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Modelling of the atmospheric transport and fallout of the releases from the Fukushima Daiichi accident

In 2012, IRSN made an initial assessment of the atmospheric transport and fallout models for releases emitted during the Fukushima Daiichi nuclear accident [IRSN (2012)]. The simulations lacked realism due to the difficulty in reproducing several transport episodes of these releases, and the cause of the differences found between the modelling results and the measurements was sought. Since then, the work on atmospheric dispersion modelling by the international community focused on reducing the uncertainties, both those relating to the input data of the atmospheric transport models and those relating to the models themselves. This work is still underway.

The weather conditions and the quantification of the atmospheric releases are the main input data of the atmospheric transport models. The most significant progress has been the result of efforts focused on improving these data.

Weather conditions

Weather conditions (winds, atmospheric stability, etc.) determine the transport of the radioactive plume through the atmosphere. Rainfall is responsible for soil contamination due to leaching of the plume. This data is provided by weather forecast models.

One feature of the Fukushima accident concerns the local geography. The accident took place on the Pacific coast, in an environment with complex orography, with marked reliefs only a few kilometres inland. This configuration greatly penalises the quality of weather forecasts. Furthermore, the accident followed the earthquake and tsunami that destroyed part of the infrastructure rendering a number of meteorological observations unavailable. However, these are used to constrain the models. The operating conditions in the weather models are consequently degraded from their nominal operation.

As from 2012, the difficulty of properly taking into account the impact of the orography on the weather forecasts was raised by IRSN [Mathieu *et al* (2012), Korsakissok *et al* (2013)]. Rainfall forecasts do not always accurately reflect reality. However, accuracy is essential to simulate soil contamination. The rainfall fields resulting from "radar" observations can be used as input for dispersion models. Using this set of data has long been considered as the best option; however, the use of these data remains delicate. One of the difficulties identified concerns light rain. It is not detected by "radar" observations but appears to have played an essential role in the ground contamination on 14-16 March.

Since 2011, many weather forecasts were produced. Most of the teams working on the simulation of the transport and fallout of the releases from the Fukushima accident first used forecasts whose spatial resolution was about ten kilometres, which is insufficient to properly take into account the influence of the relief. The time resolution was often 3h, which is a frequency that was too low to assess when the wind shifted or when rainfall had just begun. Efforts were therefore focused on the production of weather forecasts with finer resolution. The first IRSN estimates were made using the forecasts of

Météo-France and those of the European Centre for Medium Range Weather Forecasting (ECMWF[1]) [Mathieu *et al* (2012), Korsakissok *et al* (2013), Saunier *et al* (2013)]. Within the framework of the UNSCEAR report on the Fukushima accident, experts from the WMO[2] compared several meteorological fields [WMO (2011), Draxler *et al* (2015)] and the rainfall fields were the subject of particular attention [Arnold *et al* (2015)], without however managing to clearly identify a preferred weather forecasting source for the simulations. As part of this workgroup, IRSN had access to fields from the Japanese weather forecasting centre JMA. Finally, the MRI studied the difficulties related to the influence of the orography and generated weather simulations of the month of March 2011 at a fine resolution, seeking to minimise modelling errors [Sekiyama *et al* (2013) ; Sekiyama *et al* (2015)]. IRSN had access to these simulations as part of the SAKURA project. Observations of rainfall by radar were also used in the simulations. Given the lack of meteorological fields without uncertainties, many meteorological data sources were used in order to qualify the interpretation of the results.

Table 1: Description of the meteorological data used by the IRSN for its modelling of the Fukushima accident

Weather data source used by the IRSN	ECMWF	JMA (UNSCEAR)	MRI	WRF (Winiarek (2014))
spatial resolution	0.125 ° (Approx. 12.5 km)	5 km	3 km	5 km
temporal resolution	3h	3h	1h	1h

Characterisation of the releases

The source term, i.e., the evolution over time of the rate of each radionuclide released into the atmosphere, is essential input data for atmospheric dispersion models. Five years after the accident, its accurate assessment still remains uncertain. There are two main families of methods for estimating releases.

1. *An approach based on reactor physics and the knowledge of the initial state of the system*. It consists in modelling the evolution of the state of the power plant and the events that led to the radioactive releases. This approach requires a lot of data. The accuracy of the estimated source term is directly dependent on the uncertainties in the modelling of the state of the reactors, the precise knowledge of the events that occurred in the facility and the effectiveness of some of the release mitigation means implemented. To date, there is no complete source term (including release kinetics for various radionuclides) obtained from this approach. Only estimates of total amounts were provided, immediately after the accident [NISA (2011), NSC (2011)].
2. *Methods coupling the environmental measurements and the atmospheric dispersion simulations to infer release rates likely to explain the measurements*. Inevitably, the quality of the source term correlates to the accuracy of the weather fields used as input for the dispersion model and the quantity and relevance of the measurements, since an event can only be reconstructed if it is observed. There are methods called "simplified" and "inverse" methods. The first are manual or semi-automatic and are based on a limited set of measurements. The inverse modelling techniques are more operational automatic methods based on mathematically rigorous approaches.

[1] European Centre for Medium-range Weather Forecast
[2] World Meteorological Organisation

Since 2011, various estimates of the source term have been published in scientific journals. They are all the result of methods coupling environmental measurements and atmospheric dispersion models. Simplified approaches are preferred by JAEA[3] [Chino *et al* (2011), Terada *et al* (2012), Katata *et al* (2015)]. Initially, IRSN also adopted them [IRSN (2012), Mathieu *et al* (2012)]. The inverse modelling methods that existed before the Fukushima accident enabled a source term to be reconstructed on the basis of activity concentrations in the atmosphere. They have been applied to the case of Fukushima in the work by Stohl *et al* (2011) and Winiarek *et al* (2012), of which IRSN is co-author. However, the application of these methods was limited by the low number of measurements of activity concentrations available at the time. The IRSN team was the first to develop an inverse modelling method to use the dose rate measurements [Saunier *et al* (2013)]. The same team was also the first to invert the activity concentration measurements of Tsuruta *et al* (2014).

According to estimates, the total activities of ^{137}Cs released to the atmosphere varies between 8 and 20 PBq (Table 1). The first source terms overestimated the releases. The released activities whose effects were measured on Japanese territory vary between 5.5 and 12.3 PBq. It is especially the evolution over time of the release rates that differentiates the most recent source terms. The rates vary substantially for some time sequences. There has been no clear consensus to identify a source term that is more realistic than the others. The differences are due to the weather conditions used as input data for the atmospheric dispersion model used and the types of measurements (activity concentration, dose rate or total deposition); they reflect the uncertainties that persist in the estimation of the source term and with regard to the meteorological fields.

[3] Japan Atomic Energy Agency

Table 1 : Main source terms estimated from measurements in the environment. In blue, the total quantities estimated by CSNI and NSC on the basis of information from the facility. In green, the first source terms constructed from inverse or simplified methods (combining radiation and meteorological measurements) in 2011-2012. In purple, recent source terms estimated using inverse or simplified methods. The total quantities of the releases whose consequences have been observed on the Japanese territory are specified.

source term	Total quantity of ^{137}Cs released (PBQ)		Method	observations
	Over Japan and the ocean	Over Japan only		
CSNI (2011)	15		Facility	Total quantity alone (not kinetics)
NSC (2011)	12		Facility	Total quantity alone (not kinetics)
Chino *et al* (2011)	13	7.2	simplified	Activities in the atmosphere, dose rates in Japan and facility events
Stohl *et al* (2012)	34.9	23.5	inverse	Activities in the atmosphere over the northern hemisphere and facility events
Winiarek *et al* (2012)	19	12	inverse	Activities in the atmosphere over Japan, the USA and Canada
Mathieu *et al* (2012)	20.6	12.6	simplified	Activities in the atmosphere, dose rates close to the facility and facility events
Terada *et al* (2012)	8.8	5.5	simplified	Activities in the atmosphere, dose rates close to the facility and facility events
Saunier *et al* (2013)	15.5	12.3	inverse	Dose rates in Japan
Winiarek *et al* (2014)	11.6 to 19.3	7.4	inverse	Activities in the atmosphere and deposition measurements in Japan
Katata *et al* (2015)	12.4	8.7	simplified	Activities in the atmosphere, dose rates close to the facility, measurements at sea and facility events
Unpublished 2015 IRSN		8	inverse	Activities in the atmosphere over Japan (including Tsuruta *et al*, 2014)

A complete source term estimated by modelling the state of the reactors would be complementary since it would be free of uncertainty sources related to the meteorology and environmental measurements, and would enable progress with regard to some release episodes.

Since 2012, the NEA[4] launched a major international project[5] to improve severe accident models and analyse the progression of the Fukushima accident. The assessment of the source term of the accident

[4] Nuclear Energy Agency of the Organisation for Economic Cooperation and Development (OECD)

using modelling of the reactor physics is among the stated objectives of this project, in which IRSN is heavily involved.

Atmospheric dispersion modelling

The source term and meteorological fields are used as input for atmospheric dispersion models to simulate the transport of radioactive plumes in the atmosphere and their impact on the ground. The quality of the simulation is evaluated by comparison with the radiation measurements in the environment.

Since 2011, the simulations have become more realistic and now the model - measurement differences have been significantly reduced. Decisive progress was made through the use of various weather forecasting sources, more realistic source terms and a better understanding of environmental contamination episodes [Tsuruta *et al* (2014)]. However, all studies still report weaknesses and often face the same difficulties in modelling certain sequences [Morino *et al* (2013) ; Terada *et al* (2012) ; Korsakissok *et al* (2013) ; Saunier *et al* (2013) ; Katata *et al* (2015) ; Draxler *et al* (2015)].

[5] The BSAF project: https://www.oecd-nea.org/jointproj/bsaf.html

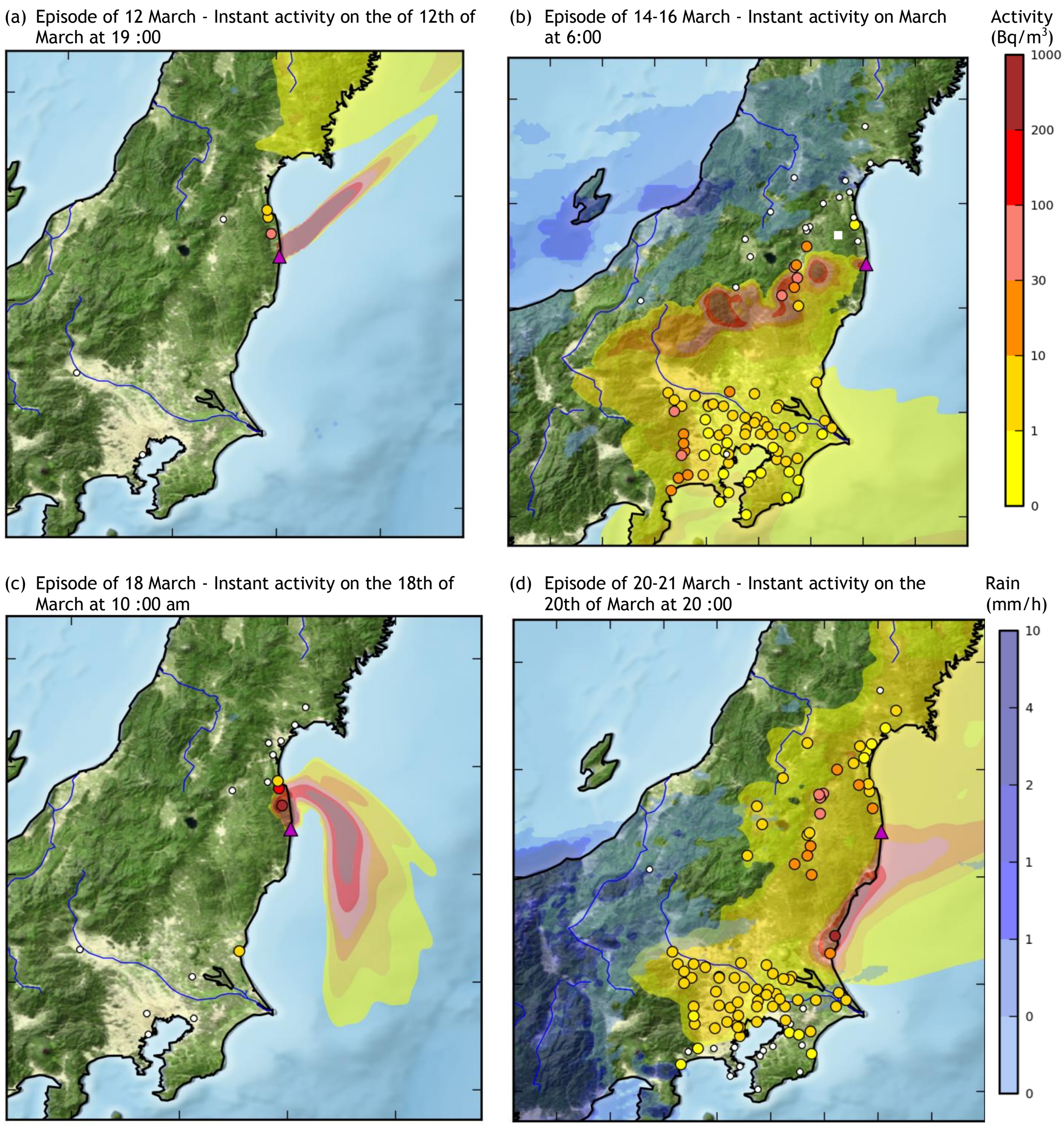

Figure 1 : Instant activities of ^{137}Cs for the simulated plume compared with the measurements (coloured circles). Rainfall is represented by the blue palette and is transparent on the maps. Each map represents an instant of the main contamination episodes. 12 March at 19:00 (a); 15 March at 6:00 (b); 18 March at 10:00 am (c) and 20 March at 20:00 (d). The Idate location is indicated by means of a white square in Figure (b).

The episode of 12 March was correctly simulated in the first phase but the models fail in the second one, in which the strongest activities are measured. Whatever the weather data source, the plume does not move along the coast enough (compared to the facts) but rather is transported towards the Pacific Ocean in the Northeast direction. Figure 1 illustrates this behaviour, which highlights the lack of realism of the wind along the coast.

The episode of 14 to 16 March is now significantly better modelled, but progress still needs to be done.

The simulation of the strong deposits area between the nuclear site and the Fukushima basin is much more realistic but its location is still slightly off and the leaching of the plume starts at best one to two hours later than in the measured reality. The lack of precision of the rainfall data is directly responsible for these assessment faults (Figure 1b[6]).

A difficulty that is common to all of the models is the simulation of the fallout in the Nakadori Valley. Indeed, the vertical distribution of the activity of the plumes and the direction of the wind are not realistic enough due to insufficient consideration of the influence of the relief.

The episode of 18 March has now been well modelled (Figure 1 c).

The episode of 20 to 21 March has, recently, been modelled much better and the various phases of this sequence have now been properly reconstructed. For example, due to the weather forecasts provided by the MRI [Sekiyama *et al* (2013) ; Sekiyama *et al* (2015)], the modelling of plumes transported toward the South has been significantly improved. So far, the delay of the plume did not allow the contamination of the Tokai region to be simulated, which also deteriorated the simulations in metropolitan Tokyo. The MRI weather forecasts allow simulations of the coastal zone to be better addressed. Thus, the simulations of IRSN have achieved a good agreement with the environmental measurements, as shown in Figure 1 d.

Improvement of the atmospheric dispersion models and the representation of physical processes

Beyond the objective of reaching a better understanding of the Fukushima accident, the challenge of the work undertaken by the international community on atmospheric dispersion modelling is to improve the representation of physical processes in the models. For IRSN, this means the improvement of the operational assessment tools in order to improve the adequacy of the response of the Institute to a nuclear accident.

From the perspective of the population exposure, modelling the deposition is a major challenge, both due to the doses induced by the deposition and by the depletion of the plume that it generates. The realism of the depositions simulated is thus the subject of special attention and the difficulty in reproducing the depositions of the 14-16 March episode have led several teams, including IRSN, to study the modelling of the wet deposition processes [Leadbetter *et al* (2015); Katata *et al* (2015) ; Quérel *et al* (2016) ; the MRI teams]. The dispersion models used in an operational context are generally based on very simplified depositions models. Also, the challenge was to know whether complex models taking into account the aerosol physics, particle size, rainfall, etc., would better simulate depositions.

Simulating the consequences of the Fukushima accident with a complex deposition model does not solve the difficulties in reproducing some episodes. These difficulties seem mostly due to remaining uncertainties with regard to the input data and the modelling of the plume behaviour in the context of a complex orography influencing its vertical distribution. However, it is essential to model, even simply,

[6] Figure 1 b illustrates the problem of accuracy of the rainfall data. The simulation is consistent with the activities of ^{137}Cs measured. At 6:00, the leaching of the plume should start in the Idate region (indicated by a white square). The lack of rain in the simulation excludes this. The rainfall data used in this example are still radar observations.

the leaching process in the cloud as well as the leaching processes below the cloud [Quérel *et al* (2016)].

The investigation of this subject continues, particularly through model inter-comparisons. IRSN is contributing actively to this work, particularly with the Science Council of Japan with regard to the Fukushima accident.

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