ESTIMATION OF THE CESIUM-137 SOURCE TERM FROM THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANT USING AIR CONCENTRATION AND DEPOSITION DATA

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Abstract

A major difficulty when inverting the source term of an atmospheric tracer dispersion problem is the estimation of the prior errors: those of the atmospheric transport model, those ascribed to the representativeness of the measurements, the instrumental errors, and those attached to the prior knowledge on the variables one seeks to retrieve. In the case of an accidental release of pollutant, and especially in a situation of poor observability, the reconstructed source is very sensitive to these assumptions. This sensitivity makes the quality of the retrieval dependent on the methods used to model and estimate the prior errors of the inverse modeling scheme.

In order to use all the available data, we propose to extend the methods developed in Winiarek et *al*. (2012), which were designed for the inversion of one type of data, to the use of several types of data in the same inversion, such as activity concentrations in the air and fallout measurements. The idea is to simultaneously estimate the prior errors related to each dataset, in order to fully exploit the information content of each one. Using the activity concentration measurements, but also daily fallout data from prefectures and cumulated deposition data over a region lying approximately 150 km around the nuclear power plant, we can use a few thousands of data in the inverse modeling algorithm to reconstruct the cesium-137 source term. As expected, the different methods yield closer results as the number of data increases. The updated cesium-137 releases are estimated to be in the range 12 – 19 PBq, with a std. of 15 – 25 %, depending on the methods and the data sets used in the inversion.

Key words: Data assimilation, Atmospheric dispersion, Fukushima accident, Source estimation.

METHODOLOGY

The inverse modeling algorithm is based on the minimization of the cost function

$$J(\boldsymbol{\sigma}) = \frac{1}{2}\left(\mathbf{H}\boldsymbol{\sigma} - \boldsymbol{\mu}\right)^T \mathbf{R}^{-1}\left(\mathbf{H}\boldsymbol{\sigma} - \boldsymbol{\mu}\right) + \frac{1}{2}\left(\boldsymbol{\sigma} - \boldsymbol{\sigma}_b\right)^T \mathbf{B}^{-1}\left(\boldsymbol{\sigma} - \boldsymbol{\sigma}_b\right) \qquad (1)$$

$\boldsymbol{\sigma}$ represents the source vector (to be reconstructed), $\boldsymbol{\mu}$ the observation vector and $\mathbf{H}$ is the jacobian matrix of the Atmospheric Transport Model (ATM) which is linear in this context. $\boldsymbol{\sigma}_\mathbf{b}$, called the background term in the data assimilation terminology, is the first guess of the source term. In an accidental context like the Fukushima accident and to ensure the independence of our estimation, we choose $\boldsymbol{\sigma}_\mathbf{b} = \mathbf{0}$.

R is the observation error covariance matrix defined by

$$\mathbf{R} = E\left[\left(\mathbf{H}\boldsymbol{\sigma} - \boldsymbol{\mu}\right)\left(\mathbf{H}\boldsymbol{\sigma} - \boldsymbol{\mu}\right)^T\right] \qquad (2)$$

and **B** is the background error covariance matrix

$$\mathbf{B} = E\left[\left(\boldsymbol{\sigma} - \boldsymbol{\sigma}_b\right)\left(\boldsymbol{\sigma} - \boldsymbol{\sigma}_b\right)^T\right]. \qquad (3)$$

In an accidental context, where the number of observations is low, the reconstructed source term and its uncertainty is sensitive to the matrices **R** and **B**.

In the case where one type of data is used in the inversion, one simple choice is to assume that these matrices are diagonal. In this case one has to estimate two scalars (called hyper-parameters): r^2 the observation error variance and m^2 the background error variance. In Winiarek et al. (2012) we proposed different methods to estimate these two hyper-parameters that we applied to the reconstruction of the cesium-137 and iodine-131 source terms from the Fukushima Daiichi accident using activity concentrations in the air. The total released activities were estimated to be 12 PBq for cesium-137 and in the range 190 – 380 PBq for iodine-131. These estimations were considered as lower bounds of the true releases, because the meteorological situation and the low number of observations did not allow to reconstruct the source term in all the time windows. That is why a method that would allow to use as many data as possible in the same inversion is needed.

In the case where several types of data are used in the inversion, one has to estimate a variance corresponding to each data set and a variance for the background errors, i.e. $N_d + 1$ hyper-parameters where N_d is the number of data sets. In Winiarek et al. (2013) we propose the extension of the methods developed in Winiarek et al. (2012) to the simultaneous estimation of prior errors parameters of several types of data.

The key point of the methods is that the prior error variances are simultaneously estimated, hence the information content in the system is well balanced. A bad estimation of prior errors would lead the algorithm to be over-confident in a data set or in the first guess and being ineffective to perform an accurate reconstruction of the source term.

We applied these extended methods to the reconstruction of the cesium-137 source term from Fukushima Daiichi using three data sets : the activity concentrations in the air, daily measurements of fallout and measurements of total deposited cesium-137. We also considered averaged data for the third data set which is very densely distributed. Posterior uncertainties were also computed through a Monte-Carlo analysis. This estimation is only possible once the prior errors have been properly estimated.

The total released activities are now estimated to be in the range 12 – 19 PBq with a std. in the range 15 – 25 %. The “blind” time windows where the uncertainty remains high have been largely reduced compared to the inversion with only one data set.

The absolute magnitude of the peaks should still be considered carefully, especially the peak on 25 March, which is clearly over-estimated in the reconstructed source. This is the consequence of an under-constraint of the system, probably due to the lack of data with direct information on time (activity concentration in the air or daily measurements of fallout) before March 18. Nevertheless the instant of release and the total released activity are perfectly consistent with in-situ observations and other estimations, proving the abilities of the data assimilation algorithm.

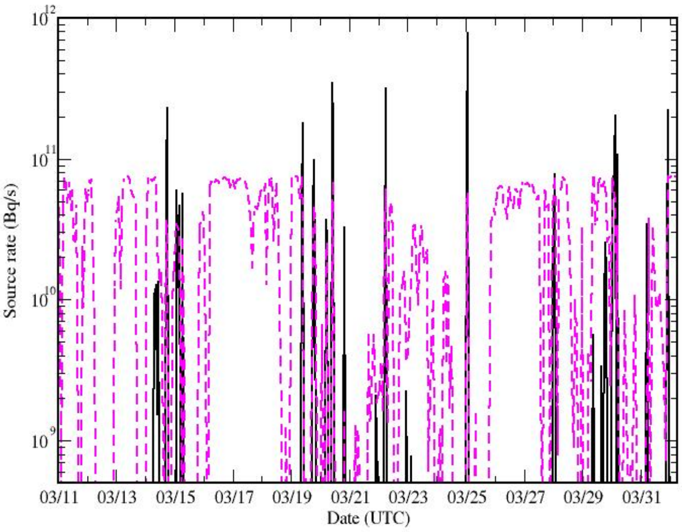

Figure 1. Full line: Reconstructed source of cesium-137 using three data sets: activity concentrations in the air, daily measurements of fallout and raw measures of cumulated deposition of cesium-137. Dashed line: Related uncertainty computed via a Monte Carlo analysis.

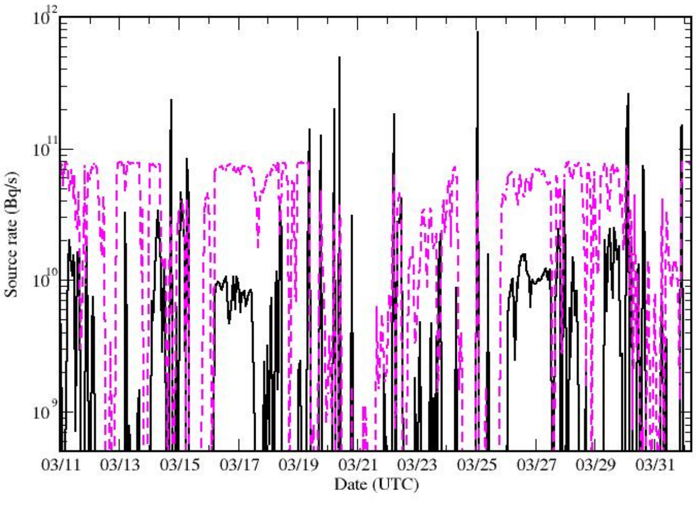

Figure 2. Full line: Reconstructed source of cesium-137 using three data sets: activity concentrations in the air, daily measurements of fallout and averaged measures of cumulated deposition of cesium-137. Dashed line: Related uncertainty computed via a Monte Carlo analysis.

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