INVERTING TIME DEPENDENT CONCENTRATION SIGNALS TO ESTIMATE POLLUTANT EMISSIONS IN CASE OF ACCIDENTAL OR DELIBERATE RELEASE

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Abstract:
We test the reliability of an inverse model to estimate the amount of mass released instantaneously by a source of pollutant in a turbulent boundary layer. To that purpose we use wind tunnel experiments simulating the dispersion of puffs due to the impulsive release of pollutant. For each of these emissions we recorded time dependent signals at fixed receptors. These single signals have been used as input data for an inverse dispersion model in order to evaluate its error in estimating the real emission of pollutant. The inversion has been also performed using the ensemble average of the 100 signals as input data. The comparison of both approaches allows us to discuss the reliability of an atmospheric dispersion inverse model in real situations.

Keywords: Inverse modelling, wind-tunnel experiments, short accidental release, deliberate release, risk management, atmospheric dispersion,

INTRODUCTION
Accidental releases of toxic substances due to industrial activities (Fukushima in 2011 and nuclear accidents in Saint-Laurent-des-Eaux, Loir-et-Cher, in 1966 and 1980 respectively) or terrorist actions (event of 11 September 2001 in the USA and the attacks in London and Madrid in 2005 and 2004) present a major risk for the humans and the environment. The management of the subsequent crisis requires a rapid identification of the position and the strength of the pollutant release source. This can be achieved by using inverse dispersion models, which simulates the dilution of an ensemble average of puffs in the atmosphere. A main limitation of this approach is that the concept of "ensemble average" is no more pertinent as we deal with short accidental or deliberate releases, since these represents a single realisation of the dispersion phenomenon. This study aims in evaluating the statistical properties of the errors obtained in applying an inverse model to real turbulent concentration signals in order to discuss the reliability of this approach for operational purposes.

WIND TUNNEL EXPERIMENTS

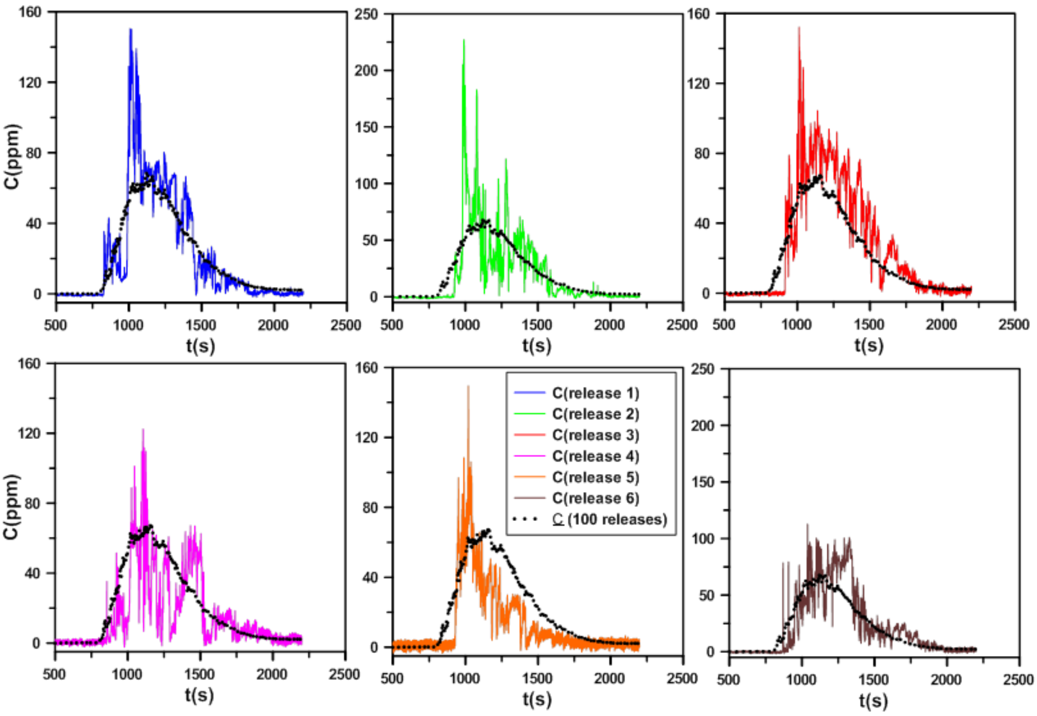

Fig.1. Comparison between the concentration measurements for six different realizations and the average concentration (dashed line) over 100 realizations in receptor located at coordinates (X= 1200m, Y=0, Z= 24m, X being the wind direction).

The experimental measurements used in this study are those presented by Cierco et al., (2009b) and carried within the wind tunnel of the Laboratoire de Mécanique des Fluides et d'Acoustique of the Ecole Centrale de Lyon. In the experiments we produced unsteady releases of a passive scalar (ethane) in a turbulent boundary layer over a rough surface. Time dependent signals of passive scalar concentrations were measured downwind the source at fixed positions by means of a Flame Ionisation Detector.

In the present study we used only the concentration profiles measured at a single receptor, located at a distance X=2m downwind the source. This corresponds to a real distance of 800m at the 1:400 scale. Examples of single signals are given in Figure 1. Each signal is compared with the mean time dependent concentration, obtained by an ensemble average over 100 signals.

THE DIRECT MODEL: SIRANERISK

SIRANERISK is an urban dispersion model for operational purposes. It is able to simulate the dispersion of a time dependent release in urban area, responding to crisis management constraints problem. SIRANERISK allows us to take into account the main effects controlling the dispersion of substances in a turbulent boundary layer as well as in district city, adopting the same parameterisations implemented in the model SIRANE (Soulhac et al., 2011).

The dispersion of pollutants into the overlying boundary layer flow is simulated by means of a Gaussian puff model that takes into account the effect of the mean velocity shear on the transfer and dispersion of the puffs. Details on the code and on its validation against wind tunnel experiments are presented by Cierco et al. (2010) and by Lamaison et al. (2011b). As an example, we show here some of the results obtained in a validation of the model in the case of a puff dispersion in a boundary layer flow over a rough surface. A comparison between model results and wind tunnel measurements is presented in Figure 1 and shows a good agreement between the two sets of data. Concentrations are expressed in a standard dimensionless form $K(x,y,z) = \frac{C U_{H_r} \delta^3}{M}$, where C is the measured mean concentration in kg.m^{-3}, $\delta(m)$ is the depth of the boundary layer, M is the mass released in kg and U_{Hr} is the velocity at height Hr = 0.025m.

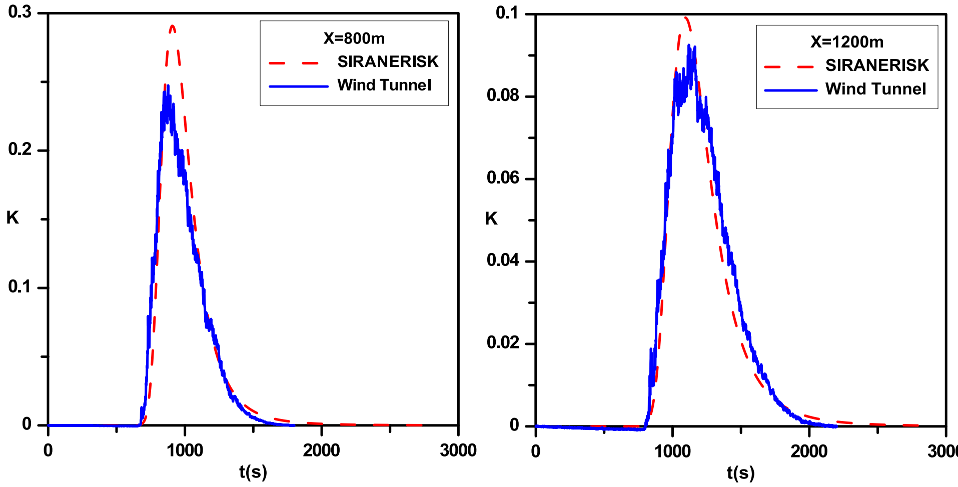

Fig. 2. Time evolution of non-dimensional concentrations at two different distances (X = 800m and X = 1200m) from the source. Comparison between experimental results (continuous line) and numerical results (dashed line).

INVERSE MODEL

The inverse model is the same as that presented by Ben Salem et al. (2013). It is conceived in order to identify the position and the strength of a pollutant source Q, taking advantage of the linearity with the concentration C observed at the receptors:

$$C\ (m,1)\ =\ ATC\ (m,n) * Q\ (n,1) \tag{1}$$

with **m** equations and **n** unknowns. **ATC** (Atmospheric Transfer Coefficient) is the mathematical operator that models the physical mechanisms that are responsible for the dilution of the concentration in the atmosphere, and is here computed by applying the code SIRANERISK.

The system (1) is here inverted by minimising a quadratic cost function of the error $\varepsilon = C - CTA * Q$

$$J = \frac{1}{2}\|\varepsilon\|^2 + 2\lambda\|DQ\|^2 \tag{2}$$

The cost function (2) includes a regularization parameter λ that is used to minimize the uncertainty due to the noise in the time dependent signal.

In order to estimate the regularization parameter we used an iterative algorithm using another cost function

$$\lambda = \arg\min_{\lambda \epsilon \mathbb{R}} \quad {}_{t_0}^{t_f} q^{true} * \Delta t - {}_{t_0}^{t_f} q^{est.} * \Delta t \qquad (3)$$

based on the comparison between the real mass of pollution used to validate SIRANERISK and the mass estimated with the inverse model using average concentrations measured in the wind tunnel. The value found of λ is 2.E-9. Generally, the algorithm is applied using m time dependent values of concentration in order to estimate n time dependent values of the source emission rate. An example of the results obtained inverting the ensemble averaged signal of concentration at a fixed receptor, with and without regularization parameter and for two different time steps of the source emission rate, is shown in Figure 3.

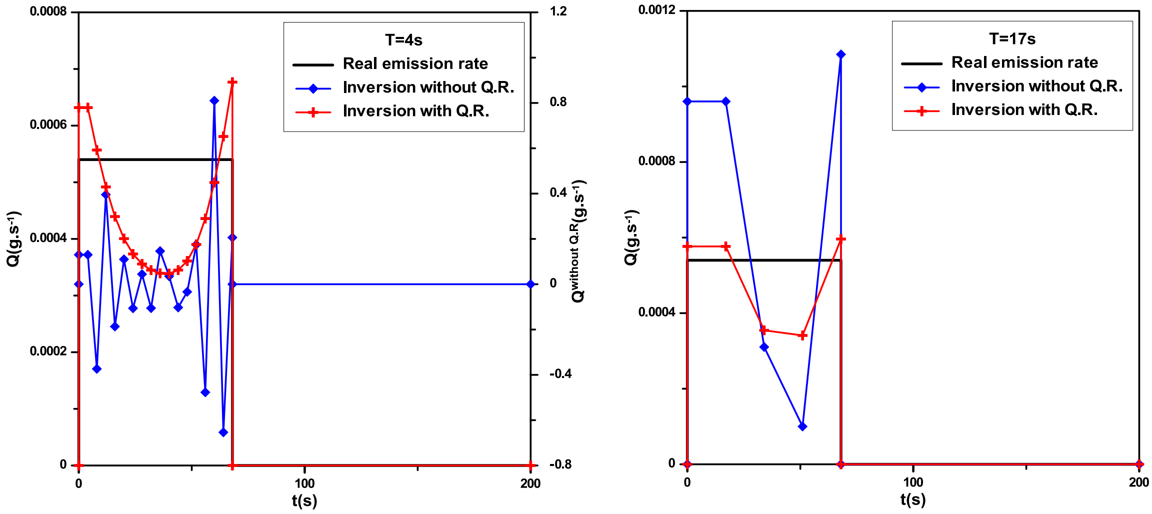

Fig. 3. Comparison between inversion with and without quadratic regularization (Q.R.) algorithm for cases T=4s and T=17s.

RESULTS

We evaluate the performance of the inverse model to estimate the mass of pollutant rejected by an impulsive emission using respectively the max relative error *Er* (3) and the relative error of mass quantities *Eq* (4):

$$Er(\%) = max \quad q_{True}^{t_i} - q_{est.}^{t_i} \quad * 100 \quad / q_{True}^{t_i} \qquad (3)$$

$$Eq(\%) = \quad {}_{t_0}^{t_f} q^{true} * \Delta t - {}_{t_0}^{t_f} q^{est.} * \Delta t \quad * 100 \quad / \quad {}_{t_0}^{t_f} q^{true} * \Delta t \qquad (4)$$

The error *Eq* allows global information for the quality of inversion because it represents only the difference between the inverted and true mass quantities. But the second error *Er* represents the local and instantaneous gap between signals i.e. it resumes the difference between the forms of the inverted and true signals.

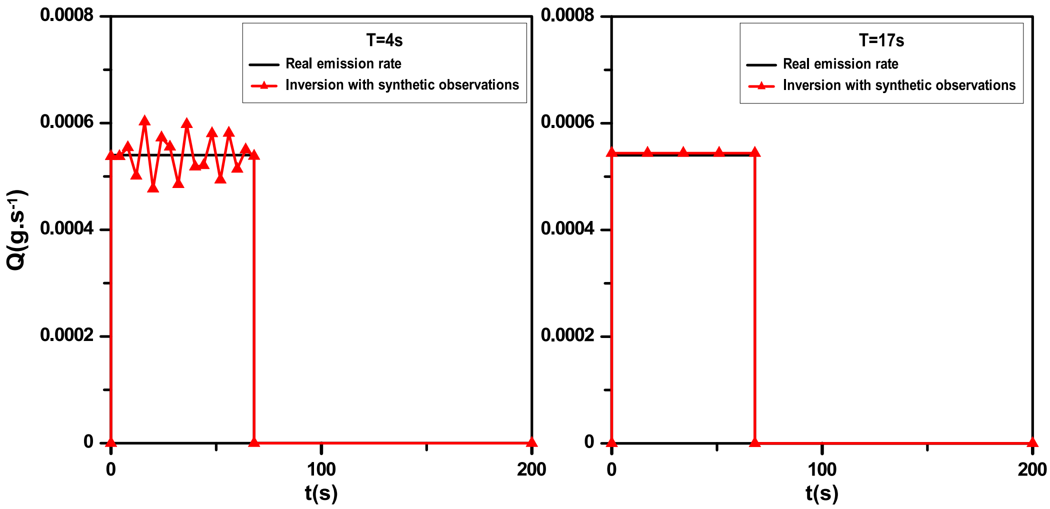

Fig. 4. Comparison between the real emission rate and the model results inverting the synthetic observations provided by SIRANERISK with different time steps.

Firstly, we use the synthetic observations provided by SIRANERISK as input for the inverse model, in order to validate its resolution algorithm. We show on Figure 4 some comparisons illustrating that the inverse code reproduces successfully the characteristics of the emission at the source with a relative error less than 13%.

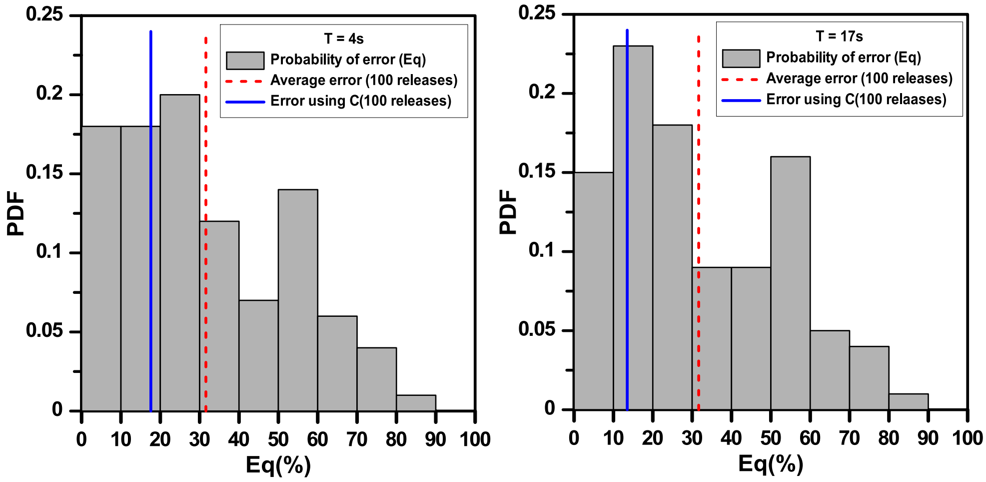

Fig.5. The PDF of the relative error of mass quantities. For example, the probability of an error *Eq* between 0% and 10% is 0.15 in the case T=17s. The continuous blue line presents the relative error of mass quantities estimated using an ensemble average over 100 signals.

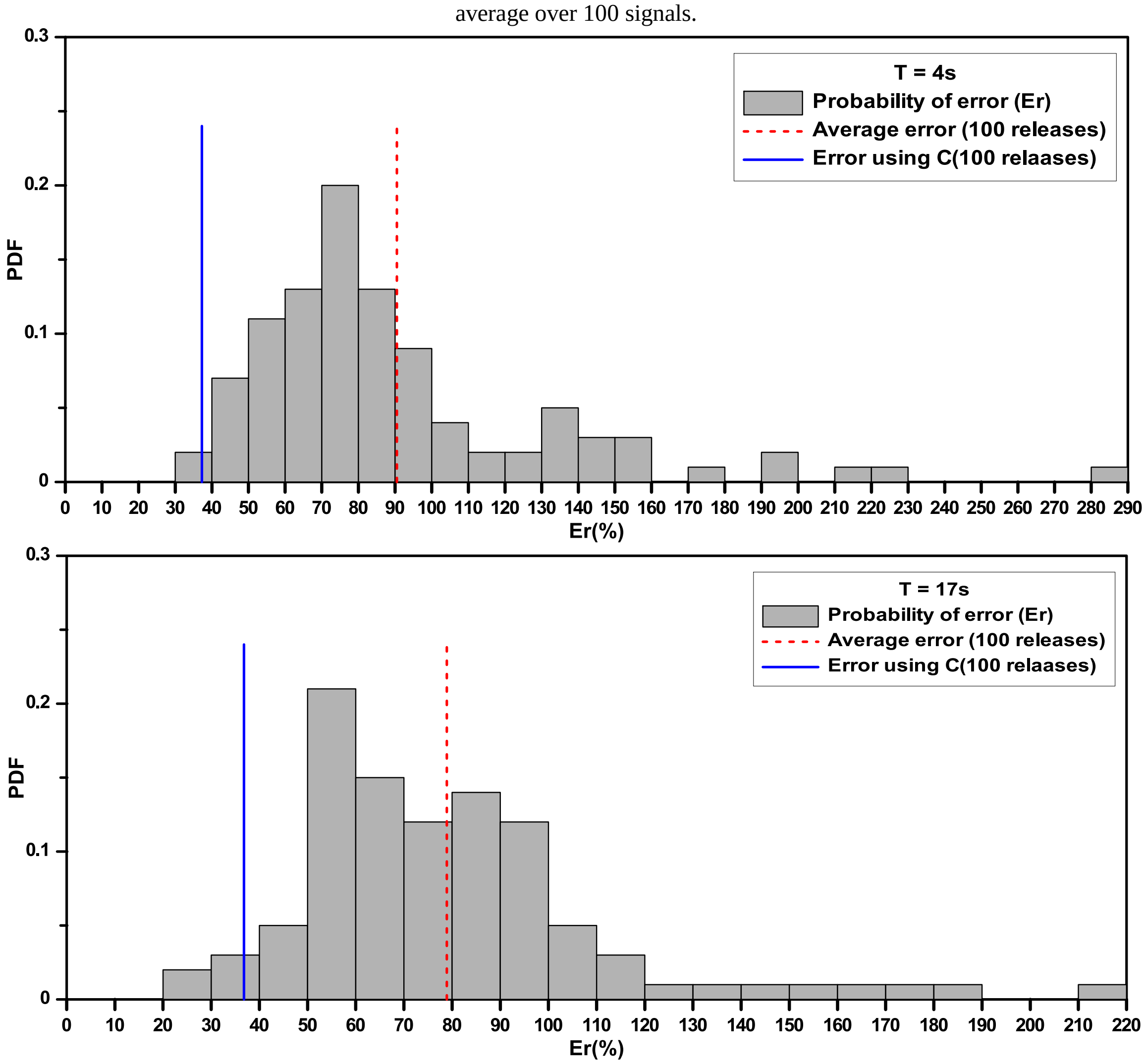

Fig.6. The PDF of the maximal relative error. Comparison between the maximal relative errors of inversion using an ensemble average over 100 signals (continuous blue line) and the average error of all releases (dashed red line).

We then consider the errors obtained inverting single experimental signals. Results are shown in Figure 5 and Figure 6 where we plot the pdf of *Eq* (Figure 5) and *Er* (Figure 6) obtained considering the statistics of the inversions of 100 signals. The pdf of both *Er* and *Eq* are estimated for different time steps for the discretisation of the source emission rate.

The relative error of mass quantities *Eq* does not exceed 90% (Figure 5) for any of the inverted signal. The average relative error of mass quantities is almost the same in two cases (T = 4s and T = 17s) but the average maximum relative errors are greater for T = 4s. This shows that the ability of the inverse model in determination the total amount of mass emitted does not depend on the time discretization. Conversely (Figure 6), the relative error *Er* can reach 286% in the case T = 4s and 213% in the case T = 17s. This shows that the choice of the time step is important if we want determinate the time dependence of the emission rate. With T = 4s, the error *Er* usually is greater than 30% and we have more than 25% of errors that exceed 100% (Figure 6) but in the cases T = 17s, we have more than 25% of relatives errors that does not exceed 60%.

These Figures 5 and 6 show that the reliability of the inversion is better using the ensemble averaged signal of measured concentrations. In fact, the relative error estimation of the mass quantities *Eq* and the maximal relative error *Er* do not exceed 20% and 40% respectively for both cases but the average of these errors results of inversion with the all releases signals (Figures 5 and 6 – dashed red lines) are greater than 30% (*Eq*) and 75% (*Er*) respectively.

CONCLUSIONS AND PERSPECTIVES

In this study we examined the reliability of an inverse model in reproducing the unsteady pollutant emissions from concentration signals recorded at fixed receptors. We have discussed the role of a quadratic regularization to reduce the effects of the noise in the signals and we tested our inverse code using synthetic concentrations provided by the direct model SIRANERISK.

The inverse model is shown to reliably estimate the total amount of mass emitted at the source. However the model has to face major difficulties when we aim in identifying the time variability of the emission. In the future, a sensitivity analysis will be completed in order to identify for different receptors the optimal time step, providing the lowest error in the estimate of the pollutant emission rate at the source.

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