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Screening sensitivity analysis of a radionuclides atmospheric dispersion model applied to the Fukushima disaster

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HIGHLIGHTS

- We analysed the sensitivity of radionuclides dispersion after the Fukushima disaster.
- Winds and source-term related inputs are the most influential.
- Clouds characteristics and horizontal diffusion have a very weak influence.
- We assessed the inputs probability distributions with gamma dose rate observations.

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ABSTRACT

Numerical models used to forecast the atmospheric dispersion of radionuclides following nuclear accidents are subject to substantial uncertainties. Input data, such as meteorological forecasts or source term estimations, as well as poorly known model parameters contribute for a large part to this uncertainty.

A sensitivity analysis with the method of Morris was carried out in the case of the Fukushima disaster as a first step towards the uncertainty analysis of the Polyphemus/Polair3D model. The main difficulties stemmed from the high dimension of the model's input and output. Simple perturbations whose magnitudes were devised from a thorough literature review were applied to 19 uncertain inputs. Several outputs related to atmospheric activity and ground deposition were aggregated, revealing different inputs rankings. Other inputs based on gamma dose rates measurements were used to question the possibility of calibrating the inputs uncertainties.

Some inputs, such as the cloud layer thickness, were found to have little influence on most considered outputs and could therefore be safely discarded from further studies. On the contrary, wind perturbations and emission factors for iodine and caesium are predominant. The performance indicators derived from dose rates observations displayed strong sensitivities. This emphasises the share of the overall uncertainty due to input uncertainties and asserts the relevance of the simple perturbation scheme that was employed in this work.

1. Introduction

Numerical simulations of the atmospheric dispersion of radionuclides are used during the early stages of nuclear accidents as input to the decision making. They also provide a valuable complement to field measurements for the long term assessment of environmental and sanitary impact, as illustrated by the cases of the Chernobyl and Fukushima disasters.

The meteorological fields fed into the model are typically issued from operational forecasts by meteorological models and involve substantial uncertainties. The source term itself is also subject to high uncertainties, even several years after the accident. For instance, several estimations of the atmospheric release induced by the Fukushima Daiichi power plant have been proposed after the crisis with the help of environmental data (see for instance Terada et al., 2012; Stohl et al., 2012; Saunier et al., 2013; Winiarek et al., 2014). Despite the amount of field measurements, and the better understanding of the installation events, the range of variation in these source terms show that the knowledge of the release rate and kinetics is still partial and uncertain. Other important sources of

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uncertainty lie in the dry deposition, the wet scavenging, the computation of the vertical diffusion coefficient, and possibly the numerical schemes for the integration of the transport equations.

All these elements have an influence on the output of the model and induce uncertainties which undermine predictions solely based on a deterministic approach. The present study is a first step in an effort to account for uncertainties of the Polyphemus/Polair3D model in predicting the dispersion of an accidental release of radionuclides in the atmosphere. It is difficult to study the model in a fully generic context because its input include complex spatio-temporal fields. The case studied here is the atmospheric release of radionuclides following the Fukushima Daiichi disaster.

Below is a rough outline of how the uncertainty characterisation could be carried out:

1. Determine the main sources of uncertainty and select the input variables to the model that adequately represent them.
2. Define model output variables relevant to crisis management or long-term impact evaluation.
3. Model the uncertainty of each input variable by a random variable with given probability distribution.
4. Propagate the uncertainty with a Monte Carlo scheme by sampling from the probability distributions built at step 3.
5. Use available observations to assess the choice of input variables and calibrate the associated uncertainty models.

This process may be iterated until the output uncertainty is consistent with available observations.

There are several issues that arise when dealing with detailed environmental models which are often of high dimensionality and computationally demanding. The raw outputs of the dispersion model are spatio-temporal fields of radionuclides concentrations or gamma dose rates. Simply constructing confidence intervals for each species at each time step and location would be fastidious and weakly informative. In addition, ignoring spatio-temporal correlations is likely to deteriorate the uncertainty estimates, a fact that geostatisticians or practitioners of data assimilation are familiar to. Hence, step 2 of the procedure above can be seen as a problem of dimension reduction. The objective of this step is to derive new model outputs of sufficiently low dimension to allow for computation and interpretation while preserving most of the information carried by a spatio-temporal analysis.

Step 3 is particularly challenging when complex inputs, such as meteorological fields, are involved. High dimensional inputs are indeed difficult to handle, especially when they display spatial correlation, temporal correlation or singularities that are structurally characteristic of the physical phenomenon at hand. Precipitation fields for instance are made of patches of varying shape that appear, deform and move over time, which cannot be modelled by a simple probability distribution. The emitted amount of a given species seen as a time series displays strong auto-correlation but also very temporally localised peaks. Additionally, several fields are constrained by physical relations, such as wind fields that need to satisfy the continuity equation. The choice of input variables and their uncertainty description are set out in Section 4.

Given these difficulties, the observations mentioned in step 5 are an invaluable assessment tool. They may intervene for instance to ensure that no major source of uncertainty was left aside or to appreciate the quality of the input uncertainty descriptions.

The details of step 4 will be relevant when the actual problem of uncertainty analysis will be tackled. For now, the present paper deals with *sensitivity* analysis, an approach differing in its objectives, but related to uncertainty quantification (Saltelli et al., 2008). The rationale for this preliminary step is that undertaking the issues evoked above all at a time seemed too complicated. The generic motive of sensitivity analysis is to quantify the relative influence of a set of inputs on the output of a model. The method employed here and detailed in Section 3 belongs to the *screening methods* category which aims at classifying input variables into influential and negligible with a view of reducing the computational burden for further studies by setting aside those of smaller influence. While the focus is clearly on step 1 of the procedure given above, this work constitute a starting point in the reflection upon the subsequent problem of uncertainty quantification, especially steps 2 and 3 but also step 5, as will be seen in Section 5.4. The results of the sensitivity analysis are presented in Section 5.

2. Polyphemus/Polair3d

The atmospheric dispersion of the radionuclides is carried out with the air quality modelling system Polyphemus (Mallet et al., 2007) and its Eulerian transport model Polair3D. Polair3D is essentially a numerical solver for a system of 3D advection–diffusion equations. The equation of this system for a given radionuclide denoted by a subscript r reads

$$\frac{\partial c_r}{\partial t} + \mathrm{div}(\boldsymbol{w} c_r) = \mathrm{div}\left(\rho \mathbf{K} \nabla \frac{c_r}{\rho}\right) - \mathbf{F}\boldsymbol{c} + E_r - \Lambda c_r, \tag{1}$$

where c_r is the concentration in the air, $\boldsymbol{c}$ the vector of the concentrations of all considered radionuclides linked a matrix $\mathbf{F}$ of decay coefficients, $\boldsymbol{w} = (w_u, w_v, w_z)^T$ the wind velocity, ρ the air density, $\mathbf{K}$ the turbulent diffusion matrix assumed to be a diagonal matrix with diagonal (K_u, K_v, K_z), E_r is the emission source term and Λ the scavenging coefficient. On the ground, the boundary condition reads $\rho \mathbf{K} \nabla c_r / \rho \cdot \boldsymbol{n} = v_d c_r$, where $\boldsymbol{n}$ is the normal to ground oriented towards higher altitudes and v_d is the deposition velocity.

The equation is solved using first-order operator splitting, with diffusion integrated after advection. The advection scheme is a third-order direct-space-time scheme with flux limiting (Verwer et al., 2002). The spatial resolution is 0.125° and the numerical time step is 10 min. The simulations are carried out with 10 vertical layers, whose centre altitudes are 20 m, 100 m, 220 m, 340 m, 500 m, 700 m, 1000 m, 1500 m, 2200 m and 3000 m.

3. Morris method for sensitivity analysis

Sensitivity analysis is the study of how variations in the inputs of a model affect its outputs. Here, the word *model* refers to any deterministic process that can be associated to a mathematical application mapping a set of input variables to one output value. The case of multivariate outputs is usually handled one variable at a time.

Local sensitivity analysis is concerned with the response of the model in the vicinity of a reference point. In this respect, it pertains to Taylor expansion and derivatives approximation. Should the model response be resolutely non-linear, extrapolation of the local sensitivity measures to regions far from the reference point are likely to be seriously flawed (Saltelli and Annoni, 2010). By contrast, *global* sensitivity analysis aims at estimating the relative importance of the inputs over their whole domain of variation.

Another desirable feature of a sensitivity analysis method is its ability to estimate *interactions*. Interactions are effects that appear when two or more inputs vary simultaneously. For instance, variations in the wind direction or delays in emissions can induce the plume to avoid a rain event at some location, which may remove any sensitivity to the rain intensity at the given location. The rain intensity is therefore in interaction with the wind and the emissions. Our purpose here is to sieve the inputs and eliminate the least influential from further studies. In this context, estimating