0.602	0.366	0.472	0.349	0.439
	i_r	0.295	0.286	0.227	0.302	0.248

It is worth noting that, in case of non-steady releases, the estimates of M and i_r through data fitting were not reliably close to the source due to significant scatter in the experimental results.

Both M and i_r decrease with the stream-wise direction in configuration R20. i_r is reduced as the puff travels downstream because of the increasing dilution within the puff path. M also decreases as the linear dimension of the puff increases and attains the integral length scale of the boundary layer flow. This excepted trend is not systematically observed in B30. In that situation, the scatter in the results is more important due to the presence of obstacles, so that important uncertainties are suspected in the estimates of the second order moment of the concentration and, therefore, in the estimates of M and of i_r.

4.2 Intensity of the concentration fluctuations

Since the crosswind profiles of both the averaged concentration and the concentration standard deviation were independent on release duration and source location, the same trend was expected in the crosswind profiles of the concentration fluctuation intensity $i_C = \sigma_C / \overline{C}$ in the mean plumes or puffs (See Figure 4(a)).

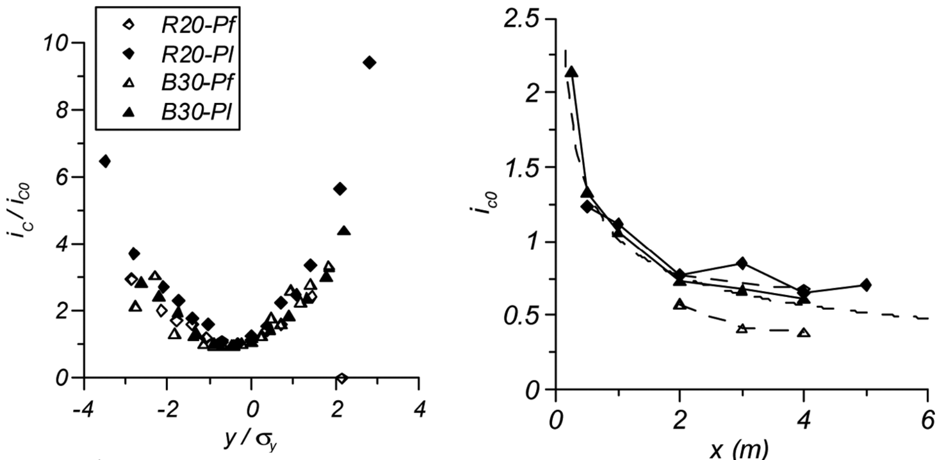
Furthermore, the longitudinal evolution of i_{C0} was also found to be almost independent on release duration and source position (Figure 4(b)), and could be fitted by the following power law:

$$i_{C0} = \sigma_{C0} / \overline{C_0} = x^{-a} + b, \tag{5}$$

where $a = 0.424$ and $b = 1.025$.

Since the behaviour of i_{C0} is independent of the source position, equation (5) can be used to model the decrease of i_{C0} with distance in a neutrally stratified atmosphere above urban areas. Therefore, the combination of equations (5) and (2) provides a simple model to compute concentration fluctuations on plume axis or at puff centre.

Figure 4 (a) Lateral profile of i_C and (b) longitudinal profile of i_{C0} fitted by equation (5) (dashed line)



a) b)

However, further investigations are still needed so as to quantify the lateral distribution of *M* and i_r as well as the evolution of those parameters in other atmospheric conditions like stable or convective boundary layer.

5 Conclusions

This study presents the experimental results of steady and unsteady releases in a turbulent boundary layer developing over urban-like roughness elements.

The experimental results were analysed to get quantitative estimates of the two parameters *M*, and i_r involved in the model proposed by Yee and al. (1994), for higher order moments predictions of the concentration distribution. The experimental results allowed us to infer the simple parametric law dependence of these parameters on the spatial coordinates and to test the sensitivity of that parameterisation on varying source position.

The robustness of equation (5) still requires further confirmation, and new measurements are presently processed with that aim. However, equation (5) was implemented in a research version of SIRANERISK, an operational model for crisis management after accidental or deliberate releases, to estimate the magnitude of the spreading of experimental results around the simulated mean concentrations.

References

Cassiani, M., Franzese, P., Giostra, U. (2005) 'A PDF micromixing model of dispersion for atmospheric flow. Part I: development of the model, application to homogeneous turbulence and to neutral boundary layer. *Atmos. Env.*, Vol. 39, pp.1457–1469.

Csanady, G.T. (1973) 'Turbulent diffusion in the environment', in Dordrecht, D.R. The Netherlands, p.248.

Gifford, F.A. (1959) 'Statistical properties of a fluctuating plume dispersion model', *Adv. Geophys.*, Vol. 6, pp.117–138.

Lewellen, W.S. and Sykes, R.I. (1986) 'Analysis of concentration fluctuations from lidar observations of atmospheric plumes', *J. Clim. Appl. Meteorol.*, Vol. 25, pp.1145–1154.

Lewis, D.M. and Chatwin, P.C. (1995) 'A new model probability density function for contaminants dispersing in the atmosphere', *Environmetrics*, Vol. 6, pp.583–593.

Mavroidis, I., Andronopoulos, S., Bartzis, J.G. and Griffiths., R.F. (2007) 'Atmospheric dispersion in the presence of a three-dimensional obstacle: modelling of mean concentration and concentration fluctuations', *Atmos. Env.*, Vol. 41, pp.2740–2756.

Mylne, K.R. and Mason, P.J. (1991) 'Concentration fluctuations measurements in a dispersing plume at a range up to 1000 m', *Q. J. R. Meteorol. Soc.*, Vol. 117, pp.177–206.

Reynolds, A.M. (2007) 'Dissipation conditioned stochastic modelling of scalar concentration fluctuations in turbulent flows', *Phys. Fluid*, Vol. 19, No. 7, article 075101, doi:10.1063/1.2747681.

Sawford, B.L. (1987) 'Conditional concentration statistics for surface plumes in the atmospheric boundary-layer', *Boundary-Layer Meteorol.*, Vol. 38, p.209.

Soulhac, L., Salizzoni, P., Cierco, F-X. and Perkins, R.J. (2011) 'The model Sirane for atmospheric urban pollutant dispersion: PART I: presentation of the model', *Atmospheric Environment*, Vol. 45, pp.7379–7395.

Wei, G., Vinkovic, I., Shao, L. and Simoëns, S. (2006) 'Scalar dispersion by a large-eddy simulation and a Lagrangian stochastic subgrid model', *Phys. Fluid*, Vol. 18, No. 9, article 095101, doi: 10.1063/1.2337329.

Xie, Z., Hayden, P., Voke, P.R. and Robins, A.G. (2004) 'Large-eddy simulation of dispersion: comparison between elevated source and ground level source', *J. Turbulence*, Vol. 5, pp.1–16.

Yee, E. and Chan, R. (1997) 'A simple model for the probability density function of concentration fluctuations in atmospheric plumes', *Atmos. Env.*, Vol. 31, pp.991–1002.

Yee, E., Chan, R., Kosteniuk, P.R., Chandler, G.M., Biltoft, C.A. and Bowers, J.F. (1994) 'Incorporation of internal fluctuations in a meandering plume model of concentration fluctuations', *Boundary-Layer Meteorol.*, Vol. 67, pp.11–39.