Assessment of Atmospheric Dispersion for the Fukushima Dai-ichi Nuclear Power Plant Accident

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Abstract

Dispersion of radioactive material released to the atmosphere from the Fukushima Daiichi Nuclear Power Plant Accident in Japan was modeled in real time to advice the French Government. The technical crisis centre of the Institute for Radioprotection and Nuclear Safety (IRSN) was activated to provide on a daily basis, the diagnosis of the different reactors, forecast their status and evaluate the radiological consequences of these different scenarios.

Since March 11, IRSN improved the assessment of the environmental contamination due to the Fukushima accident. The source term is still highly uncertain in terms of quantity and timing. This paper presents the approach which justifies the release scenario by coupling monitoring data with atmospheric simulations. Four different period of release were identified. For each event, a description of the atmospheric dispersion at local scale, country-scale and global scale dispersion as well as doses assessment will be proposed.

Finally, the Fukushima accident showed the interest to develop new tools to help the nuclear crisis management. One tool is based on the use of gamma dose rate observations with inverse modeling techniques to estimate the source term. Another tool is based on the use of ensemble forecasting approach to narrow uncertainties.

Keywords: Fukushima Daiichi nuclear power plant, nuclear accident, contamination, atmospheric dispersion models, radioactive release

1 Introduction

On March 11th 2011, an earthquake of magnitude 9.0 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 on the plume dispersion and radiological consequences, in support of the French Government. Since then, the institute has been working on improving its assessment of the environmental contamination (Korsakissok et al, 2011; Mathieu et al, 2012).

Understanding the formation process of highly contaminated areas cannot be achieved through measurements only, especially since many devices (radiation and meteorological monitoring stations) had been damaged by the earthquake and tsunami. Thus, improving atmospheric dispersion simulations remains a key issue. This paper presents the evolution of atmospheric, ground activity simulated and doses assessment at local scale (within 80 kilometers of FNPP1) and large scale (at the Japan scale and the global scale).

2 Atmospheric dispersion models and input data

2.1 Atmospheric dispersion models

Models used to simulate the plume behavior and the radiological consequences are part of the operational system C3X. C3X system is the operational system developed by IRSN for radiological consequences assessment in case of an emergency situation. Consequences (dose and dose rate) against time was assessed with the consX model of the C3X system.

The long-range Eulerian operational model ldX was used to model the dispersion at the Japan-scale and global scale (Quélo et al. 2007). Since Eulerian models are known to have difficulty in resolving steep gradients near point sources, the operational Gaussian puff model, pX (Soulhac and Didier 2008), was used within 80 km of the source.

pX and ldX take into account radioactive decay. Dry deposition is modelled through apparent deposition velocities: v_{dep} = 2e-3 m/s. As far as wet scavenging was concerned, the parameterization used was of the form $\Lambda_s = \Lambda_0 \, p_0$ with Λ_0 = 5e-5 h/mm/s and p_0 the rain intensity in mm/h (Baklanov and Sørensen 2001). Depending on the atmospheric stability, the vertical diffusivity in ldX followed either Louis (Louis 1979) or Troen-Mahrt schemes (Troen and Mahrt 1986). Pasquill stability classes (Pasquill 1961) were used for pX. The spatial resolution for ldX simulations was the same as the meteorological data input and ten vertical levels were used.

2.2 Meteorological data

The meteorological data used are ECMWF forecasts at 0.125° resolution, with a 3-hour time step. At this resolution, the model fails to reproduce the complex orography, leading to uncertainties in the wind fields.

Measurements of wind or rainfall rate, collected from various sites in Japan, were used to evaluate the quality of the meteorological forecasts. The comparisons showed a rather good model-to-data agreement except for three events: wind fields appear to be inaccurate during March 15 in the Fukushima region, and March 16 and 21 in the Ibaraki region. Therefore, ldX and pX simulations were driven by ECMWF data, except for March 15 where the use of uniform wind fields built with wind observations at the Daiichi site was preferred for local-scale simulations. This solution had its own limitations, since the assumption that wind observed at Daiichi was homogeneous for the domain of simulation (80 km) did not take into account the spatial heterogeneity of flow.

Several rain events occurred in Japan during the Fukushima accident. The timing, the spatial resolution and intensity of rain fields are of prime importance for the proper simulation of scavenging and deposition caused by rain. The resolution of meteorological models is too crude to accurately represent the spatial and temporal variability of rain episodes. Thus, rain radar observations available at a frequency of 10 min are best suited but available in a short spatial domain around FNPP1. Thus rain radar observations were used for pX simulations.

2.3 Source term

The radioactive species released into the atmosphere during the NPP accident can be classified into three categories: aerosols, gases and noble gases. Noble gases are unique in that they neither react with other species nor are deposited on the ground.

The source term used for the presented simulations was estimated first with the analysis of the state of the reactors. Seventy-three different radioisotopes have been considered. The approach led to an overall estimate of 7.2e+18 Bq discharged into the atmosphere including: 5.9e+18 Bq of ^{133}Xe; 1.9e+17 Bq of ^{131}I and 2.0e+16 Bq of ^{137}Cs. The proposed assessment is consistent with the released amount provided by NISA (2011) and NSC (2011) except for noble gas where xenon is underestimated by a factor of two.

The time evolution of the release is more difficult to determine. The quantity of each radioactive species released during venting or an explosion, as well as the release duration are uncertain.

In this study, the release kinetics were defined, firstly by the chronology of events as provided by Tokyo Electric Power Company (TEPCO) (time of containment venting, flushing, onset of smoke, etc.) and plant measurement parameters (water level and pressure in the reactor vessel, pressure in the containment), and secondly, in alignment with dose rate peaks measured by on-site monitoring devices. In order to improve estimates of release rates and duration, dose rate measurements distributed over Japan have been used. The resulting source terms induced by damage to reactors 1, 2 and 3 are respectively plotted in red, blue and green in Figure 1. Four main periods of emission have been identified. Until March 16, the timing of the releases is based on specific events, such as venting and explosions, and thus, they are fairly reliable. The release rate and its distribution between radioisotopes were highly uncertain until March 14. From March 15 until March 17, many measurements have helped in estimate of the release rate, but the composition of the release, in particular, the proportion of noble gases, remains uncertain. From March 17 until March 26 many uncertainties remained concerning both the sequence of events and the composition (rate and isotopic repartition) of the source term.

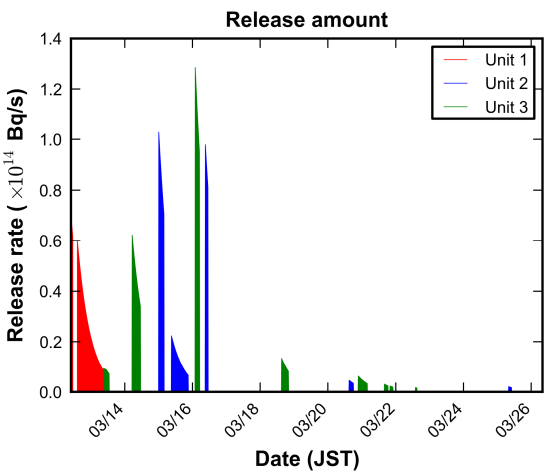

Figure 1 Rate of released activities per reactor in Bq/s, including the contribution of 73 radioisotopes. Red colour is used for unit 1, blue for unit 2 and green for unit 3.

3 Dispersion analysis for each event

3.1 Event 1: venting and hydrogen explosion of unit 1

The first release followed the explosion of unit 1 on March 12 at 15h36 JST (Japanese Standard Time). Simulations suggest that the radioactive plume traveled first to the north along the Japanese coast and then turned towards the Pacific Ocean (Fig. 2a). Simulations show that the contamination of Japanese land due to the first event was only due to the plume exposure and dry deposition northward along the coast. Only one gamma dose rate station located in Minamisoma, about 25 km north of the NPP, detected the plume. The observed signal is in good agreement with pX simulations (Fig. 2b). However, the use of only one dose rate station is not sufficient to validate the release scenario.

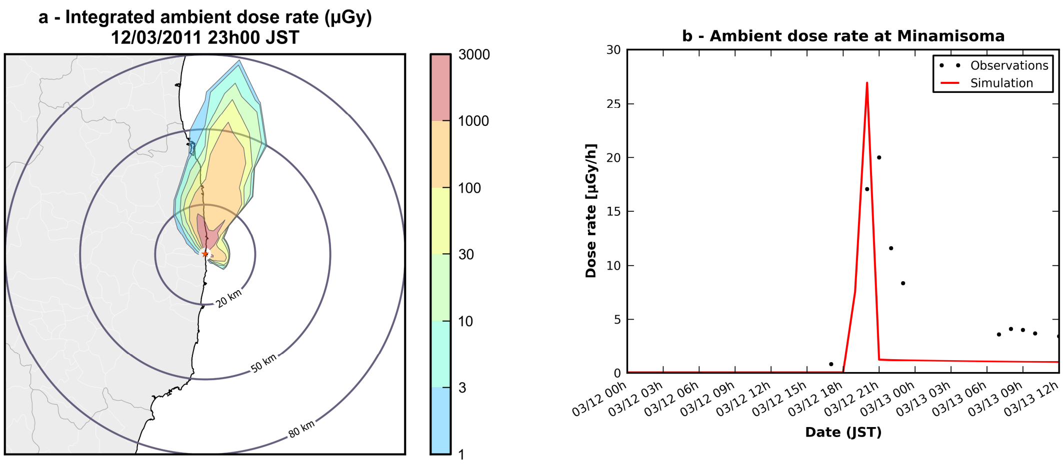

Figure 2 Map of the integrated ambient dose rate (cloud shine only) due to event 1 simulated with pX (a) and comparisons between dose rate (cloud and ground shine) observed in Minamisoma and simulated by pX (b).

3.2 Event 2: venting and hydrogen explosion of unit 3

The second event occurred between March 13 and 14, triggered by venting and an explosion at unit 3. Fortunately, the wind blew towards the ocean, and no contamination of the Japan Islands was detected. Again, the lack of observation stations prevents us from validating the release scenario. Consequences of the first two events on the Pacific Ocean have been described by Bailly du Bois et al. (2012).

3.3 Event 3: venting and breach of the wetwell of unit 2

The third event occurred around March 15. During the night, venting of unit 2 led to a release plume that moved to the south and then west.

The following day, the pressurizing of reactor vessel 2 created a breach on the wetwell. During one day, the reactor vessel has been totally depressurized, leading to significant atmospheric releases. The subsequent plume first went west, then northwest and finally turned south toward the Pacific Ocean. Moreover, significant precipitation over Japan occurred when the flow blew to the northwest. The most contaminated areas are those that experienced plume wash-out by precipitation.

Forecasts provided by most of the meteorological services did not reproduce correctly the wind field carrying the plume to the northwest. Therefore, LdX driven by ECMWF data failed to accurately simulate the contamination to the northwest. The high dose rate area predicted by ldX is too far west, whereas pX simulations driven by wind observations at the Daiichi site and rain radar observations are in better agreement with observations even if slightly too north (Fig. 3). Simulations show that contamination in the northwest was caused by wet deposition probably between March 15 at 21h JST and March 16 at 3h.

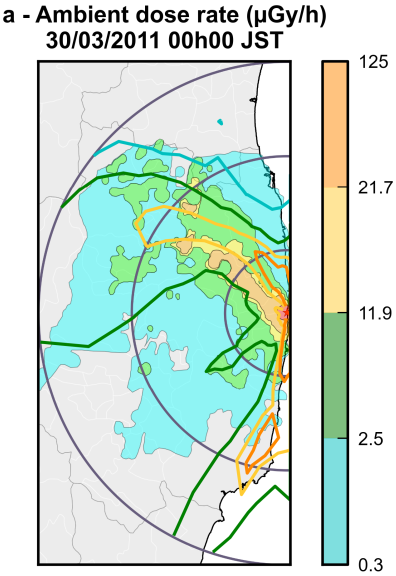

Figure 3 Map of ambient dose rate due to ground shine on March 30 observed (painted areas) and simulated with pX (iso-contour). The circles correspond to the distances 20 km, 50 km and 80 km from the FNPP1.

3.4 Event 4: damage on reactors 1, 2 and 3, sprayings and smokes

Between March 19 and 22, new releases occurred due to the very poor condition of the reactors and maybe re-suspension of materials because of flushing. White and grey smokes on units 2 and 3 have also been reported by TEPCO, especially on March 21 and 22 (TEPCO, 2011). These releases are probably less significant but cannot be ignored because they explain some of the contamination caused mainly by wet deposition in the Tokyo and Ibaraki areas. According to our release assessment, various plumes traveled first east, and then turned west. Figure 4a show that on March 21, a plume was measured in the morning in the Ibaraki region. Later in the morning, the plume arrived in the Tokyo area (Fig. 4b).

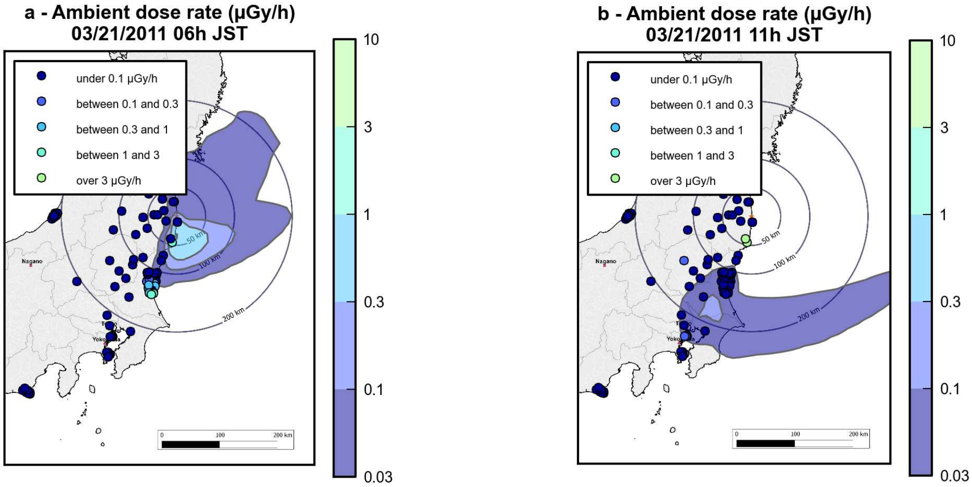

Figure 4 Ambient dose rate (cloud shine only) comparisons between ground observations (dots) and ldX simulations (painted areas). The circles correspond to the distances 50 km, 100 km and 200 km from the FNPP1.

3.5 Dispersion, deposition and dose in Japan and in the northern hemisphere

Model-to-data comparisons have been completed using available gamma dose rate observations (SPEEDI and prefectural measurements). The comparison between observed and modelled gamma air dose rate due to ground shine (after the plume is supposed to have left the area) shows an agreement within a factor 5 and 10, and most of the time a factor of two. Model-to-data comparisons show an agreement within a factor of 5 for the gamma air dose rate during the plume passage. Most of the time, the dose rate due to radionuclides in the air (“cloud shine”) is underestimated, and the dose rate due to ground shine only is often overestimated.

The following maps represent the doses likely to be received by a child of 1 year without protection for an exposure to contamination taking place before March 26 (Figs. 5, Figs. 6). Evaluations of doses over the sea do not have to be considered. These maps show that, before March 26, the most important contamination in the Japan territory was due to the contamination in the south and in the northwest of the FNPP1. However the most important long term exposure is due to the consequences of the wet deposition in the northwest area.

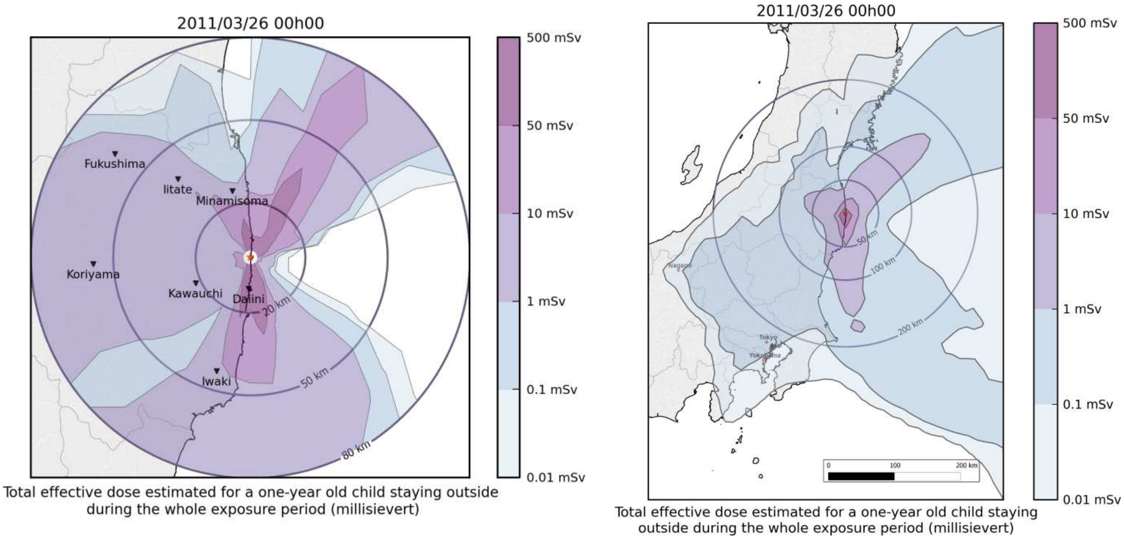

Figure 5: Total Effective dose (whole body) at the end of the releases - Simulation pX on the left, ldX on the right

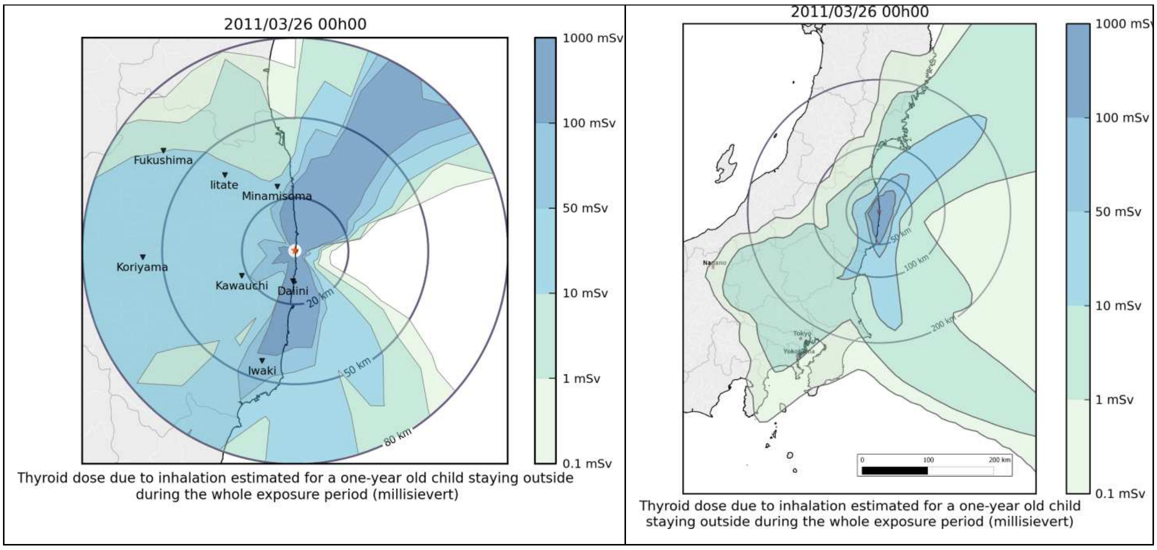

Figure 6: Thyroid dose due to inhalation at the end of the releases - Simulation pX on the left, ldX on the right

An indirect evaluation of the proposed scenario for the Fukushima accident would be to compare simulations with observations recorded on other continents. Indeed, radioactive materials were detected on the western coast of US as early as March 16 (Bowyer et al, 2011; Leon et al, 2011), and arrived in most European countries on March 23-24 (Masson et al., 2011). LdX has been used to model the transport and evolution of the plume in the northern hemisphere. Preliminary comparisons in Masson et al. (2011) show that the plume arrival times and global pattern are consistent with observations over Europe.

4 Conclusions and perspectives

Models have been used to describe four different periods of release of radioactivity as a result of the accident at the FNPP1. Three of the releases resulted in exposures to the population as a result of the movement of plumes. The main ground contamination for Japan was caused by wet deposition in the northwest and south of the NPP. When comparisons between model and observations are possible, results show that the modeled results are realistic. For some events, the lack of actual observations prevents validation.

Despite the good agreement obtained by comparing model and observations, many uncertainties remain in the source term and the meteorological conditions. An inverse modeling approach as proposed by Winiarek et al. (2012), which was extended to gamma dose rates measurements, may improve the source term assessment. For uncertainties, an ensemble approach may also be used (Mallet and Sportisse 2008). This method is based on an ensemble of simulations, and completed with several dispersion models and/or a set of perturbed input data. This approach allows one to quantify the uncertainties in the model output. Inverse modeling and ensemble methods appear to be powerful tools that should be used for operational purposes during emergency management.

The Fukushima accident has also highlighted other needs, such as the importance of having a monitoring strategy. As an example, gamma dose rate observations are very useful and airborne observations played a key role during the crises. Nevertheless, even with these methods, the uncertainties are large. More activity concentration measurements and gamma-ray spectroscopy measurements combined with rainfall measurements would have significantly reduced the uncertainty in the modeled values.

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