THE FUKUSHIMA DAIICHI POWER PLANT ACCIDENT: A CASE STUDY FOR MODEL EVALUATION AND SENSITIVITY SIMULATIONS AT LOCAL SCALE

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Abstract: Following the Fukushima Daiichi Nuclear Power Plant accident on March 2011, radioactive products were released in the atmosphere. Simulations at local scale (within 80 km of the plant) were carried out by the Institute of Radiation Protection and Nuclear Safety (IRSN) with the Gaussian Puff model pX, during the crisis and since then, to assess the radiological and environmental consequences. The Fukushima accident provides an unprecedented case to evaluate atmospheric dispersion models devoted to radionuclides, with many environmental measurements. The aim of this study is twofold: (1) providing a better understanding of the environmental contamination at local scale and the sources of uncertainties, (2) giving new insights on model evaluation tools and indicators applied to the simulation of radionuclides for accidental situations. The evolution of atmospheric and ground activity simulated at local scale is presented with a "reference" simulation, whose performance is assessed through comparisons with environmental monitoring data (gamma dose rate and deposition). The results are within a factor of 2 to 5 of the observations for gamma dose rates (0.52 and 0.85 for FAC2 and FAC5), and 5 to 10 for deposition (0.31 for FAC2, 0.73 for FAC5 and 0.90 for FAC10). A focus is also made on the sensitivity to input data (meteorology and release estimation), and simulation parameters (dry and wet deposition parameterizations, dispersion schemes).

Key words: *Fukushima, atmospheric dispersion, Gaussian model, gamma dose rates, model evaluation*

INTRODUCTION

On March 11th 2011, an earthquake of magnitude 9 occurred off northeastern Japan, causing a tsunami and damaging the Fukushima Daiichi Nuclear Power Plant (FNPP1). As a result, radioactive products were released in the atmosphere. During the emergency phase, the Institute of Radiation Protection and Nuclear Safety (IRSN) was asked to provide its expertise in support of the French authorities. Since then, the institute has been working on improving its assessment of the atmospheric release (Saunier et al., 2012), and of the terrestrial and marine contamination (Mathieu et al., 2012, Bailly du Bois et al., 2012, Korsakissok et al., 2013, Champion et al., 2013). Understanding the formation process of highly contaminated areas cannot be achieved through measurements only. While several kinds of measurements are available, they only yield partial information: gamma dose rates devices have a high temporal resolution, but are integrated over all gamma-emitters, and are too scarce to provide a good spatial coverage. Soil samplings and airborne readings provide maps of the contamination, but no information on short-lived species, noble gases, and release kinetics. Thus, improving atmospheric dispersion simulations remains a key issue, especially for dose assessments.

This paper presents the evolution of atmospheric and ground activity simulated at local scale (within 80 km of FNPP1). Simulations are made with pX, IRSN's Gaussian puff model (Soulhac and Didier, 2008). The pX model is part of the operational platform C3X, which is used by IRSN's Emergency Response Center in case of an accidental radioactive release. The aim of this study is to better understand the formation processes of the contaminated areas, but also to give new insights on the pertinence and limitations of model evaluation tools and indicators in accidental situations. Indeed, usual Gaussian model evaluations are made on simple, well-known dispersion experiments, but do not take into account the specificities of radionuclides measurements. We try to highlight advantages and shortcomings of each kind of measurements and of statistical indicators used to evaluate a model's performance.

Two years later, many uncertainties remain, especially on the source term (release kinetics, source height, and isotopic composition) and meteorology. Besides, uncertainties in simulation parameters such as dry deposition velocities and scavenging coefficients cannot be neglected. A sensitivity study aimed at identifying the most sensitive simulation parameters and input data is therefore presented.

SIMULATION SET-UP AND INPUT DATA

Meteorological data

The meteorological data used are ECMWF forecasts at 0.125° resolution, with a 3-hour time step. At this spatial and temporal resolution, the model fails to reproduce the complex orography and temporal variations, leading to uncertainties in the wind fields. Thus, wind observations at FNPP1 with a 10-minutes frequency are used during crucial time periods, namely on March 15th when most of the wet deposition occurs. Since wet deposition is a key process in the contamination, rain radar data at a 10-minutes time period are used to model the precipitations.

Source term

The source term was evaluated using available information on the reactors status (pressure, water level) and events chronology (ventings and explosions). 73 isotopes were included (135 with decay products). Additional information was inferred from air dose rate measurements at local and Japan scales (Mathieu et al 2012). The total estimated activity released in the atmosphere was 7.18×10^{18} Bq (Becquerel). Noble gases (xenon and krypton) contributed to most of the released activity (91% of the activity). The estimated released quantity was 1.97×10^{17} Bq for ^{131}I, 1.68×10^{17} Bq for ^{132}I, 1.08×10^{17} Bq for ^{132}Te, 2.06×10^{16} Bq for ^{137}Cs, 2.78×10^{16} Bq for ^{134}Cs and 5.94×10^{18} Bq for ^{133}Xe. Two main release heights were considered. A 20-meter height (reactor pressure vessel) was taken whenever pressure decreases happen in the unit, and a 120-meter height (exhaust stack) was preferred for specific venting actions. For releases not related to particular installation events (especially after March 17th), simulations were used to infer the source height.

Deposition parameters

Without knowledge of the release composition (gas/aerosols partitioning, aerosol size distribution), dry deposition was modelled through apparent deposition velocities: over land, 0.2 cm/s was taken for all particles, and 0.7 cm/s for molecular iodine I_2. Dry deposition over water was considered to be much lower, namely 0.05 cm/s for all species. The scavenging coefficient was given by $\Lambda s = \Lambda_0 \times p_0$, with $\Lambda_0=5\times10^{-5}$ h/mm/s and p_0 the rain intensity in mm/h. 2/3 of released iodine quantity is assumed to be gaseous (I_2) and 1/3 in particulate form.

Simulation set-up

The Gaussian puff model pX handles radioactive decay and decay products with a comprehensive mechanism. The Pasquill standard deviation laws were used in the reference configuration. The stability class was determined using the temperature gradient between 2m and 100m in the meteorological forecasts, for each cell and time step. Dose coefficients were used to infer dose rates from each species' volume and surface activities. Since the Gaussian model gives an analytical formula of the concentration, dose rates were directly computed at the stations' locations and no simulation grid was used. To compute deposition, a polar mesh was used, with circles at 2.5, 5, 10, 15, 20, 25, 30, 40, 50, 65 and 80 km from FNPP1, and a ten-degree step for the angle.

Sensitivity simulations

Simulations were carried out independently for each sensitivity parameter. For dispersion, several Gaussian standard deviation formulations were used: Pasquill, Briggs rural, Briggs urban, and using a constant diffusion coefficient (called "diff"). For dry and wet deposition, values were taken within the range of the literature, i.e. within a decade (see Table 1). Mixing the release between 0 and 150m allowed highlighting the sensitivity to the release height. Several source terms were also compared: those from Katata et al. (2012), Stohl et al. (2011) and Winiarek et al. (2012), and Saunier et al. (2013), called "release_inverse" in the figures. The influence of rain (ECMWF rain forecasts without observations) and wind fields (ECMWF wind forecasts without observations) was evaluated.

Table 1 : Reference, minimum and maximum values for deposition parameters over land. In the following, simulations with minimum (resp. maximum) deposition velocities are labelled "vdmin" (resp. "vdmax"). Simulations with minimum (resp. maximum) scavenging coefficients are labelled "lmin" (resp. "lmax")

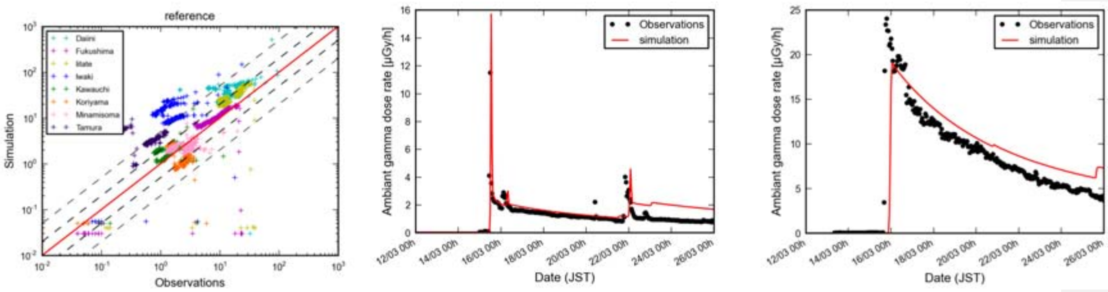
	Reference value	Minimum value (vdmin, lmin)	Maximum value (vdmax, lmax)
Vd particles (cm/s)	0.2	0.05	0.5
Vd iodine I_2 (cm/s)	0.7	0.1	1
Λ (h/mm/s)	5×10^{-5}	1×10^{-5}	1×10^{-4}

GAMMA DOSE RATES

Model-to-data comparisons

Several gamma dose rate measurement stations were down because of the tsunami during the first days of the accident. Thus, we retained only those who covered a sufficient period of time, which amounts to eight monitoring stations, with a 10-minutes frequency or 1-hour frequency, within 60 km of the plant. The overall model performance on stations is satisfactory: 52% of data are within a factor of 2 of the observations (FAC2), and 85% are within a factor of 5 (FAC5). The fractional bias is 0.44, which indicates a tendency to overestimation, the correlation is 0.72, and the figure of merit in time (FMT[1]) is 0.43. This compares well to typical Gaussian models performance on dispersion experiments, even though uncertainties on input data are much higher.

[1] The Figure of Merit in Time (FMT) is the percentage of overlap between measured and predicted integrated time series at a given location



(a) Scatter plot at 8 stations (b) Kawauchi (22 km west) (c) Fukushima (60 km north-west)

Figure 1. Model-to-data comparisons of gamma dose rate values (µGy/h), for the reference simulation (hourly-averaged values). (a) Scatter plot at the eight monitoring stations (Red line: perfect agreement. Dashed line (bold): factor 2. Dashed line: factor 5). (b) Time series at Kawauchi station. (c) Time series at Fukushima station.

Figure 1(a) shows the scatter plot on all stations, with most values within a factor 5, and a few singular underestimated values, which correspond to a few hours delay in the forecast plume arrival times. Figure 1(b) shows a station where no rain occurred. There is a peak, during a short time, coming from the direct plume contribution, followed by a much lower contribution from remaining radionuclides deposed on the ground ("ground-shine"). Figure 1(c) shows a station where wet deposition occurs: the plume is washed-out by the rain, which induces a peak that only decreases slowly after the plume departure, mainly because of radioactive decay.
Thus, most gamma dose rate values are due to ground-shine (dry and/or wet deposition), and classical indicators such as FAC2 and FAC5 mainly depend on the simulation's ability to forecast deposition. In case of an accidental release of radionuclides, an operational simulation should be able to forecast peak values, since they represent an important part of human exposure (through direct radiation and inhalation), and plume arrival times (i.e. the first date when the gamma dose rate value is higher than background value).

Sensitivity results

The sensitivity study on gamma dose rates is not detailed here. On all sensitivity simulations, FAC2 values ranged between 0.25 (with Briggs urban dispersion parameters) and 0.62 (with ECMWF rain forecasts), and FAC5 ranged between 0.5 (without wind observations) and 0.97 (with low deposition velocities). Peak values show a high sensitivity to most parameters, especially source terms but also dispersion schemes, source height, and meteorology. This is especially the case on coastal stations (Minamisoma, north of FNPP1, Daini and Iwaki south), since wind direction is difficult to forecast along the coast. Besides, situations are often stable, which induces a very thin plume, hence a strong sensitivity to uncertainties in wind direction, plume height, and station location. Besides, the peak duration is very small (less than one hour), so the time resolution of wind fields and/or gamma dose rate measurements may not be sufficient to account for the temporal variability of the signal. For instance, the peak value at Iwaki (40 km south) ranges between 5 µGy/h for the Katata release, to near 250 µGy/h for the Briggs rural scheme. The reference value is 160 µGy/h, and the observed value is 23 µGy/h. For inland stations, source term and meteorology are the most important parameters.

^{137}CS DEPOSITION

Model-to-data comparisons

Simulation results are compared with the observations of ^{137}Cs deposition provided by Ministry of Education, Culture, Sports, Science and Technology (MEXT). About 1800 measurements are within our simulation domain. In all, 31% of simulated values are within a factor 2 of the observations, 73% within a factor 5, and 90% within a factor 10. The correlation coefficient is 0.34. The figure of merit in space (FMS[2]) depends on the chosen threshold. A high threshold would focus on the model's ability to forecast extreme values. For 10^4Bq/m^2 (94% of measurements), the FMS is very good (0.85). For 10^5Bq/m^2 (30% of measurements, mainly northwest), it goes down to 0.43, probably because of the misplaced wet deposition zone: the highest values are simulated too north (see Figure 2). Very close measurement points may differ by a factor 5 to 10, which may be due to running water or changes in terrain type (school yard, agricultural field...). The simulation gives averaged values, and does not account for local-scale variability. Thus, further analyses of the datasets and aggregating close measurements could improve these comparisons.

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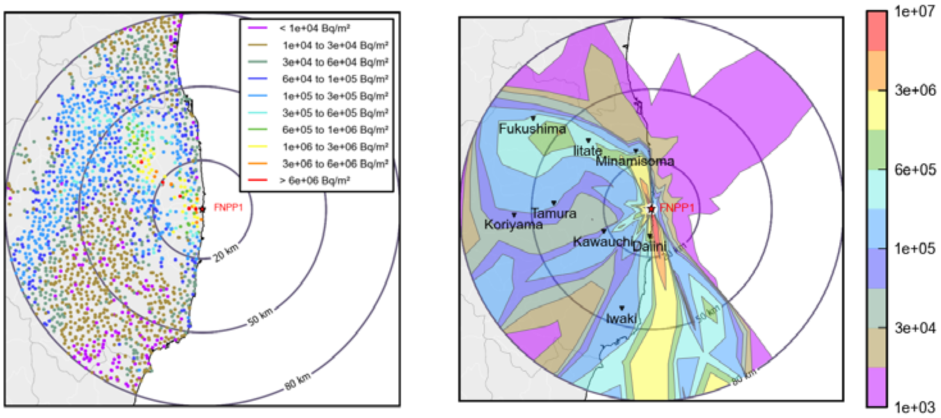
[2] The Figure of Merit in Space (FMS) is the percentage of overlap between measured and predicted areas above a threshold *T* at a given time



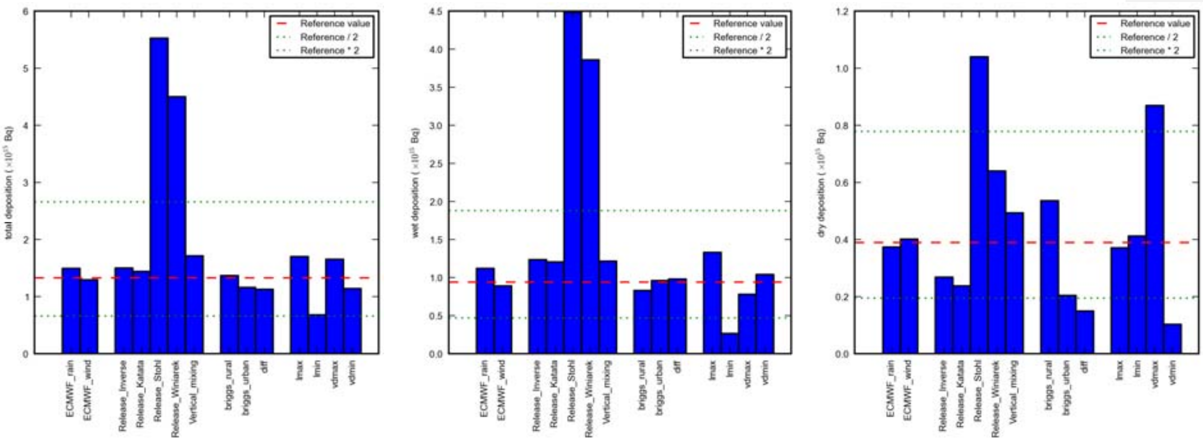
(a) MEXT observations of ^{137}Cs (Bq/m^2)

(b) Simulated deposit of ^{137}Cs (Bq/m^2)

Figure 2. Model-to-data comparisons of ^{137}Cs deposition (Bq/m^2): (a) MEXT observations (1800 points), (b) reference simulation (same scale).

Sensitivity results

The total deposition budget over land is the cumulated quantity deposed within 80 km of the plant, corrected for radioactive decay. Our reference values are 1.33 PBq for ^{137}Cs and 14 PBq for ^{131}I, which is close to the values estimated by Morino et al. (2011) for the Fukushima prefecture. Figure 3 illustrates the sensitivity of the deposition budget of ^{137}Cs over land. The sensitivity of total deposition is conditioned by that of wet deposition, which accounts for 2/3 of total deposition for ^{137}Cs in our simulation. For total deposition, most simulations are within a factor 2 of the reference simulation, except when using the Stohl and Winiarek releases. Apart from these two results, most simulations are between 1 and 2 PBq, which is consistent with the estimation made from airborne observations[3]. Dry deposition (Figure 3(c)) is also sensitive to deposition velocities and vertical diffusion. Indeed, Briggs urban and constant diffusion parameterizations enhance vertical diffusion, which induces lower dry deposition, since the plume is less concentrated near the ground. Finally, a compensation mechanism between dry and wet deposition appears: lower deposition velocities (*vdmin*) imply that the plume is less depleted near the source. Hence, the plume wash-out by the rain is more efficient, and wet deposition increases (Figure 3(b)).



(a) Total deposition budget (PBq) (b) Wet deposition budget (PBq) (c) Dry deposition budget (PBq)

Figure 3. Deposition budget over land for total, wet and dry deposition of ^{137}Cs: sensitivity to meteorology, source term, dispersion scheme and deposition parameters. Red dashed line: reference results. Dotted lines: factor 2 of reference results.

[3] http://www.mext.go.jp/english/incident/1304796.htm

CONCLUSIONS

The results were within a factor of 2 to 5 of the observations for gamma dose rates, and 5 to 10 for deposition. The total quantity of ^{137}Cs deposed over land was consistent with observations and with other estimations. The gamma dose rates in the northwestern area, highly contaminated by wet deposition, were correctly reproduced but the wet deposition zone was slightly misplaced. While uncertainties in the input data (wind direction, rain, source term kinetics and quantity) are huge, simulation parameters are also uncertain. The influence of each parameter was assessed separately. As expected, source terms had the highest impact on the results. Total deposition budget was within a factor 2 of the reference most of the time. Gamma dose rates, especially peak values, were quite sensitive: source terms, standard deviations, and wind direction had huge impacts on the results~~. However, with only eight monitoring stations, each station has a particular behavior and no general conclusions can be made~~. This study is a first step towards ensemble modeling to account for model and data uncertainties. Updating model evaluation tools and proposing new indicators for modeling accidental releases of radionuclides are also among the main perspectives.

~~This study is a first step towards updating model evaluation tools and proposing new indicators for modeling accidental releases of radionuclides. Despite the situation complexity and the remaining uncertainties, the results presented here are satisfactory compared to standard dispersion model evaluations. They can therefore be used as a benchmark for atmospheric dispersion models' evaluation and improvement with respect to emergency purposes. The main perspective is to use ensemble simulations instead of a single, deterministic model, in order to account for uncertainties.~~

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