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VALIDATION OF SIRANERISK-2.0 OPERATIONAL MODEL AGAINST A LAGRANGIAN PARTICLE DISPERSION MODEL AND A NEW CAMPAIGN OF DISPERSION EXPERIMENTS PERFORMED IN THE LMFA-ECL WIND TUNNEL IN AN IDEALIZED URBAN MOCK UP

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Abstract: Atmospheric dispersion modelling of short releases in urban area is an important issue to help authorities during a scenario planning or a crisis management. In such situations, the dispersion model should be able to predict:

- The travel time of pollutant from source to specific receptors, in a context where the puffs interacts with complex buildings and obstacles. These complex obstacles reduce the wind velocity within the canopy and retain the pollutant within recirculating zone.
- The longitudinal, transverse and vertical spread of the puff wich controls the dilution of the pollutants and which is influenced by the complexity and the organisation of the buildings pattern.

In order to represent these effects, the operational urban dispersion model SIRANERISK has been developed to simulate the temporal evolution of concentration fields, over a whole city with a spatial street scale resolution. SIRANERISK is based on a representation of a city as a network of interconnected streets.
In this paper, we present a comparison between the SIRANERISK model and two other approaches: a Lagrangian dispersion model and a wind tunnel experiment, on a rough flat ground and on an idealized European network of streets. The experiment was performed in the atmospheric wind tunnel of the Ecole Centrale de Lyon. A neutral atmospheric surface layer was reproduced upwind of the model with a 1/400 scale ratio. An instantaneous release was considered and ensemble averages were obtained using about 100 realizations of the release. The Lagrangian model, based on the classical Langevin equation (Thomson, 1984) was specifically developed for the comparison on the flat ground, in order to evaluate the modelling of longitudinal shear effect in SIRANERISK.
The results show that the SIRANERISK model is able to reproduce the travel time from source and the puff spreading, using a generalised formulation of the Gaussian puff. We show that one of the key parameters in the model is the height of evaluation of the velocity gradient to take into account the effect of wind shear. We therefore propose a parameterisation of this height related to the vertical standard deviation of the puff.

Key words: *Operational dispersion model, Wind tunnel experiment, Lagrangian particle, Shear effects.*

INTRODUCTION

Due to industrial densification in one hand and growth of terrorist threat in the other hand, authorities has to face the very specific problematic of short unsteady releases of hazardous pollutant in the atmosphere. Crisis management or scenario planning require powerful numerical tools to understand what happens and what is going to happen in the next few minutes. Due to turbulence unpredictability as well as complex urban topography, exact prevision of the travel of cloud pollutant over a town is not a reasonable goal to reach when modelling atmospheric dispersion in such situations. Statistical tools are well suited to give interesting information to help authorities in their decision process. Sophisticated methods exist now to compute the wind field and the pollutant concentration evolution over a city. Indeed, Computational Fluid Dynamics has produced many high-performance models in the last 30 years such as RANS model, Large Eddy Simulation (LES) or Lagrangian particle model. Despite exponential growth of computational devices, the direct calculation of unsteady releases in a crisis scenario with these complex models will keep being irrelevant for years. To save computational cost and substantially reduce the response time, simpler models are employed such as Gaussian puff models.
In this paper, we present the validation of our atmospheric dispersion model named SIRANERISK which belong to Gaussian puff model family. Indeed, the dispersion over the urban canopy is modelled in SIRANERISK by advection and dispersion of Gaussian puffs. Moreover, the model simultaneously transports pollutant within the urban canopy which is modelled as an interconnected streets network. The SIRANERISK model is so able to provide estimates of the mean and the standard dispersion of a passive scalar rejected during an accidental or deliberate release within an urban district. The resolution scale of order of the street length scale permits to produce detailed cartographies of pollutant concentration over a city that can help authorities.
Based on Gifford (1959) the modelling of concentration fluctuations in the SIRANERISK model has been presented and validated in a previous paper (Cierco et al, 2010). A new aspect has been implemented since last year to take into account the shear effects due to mean velocity gradients. This approach follows the work of Sykes and Henn (1995) and its efficiency is here evaluated by comparing SIRANERISK calculations to a Lagrangian particle model and to experimental results in realistic configurations. The Lagrangian particle model has been specially developed for comparison of dispersion over a flat ground. Experimental results have been obtained in the wind tunnel of Ecole Centrale de Lyon by measuring wind field and concentration of a pollutant due to a short release within an idealized district.

THE SIRANERISK MODEL

SIRANERISK is a model dedicated to pollutant dispersion over urban areas in unsteady situations due to unwished releases. It is formed of the coupling of a Gaussian puff model and a specific mass-consistent model that accounts for the dispersion of the pollutants inside the urban canopy. Previous version of the SIRANERISK model was presented by Cierco *et al.*(2010) and the latest implementations are shown by Lamaison *et al.* (2011).

The urban or street canyon model

In SIRANERISK, the urban canopy is modelled by a network of interconnected streets. Streets are simplified as parallelepiped boxes which can exchange mass of pollutant either with other streets or with atmosphere above the urban canopy. For each time step of calculation, meteorological parameters are computed and then air fluxes are determined for each street of the whole canopy. Subsequently, mass budget of each studied pollutant can be dressed (figure 1 and equation 1).

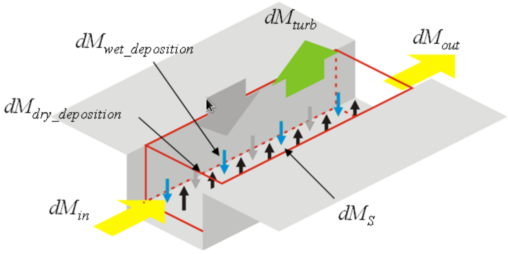

Figure 10: Mass budget in a canyon-street

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

Where M_{street} is the mass of pollutant in the street, $dM_{in}-dM_{out}$ is the mass budget due to air flow exchange with connected streets, dM_{turb} is the mass budget due to turbulent exchanges with atmosphere, dM_s is the mass of pollutant produced by sources within the street and the mass budget due to deposition are $dM_{dry\_deposition}$ and $dM_{wet\_deposition}$.

The Gaussian puff model

Above the urban canopy, the pollutant is transported thanks to Gaussian puffs whose concentration distribution is supposed to be known at release instant: a puff can of course be emitted by an explicit source but also at the roof level due to coupling with street canyon model. During time advancement of calculation, puffs are advected and diffused by the contribution of local meteorological effects. Mean velocity flow is responsible for advection whereas turbulent fluctuations cause diffusion. In SIRANERISK, the diffusion laws that govern the growth of concentration distribution standard-deviations are based on the Monin-Obukhov similitude theory of dispersion. Moreover the 2.0 version of SIRANERISK also takes into account shear of mean wind field which is crucial in evolution of longitudinal standard deviation. Tennekes and Lumley (1973) showed that pure shear $\frac{\partial U_x}{\partial z}=\eta=$ constant implies for $t \gg {}^1\!/_\eta$:

$$\sigma_x{}^2=\frac{1}{3}\eta^2 t^2\sigma_z{}^2 \quad \text{and} \quad \sigma_{xz}=\frac{1}{2}\eta t\sigma_z{}^2 \quad (2)$$

Following Sykes and Henn (1995), our model assigned a variance-covariance matrix at each puff. Temporally evolution of this matrix is governed by diffusion process as well as shear action. Due to the shear and the initial source geometry, the concentration distribution cannot be written as equation (2) and (3) of Cierco (2010) anymore. Details are provided in Lamaison (2011) and finally, the concentration distribution due to a punctual source is written:

$$C=\frac{\sigma_y}{\sigma_{x*}}\frac{M}{(2\pi)^{3/2}\,\sigma_y\sigma_y\sigma_z}\exp\left(-\frac{1}{2}\left(\frac{x^{**2}+y^2}{\sigma_y{}^2}+\frac{z^2}{\sigma_z{}^2}\right)\right) \quad (3)$$

where $x^{**}=x^*\frac{\sigma_y}{\sigma_{x*}}$, $x^*=x-zR_{xz}\frac{\sigma_x}{\sigma_z}$, $\sigma_{x*}=\sigma_x\sqrt{1-R_{xz}{}^2}$ and $R_{xz}=\frac{\sigma_{xz}}{\sigma_x\sigma_z}$. Main limitation of this approach is the fact that the shear η is assumed to be homogeneous at the puff length scale. Its height of evaluation z_s is chosen as a function of vertical spread and z_c, height of the puff mass centre:

$$z_s=\max(z_c, 0.65\sigma_z) \quad (4)$$

THE LAGRANGIAN PARTICLE DISPERSION MODEL

A Lagrangian particle dispersion model is used in this study. Particles are released in an analytically known turbulent flow. Both position and velocity of each particle are assumed to evolve as a Markov process. Position is computed from

$$dx_i=v_i dt \quad (5)$$

where **x** is the position and **v** the velocity which evolution is governed by the Langevin equation (Thomson, 1984) for each spatial component

$$\mathrm{d}v_i=-\frac{u_i}{T_L}\mathrm{d}t+\sigma_{u_i}\sqrt{\frac{2\mathrm{d}t}{T_L}}N(0,1) \quad (6)$$

where T_L is the lagrangian time, σ_{u_i} the standard deviation of the velocity and $N(0,1)$ the standard normal distribution function. Concentration in a non-zero volume area can easily be determined by summation of mass pollutant of each particle located inside this volume. Because each particle is advected by the local velocity, this model is well suited to represent the effect of mean wind shear on turbulent dispersion.

EXPERIMENTAL SET-UP

A campaign of measures has been performed in the atmospheric wind tunnel of Ecole Centrale de Lyon (Cierco *et al.*, 2010 and Nironi *et al.*, 2011). Four configurations were tested in this 14.0 m long, 3.8m wide and 2.0 m high tunnel : two roughs surfaces covered of roughness elements of 0.02m and 0.05m and an idealized urban area for two wind directions 30° and 45°, where streets height *H*, width *W* and length *L* are given by $H=W=L/5=5$cm. Figure 11 shows the wind tunnel with roughness elements at the ground.

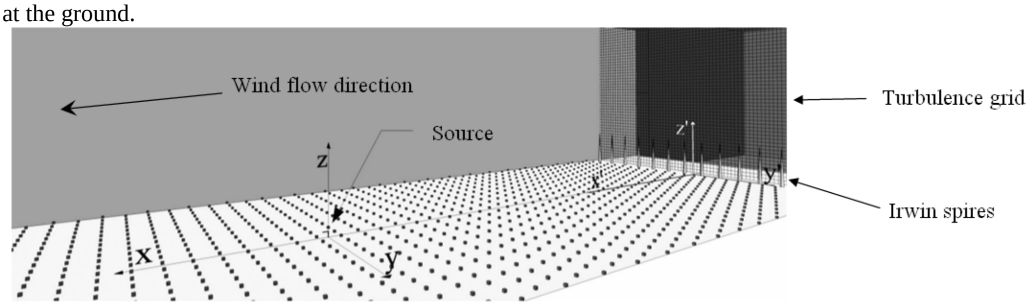

Figure 11 : Experimental set-up in the wind tunnel. XYZ : reference system of measures.

Experiments on rough surfaces will be named respectively by R20 and R50 and experiments on urban area by B30 and B45. Flow dynamics were investigated by measuring vertical profiles of mean and fluctuating wind velocities with hot wire anemometry. In each of these configurations, a short reproducible release of a tracer gas (ethane) has been performed and time evolution was recorded at different downstream locations. By reproducing 100 to 150 times the release, it comes possible to compute statistics of the puff behaviour. Concentrations were measured by a Flame Ionization Detector (FID).

Figure 12 shows a top view of B45 and B30 configurations. In grey appears the idealized block of buildings drawing a Cartesian streets network. Red crosses show some of measurement locations. For each location, measurements have been done within and above the canopy.

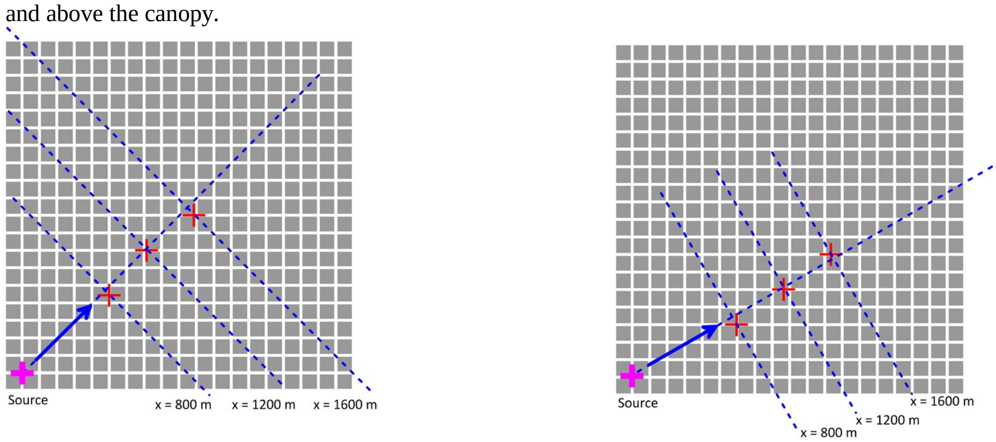

Figure 12: B45 (left) and B30 (right) configurations. Red marks: sensor. Purple mark: source. Blue arrow: wind direction

Figure 13 shows a typical temporally evolution of the pollutant concentration at a fixed point. For practical reasons of comparison between measurements and computations, three characteristic times are defined.Time of pollutant cloud arrival can be well estimated by t_{max} whereas $t_{upstream}$ and $t_{downstream}$ (corresponding to $C=Cmax/2$) are representatives of diffusion process.

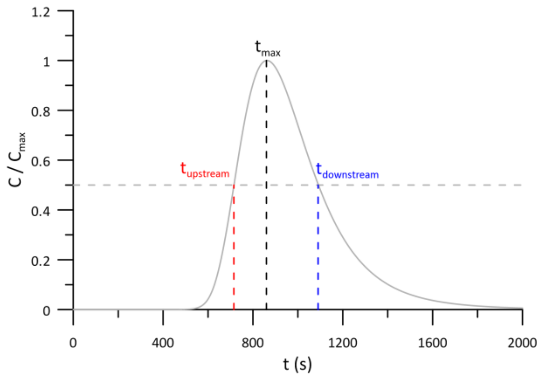

Figure 13 : Definition of characteristic times $t_{upstream}$, t_{max} and $t_{downstream}$ of a temporally evoluting normalized concentration.

COMPARISONS FOR ROUGH FLAT GROUNDS

Comparisons between computations with Lagrangian particle model and SIRANERISK model are presented here, for dispersion over rough flat grounds. An interesting point in this comparison is that the numerical implementation of both models allows us to impose exactly the same turbulent wind fields in the two compared computations. Moreover, it permits us to study the behaviour of a single puff over a flat ground in the SIRANERISK model without effects of complex interactions with other puffs or an urban canopy. It is of particular interest to be sure that the model reproduces correctly the main phenomena transport: advection by mean velocity field, dispersion by shear and turbulent diffusion and confinement due to solid walls. In calculations presented here, the release consists in 100 000 particles for the Lagrangian model and in only one single initially spherical puff for the SIRANERISK computation. Figure 14 shows isocontours of concentration at three different instants in the XZ cutting plane. It gives a quite good overview of puff advection by mean flow and of shear effects on puff dispersion. Qualitatively, these two effects are very well reproduced by SIRANERISK meaning that the global evaluation of advection velocity and amount of shear is relevant for puff in such situations.

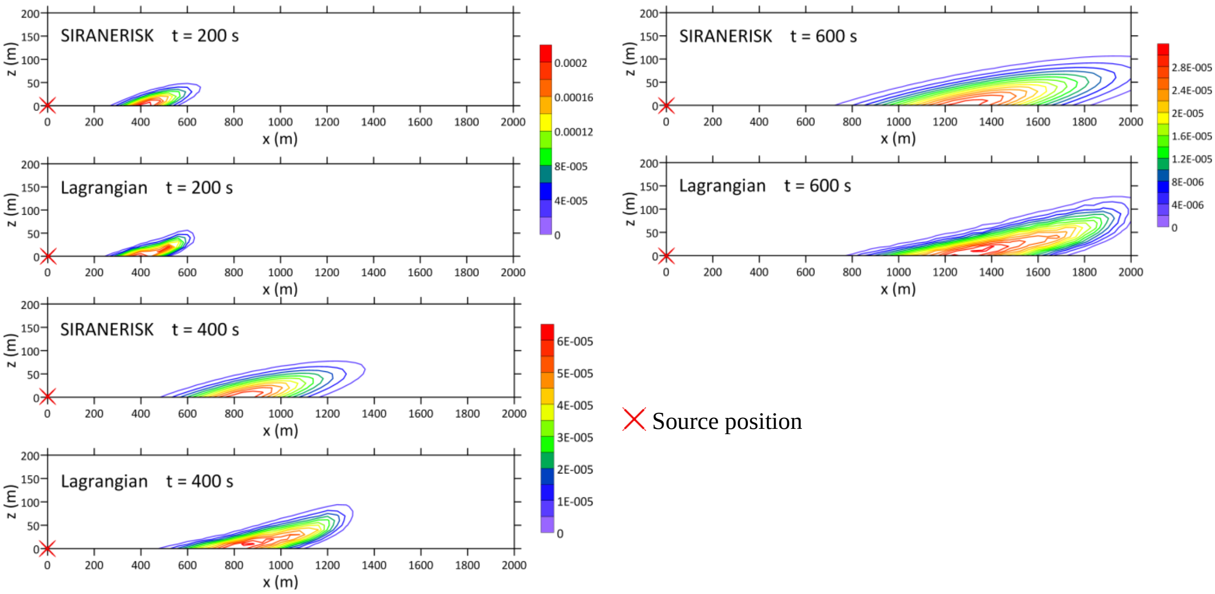

Figure 14 : Comparison of isocontours of concentration between a SIRANERISK and a Lagrangian particle in the R20 configuration.

Figure 15 and Figure 16 confirm quantitatively the good agreement between the two models. The SIRANERISK model is so able to well reproduce the evolution of unsteady releases above rough grounds even very far from the source point. Even it is not explicitly shown here, it’s also very interesting to notice the key role play by shear effects in the longitudinal diffusion process which seems much bigger than turbulence effects. It therefore appears crucial that shear has to be correctly taken into account in such situations.

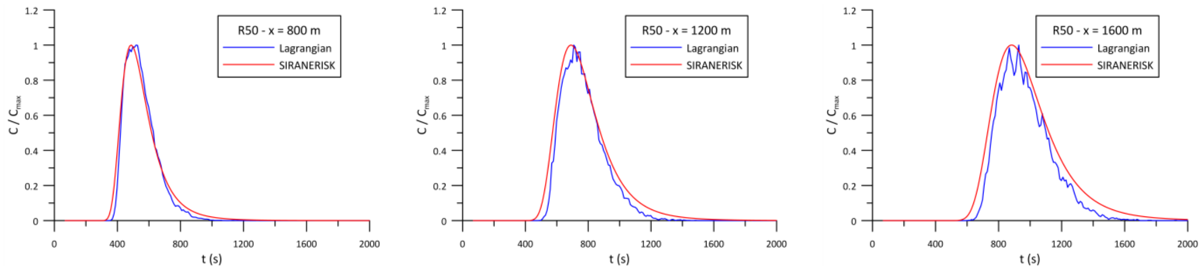

Figure 15 : Time evolution of normalized concentration at three downstream locations in the R50 configuration.

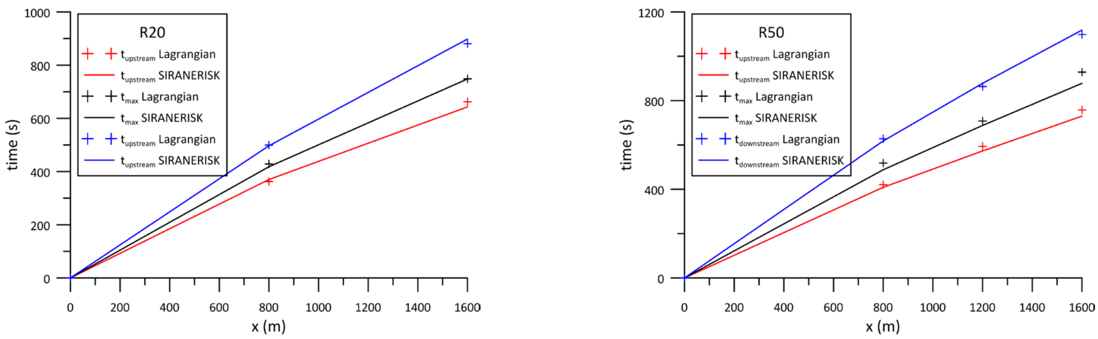

Figure 16 : Longitudinal evolution of characteristic times of concentration signal.

COMPARISONS FOR IDEALIZED STREETS NETWORK

The SIRANERISK model has exhibited a very good comportment in dispersion over rough grounds. The model also contains a specific representation of urban canopy effects and is compared in this part with experimental measures of the dispersion of an unsteady release within the canopy. Figure 12 shows the source and three sensors locations: measures of concentration have been performed within and above the canopy. In the SIRANERISK model, the short experimental releases have been reproduced by 200 successively released puffs (one puff released each second during 200 seconds). Figure 17 compares the three characteristic times for the two district configurations B30 and B45. In the two top pictures, sensors were above the canopy (at $z=3H/2$) and in the two bottom ones, sensors were in the canyon street (at $z=H/2$). Quick overview shows that characteristic times are much bigger within the canopy than above the roofs because the mean velocity is muche lower within the streets than over the roof level. In unwished toxic releases context, crisis management have to rely on model which well reproduce this kind of comportment to correctly and quickly react. Figure 17 also shows that arrival times are very well predicted by SIRANERISK both within and above the urban canopy. Whereas cloud transit time is slightly underestimated above the canopy in B45 configuration, model predictions are satisfying every where else.

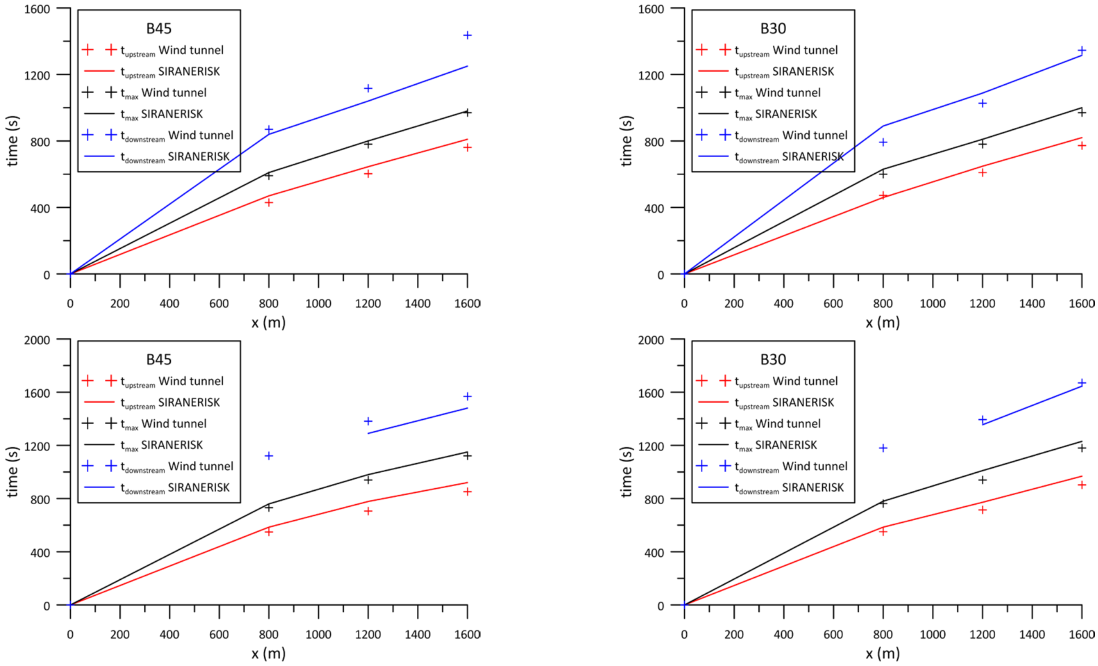

Figure 17 : Longitudinal evolution of characteristic times of concentration signal. Left: B30. Right: B45. Top: above the canopy. Bottom: in the canyon street.

CONCLUSION

We have compared our SIRANERISK dispersion model to Lagrangian particle model calculations and to experimental results obtained in our wind tunnel. This model was developed in Ecole Centrale de Lyon and is dedicated to crisis management after accidental or deliberate releases. Pollutant dispersion of an unsteady release within a turbulent neutral boundary layer has been tested in two configurations: roughs ground (R20 and R50) and idealized urban areas (B30 and B45). Comparison with Lagrangian particle model in the R20 and R50 showed that shear modelling in SIRANERISK by temporally varying a variance-covariance matrix for each puff is relevant. In particular, the choice of the evaluation’s height of a homogeneous shear for each puff is satisfying. Comparison with experimental results showed overall good agreement for pollutant cloud both arrival and transit times. These two quantities are crucial in a crisis management context, when authorities have to know very quickly when and where pollutant will impact a district and how long will the pollutant stay in the streets. We therefore conclude that our model is correctly answering to this problematic: despite the computations are fast, urban complexity and atmospheric shear effects are very well modelled.

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