Comparison of atmospheric dispersion model outputs and radioactivity measurements made in Ireland following the Fukushima nuclear emergency

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Abstract

The Radiological Protection Institute of Ireland (RPII) employs atmospheric dispersion models (ADMs) to predict the dispersion and deposition of radionuclides in the environment. This is of particular use in the case of an unplanned atmospheric release of radionuclides before field measurements are available. The RPII use the Hybrid Single-Particle Lagrangian Integrated Trajectory (HySplit) model to assess the long range (>200 km) atmospheric dispersion of radionuclides. This model requires forecast and/or retrospective meteorological data (wind fields, atmospheric pressure, etc).

Iodine and caesium were released to the environment during the accident at the Fukushima Dai-ichi nuclear power plant in Japan. The majority of the atmospheric releases took place between March 12 and March 22, with a maximum release phase from 14 to 17 March. Traces of iodine-131 from Fukushima were initially detected in Europe (Iceland) on 23rd March. In Ireland, iodine-131 was first detected on air particulates collected on a high-volume air sampler during 26-27 March. Within 15 days of the accident, radioactive material released from Fukushima had spread all across the northern hemisphere.

In response to the accident at Fukushima, the RPII used the HySplit model to provide long-range radioactive plume forecasts. The model was initialized using estimates available at the time of the quantities and types of radioactivity released along with a combination of archive (Global Data Assimilation System, GDAS) and forecast (Global Forecasting System, GFS) meteorological data. The dispersion model predicted the arrival time in Ireland of the Fukushima radioactive plume as well as air concentrations and duration of the plume passage over Ireland.

This paper outlines the HySplit model set-up used to predict the movement of the Fukushima plume. It will also compare the model predictions with measured air concentrations, demonstrating that the model predictions were broadly in agreement with the magnitude and timing of the observed radionuclide concentrations.

Key Words: Fukushima, atmospheric dispersion, HySplit, RPII

1. Introduction

The Great East Japan Earthquake and tsunamis on 11 March 2011 resulted in the development of severe accident conditions at the Fukushima Dai-ichi Nuclear Power Plant (NPP) and, subsequently, releases of radioactivity to the environment. The majority of the releases to the atmosphere occurred during the period 12 to 22 March, with a maximum release phase from 14 to 17 March. The radioactivity released was dominated by volatile fission products including isotopes of the noble gases xenon and krypton; iodine; caesium; and tellurium

The Radiological Protection Institute of Ireland (RPII) has responsibility under Ireland's National Emergency Plan for Nuclear Accidents (NEPNA) for assessing the potential contamination of the Irish environment and food and doses to the population following an unplanned release of radionuclides to the atmosphere. Atmospheric dispersion models are a tool used as part of this assessment.

The RPII ran the Hybrid Single-Particle Lagrangian Integrated Trajectory (HySplit) model using estimates available at the time of the quantities of radioactivity released. The model predicted the arrival time in Ireland of the Fukushima radioactive plume, as well as radioactive air concentrations and duration of the plume over Ireland.

2. Dispersion of Radioactive Material

Air monitoring activity across the northern hemisphere was increased following the first reports of atmospheric releases from Japan. Radioactivity was detected by a range of monitoring systems, including national monitoring networks and the Comprehensive Test Ban Treaty Organisation's (CTBTO) global network of monitoring stations (designed to detect trace levels of radionuclides from clandestine nuclear operations including testing of nuclear weapons).

Data from the CTBTO network showed that radioactivity from Fukushima was first detected on 12 March at the Takasaki CTBTO monitoring station in Japan indicating that the radioactive plume had initially travelled in a south westerly direction. The radioactive plume next travelled to eastern Russia (14 March) and then crossed the Pacific towards the North American continent to Europe and to Central Asia. A CTBTO monitoring station in Iceland detected radioactive isotopes indicating that the plume had reached Europe on 20 March. This was also confirmed by other European monitoring networks (Masson et al., 2011). Radioactive material released from Fukushima was detectable all across the northern hemisphere 12 to 15 days after the accident. The radioactive materials remained confined to the northern hemisphere for the first four weeks following the accident. On 13 April radioactivity was detected at stations located in Australia, Fiji, Malaysia and Papua New Guinea indicating that it had reached the southern hemisphere (CTBTO, 2011; BfS, 2011).

The RPII increased the frequency of sampling and analysis of air, rainwater, and milk in anticipation of the arrival of the radioactive plume in Ireland. The objective of this work was to assess the levels of radioactivity from the accident reaching Ireland and to provide data on which to base the RPII's advice to the Irish Government and to the Irish population (RPII, 2012). In addition, the RPII used the HySplit model to estimate the arrival time and duration of the plume over Ireland. The outputs from the model helped the RPII to efficiently plan its enhanced environmental radioactivity monitoring programme.

2.1. Atmospheric Releases

The Japanese Nuclear and Industrial Safety Agency (NISA) estimated the total activity of iodine-131 and caesium-137 discharged from Fukushima Dai-ichi to be 1.6 x 10^{17} Bq and 1.5 x 10^{16} Bq respectively. These values represent, respectively, approximately 9% and 18% of the amounts of iodine-131 and caesium-137 released as a result of the 1986 accident at the Chernobyl NPP in Ukraine. Other estimates were marginally higher (Stohl et al., 2011; Chino et al., 2011; IRSN, 2011) but of the same order of magnitude. For example, Stohl et al. (2011) used inverse modelling techniques, optimising the agreement between atmospheric dispersion model results and measurement data in order to estimate the source term, to calculate a total release of caesium-137 to air of 3.6 x 10^{16} Bq.

Recent estimates of the temporal emission variation based upon model estimates and back-calculations from air concentration measurements have been reported by Draxler & Rolph (2012) and are available on the US National Oceanic and Atmospheric Administration website (NOAA ARL, 2012). These data, shown in figure 1, provide hourly emission rates for (gaseous) I-131 and Cs-137. Also shown in this figure are early estimates of the temporal releases based on information reported during the accident by, among others, the Nuclear Safety Commission of Japan, the IRSN (France), IAEA, the Central Institute for Meteorology and Geodynamics Austria, etc.

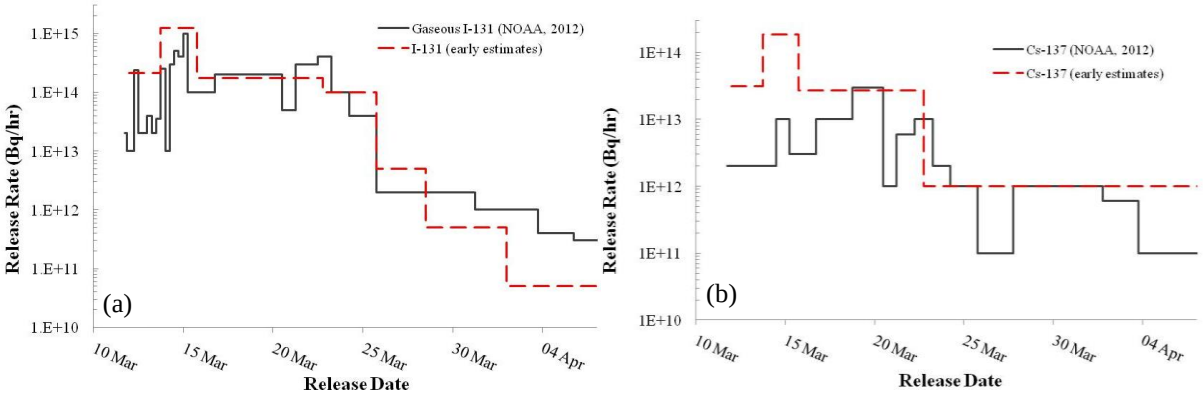

Figure 1. The (gaseous) I-131 (a) and Cs-137 (b) hourly emission rates used in the HySplit model (NOAA ARL, 2012). The figures also show (red dash line) early estimates of the emission rates used.

3. Atmospheric Dispersion Modelling of Radioactivity

The RPII routinely runs and tests atmospheric dispersion models in order to predict the transport and deposition of radionuclides in the environment. Dispersion models are of particular use in the case of an unplanned atmospheric release of radionuclides before field measurements are available. This modelling capability is maintained by the RPII with the assistance of the Irish National Meteorological Service (Met Éireann) and other specialist agencies.

Currently, there are two operational dispersion models in the RPII. The first, RIMPUFF (Riso Mesoscale PUFF) forms part of the nuclear emergency decision support tool ARGOS (Accident Reporting and Guiding Operational System) and is valid for dispersion up to ~200 km (Thykier Nielsen et al., 1999). The second model, HySplit (Hybrid Single-Particle Lagrangian Integrated Trajectory) (Draxler & Hess, 1998), can simulate the dispersion of radionuclides over longer distances.

The HySplit model simulates the dispersion of a pollutant by assuming either a puff or particle dispersion. Advection and diffusion calculations are made in a Lagrangian framework while concentrations are calculated on a fixed (Eulerian) grid (Draxler & Hess, 1998). HySplit requires gridded meteorological data (e.g. wind fields, temperature, atmospheric pressure, etc) defined at regular (three hourly) time intervals.

In response to the accident at Fukushima, the HySplit model was used due to the large distance between Japan and Ireland. The model was run using estimated radioactive discharges available at the time and a combination of archive (Global Data Assimilation System, GDAS) and forecast (Global Forecasting System, GFS) meteorological data.

3.1 HySplit Model Setup

The dispersion modelling approach used by the RPII was developed in three phases over the course of the RPII's response to the accident at Fukushima. In the first week of the event little information was available on the quantity and timings of radioactive releases from the NPP. During this first phase, HySplit was run assuming a unit (1 GBq/hr) release rate over the modelled period. Modelling the dispersion of I-131 and Cs-137 in air provided an indication of the arrival time of the radioactive plume in Ireland.

In the second phase of the modelling (mid March to end of April), estimates of the quantities and timings of the releases became available. These 'early' release estimates are shown above in figure 1. This allowed the RPII to estimate the radionuclide air concentrations expected in Dublin.

In the final (post accident analysis) phase, the RPII used estimates of the temporal emission variation provided by NOAA ARL (2012) (shown above in figure 1). In this phase, modifications

suggested by Draxler & Rolph (2012) to some of the model input parameters (e.g. scavenging coefficients) have also been incorporated. This has been performed to allow the model to be improved for future use.

All simulations were performed using a 3-dimensional particle approach. In this approach HySplit represents gaseous I-131 as a gas (with wet and dry deposition). Particulate I-131 and Cs-137 are both modelled as a (light) particle with a small deposition velocity (Draxler & Rolph, 2012). The 3-D approach involved releasing ~5,000 particles per hour over the duration of a simulation. At the end of a simulation, a considerable number of particles were being tracked and some model runs took ~24 hours of computational time to complete.

In the first and second phases, the model was generally run using a combination of archive (Global Data Assimilation System, GDAS) and forecast (Global Forecasting System, GFS) meteorological data. These data sets have a 1-degree horizontal resolution with meteorological fields available every three hours. In the post accident analysis phase, the model was run using a 0.5-degree horizontal resolution archive meteorological data set from NOAA's Global Forecast System (GFS). In each of the modelling phases, the output concentration grid was global at 1-degree horizontal resolution with a vertical extent of 500 m.

4. Results and Discussion

On completion of a model run, time series I-131 and Cs-137 concentration data, at the latitude-longitude corresponding to RPII's high volume air particulate sampler (located in Dublin), were extracted to a text file. These data were then graphed and compared with the RPII air concentration measurements. An example of the results obtained in each of the three modelling phases will be presented below.

4.1 First Modelling Phase Results

As mentioned earlier, the initial atmospheric dispersion modelling performed in the RPII assumed a 1 GBq hourly release of I-131 and Cs-137. The resulting time series air concentrations for gaseous I-131, particulate I-131 and, Cs-137 are shown in figure 2. These early results predicted that the Fukushima radioactive plume would reach Ireland by 21st -22nd March 2011.

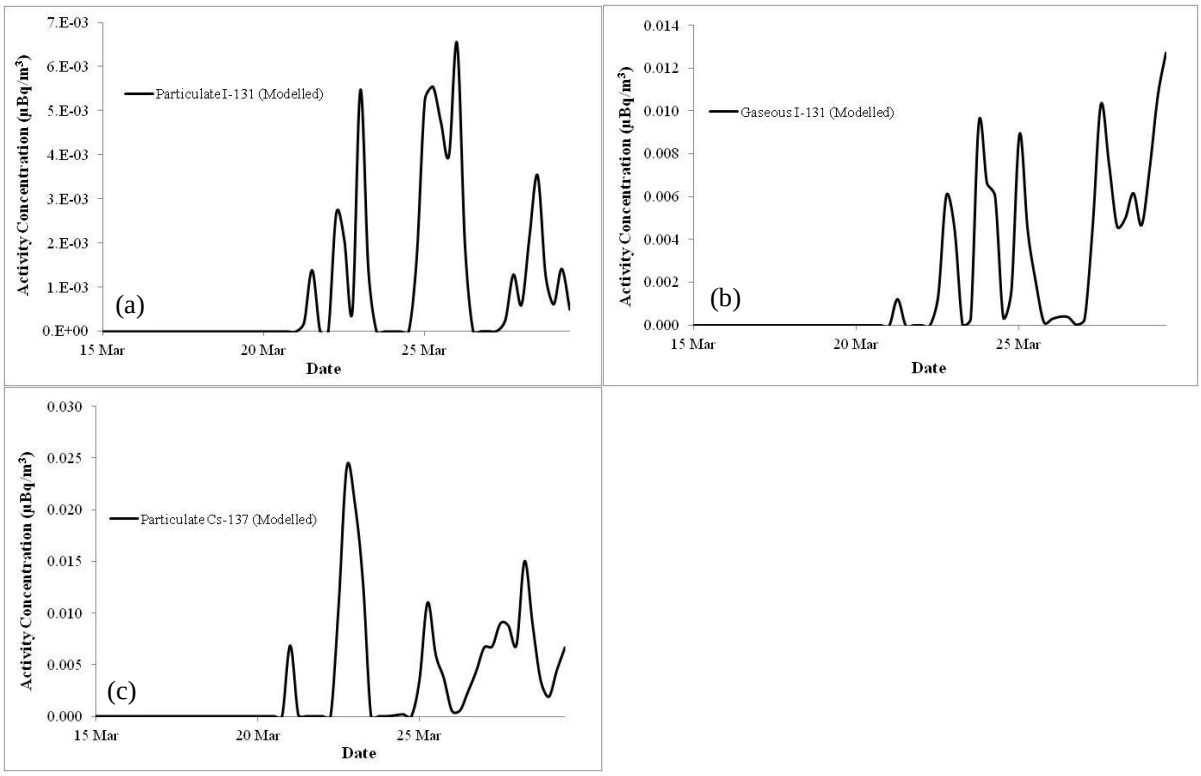

Figure 2. First modelling phase predicted time series air concentrations of gaseous I-131 (a), particulate I-131(b), and Cs-137 (c) in Dublin.

4.2 Second Modelling Phase Results

The 'early' release estimates, shown in figure 1, were used in HySplit to predict the radionuclide air concentrations expected in Dublin. The predicted radionuclide air concentrations for I-131 were found to be a significant overestimation of the measured value while the predicted Cs-137 concentrations were found to slightly underestimate the measured values.

The model was re-run and time series concentrations were calculated at a number of additional locations corresponding to CTBTO monitoring stations. These included CTBTO measurement locations at various distances from the release point (Hawaii, Japan, Germany, Iceland, and California). At each of these locations, the modelled concentrations overestimated the particulate I-131 measurements and underestimated the Cs-137 measurements. It was also noted that the degree of under- and overestimation was reasonably constant across each of the CTBTO stations. (Note: The CTBTO data can be viewed on the German radiation protection authority's website (BfS, 2011)).

It was assumed that this was a result of a combination of large uncertainties in the model inputs, including a lack of definitive data on the quantities and timings of the radioactive release. It was also assumed that the wet and dry deposition parameters required some modification. Finally, it was also noted that the meteorological data used during this phase of the modelling was a rather 'coarse' (one degree) data set and so may not adequately model precipitation along the path of the plume.

On this basis, the model predictions were adjusted and better agreement was obtained between the measurements and the adjusted time series for Cs-137 and I-131 as shown in figure 3.

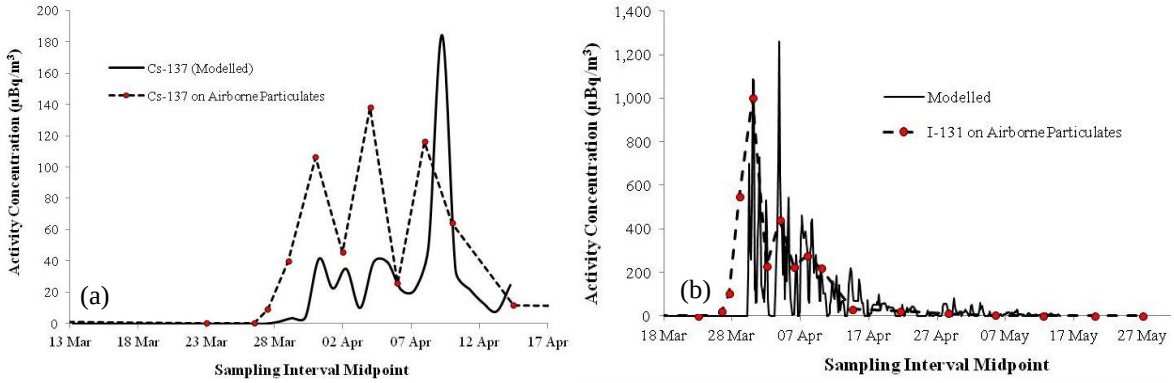

Figure 3. Comparison between the (second phase) model predicted time series air concentrations and measurements of Cs-137 (a) and I-131(b) on Airborne Particulates sampled in Dublin.

4.3 Third Modelling Phase Results

As noted earlier, modifications suggested by Draxler & Rolph (2012) to model input parameters (scavenging coefficients) were incorporated into the model. The model was also run using a meteorological data set with a higher resolution than in the previous phase. Finally, the latest estimates of the radionuclide emissions (quantities and timings) were used in the model. In Figure 4, the predicted time series air concentrations for particulate I-131 and Cs-137 are compared with the RPII measurements.

HySplit was initialised with the assumption that the total released iodine was equally distributed (50/50) between the gaseous and particulate species. The average model predicted value of the ratio between gaseous iodine and total iodine resulting in Dublin is ~66%. This compares reasonably well with the measured value (~83% ± 19 %) calculated using gaseous and particulate iodine measurements from a number of locations in Ireland (RPII, 2012).

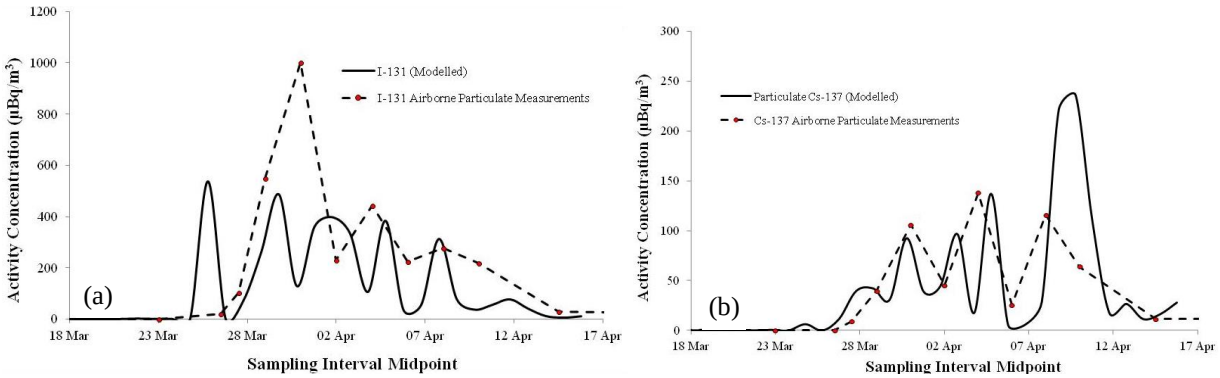

Figure 4. Comparison between the (third phase) model predicted time series air concentrations and measurements of I-131(a) and Cs-137 (b) on Airborne Particulates sampled in Dublin.

5. Conclusions

The HySplit atmospheric dispersion model played an important role in the technical assessment of the Fukushima accident. Using the model predictions, information from Japan received through official channels, and the experience gained during modelling exercises of accident scenarios, the RPII anticipated that the levels of radioactivity reaching Ireland would be extremely low.

In general, HySplit made reasonable estimates of the timing and duration of the radioactive plume over Dublin. And, once adjustments were made to the model inputs, the radionuclide concentrations in air were also adequately estimated by the model. The post accident analysis phase is ongoing. It is most likely that estimated releases (quantities and timings) will be revised. HySplit will be run using additional information, if and/or when it becomes available.

This study shows that while atmospheric dispersion prediction models cannot substitute for environmental measurements in a nuclear emergency, they are a useful supplementary tool; both in the early phase before any releases have occurred or before the plume has reached the territory of concern, and to allow estimations of environmental concentrations where measurements cannot be made (e.g., due to remote location or resource constraints).

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