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MODELLING THE REGIONAL DEPOSITION OF RADIONUCLIDES FROM THE FUKUSHIMA DAI-ICHI NUCLEAR POWER PLANT WITH NAME

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Abstract: In March 2011 an earthquake and tsunami severely damaged the Fukushima Dai-ichi (Fukushima 1) nuclear power plant resulting in the release of large amounts of radioactive material. Interactions between the meteorological conditions and the airborne radioactive material lead to large deposits of radionuclides in Fukushima and neighbouring prefectures. This has provided a unique opportunity for the validation of deposit estimates from dispersion models. In this study we investigate the sensitivity of the modelled deposition patterns, using the Met Office dispersion model NAME, of Iodine-131 and Caesium-137 to variations in the source term and the wet scavenging parameters. .

Key words: *Fukushima, wet deposition, radionuclides, Lagrangian*

INTRODUCTION

Radionuclides deposited on the ground following a nuclear accident are an important contribution to the radioactive dose received by people in the area. Therefore any dispersion model which is to be used to provide activity fields for dose estimates must be able to provide a reasonable estimate of the amount and location of material deposited on the ground.

Air concentration output from dispersion models has been validated in a number of field experiments. However, these experiments are often carried out during dry weather and/or do not include sampling of deposits so there are very few data sets against which to validate deposition data. In contrast, an extensive deposit sampling campaign was carried out following the accident at the Fukushima Dai-ichi nuclear power plant on the east coast of Japan in March 2011. Although much of the radioactive material was transported eastwards over the Pacific Ocean there were a number of days when material was transported inland over Honshu resulting in significant deposits in Fukushima and neighbouring prefectures. These data provide a unique opportunity for the validation of model simulations of deposits.

Uncertainty in dispersion modelling can be considered in three categories, uncertainty in the driving meteorology, uncertainty in the source term and uncertainty in the dispersion model. In this study uncertainty in the source term is investigated by using a number of different estimates of the amount of Caesium-137 and Iodine-131 released from Fukushima. Then uncertainty in the dispersion model deposition mechanism is investigated by using a number of different wet scavenging parameters.

NAME MODEL SETUP

NAME (Numerical Atmospheric-dispersion Modelling Environment) is the UK Met Office's Lagrangian particle dispersion model and is used to model the atmospheric transport and dispersion of a range of gases and particles (Jones A.R. et al., 2007). In NAME, large numbers of computational particles are released into the model atmosphere with each computational particle representing a proportion of the mass of the material (gases or aerosols) being modelled. Computational particles are advected within the model atmosphere by three-dimensional winds from numerical weather prediction models and turbulent dispersion is simulated by random walk techniques. In this study three loss processes, wet and dry deposition and radioactive decay, are included.

Wet deposition is parameterised in NAME. Material is removed using a depletion equation:

$$\frac{dC}{dt} = -\Lambda C \qquad (1)$$

where C is the air concentration and the scavenging coefficient Λ is given by:

$$\Lambda = Ar^{B} \qquad (2)$$

where r is the precipitation rate in mm/hr and A and B are scavenging parameters which can be varied for different types of precipitation (rain or snow) and different wet deposition processes (wash-out or rain-out) (Webster H. and D. Thomson, 2014).

Dry deposition is modelled in NAME using the concept of the deposition velocity, v_d. The flux of pollutant to the ground, F, is proportional to the concentration, C, of pollutant and is given by

$$F = v_d C \qquad (3)$$

where v_d is the constant of proportionality.

Meteorology

In this work meteorological data from the ECMWF global model is used to drive the dispersion model. A study carried out by the authors of this work (Leadbetter, S.J., et al., 2014) showed that, for the Fukushima 1 accident in 2011, there was a better correlation between model predictions and observed deposits of Caesium-137 when ECMWF meteorological data was used compared to when UK Met Office global meteorological model data was used. The ECMWF operational meteorology has a spatial resolution of 0.125 by 0.125 degrees (approximately 16 km) and a temporal resolution of 3 hours.

SENSITIVITY TO SOURCE TERM

The sensitivity of the model deposits to the source term is explored using three openly published source terms for Caesium-137 and Iodine-131 (Figure1, Table 1). All three studies combine measurements of radionuclide concentrations or gamma dose with dispersion models to determine the timing and amount of material emitted from Fukushima 1. For the remainder of this report the source terms are referred to by the surname of the first author. There are some differences between the three source terms, particularly in the temporal variation of the release rates (Figure 1).

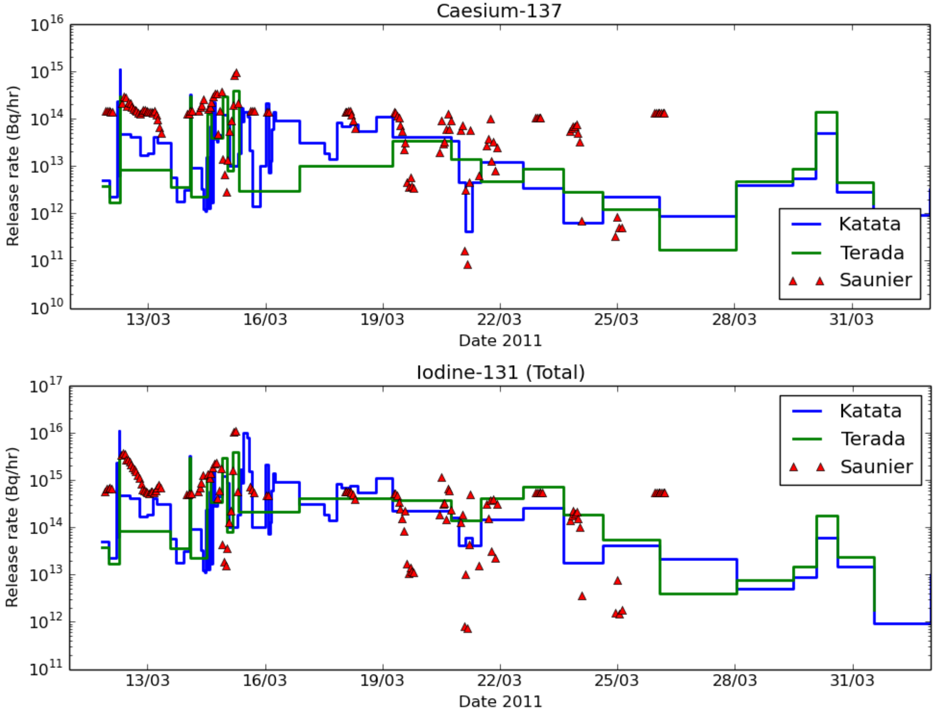


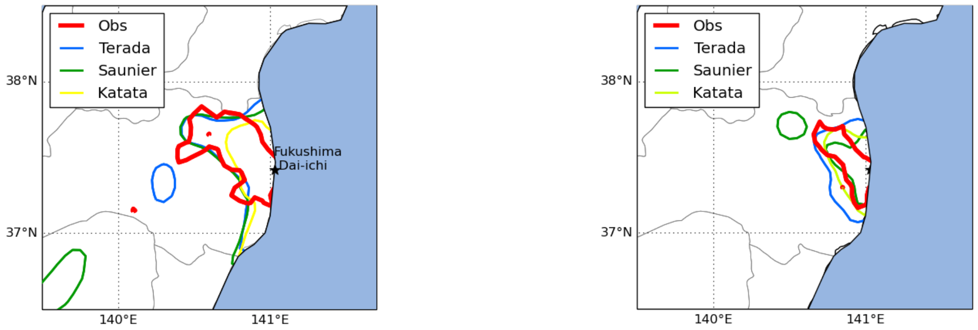
Figure 1: Estimates of release rates of Caesium-137 (top) and Iodine-131 (bottom) from three openly published source terms (Katata, G., et al., 2014, Terada, H., et al., 2012, and Saunier, O., et al., 2013) and used in this study.

Reference	**Run ID**	**Measurement Data**	**Dispersion Model**
Terada, H., et al., 2012	Terada	Soil measurements within Japan	WSPEEDI-II
Saunier, O., et al., 2013	Saunier	Gamma dose rate measurements within Japan	ldX
Katata, G., et al., 2014	Katata	Environmental measurements within Japan and sea surface concentrations in the northwest Pacific	WSPEEDII-II and SEA-GEARN-FDM

Table 1: Origin of source terms used in this study

Observed deposits are produced by combing soil measurements (Saito, K., et al., 2014) and air survey measurements (NRA, 2014, Torii, T. et al., 2013) onto the same output grid as the model deposits (0.5º longitude by 0.5º latitude). The model deposits are then compared to the observed deposits by plotting threshold contours for the observations together with threshold contours for the modelled deposits. The 200 and 1000 kBqm^{-2} contours are chosen as threshold contours for Caesium-137 and Iodine-131 respectively as they are the smallest value closed contours for the observed deposits. All deposits (modelled and observed) are decay corrected to 00 UTC on 03/04/2011.

A large proportion of the regions of deposits within the threshold contour lie to the northwest of Fukushima 1 and all model runs are able to produce this pattern (Figure 2). However, the model predictions overestimate the southward extent of the Caesium-137 threshold contour and the northward extent of both Caesium,-137 and Iodine-131 contours immediately along the coast.


(a) Caesium-137

(b) Iodine-131

Figure 2: (a) Location of the 200 kBqm^{-2} contour for model predictions of Caesium-137 deposits and (b) location of the 1000 kBqm^{-2} contour for model predictions of Iodine-131 deposits for model runs using different source terms and the default scavenging parameters. The equivalent contour for the observations is shown in red. An explanation of the run ID's used in the legend can be found in Table 1.

To quantify the comparison between the modelled and observed deposits of Caesium-137 and Iodine-131 four statistical functions were computed:

- Correlation coefficient which indicates the degree of agreement between values collocated in space.
- Fractional bias, which indicates the degree of any over- or underestimate of the values. Here negative values indicate an underestimate and positive values indicate an overestimate.
- Percent within a factor of two.
- Kolmogorov-Smirnov parameter (KSP) which indicates the degree of agreement between the distribution of unpaired measured and predicted values. KSP values range from 0 to 100 where 0 denotes a perfect agreement.

In general there was good agreement between all model runs and the observations (Table 2). However, the fractional bias shows that only the model run with the Katata source term did not overestimate the amount of Caesium-137 deposition and all runs overestimated the Iodine-131 deposition. This can also be seen in Figure 2 where the threshold contours for all runs except the Katata run enclose a greater spatial area than the observations. For Iodine-131 the lowest fractional bias was achieved by the Saunier run but the highest correlation was achieved by the Katata run.

Run ID	**Radionuclide**	**Correlation**	**Fractional Bias**	**Percent within a factor of 2**	**Kolmogorov-Smirnov**
Terada	Cs-137	0.83	0.24	50	34
Saunier	Cs-137	0.75	0.69	46	27
Katata	Cs-137	0.86	-0.10	55	20
Terada	I-131	0.85	0.77	56	26
Saunier	I-131	0.84	0.57	46	21
Katata	I-131	0.90	0.85	51	21

Table 2: Statistical comparison of model predictions of deposits of Caesium-137 and Iodine-131 with observed deposits for model runs with different source terms.

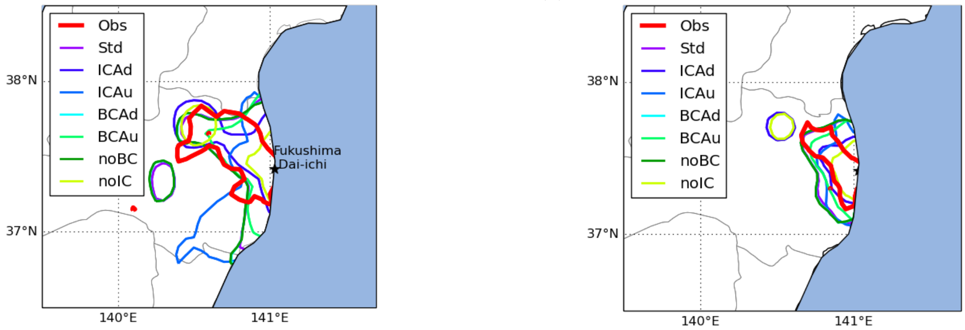
SENSITIVITY TO SCAVENGING PARAMETERS

The sensitivity to the scavenging parameters was investigated by increasing and decreasing the ‘A’ parameter in equation (2) for in-cloud and below-cloud scavenging by a factor of 10 and by removing in-cloud and below-cloud scavenging completely. The parameters used in the six different model runs are shown in Table 3. In this experiment all model runs used the Terada source term (as this was the first published source term).

Run ID	**Below-Cloud Rain**		**Below-Cloud Snow**		**In-Cloud Rain**		**In-Cloud Snow**	
	A	**B**	**A**	**B**	**A**	**B**	**A**	**B**
Std	8.4e-5	0.79	8.0e-5	0.305	3.36e-4	0.79	5.2e-5	0.79
ICAd	8.4e-5	0.79	8.0e-5	0.305	3.36e-5	0.79	5.2e-6	0.79
ICAu	8.4e-5	0.79	8.0e-5	0.305	3.36e-3	0.79	5.2e-4	0.79
BCAd	8.4e-6	0.79	8.0e-6	0.305	3.36e-4	0.79	5.2e-5	0.79
BCAu	8.4e-4	0.79	8.0e-4	0.305	3.36e-4	0.79	5.2e-5	0.79
noBC	0	0	0	0	3.36e-4	0.79	5.2e-5	0.79
noIC	8.4e-5	0.79	8.0e-5	0.305	0	0	0	0

Table 3: Scavenging parameters used in this study. The grey shading highlights parameters which differ from Std.

The threshold contours from most of the runs with different scavenging parameters show reasonable agreement with the threshold contours from the observations (Figure 3). For the Caesium-137 deposits the threshold contours of five of the seven runs extend further south along the coast than the observations. The model runs also overestimate the northwards extent (along the coast) of the threshold contours for both Caesium-137 and Iodine-131.


(a) Caesium-137

(b) Iodine-131

Figure 3: (a) Locations of the 200 kBqm^{-2} contour for model predictions of Caesium-137 deposits and (b) location of the 1000 kBqm^{-2} contour for model predictions of Iodine-131 deposits for model runs using different scavenging parameters. The equivalent contour for the observations is shown in red. An explanation of the Run ID’s used in the legend can be found in Table 3.

A statistical evaluation of the model runs with different scavenging parameters was also carried out. According to the statistical comparators used here no one model runs outperforms the rest in all comparisons. It can be seen that most of the model runs overestimate the amount of deposition; they have a positive fractional bias (Table 4) and the threshold contour encloses a greater region for the model runs than the observations (Figure 3). However, all runs correlate well with the observations.

Model ID	Radionuclide	Correlation	Fractional Bias	Percent within a factor of 2	Kolmogorov-Smirnov
Std	Cs-137	0.83	0.24	50	34
ICAu	Cs-137	0.69	0.40	22	13
ICAd	Cs-137	0.70	-0.33	51	18
BCAu	Cs-137	0.72	0.50	45	29
BCAd	Cs-137	0.79	0.16	50	34
noBC	Cs-137	0.78	0.15	50	34
noIC	Cs-137	0.62	-0.79	28	36
Std	I-131	0.85	0.77	56	26
ICAu	I-131	0.86	1.00	37	13
ICAd	I-131	0.77	0.37	55	19
BCAu	I-131	0.76	1.04	59	19
BCAd	I-131	0.90	0.77	52	30
noBC	I-131	0.90	0.76	52	30
noIC	I-131	0.73	0.11	45	25

Table 4: Statistical comparison of model predictions of deposits of Caesium-137 and Iodine-131 with observed deposits for model runs with different wet scavenging parameters. An explanation of the Run ID's can be found in Table 3.

CONCLUSIONS

This study compared model predictions of deposits of Caesium-137 and Iodine-131 from Fukushima-1 from model runs with different source terms and different wet scavenging parameters. The best model prediction of Caesium-137 deposits is provided by the run with default scavenging coefficients and the Katata source. This run has the highest correlation coefficient, the lowest fractional bias and the highest percent within a factor of two. A lower KSP is achieved by the run with increased in-cloud wet scavenging.

All model predictions overestimate the amount of Iodine-131 deposits. This is evident in the fractional bias and the comparison of the 1000 $kBqm^{-2}$ threshold. The model run with the lowest fractional bias is the run with no in-cloud wet scavenging. One possible explanation for this is that two of the three source terms (including the source term used when exploring the sensitivity to the wet scavenging parameters) used dispersion models which didn't include in-cloud scavenging. This could potentially result in an overestimate of the source release rate and an overestimate of the deposits in dispersion models like NAME which include in-cloud wet scavenging. Alternatively the overestimate could be due to not accounting for the split between gaseous and aerosol forms of Iodine-131. In the current setup of NAME gaseous and aerosol forms of Iodine-131 use the same scavenging parameters for wet deposition which could result in excessive wet scavenging of Iodine-131.

By comparing the spatial extent of the threshold contours it can be seen that all the model runs in this study overestimate deposits along the coast to the north and south of Fukushima 1. It is unlikely that this overestimate is caused by the wet scavenging parameter as varying the wet scavenging parameter only results in small increases and decreases in the size of the overestimate. All of the source terms presented in this study also overestimate the deposits along the coast pointing to the meteorological data as a possible cause of this feature.

This study has shown that NAME is able to reproduce observed deposits of Caesium-137 and Iodine-131 from the accident at Fukushima 1. However, although the current scavenging parameters provide the best estimate of Caesium-137 deposits, more work needs to be done to improve the wet scavenging of Iodine-131.

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