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Optimizing the calculation grid for atmospheric dispersion modelling

S. Van Thielen [a, *], C. Turcanu [b], J. Camps [b], R. Keppens [c]

[a] KU Leuven, CIB, Celestijnenlaan 300, Box 2422, 3001 Leuven, Belgium
[b] SCK•CEN, Belgian Nuclear Research Centre, Boeretang 200, 2400 Mol, Belgium
[c] KU Leuven, Department of Mathematics, Celestijnenlaan 200B, 3001 Leuven, Belgium

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ABSTRACT

This paper presents three approaches to find optimized grids for atmospheric dispersion measurements and calculations in emergency planning. This can be useful for deriving optimal positions for mobile monitoring stations, or help to reduce discretization errors and improve recommendations. Indeed, threshold-based recommendations or conclusions may differ strongly on the shape and size of the grid on which atmospheric dispersion measurements or calculations of pollutants are based. Therefore, relatively sparse grids that retain as much information as possible, are required. The grid optimization procedure proposed here is first demonstrated with a simple Gaussian plume model as adopted in atmospheric dispersion calculations, which provides fast calculations. The optimized grids are compared to the Noodplan grid, currently used for emergency planning in Belgium, and to the exact solution. We then demonstrate how it can be used in more realistic dispersion models.

1. Introduction

Modelling of atmospheric dispersion is an important tool for the preparedness and response to nuclear emergencies. This helps assessing the potential health consequences for the people exposed to the radioactive plume, resulting from direct inhalation of radioactive particles, external irradiation from the plume or from its deposition to the environment. Atmospheric dispersion modelling may be used both in the preparedness phase, to simulate accident scenarios and draft emergency plans, as well as in a real situation. Advanced atmospheric dispersion models (ADM) form a key ingredient to operational crisis and emergency management consortia, such as the European Real-time On-line DecisiOn Support (RODOS) project (Raskob and Ehrhardt, 2000), or the ARGOS decision support system (Hoe et al., 2002) that originated from a Danish emergency management agency. At the beginning of this century, RODOS pilot and prototype versions (4.0) incorporated several atmospheric dispersion models like RIMPUFF (Mikkelsen et al., 1984; Thykier-Nielsen et al., 1999), ATSTEP (Pasler-Sauer, 2007) (for local scale, up to about 80 km), and MATCH (Robertson et al., 1999) (for far range modelling). ARGOS has also the RIMPUFF model as its main dispersion model. Recent intercomparisons of various ADM outputs (including RIMPUFF) with measured concentrations of radioactive noble gases reveal that they do well under steady wind conditions, but at mesoscale (several ten kilometres) distances, can underestimate peak concentrations especially also in varying wind conditions (Connan et al., 2013). RIMPUFF (the RIsø-Mesoscale-PUFF) model (Mikkelsen et al., 1984) computes how a series of puffs (with Gaussian profiles) gets advected, diffused and deposited according to local weather conditions, in a Lagrangian fashion. MATCH (Robertson et al., 1999) exploits a Eulerian approach which has evolved to a full 3D model for transport and chemistry, taking weather data from numerical weather prediction tools. In Eulerian approaches, one may need to combine dispersion models with some way of adaptive grid functionality, such that the continuously moving and deforming contaminated regions are treated at high resolution. Grid adaptive approaches can save computational resources, as has been demonstrated in a variety of physics contexts (e.g. Keppens et al., 2003, 2012), including the one of pollutant dispersion (Lagzi et al., 2004).

In order to be effective in an emergency situation, the models used should be both precise and fast, allowing nearly real-time updates of the existing situation and predictions of its potential evolution. The requirement for precision stems from the need to verify if triggering thresholds for the application of protective actions (e.g. sheltering) are exceeded. In addition, in case of large scale contaminations, non-contaminated areas should be delimited as precisely as possible, to allow an optimal allocation of resources.

* Corresponding author.
E-mail address: sofie.vanthielen@kuleuven.be (S. Van Thielen).

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Models currently used for decision-support in nuclear emergency situations (Raskob and Ehrhardt, 2000; Hoe et al., 2002) report the calculation results in an a priori determined fixed number of points, either on rectangular (e.g. Pasler-Sauer, 2007; Raskob and Ehrhardt, 2000) or on polar grids (Camps et al., 2010), with a fixed cell size or telescopic grid.

Naturally, model predictions have to be complemented by measurements. Predictions are useful since they cover a large area and can help directing and protecting measurement teams, whereas measurements give accurate assessments of the concentration of pollutants in air or deposited on the environment. European countries have developed their own fixed monitoring systems as part of their emergency plans. In addition to these, mobile units can be used, that can be placed before or during the release in order to get an as accurate as possible assessment of the situation. Finding optimal places for the mobile stations is of particular interest when a nuclear emergency occurs.

One of the most recent European projects, DETECT (Astrup et al., 2012), which stands for 'Design of optimized systems for monitoring of radiation and radioactivity in case of a nuclear or radiological emergency in Europe', optimized the design of the fixed monitoring stations (see Helle et al., 2011). In our paper we focus on the optimization of the positions of the grid points that are considered by the atmospheric dispersion model, based on current local weather conditions. This can be useful for two purposes. First, the methodology can be used to derive optimal positions for the mobile monitoring stations. These stations would be additional to the fixed ones that take measurements continuously. Second, it can resolve certain discretization problems. Recommendations derived from atmospheric dispersion calculation are noticeably sensitive to the calculation grid. Running the model under the same conditions but using another grid could affect the recommended countermeasures. For instance, suppose that the calculation results are reported only in the centre of each 1 km sized cell on a rectangular grid. If the cell is located towards the edge of the plume, characterized by a higher gradient of the concentration of radioactive particles, the centre of the cell might be located outside the most contaminated area of the cell and accordingly may lead to an advice that countermeasures are not necessary. The purpose of our paper was to develop a methodology that helps reducing this effect. Clearly, using an extremely fine grid would allow to capture all necessary information accurately, but this may be unacceptable from a computational point of view in case of a real emergency. Hence, optimization of the location of the calculation points is envisaged. In the current work, three different approaches are developed. The main focus is capturing the maximal concentration levels and the spatial integral of the concentration. These are two quantities that are directly related to application thresholds of countermeasures. For convenience sake, the classical Gaussian plume model, which is fully described by analytical expressions, is used to evaluate the spatial distribution of the concentration. We verify its usefulness for more realistic scenarios by including a case based on actual RIMPUFF data.

The rest of the paper is organized as follows. First, the model setup is explained starting by defining the underlying model and the model parameters necessary for the simulations later. Section 3 describes the optimization problem in terms of its objective function and suitable constraints. In the following section, an appropriate solution is given for the optimization problems, followed by a practical example. Section 4 makes a comparison between the different optimal models. Improvements are presented in Section 5, where a more realistic model is used. All calculations performed in this article are executed using the mathematical software Matlab (MATLAB, 2010).

2. Model setup

2.1. Underlying model

The atmospheric dispersion model used in the following is the Gaussian plume model. Although it makes several simplifying assumptions, the fact that it renders fast calculations possible makes it suitable for use in emergency situations, at least on short ranges (up to several tens of kilometres), while it is also a simple model used on longer ranges for continuous releases during regular operation of power plants. The Gaussian plume model assumes that the air pollutant dispersion follows a Gaussian normal distribution. The Gaussian, time integrated concentration (measured in Bq s/m^3) in any point in the 3D space, is given by:

$$C(x,y,z) = \frac{Q}{4\pi u\sigma_y\sigma_z}\cdot\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\cdot\left(\exp\left(\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)\right). \quad (1)$$

where σ_y and σ_z (in units of m) are the Gaussian standard deviations in the y- and z-direction, u (in units of m/s) is the wind velocity, assumed constant in time and lying on the x-axis, H (in units of m) is the emission height and Q (in units of Bq) is the total emission of radioactive material. For derivation of the above equation, see Zannetti 1990 and Stockie 2011.

The directional standard deviations σ_y and σ_z are calculated based on the Pasquill–Gifford stability class, and given by the formula

$$\sigma_y = \sqrt{\frac{2xK_y}{u}},\ \sigma_z = \sqrt{\frac{2xK_z}{u}}.$$

K_y and K_z are eddy diffusivities, which give an indication on the atmospheric conditions. There are numerous ways to choose their values, e.g. Brookhaven sigma's (see Zannetti, 1990). These sigma's differ depending on the meteorological condition and are divided into six categories (A–F), where A corresponds to extremely unstable and F corresponds to very stable. In our study, Pasquill–Gifford sigma's are implemented for the neutral stability class. Concrete, this implies that

$$\sigma_y = 0.0787\frac{x}{(1+0.0014x)^{0.135}} \text{ and}$$
$$\sigma_z = 0.0475\frac{x}{(1+0.0014x)^{0.465}},$$

with x (in units of m) the distance on the x-axis.

2.2. Model parameters

For the simulations performed subsequently, the parameters in Equation (1) have been chosen as follows. The emission height H is assumed to be 50 m, which is a typical stack height from which the radioactive plume is released. The Pasquill–Gifford stability class is taken as neutral, hence it equals stability class D. The wind velocity is chosen as 5 m/s. The total emission Q is assumed equal to 10^{15} Bq. Measurements are mostly performed at ground level, which implies that $z = 1$ m, such that the concentration as given in Equation (1) is only dependent on the x and y coordinates.