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SIRANERISK: Modelling dispersion of steady and unsteady pollutant releases in the urban canopy

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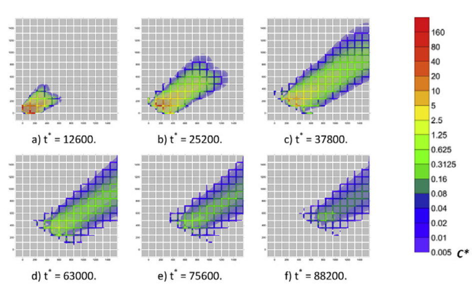
HIGHLIGHTS

- SIRANERISK is a new operational dispersion model for unsteady releases of pollutant within a built environment.
- The model is validated against wind tunnel experiments.
- SIRANERISK is a reliable tool to estimate effects of accidental releases of harmful pollutant.

GRAPHICAL ABSTRACT



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ABSTRACT

SIRANERISK is an operational model for the simulation of the dispersion of unsteady atmospheric releases of pollutant within and above an urban area. SIRANERISK is built on the same principles as the SIRANE model, and couples a street network model for the pollutant transfers within the urban canopy with a Gaussian puff model for the transfers above it. The performance of the model are here analysed by a detailed comparisons with wind-tunnel experiments. These experiments concern the dispersion of steady and unsteady pollutant releases within and above obstacle arrays with varying geometrical configurations, representing different topologies of idealised urban districts. The overall good agreement between numerical and experimental data demonstrates the reliability of SIRANERISK as an operational tool for the assessment of risk analysis and for the management of crises due to the accidental release of harmful airborne pollutants within a built environment.

1. Introduction

The release of toxic, flammable or explosive substances in the atmosphere is a major risk related to the occurrence of an accident or a terrorist act within an industrial site or a densely populated urban area. In both of these cases, the release of harmful pollutant is likely to be characterised by an unsteadiness of the source strength (short-duration release). In this case, the typical time scale related to the release is short compared to the characteristic time scale related to the advection (or to the turbulent diffusion) of the puff in

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the atmosphere. The evaluation of the consequences of the accidental releases in the surrounding areas requires estimating the temporal and spatial evolution of the pollutant concentration of the harmful substances, which determines the toxic effects on health or the risk of explosion. This is essential both for the risk assessment analysis and the crisis management. It is therefore necessary to model the atmospheric dispersion of the pollutants within a densely built environment, characterised by a complex geometry of the domain within which the dispersion process takes place.

Computational Fluid Dynamics (CFD) is widely recognized as the most suitable numerical tool to model the atmospheric dispersion of pollutant within a complex built environment (Blocken, 2015), as it permits simulation of the effects of the wide range of spatial scales characterizing geometry of the industrial sites and urban areas and influencing the dispersion process. However, CFD codes still require excessive computational resources when adopted as operational tools for crisis management in case of accidental (or deliberate) releases of harmful pollutants.

The need for a reduction of the computational costs led so far to the development of different modelling strategies (Di Sabatino et al., 2013). One approach is that provided by the so-called CFD-based fast response models. The computation of the velocity field is achieved by means of diagnostic models, based on a mass-consistent approach, or prognostic models, based on averaged (spatially or over time) formulations of the Navier-Stokes equations closed with simple algebraic models. Dispersion is simulated with an Eulerian or a Lagrangian approach. The most well-known models in this category are QUIC-URB (Brown et al., 2009) and MSS-Spray (Moussafir et al., 2004; Tinarelli et al., 2007) along with the principles first proposed by Röckle (1990).

An alternative approach relies in developing dispersion models based on a simplified description of the flow and dispersion and on the parameterisation of the main mechanisms driving pollutant dispersion within and above the urban canopy. Examples of this approach are given by ADMS-Urban (Carruthers et al., 2000) or SIRANE (Soulhac et al., 2011), which are both conceived to simulate steady releases. Among these 'simplified' dispersion models, as far as we are aware, the only one aiming at simulating the dispersion of unsteady releases within a built environment is the Urban Dispersion Model (UDM). This is basically an unsteady Gaussian puff model which is coupled with some empirically-derived formulae simulating the effects of building wakes on pollutant dispersion (Brook et al., 2003).

The aim of this paper is to present a new operational model for the atmospheric dispersion of airborne pollutant emitted by an unsteady source within a built environment. The model, named SIRANERISK, is built on the same principles as the SIRANE model and is based on the parameterisation of the main phenomena driving pollutant dispersion within and above an urban area, namely: dispersion over roof level, advection along street axes, dispersion at street intersections and vertical exchanges between street canyons and overlying atmosphere. Compared to SIRANE, the model has been modified in order to treat unsteady releases (§2). To give an overview of the model results, we present graphically in the abstract the time evolution of the simulated non-dimensional ensemble averaged concentration field induced by an impulsive pollutant emission within an idealised dense urban canopy (the same used in the experiments performed for the model validation and presented in the next sections). The figure shows the longitudinal and transversal spreading of the puff within the canopy, driven by the advective mass fluxes along the canyon axes and the transfers at the street intersections. The limited vertical mass exchange from the canopy to the atmosphere is made evident by the retention of pollutant within the streets that persists for time that exceeds a typical advective time scale of the puff. This kind of simulations on an idealised urban district requires only few minutes when run on a standard laptop. Concerning a real scenario case, the application of the parallel version of SIRANERISK on the whole city of Paris requires between 5 and 10 min (depending on the frequency at which concentration field are produced as a model output).

The model is validated against wind-tunnel experiments (§3) of passive scalar dispersion within and above idealised city districts, involving both steady and unsteady releases. A systematic comparison between experimental and numerical results allows us to discuss the advantages and the limitations of model (§4) and to draw some conclusions and perspectives to the model development (§5).

2. From SIRANE to SIRANERISK

SIRANERISK is an operational atmospheric dispersion model that is able to simulate the dispersion of an unsteady airborne pollutant release within and above the urban canopy. Based on the street-network approach (Belcher et al., 2015; Soulhac et al., 2013, 2011), SIRANERISK is built on the same principles as the model SIRANE and assumes a decoupling of the domain in two parts, the external boundary layer flow and the urban canopy (Soulhac et al., 2011). Mass transfer phenomena within the two sub-domains and between them are modelled by means of parametric relations, and namely:

- The pollutant dispersion above roof level (Soulhac et al., 2011);
- The advective transfer along the street axes (Soulhac et al., 2008);
- The transfer at street intersections (Soulhac et al., 2009);
- The trapping of the pollutant within the street canyons due to the recirculating motion within them and the exchange with the overlying boundary-layer flow (Soulhac et al., 2013).

Since the details of each of these parameterisations have been already presented in the papers cited above, in what follows we provide a very concise presentation of the basic modelling principle implemented in the model. For further details on the adopted parameterisation and the model structure the reader is referred to (Soulhac et al., 2011) and (Ben Salem et al., 2015). In order to simulate the dispersion of unsteady releases, the model presents two main differences compared to SIRANE:

- The dispersion above roof height is simulated by means of a Gaussian puff model (§2.1) that includes a module for the effects of wind shear on the longitudinal puff spread;
- The mass balance is computed over control volumes that can be smaller than that of a street canyon (§2.2) and whose size can be variable with time.

2.1. Flow and dispersion above the urban canopy

The velocity field above the urban canopy is modelled as an atmospheric boundary layer over a rough surface which has reached a dynamical equilibrium condition. Therefore the flow is assumed to be homogeneous in the horizontal plane so that the velocity statistics depend on the vertical coordinate only, and can suitably be modelled by means of similarity profiles. The temporal evolution of the pollutant concentration field induced by an instantaneous release (at $t = 0$) of a mass M of pollutant from a point source (of coordinates x_0, y_0, z_0) is simulated by a generalised Gaussian puff model of the form