H13-45
SIRANERISK: AN OPERATIONNAL DISPERSION MODEL FOR URBAN AREAS INCORPORATING A NEW METHOD TO ACCOUNT FOR CONCENTRATION FLUCTUATIONS

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Abstract: The different analytical methods developed to investigate the concentration fluctuations require inferring the form of the concentration probability function (PDF). These PDF contain additional parameters which are not correctly quantified in the cases of practical interest. That's why, the question of the concentration fluctuations can't be correctly addressed by the operational dispersion model nowadays. To bypass such difficulty, experimental results obtained in the atmospheric wind tunnel of Ecole Centrale de Lyon have been turned to derive a synthetic law that gives the along-wind evolution of the concentration fluctuation intensity on the plume centreline (respectively at puff centre) $i_{c0}(x)$. This mathematical law $i_{c0}(x)$ was incorporated in an operational dispersion model, SIRANERISK, dedicated to dispersion studies over urban areas in unsteady situations. The prediction of the mean concentration C by the model can be introduced in the empirical law giving the concentration fluctuation intensity $i_{c0}(x)$ to derive a first estimation of the concentration standard deviation. Because this method can be directly applied and because it does not require any additional parameter, it could be easily used in the operational context and give a first approximation of the magnitude order of the concentration fluctuations. Additional data from field experiment would be required to validate such an approach.

Key words: *Concentration fluctuations, Fluctuation intensity, Operational dispersion model, Wind tunnel experiment*

INTRODUCTION

Standard air quality studies generally focus on the impact of low-level concentration experienced over long periods by the population whereas after short uncontrolled releases, it becomes more important to predict the impact of potentially high concentration levels over short time lapses. The particular context of short releases gives therefore concentration fluctuations a peculiar importance. Nevertheless operational models are often limited to the prediction of the first order moment of the concentration distribution which does not make them well suited to perform the dedicated computations and to give information on the concentration fluctuations in case of accidental or deliberate releases.

The main reason for such a vacuum in the functionalities of the operational numerical tools can be found in the difficulties to adapt the available computational methods of high order moments of the concentration distribution in the operational context. However, in its early description of what could be an operational puff model, Gifford (1959) showed that any moment of the concentration distribution could be derived from his model. Nevertheless, such a method requires knowing the form of the concentration probability density function (PDF). Although many different propositions were carried out, none of the advocated form has obtained general agreement since then, neither clipped Gaussian distribution (Reynolds, 2007), nor exponential distributions (Sawford, 1987), nor log-normal distributions (Csanady, 1973) nor clipped Gamma functions (Yee and Chan, 1997), nor combinations of exponential and generalized Pareto distributions (Lewis and Chatwin, 1995)…

Moreover, all these PDF forms contain specific parameters which need to be quantified for the operational context. One can cite the meandering ratio M_r which is requested in both the Gifford (1959) model and the Yee *et al.* (1994) model. A specific concentration fluctuation intensity i_r is also needed in the Yee *et al.* (1994) model. The relevant values of such parameters remains generally unknown for cases of practical interest which disable the possibility to compute the high order moments of the concentration distribution in operational Gaussian puff models. It should be noted that the computation of the high order moment of the concentration distribution is not possible with one-particle random walk models.

Our model, SIRANERISK, consists in the association of a Gaussian puff model and a street-canyon model dedicated to crisis management for accidental or deliberate releases. In that context, we implemented a new method to account for concentrations fluctuations based on empirical laws derived from a large range of wind-tunnel experiments.

These experiments were specifically dedicated to the concentration fluctuations due to short releases. They were performed in the atmospheric wind-tunnel of Ecole Centrale de Lyon. The results allowed to derive an empirical law for the fluctuation intensity. Introducing the prediction of the mean concentration from a model like SIRANERISK in that particular law gives therefore a first approximation of the order of magnitude of the standard deviation of the concentration at puff centre.

THE SIRANERISK MODEL

SIRANERISK is a model dedicated to pollutant dispersion over urban areas in unsteady situations. It's formed of the coupling of a Gaussian puff model and a specific mass-consistent model that accounts for the dispersion of the pollutants in the urban canopy. SIRANERISK is the unsteady version of SIRANE, a steady operational dispersion model designed for air quality assessment over urban areas described by Soulhac (2000).

The urban or canyon-street model

The canyon-street model accounts for the geometric complexity of the urban area at a scale chosen to be consistent with those of an urban district. It should be noted that the main objective of SIRANERISK is to predict the pollutant concentration in each street. Therefore it becomes relevant to take into account the complexity of the street network and to neglect the effects of small topological details (such as trees, details of the buildings, etc.). The urban topography can therefore be represented with a network of simple volumes (parallelepiped as displayed on Figure -c).

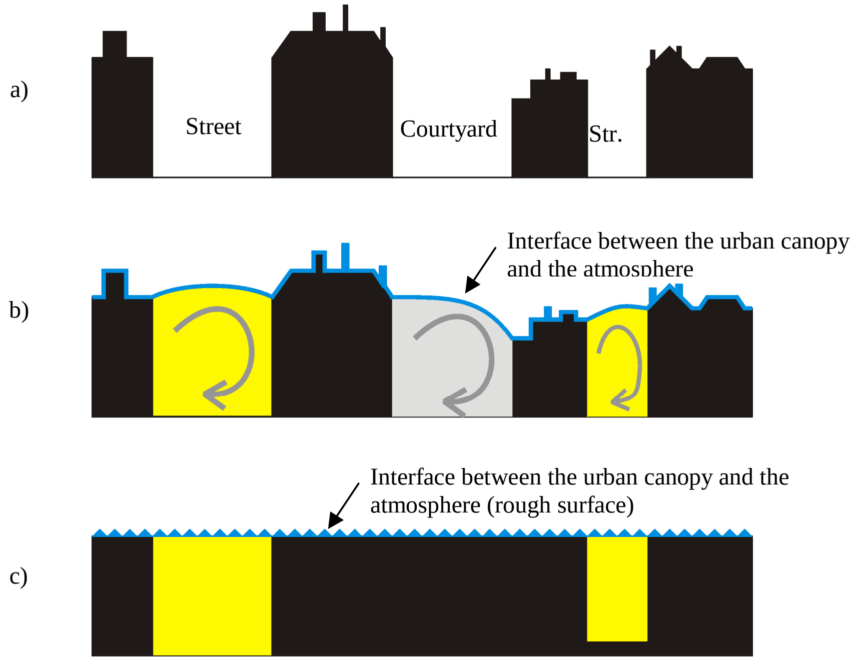


Figure 1. Description and simplified representation of an urban district in SIRANERISK: a) cross section of the real topography, b) visualisation of the interface between the atmosphere and the urban canopy and c) representation of the district in SIRANERISK

Each of this parallelepiped boxes contain a volume of contaminated air that can be exchanged with the next boxes (through the intersections of the street arrays), or with the atmosphere over the urban canopy.

The air flux can therefore be computed in each canyon-street, and consequently the mass budget of any pollutant (see Figure 2 and Equation1).

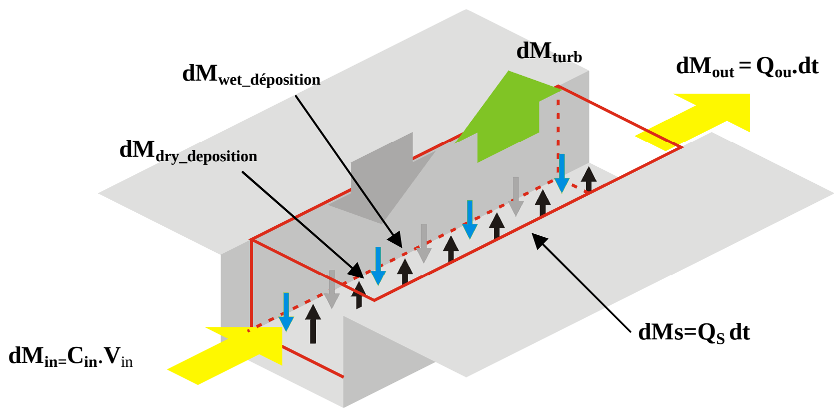


Figure 2. Mass budget in a canyon-street

$$M_{street}(t+dt) = M_{street}(t) + dM_{street,advection} + dM_s - dM_{turb} - dM_{dry\_deposition} - dM_{wet\_deposition} \qquad (1)$$

Where: M_{street} is the mass of pollutant in the street, $dM_{street,\ advection}$ is the mass budget due to the air flow in the street ($dM_{street,advection} = dM_{in} - dM_{out}$), M_{turb} is the mass budget due to turbulent exchanges with the atmosphere, dM_s is the mass of pollutant produced in the street by the different sources over dt, $dM_{dry\_deposition}$, and $dM_{wet\_deposition}$ denote respectively the mass of pollutant that deposits due to gravity effects or wet deposition over time lapse dt.

The Gaussian puff model

The mass of pollutant released above the urban canopy is accounted thanks to Gaussian puffs whose concentration distribution is supposed to be known at the time of release. This concentration distribution is modelled by a Gaussian distribution (Equation 2) whether it's released from a point source or by the sum of two erf functions (Equation 3) whether the source is considered to have an initial volume (and initial typical sizes L_i in each direction i).

$$C = \frac{M}{[2\pi]^{3/2}\sigma_x\sigma_y\sigma_z} exp\left[-\frac{1}{2}\left(\frac{(x-x_0)^2}{\sigma_x^2}+\frac{(y-y_0)^2}{\sigma_y^2}+\frac{(z-z_0)^2}{\sigma_z^2}\right)\right] \quad (2)$$

$$\begin{cases} C = M.f\left(x-x_b,\sigma_x,L\right)f\left(y-y_b,\sigma_y,W\right)f\left(z-z_b,\sigma_z,H\right) \\ f\left(x_i,\sigma_{x,i},L_i\right)=\frac{1}{2L_i}\left[erf\left(\frac{x_i+L_i/2}{\sqrt{2}\sigma_{x,i}}\right)-erf\left(\frac{x_i-L_i/2}{\sqrt{2}\sigma_{x,i}}\right)\right]\end{cases} \quad (3)$$

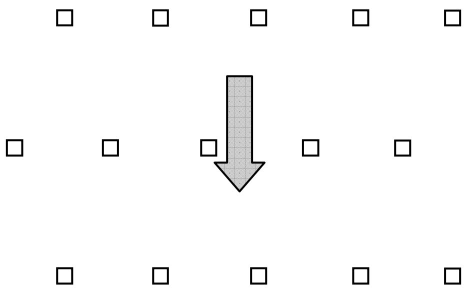
Whatever its initial characteristics, the concentration distribution can thus be described synthetically by its standard deviation $\sigma_{x,i}$ and its mass content M. The transport and diffusion of the puffs can therefore be modelled with a Gaussian puff model.

In SIRANERISK, the diffusion laws that govern the growth of the concentration distribution standard-deviation are based on the similitude theory of dispersion.

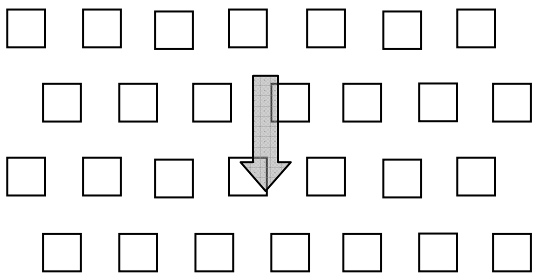
EXPERIMENTAL MEASUREMENTS OF THE CONCENTRATION FLUCTUATIONS IN PUFFS

The principle of the measurement campaign was to record the time evolution of the concentration after a reproducible short release of a tracer gas over the test area. 100 to 150 puffs were released for each of the sensor location so that a statistic study of the puff behaviour could be realised.

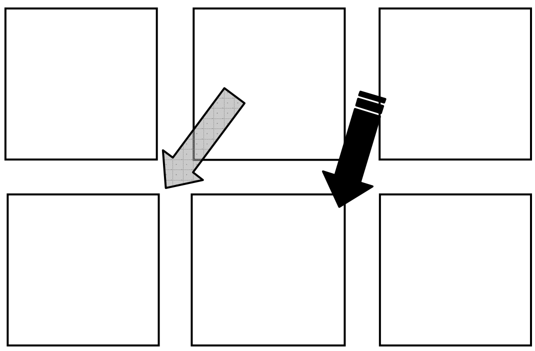
These measurements were performed in the atmospheric wind tunnel of Ecole Centrale de Lyon whose test channel is 14,0 m-long, 3.8 m-wide and 2.0 m-high. Three different configurations were tested (Figure 3): two rough surfaces covered with roughness elements of different typical sizes and an idealized urban area build of perpendicular streets between identical buildings (200 mm x 200 mm x 50 mm). This latter configuration was tested for two wind directions (30° and 45°).



a) R20



b) R50



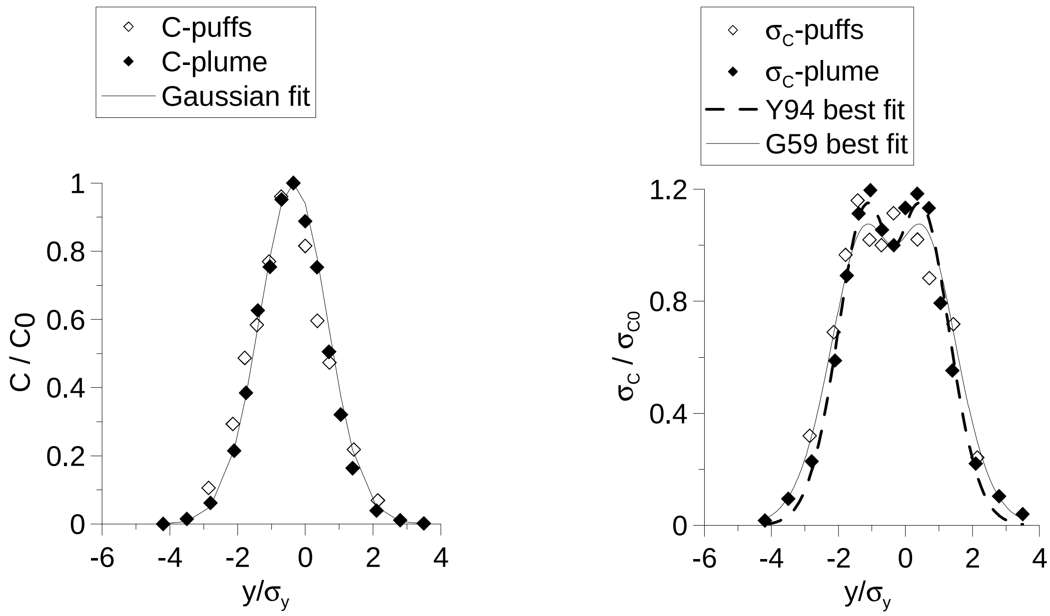
c) B

Figure 3. The different configurations tested during the wind tunnel experiments: a) rough surface with 20 mm cubic roughness elements (R20), b) rough surface with 50-mm cubic roughness elements (R50) and c) idealized urban area (UA). The grey arrows indicate the wind direction in each experiment. Note that two wind directions were tested for the B configuration: 30° (configuration B30, black discontinued arrow) and 45° (B45 grey arrow)

For each configuration, the measurements consisted in a collection of concentration samples from which we deduced the main concentration C, the concentration variance v_c, the standard deviation σ_c and the fluctuation intensity i_c. Similar measurements were also performed in a continuous release so as to enable comparisons between the behaviour of a collection of puffs and that of a plume.

In what follows, the subscript 0 stands for the particular value taken on the plume centreline (respectively at puff centre).

Typical results about the concentration distribution and the concentration fluctuation distribution obtained with plumes and puffs in the R20 configuration (at x = 4 m) are presented on Figure 4. On that Figure, the different fits were obtained as follows: data displayed on Figure 4-a are fitted with a Gaussian distribution; in Figure 4-b the two fits were computed thanks to relations given respectively by Gifford (1959) and Yee *et al.* (1994). The analytical law for the standard deviation from Gifford (1959) requires a single parameter M_e whose value was found to be 1.861. The coefficient of determination R^2 is here 0.96. The law from Yee *et al.* (1994) requests 2 parameters M_e and i_r whose values were found to be respectively 4.048 and 0.001. This analytic function gives a better fit with a coefficient of determination R^2 of 0.99. Nevertheless, the value for M_e seems questionable.



a) Non dimensional concentration

b) Non dimensional standard deviation of the concentration

Figure 4. Typical results for plume and puffs in the R20 configuration: a) Non dimensional concentration distribution, b) Non dimensional standard deviation of the concentration. Y94 and G59 denote respectively the fit laws derived from analytical relations given in Yee *et al.* (1994) and Gifford (1959).

It should be noted that our experiments were performed in a turbulent boundary layer. These experimental conditions involved that our experimental plumes and puffs were distorted by the effects of shear stress. Such effects are not assessed by operational Gaussian puff models. However, Figure 4 shows that our main results are consistent with the fundamental assumptions introduced in operational Gaussian puff models and that even the second order moment of the concentration distribution can be described correctly with different analytical laws found in the literature.

Moreover, the main characteristics of the distribution of both the first and the second moment of the concentration distribution remain unchanged for plumes and puffs.

DISCUSSION

From the distribution of both C and σ_C, it's clear that the concentration fluctuation intensity i_c can be easily derived. Figure 5 shows the along-wind distribution of i_{C0} (i.e. the value taken by i_c on plume centreline or at plume centre). The reader is reminded that i_c is defined as

$$i_c = \frac{\sigma_C}{C} \tag{4}$$

In what follows, the subscript "can" indicates that the measurements were obtained inside the idealized urban canopy. Figure 5 shows that values of i_{c0} measured inside the canopy are lower than those taken outside for both the plumes and the puffs. This observation conforms to those reported in Yee and Biltoft (2004). It should be noted that Yee and Biltoft (2004) limited their study to plumes only.

Interestingly, every experimental estimations of i_{c0} above the urban canopy collapse on a single curve whatever the configuration is. It should be noted that the changes in the roughness elements that distinguish configurations R20 and R50 brought differences of about 30% in the shear velocity u_*. Figure 5 therefore shows that such changes do not influence the longitudinal distribution of i_{c0}. The position of the source (that was located above the roughness elements in R20 and R50 and inside the canopy in B30 and B45) has also no noticeable effect.

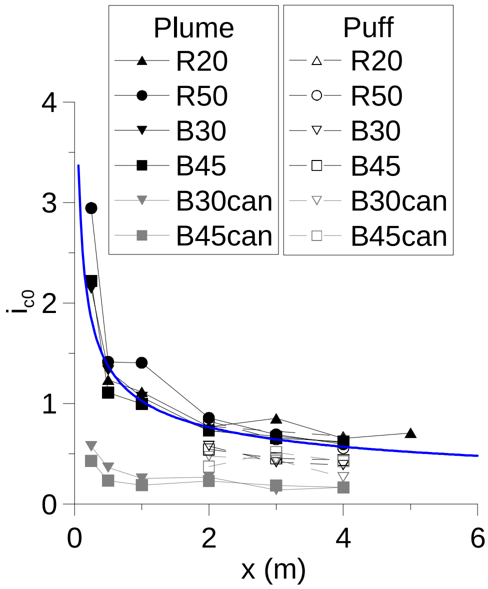


Figure 5. Evolution of i_{c0} in the wind direction for every experimental configuration. The blue curve was obtained thanks to Equations (5).

On Figure 5, the blue curve was obtained by fitting the data with a power law whose equation is:

$$i_{c0} = x^{-a} + b \tag{5}$$

Where a and b are two empirical constants. One can choose 0.424 for a and 1.025 for b.

Because the behaviour of i_{c0} is remarkably independent on the turbulent features of the flow, equation (5) was introduced into the operational dispersion model SIRANERISK. Introducing (4) in (5) and feeding the algorithm with the standard evaluation of the mean concentration C furnished by the model, this process enables SIRANERISK to give an estimation of σ_{C0}.

CONCLUSION

A dispersion model dedicated to crisis management after accidental or deliberate releases, SIRANERISK, was developed in Ecole Centrale de Lyon. Parallel to that work, wind tunnel experiments were performed so as to investigate concentration fluctuations due to short releases. The experimental results showed that the two first moments of the concentration distribution could be compared for both continuous plumes and pollutant puffs due to short releases. Moreover the concentration fluctuation intensity on plume centreline i_{c0} was shown to be independent on the turbulent features of the flow.

This observation was turned to find an empirical law for i_{c0} subsequently introduced in SIRANRERISK. This empirical law allows the further derivation of the concentration standard deviation using the estimation of the mean concentration C available as a standard result given by the dispersion model.

However, further data – particularly field data – are still needed so as to validate this new functionality of the model.

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