Evaluation of Expected Consequences of a Nuclear Power Plant Accident using Sequential Monte Carlo

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Introduction

We are concerned with probabilistic evaluation of consequences of an incident for support of appointed decision makers. Specifically, we consider scenario with an accidental release of radioactive material from a nuclear power station into the atmosphere. In such a case, the decision makers are expected to make decisions about possible countermeasures such as iodination or evacuation of the population. Key information that needs to be available in these situations are expected consequences of the release. For example, the expected map of the area where the absorbed radiation dose exceeds a predefined limit. Many existing software tools are capable of computing such estimates, however, most commonly in a deterministic way. In this paper we advocate the use of Bayesian approach, where all potential consequences are treated as random variables. Specifically, we focus on the sequential Monte Carlo techniques that represent all potential future realizations of the situation by a set of deterministic possibilities (called the particles). We show that this representation allows to answer various questions required by the decision makers.

Since we focus on the very early phase of a radiation accident, the proposed algorithm is supposed to work in a fully autonomous regime without any supervision. We demonstrate that such a tool can use the radiation measurements provided by a radiation monitoring network and significantly improve predictions of radiation situation by the means of data assimilation process. The system on-line gathers data from all the receptors around nuclear facility, combines it with forecast given by an atmospheric dispersion model and thus gradually improves the estimates of radiation situation. The system based on advanced methods of Bayesian filtering is capable of providing probabilistic answers regarding the release and its consequences, e.g. estimates of affected number of people and probability distributions of doses in inhabited areas. Moreover, the algorithm can be also used in the off-line regime, when it allows to address complex tasks such as positioning of measuring devices in order the maximize their usefulness in case of a release.

In this paper, we introduced parametric models for both the release dynamics and the meteorological forecast. Parameters of these models are assimilated together with spatial distribution of the release. Realistic model of available dose measurements from an existing radiation monitoring network was created.

Numerical experiment

The algorithm and its benefits is demonstrated on a simulated release from the nuclear power plant Temelín. We will show that even the current sparse radiation monitoring network surrounding the power plant can be successfully used for data assimilation purposes. The location of the power plant and its early warning network is displayed in Fig. 1. The systems consists of a ring of stations inside of the power plant and external measuring devices located in nearby villages. Selected points of interest where we will study the impact of the radiation situation are denoted by red pentagons. Note that the distance of the selected villages from the nearest measuring device is growing.

The simulated accident was a 1 hour long release of radionuclide $^{41}\mathrm{Ar}$ with half-life of decay 109.34 minutes. Radionuclide $^{41}\mathrm{Ar}$ was chosen for two reasons: (i) $^{41}\mathrm{Ar}$ is a noble gas which has no deposition; (ii) radionuclide $^{41}\mathrm{Ar}$ emits gamma radiation at energy level 1293.57keV with branching ratio 99.1% and thus can be treated as a mono-energetic nuclide.

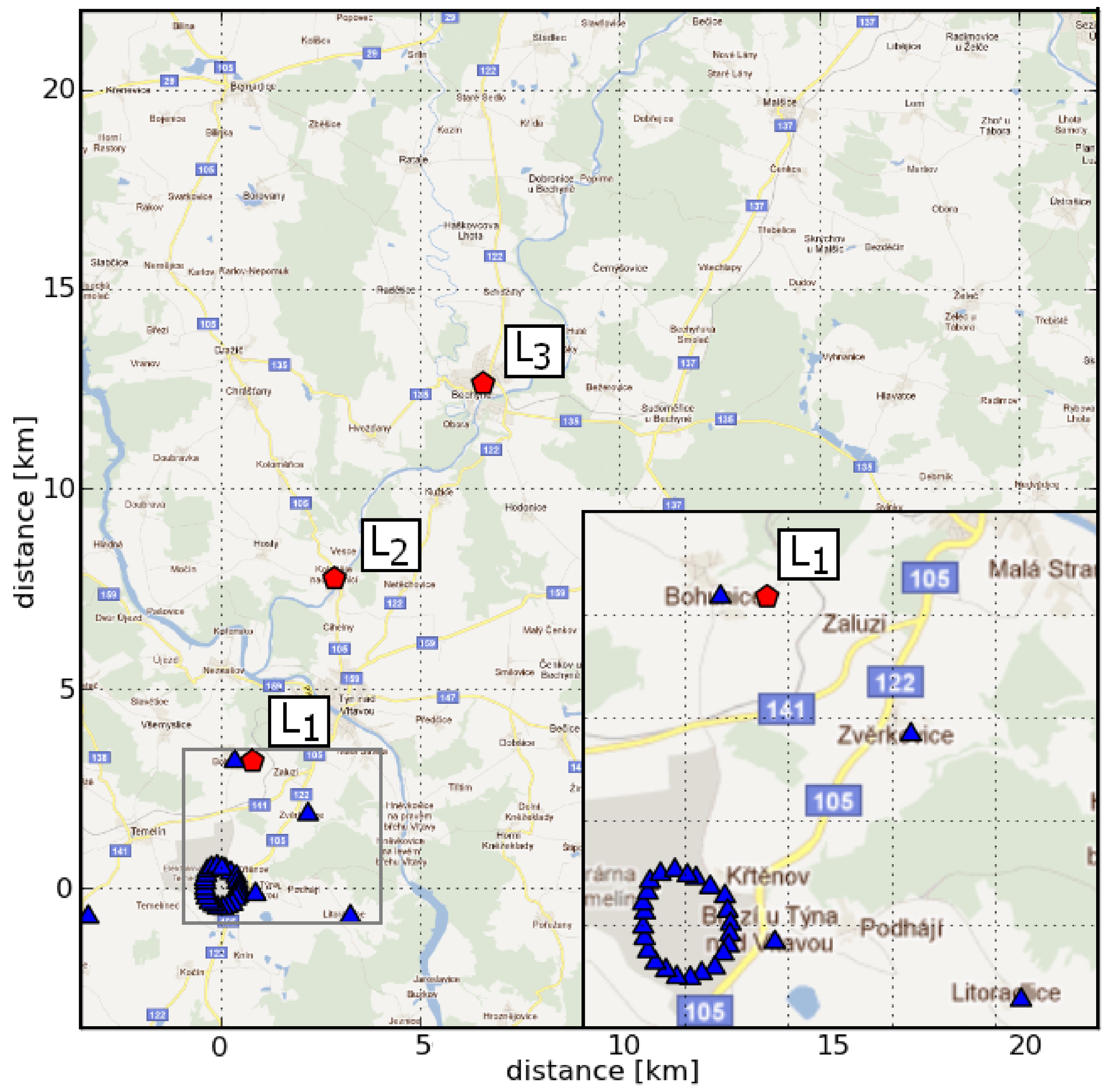


Figure 1: Location of the simulation scenario, measuring devices and points of interest on a map retrieved from maps.google.com on Oct 10, 2011. Triangles denote measuring devices, pentagon denote location of three points of interest, L1–L3.

Data assimilation is performed in time steps t=1,...,18, with sampling period of 10 minutes. This sampling period was chosen to match the sampling period of the radiation monitoring network which is assumed to provide measurements of time integrated dose rate in 10-minute intervals. The same period was assumed for the anemometer measuring wind speed and direction. The simulated release started at time t=1 with release activity $Q_{1:6} = [1, 5, 4, 3, 2, 1] \times 1e16\,Bq$.

Efficiency of the estimation algorithm for the released quantity Q_t is very good, see Fig. 2, where its posterior estimates obtained just after the first vector of measurements that is influenced by Q_t are displayed. The histograms cover at most one order of the Bq scale with significant mass concentrated around the true value.

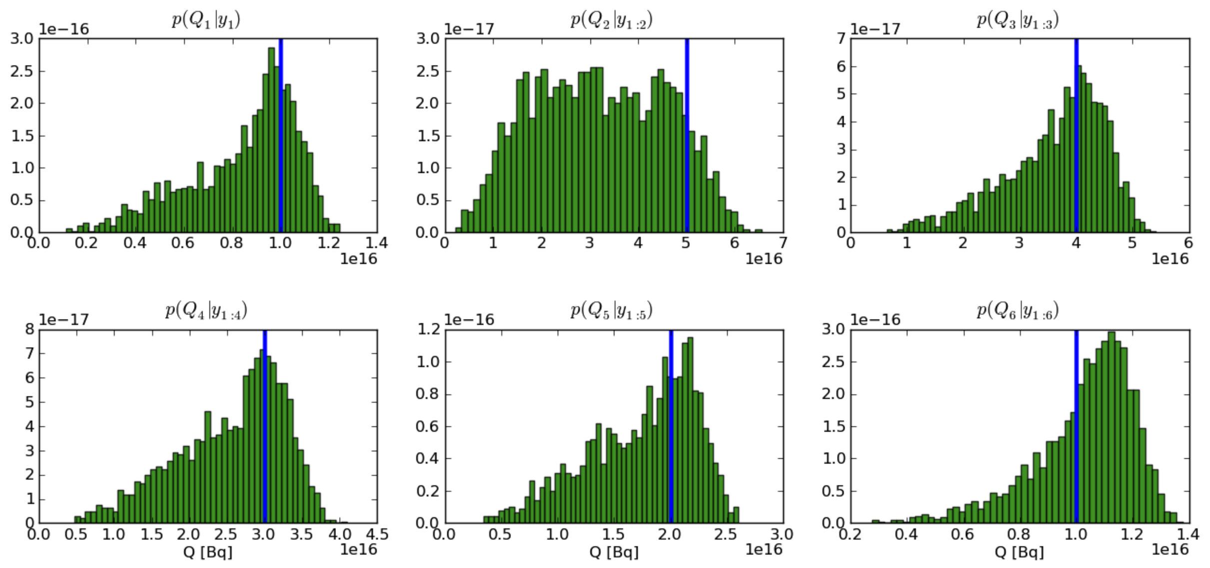


Figure 2: Posterior distributions of the released activity Q_t in time $t = 1, \ldots, 6$. True values are denoted by vertical blue lines at $[1, 5, 4, 3, 2, 1] \times 1e16\,Bq$.

Prediction results

One important task in the early phase of the radiation accident is the ability to extend the results of assimilation to short term predictions. This can be easily achieved in sequential Monte Carlo using equation. Note that the future trajectory depends on the wind speed and direction that can change rapidly and is therefore highly uncertain. Any observation is then very valuable since it considerably reduces the uncertainty about reality. This is illustrated in Fig. 3 via predicted trajectories of the puff centers after 4 hours from the start of the release assimilated using different data. The most uncertain situation is at the time of the release, t=0, when no data are available. With incoming data in time, the uncertainty is greatly reduced, the narrow part of the trajectories correspond to the assimilated trajectories, while the ever widening part is the prediction.

Prediction results - continued

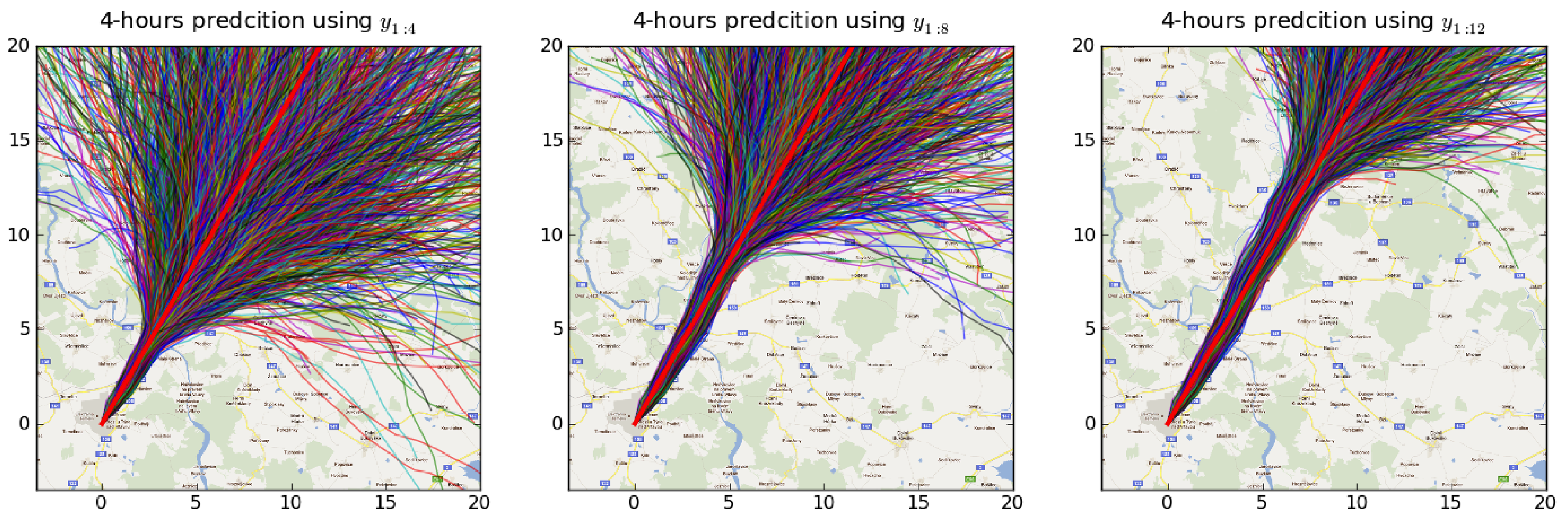


Figure 3: Trajectories of the first puff in each particle based on data assimilation in times t=4,8,12, respectively from left to right.

The posterior densities encode a lot of information that needs to be presented to the decision makers. One of the most valued supporting material results from the human point of view is the map of total absorbed dose. These are provided by many software tools. However, in the probabilistic formulation, the results has its own distribution. In Fig. 4., contour plot based on the expected value of the cumulative dose is displayed.

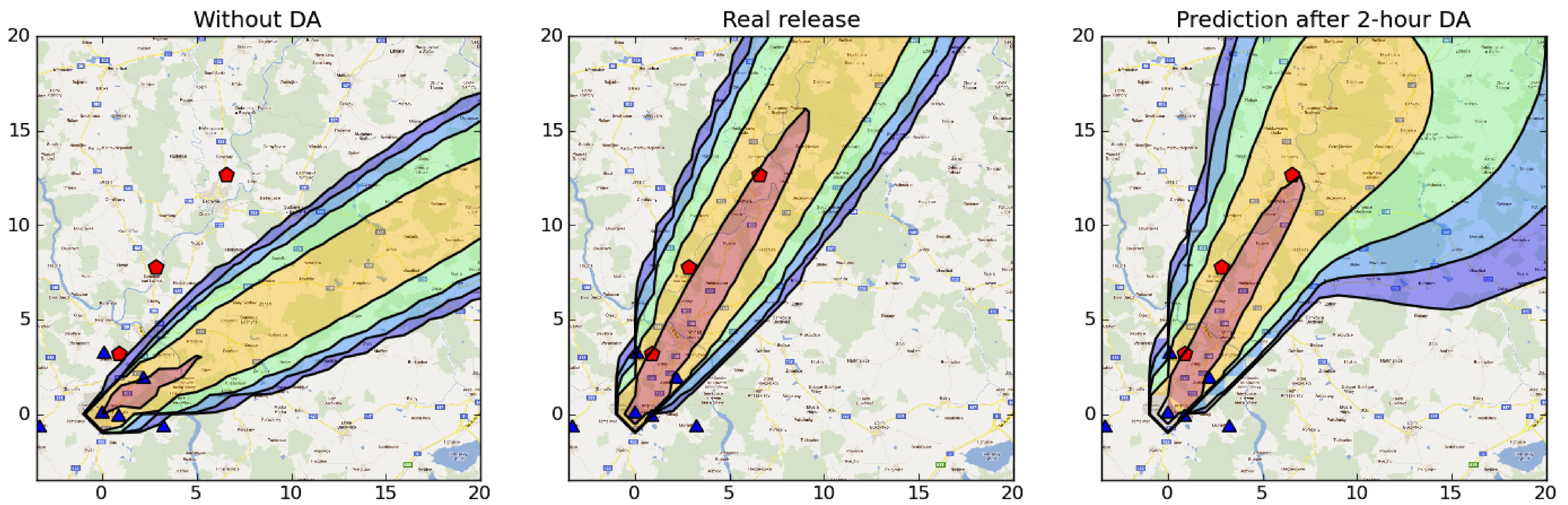


Figure 4: Contour plots of the predicted dose accumulated in 4 hours after the release.

We propose to provide also histograms of distributions of the cumulative dose at selected point of interest such as those displayed in Fig. 1. The locations of these points of interest were selected such that their distance from the release site is growing, see Fig. 5. Note that while the predicted total dose at the closest location does not change after t=4, Fig. 5 top row, the prediction of same quantity at distant locations is improving with every data record, Fig. 5, middle and bottom row.

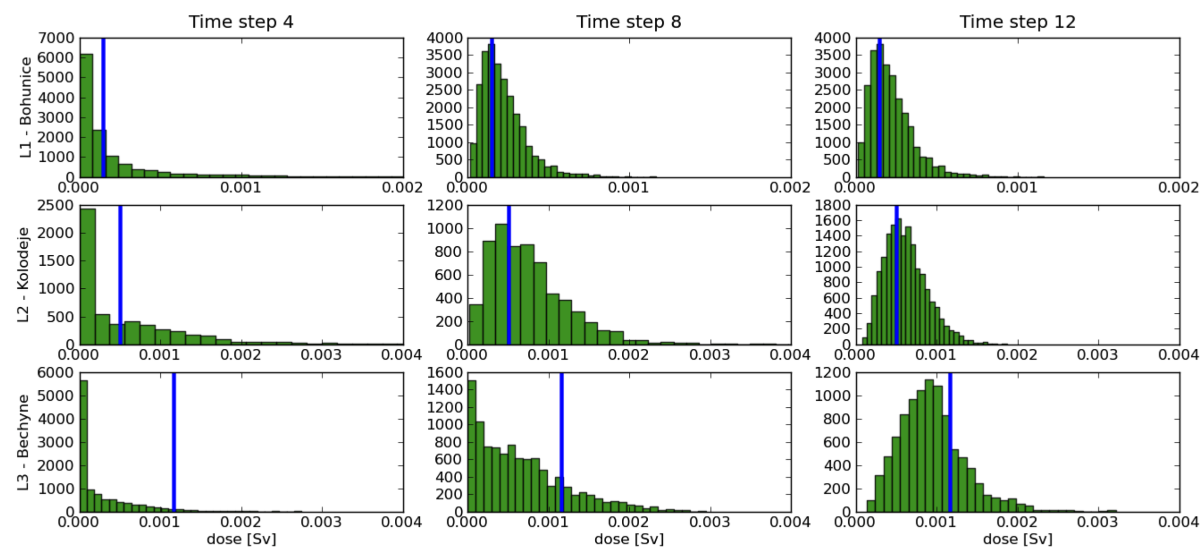


Figure 5: Distribution of total dose at different locations after 4 hours .

Conclusion

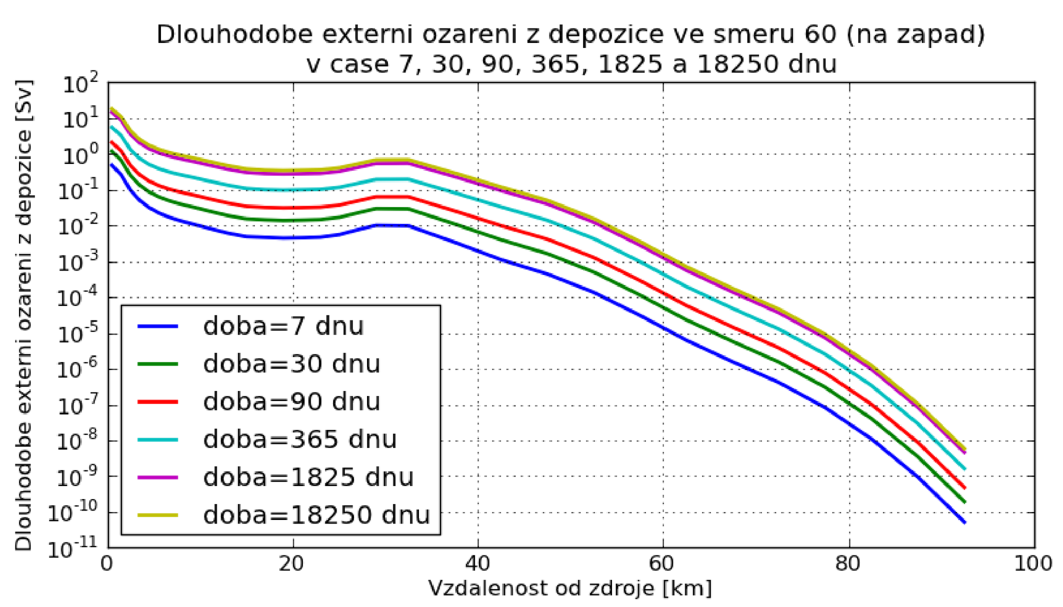
Every accidental release of a radioactive material is burdened with uncertainty in the release dynamics and meteorological conditions. The most demanding conditions for data assimilation are in the early phase of radiation accident when only on-line measurements from the radiation monitoring network are available. Bayesian methods and Monte Carlo techniques in particular has been shown to be effective tools for data assimilation and prediction of consequences of the accident under idealized conditions. Specifically, important parameters of the release were considered to be known, the concentration of activity was directly observable, and computational time was not an issue. However, in operational setting, many more parameters needs to be considered as unknown which leads to infeasible computational cost.

In this paper, we introduced parametric models for both the release dynamics and the meteorological forecast. Parameters of these models are assimilated together with spatial distribution of the release. Realistic model of available dose measurements from an existing radiation monitoring network was created. The performed twin experiment confirms that a particle filter with moderate size of 2000 particles is capable of computing realistic assimilation and short term forecast.

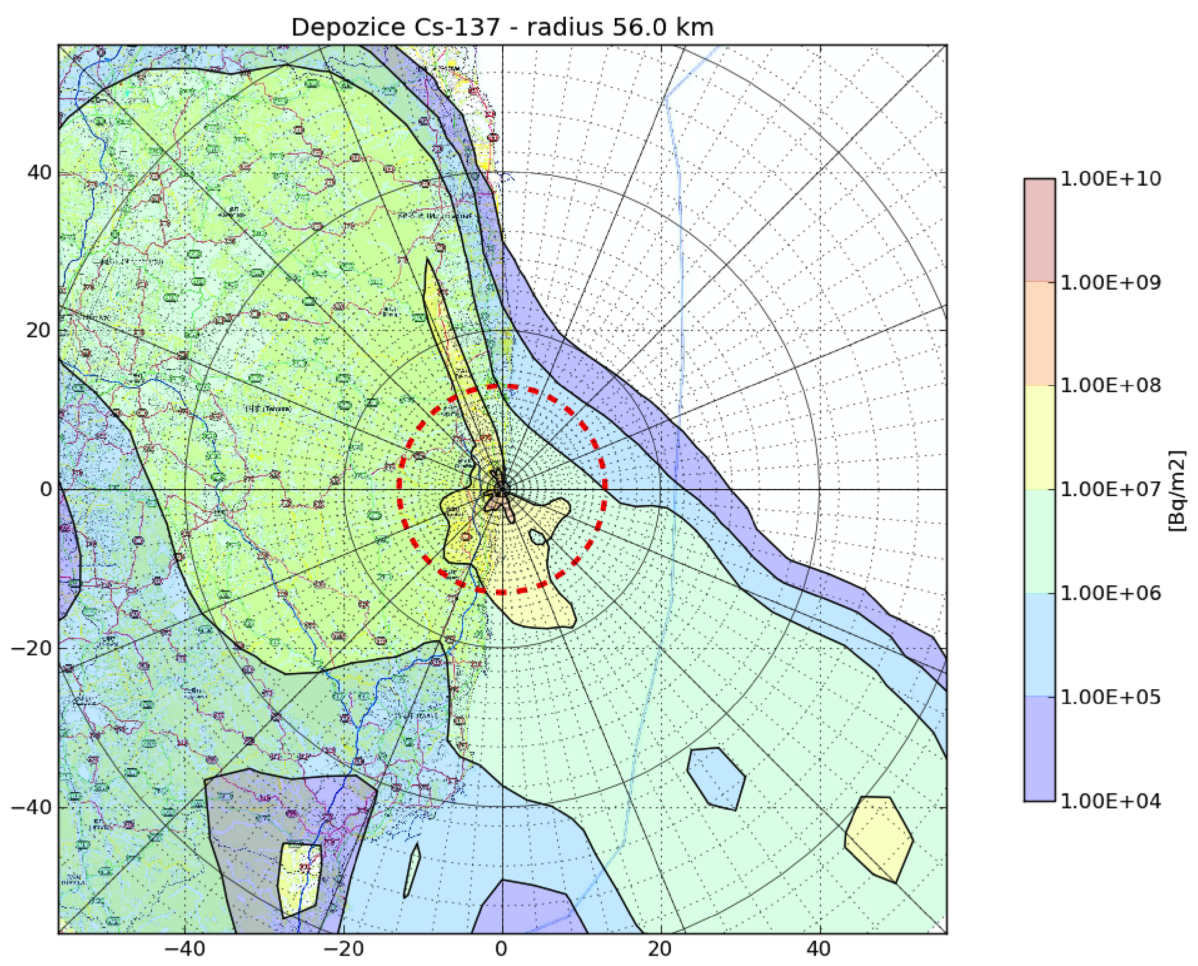
Careful analysis of the puff model and its software implementation ensures that the resulting assimilation and prediction algorithms can be evaluated in real time on a contemporary personal computer. This is very promising result for potential application of this methodology for autonomous operational use.

Improvements of HARP - Steps towards application of the assimilation methodology on reconstruction of Fukushima–Daiichi disaster

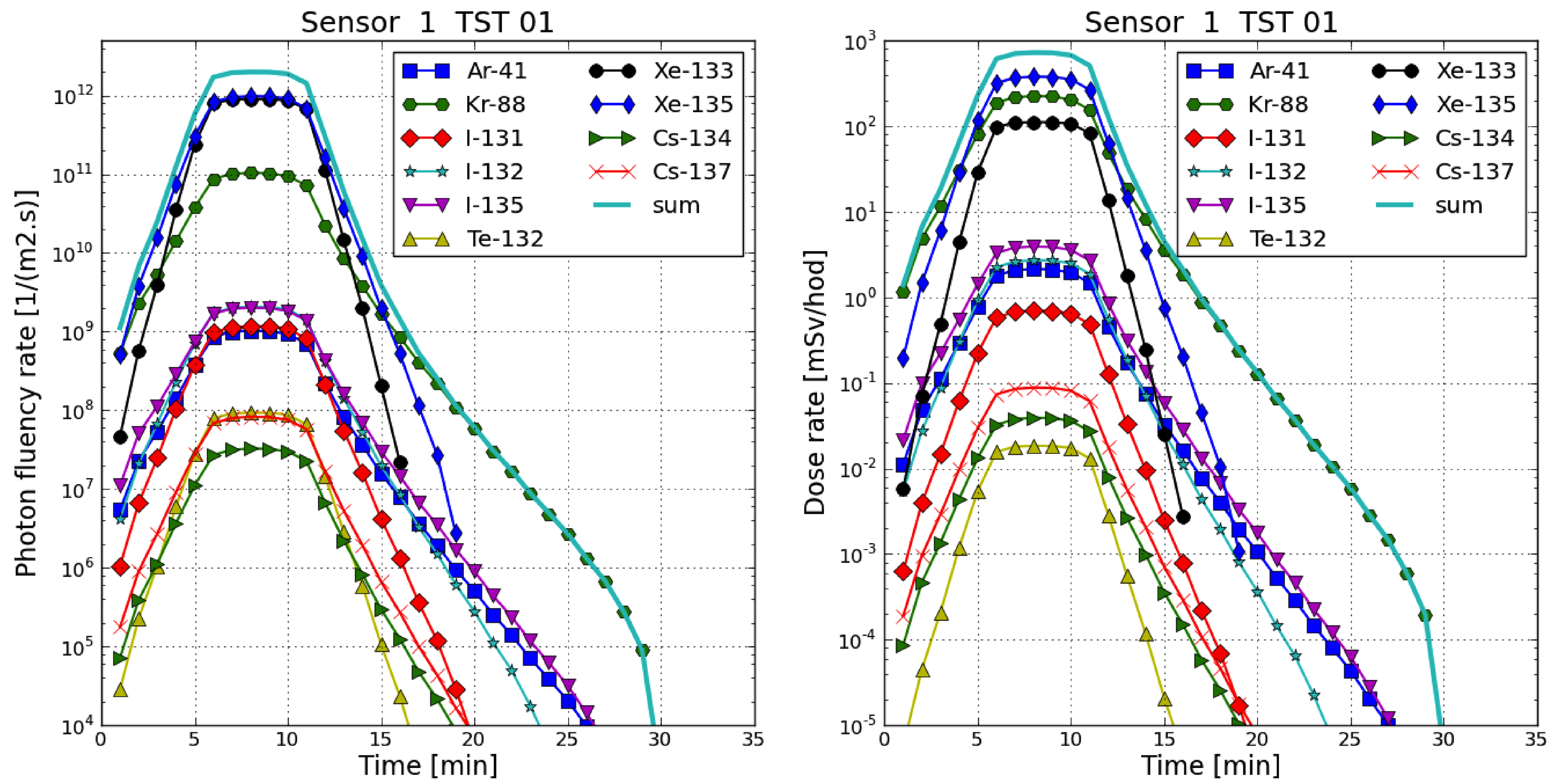
Our goal is to apply the developed data assimilation methodology for reconstruction of the source term of the Fukushima-Daiichi disaster using available observations regarding groundshine gamma dose rate from deposition.



Estimates of gamma doses from deposition cumulated over different time frames.



Model of deposition of Cs-137 in Fukushima-Daiichi area.



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