Published sets of probability maps of threshold exceedance for scenarios provided to WP4, WP5 & WP6 → 2

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D9.4 – Published sets of probability maps of threshold exceedance for scenarios provided to WP4, WP5 & WP6→ 2

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Abstract

This report presents output from ensemble dispersion simulations performed by CONFIDENCE work package 1 (WP1). It presents the Borssele case study. The case description, a list of the participants and the models used for the calculations are given. Ensemble results are summarized for the “short release” scenario. Results are shown for ensembles using only meteorological uncertainties, and with those including source term perturbations. A preliminary analysis and visualization products are proposed.

<End of abstract>

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Introduction

One of the aims of the CONFIDENCE project is to understand, reduce and cope with the uncertainty of meteorological and radiological data and their further propagation in decision support systems, including atmospheric dispersion, dose estimation, food-chain modelling and countermeasure simulation models. Work package 1 (WP1) is focused on the modelling of uncertainties during the emergency phase, from meteorological and source term inputs, and applied to atmospheric dispersion and dose estimates. WP1 will then provide output to other work packages (namely WP4-6) whose purpose is to investigate and improve decision making under uncertainty. This report presents the ensemble dispersion simulations performed by WP1 participants for a hypothetical accident scenario at Borssele nuclear power plant (Netherlands).

The first part of the report summarizes very briefly the two release scenarios (one short and one long release) and the meteorological conditions considered. Then, the second part presents the results with (a) the short release and 10 meteorological members, and (b) the same, with additional perturbations on the source term and/or physical parameters. The results for the long-release scenario are not presented here and will be analysed at a later stage.

The case study is still ongoing and the results may be modified during the course of the project. However, the figures provided here give a good view of the discrepancies due to different modelling approaches. The objective is to provide examples of outputs that can result from an uncertainty analysis. These will be provided to WP4, WP5 and WP6 in order to trigger reflection on how to use these products and integrate the uncertainty evaluation in the decision making process. Some elements of explanation are proposed here, but results will be analysed at a later stage.

The Borssele case study

In Figure 1 the location of the Borssele nuclear power plant (NPP) is shown. It is located at a latitude and longitude of 51.43 and 3.71 decimal degrees, respectively.

Figure 1: The Borssele nuclear power plant. Latitude, longitude: 51.43, 3.71

Release scenarios and associated uncertainties

Figure 2 schematically shows the timeline and names of the events during an incident at a nuclear reactor.

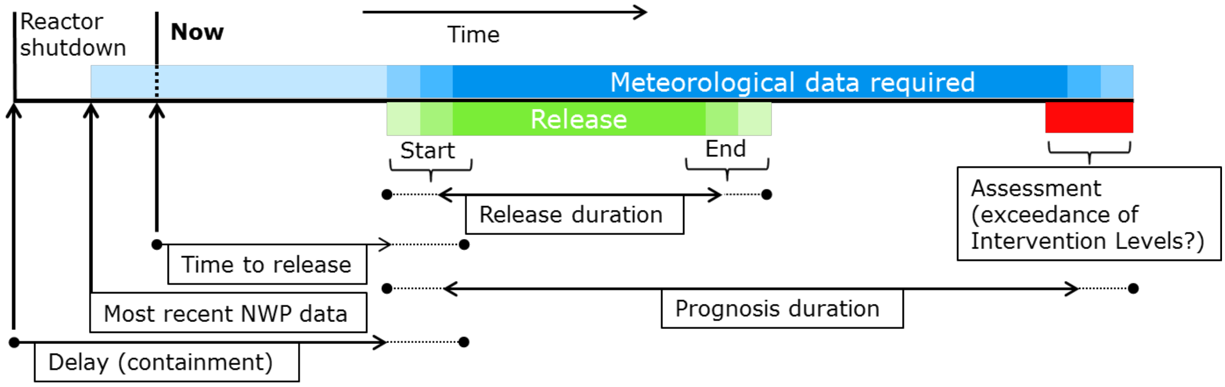

Figure 2: Timeline of the scenarios including uncertainties.

In WP1 of CONFIDENCE the Borssele case is studied, for which two release scenarios are defined:

1. A release with duration of 4 hours; this is based on an accident which is anticipated to start in 24 hours;
2. A release with duration of three days based on a 'Loss of Coolant Accident' (LOCA) scenario from the FASTNET project. There is no uncertainty on the timing of the start of the release. This scenario is representative of the uncertainties during the release phase (see Fig. 2). The construction of this ensemble of source terms was detailed in CONFIDENCE deliverable D9.1 (Mathieu et al. 2017).

Table 1 : uncertainties considered in the two release scenarios : Scenario 1 (short release) and Scenario 2 (long release).

Scenario 1	**Scenario 2**
Time to release: 24 h +/- 6 h, equally distributed **Release duration**: 4 hours **Effective release height:** 50 m +/- 50 m, equally distributed **Released activity** : Factor 1/3 to 3 of Table 2	**Time to release**: 0 hours, no uncertainties **Release duration**: 3 days **Effective release height**: 50 m +/- 50 m, equally distributed **Released activity**: given by the spread of the ensemble of source terms

In Table 1 the source terms and associated uncertainties are summarized; the timing, release height and the released activity are shown for the two scenarios. For Scenario 1 the uncertainty in the released activity is assumed to be within a factor of 1/3 to 3 of the reference values in Table 2. The nuclide composition for Scenario 1 is based on a *Delay* time of 24 h. For Scenario 2 the uncertainty in the released activity was derived from the distribution of the source terms in the FASTNET project. The median and maximum values are shown in the table.

In this deliverable, we present only the results for Scenario 1 (short duration release scenario).

Table 1: The nuclide composition of the hypothetical source terms for the Borssele case. The total released activity is shown for all nuclides in the source term. Only the eight nuclides in bold font were considered in the model runs.

	Scenario 1	**Scenario 2**
	Borssele NPP scaled to 900 MWe: Total released activity [Bq]	*FASTNET 3 inches break:* Total released activity [Bq] median (max)
	Particle size: 1 µm. Iodine group: 1/3 particulate, 2/3 elemental	Iodine form: given by the ensemble of source terms
Nuclide		
Kr-85m	8.76E+15	
Kr-85	1.53E+16	
Kr-88	2.38E+15	
Xe-133	**3.51E+18**	**6.91E+17** (5.25E+18)
Xe-135	7.46E+17	
I-131	**2.25E+16**	**5.42E+13** (7.65E+16)
I-132	**2.84E+16**	**6.35E+14** (8.83E+16)
I-133	2.15E+16	
I-135	3.04E+15	
Rb-88	1.97E+13	
Sr-89	2.36E+15	
Sr-90	2.19E+14	
Y-90	1.78E+13	
Zr-95	4.19E+14	
Ru-103	3.80E+15	
Ru-106	1.24E+15	
Rh-106	1.24E+15	
Te-131m	1.02E+15	
Te-132	**1.37E+16**	**1.73E+13** (2.41E+14)
Cs-134	**2.69E+15**	**4.70E+12** (6.02E+13)
Cs-136	**6.37E+14**	**1.77E+12** (2.22E+13)
Cs-137	**2.06E+15**	**3.17E+12** (4.06E+13)
Ba-137m	**2.78E+14**	**2.37E+12** (8.45E+13)
Ba-140	4.08E+15	
La-140	4.47E+14	
Pu-238	2.60E+11	
Pu-241	3.19E+13	
Cm-242	9.02E+12	
Cm-244	1.02E+11	

Meteorology

The meteorology was provided by KNMI for the Borssele case study. The Harmonie-AROME model was used, with a horizontal resolution of about 2,5 km (black dots in Figure 3) and a temporal resolution of one hour. The time-span of the data is 72 hours. The domain provided was 300 km x 300 km. The ECMWF ensemble was also provided, but not used.

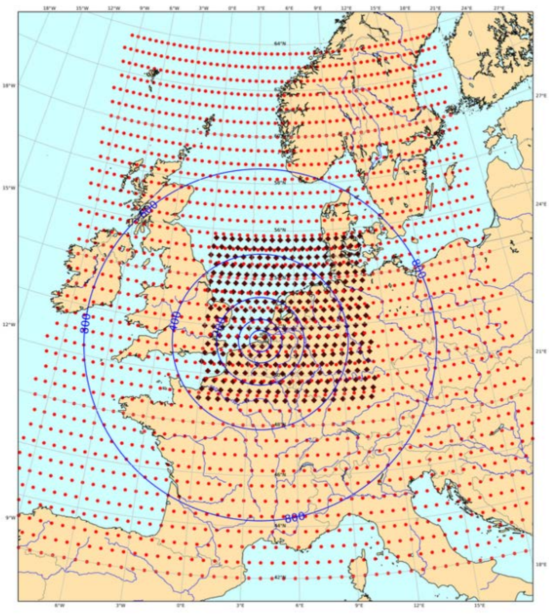

Figure 3: Meteorological domain for the Borssele case study. Black dots are the Harmonie domain, red dots are the ECMWF domain. The blue concentric circles correspond to the distance to the Borssele NPP.

The first scenario considered applies to a release on 11 Jan 2017. It was labelled “easy case”, in the sense that the wind direction is well established (Figure 4). It is an interesting case in the sense that there is rain, which adds uncertainty to the scenario (depending on the release time, the plume may or may not be scavenged by rain) and higher consequences as far as deposition is concerned.

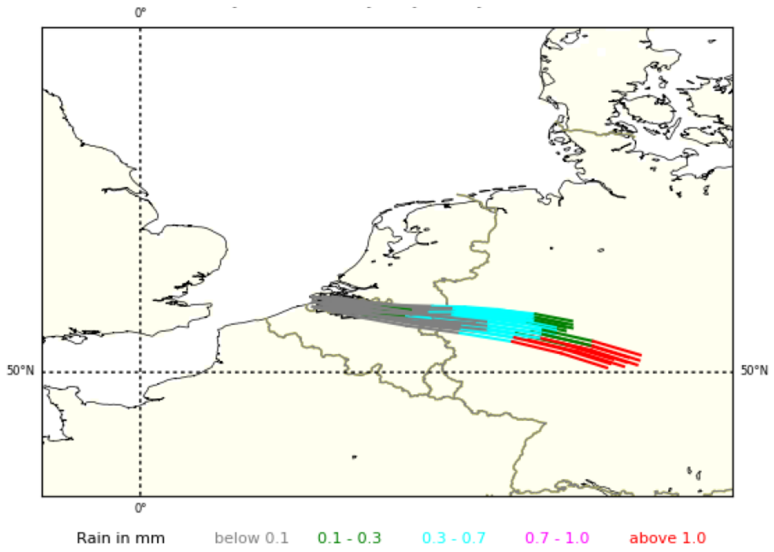

Figure 4 : Indicative plume trajectories based on analysed weather as a function of height (between 10m and 500m), for a release at 12 UTC 11/01/17, and associated rain (cumulated on one hour).

KNMI constructed a Harmonie-AROME ensemble from 2 different versions of the meteorological model, with different turbulent schemes, and combined successive deterministic forecasts to create a hybrid lagged ensemble. The ensemble is a hybrid in the sense that two different model versions are used; and lagged in the sense that successive forecasts are used. The reason to construct an ensemble in this way is that the KNMI Harmonie-AROME archive can be used to construct an ensemble where the spread of the resulting ensemble can represent a realistic ensemble spread and be used as a pilot for high resolution ensembles which start to become available. Each model version was used to construct 5 ensemble members with a forecast length of the required 72 hours (Figure 5).

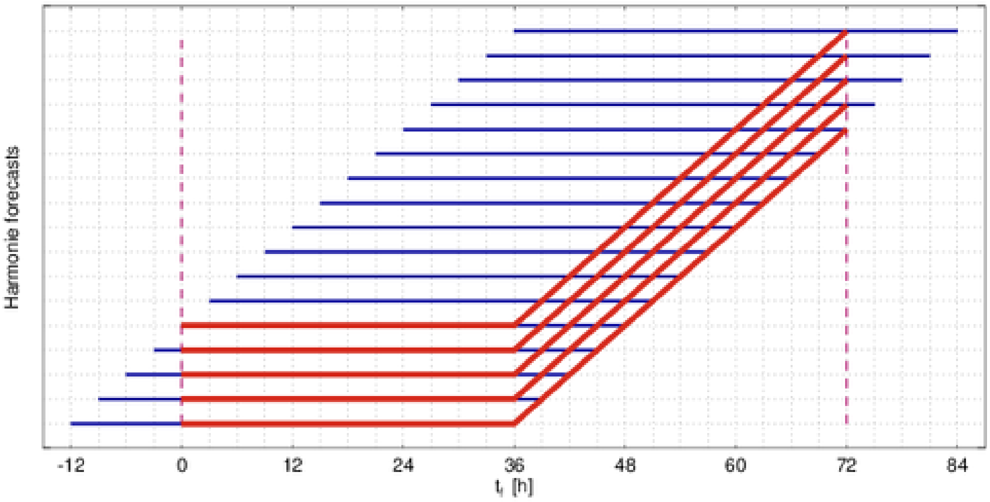

Figure 5 : Construction of a 5-member ensemble with a length of 72h. The blue lines indicate the original Harmonie-AROME 48h forecasts. The red lines indicate how each of the members is constructed.

From the start of the constructed ensemble (t_f=0), we use the forecast that starts there, and also the 4 forecasts that each started 3 hours earlier, for the first 36 hours for which they all overlap. From there, we use forecasts from successive runs to a maximum forecast of 72 hours.

Eventually, for all of the (hourly) steps, the date/time/forecast step values are changed to give 5 members that range from t_f=0–72 for the same start date/time.

Endpoints

Some participants provided their own dose calculations (see Table 3). For those who provided only atmospheric dispersion results (air and deposition concentrations for all radionuclides), the dose calculations were made by IRSN, based on the air concentrations and deposition data provided. The dose calculations were derived for 1-year-old children, with no sheltering nor any other forms of protective action. The effective dose calculation includes pathways:

- External dose due to irradiation by radionuclides in the atmosphere (plume-shine),
- External dose due to the irradiation by radionuclides deposited on the ground (ground-shine),
- Internal dose due to plume inhalation.

It does not take into account dose resulting from food intake.

The outputs proposed here are maps of probability of threshold exceedance. Instead of a single contour showing the impacted area (based on a single deterministic simulation), the probability maps are based on an ensemble of simulations and correspond to the probability that a given zone is contaminated above a given level. The reference levels chosen for this project are:

- 37 kBq/m^2 of Cs-137 deposition (Chernobyl reference level);

- 50 mSv inhalation thyroid dose for 1-year old child (IAEA reference level for iodine intake; IAEA (2011));
- 50 mSv effective dose for 1-year old (French reference level for evacuation).

The 555 kBq/m^2 reference level for Cs-137 deposition, initially chosen (Chernobyl reference level) is not shown since the threshold is too high and was not relevant for this case study. This is also the case for the 100 mSv effective dose (IAEA reference level for evacuation). Instead, for information, additional levels were considered:

- 10 kBq/m^2 deposition for Cs-137 and I-131;
- 10 mSv effective dose for 1-year old child;
- 10 mSv inhalation thyroid dose for 1-year old child.

Once the thresholds have been chosen, useful outputs for decision making are the maximum distance and surface area affected by the threshold exceedance, and associated uncertainties. In addition, to compare several uncertainty assessments, a particular percentile may be chosen and drawn for each ensemble calculation. Once a given percentile has been chosen, it may be used for decision making in the same way as a deterministic simulation. Several of these outputs are given in the following parts of this report.

Modelling set-up

Currently, the ensemble results from five participating countries have been processed. Table 3 summarizes the participants who ran simulations for the Borssele case study (except NMI who ran simulations for the Western Norway case), and the endpoints that were computed by the participants. It also presents the type of atmospheric dispersion model used: there is one Eulerian model, two Lagrangian particle models, two Lagrangian puff models and two Gaussian puff models.

Table 2 : Summary of participants, output variables computed, and type of atmospheric dispersion model. The green cells indicate the outputs provided by participants. The white cells correspond to outputs reconstructed by IRSN using activity, deposition, and IRSN's assumptions for dose calculation.

		Activity	Deposition	Dose rate	Dose	Type of model
France	IRSN	✓	✓	✓	✓	IdX – Eulerian
The Netherlands	RIVM	✓	✓	✓	✓	NPK-puff – Gaussian puff
Germany	BfS	✓	✓	✓	✓	RIMPUFF – Lagrangian puff
UK	MetOffice/PHE	✓	✓		✓	NAME – Lagrangian
Greece	EEAE	✓	✓	✓		DIPCOT – Lagrangian puff
Denmark	DTU	✓	✓			RIMPUFF – Lagrangian puff
Hungary	MTA EK	✓	✓	✓	✓	SINAC – Gaussian puff
Norway	NMI MET (*)	✓	✓			SNAP – Lagrangian

(*) Western Norway case (not shown here)

Ensemble results with the meteorological ensemble

Results are shown for the short release, assuming an unperturbed source term, and using the Harmonie-AROME ensemble of 10 members. The release time is on January 11th, 2017 at 12:00 UTC, the release height is 50 m, and the released quantities are those given in Table 2. Thus, all participants have the same meteorological and release data, only the dispersion model itself differs, as well as deposition-related data. This includes the type of model (see Table 3), the dry and wet deposition models, diffusion models (Mathieu et al. 2017), and other default hypotheses such as the initial source dilution. In addition, there may also be differences in dose calculation assumptions.

Maximum distance of threshold exceedance

In Table 4, we compare the mean of the ensemble results for each participant, 24 hours after the beginning of the release. The variable of interest is the maximum distance from the source at which the threshold is exceeded, for several of the endpoints defined earlier. For each member of the ensemble, we determine the maximal distance above the given threshold (distance of the farthest grid point over the threshold); the values given in Table 4 and Figure 6 are the average over the ensemble members (for each participant); the error bars in Figure 6 correspond to the standard deviation of this distance over the ensemble members.

Table 3 : Distance (in km from the source) of the threshold exceedance averaged over the ensemble members, for the Borssele case study (short release) and several variables of interest.

	Cs-137 Deposition		Inhalation thyroid dose		Effective dose	
	10 kBq/m^2	37 kBq/m^2	10 mSv	50 mSv	10 mSv	50 mSv
BfS	542 km	446 km	141 km	39 km	15 km	4 km
DTU	417 km	403 km	97 km	36 km	10 km	0 km
EEAE	520 km	315 km	46 km	19 km	6 km	0 km
IRSN	557 km	388 km	208 km	79 km	25 km	0 km
MetOffice/PHE	578 km	556 km	130 km	51 km	23 km	0 km

The values of Table 4 show a high variability between the participants. This variability comes from the type of model used (see Table 3). The first two lines correspond to the same model, the Lagrangian puff model RIMPUFF. However, the modelling domain is not the same, which may explain the differences in the distance reached by Cs-137 deposition (the end of the modelling domain is reached by several members in these simulations). Differences may also come from the assumptions made in deposition and scavenging values, as well as dose coefficients. BfS computed the dose directly but those from DTU were reconstructed by IRSN (Table 3); the differences between dose calculation hypotheses will be further investigated. EEAE used another Lagrangian puff model which leads to lower distances; differences may come from assumptions concerning the diffusion model, scavenging coefficients and deposition velocities. Finally, IRSN's model is Eulerian, which is known to underestimate the values near the source but gives the highest distances in this case, except for Cs-137 deposition.

Figure 6 shows that the variability across the five models is typically much greater than the individual ensemble model spread given by the standard deviation. This illustrates the importance of taking into account other uncertainties besides meteorological data, including model-related uncertainties.

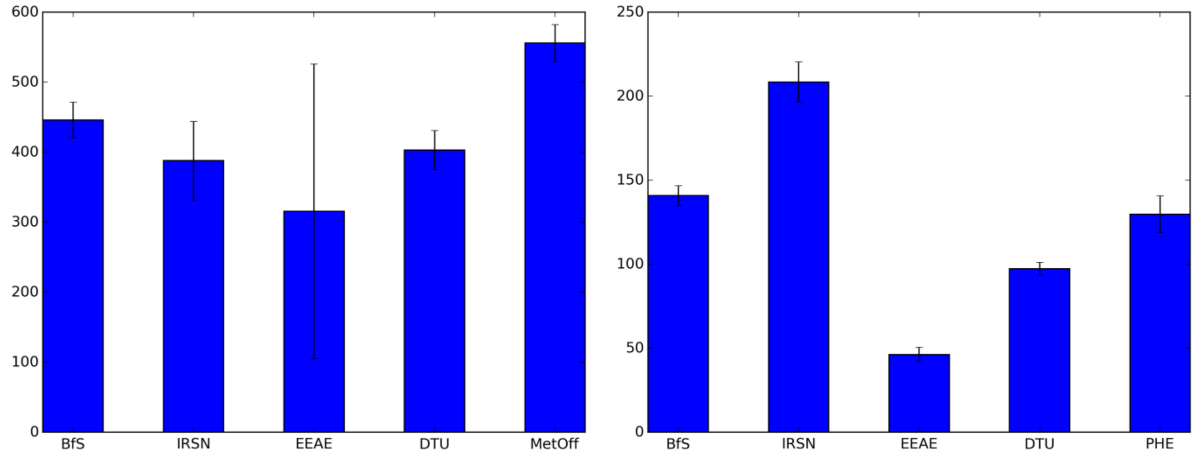

Figure 6: Ensemble mean of the maximum distance for the threshold exceedance of 37 kBq/m^2 of Cs-137 deposition (left) and for a threshold exceedance of 10 mSv for inhalation thyroid dose (right) for five participants, 24 hours after the beginning of the release, and associated standard deviations.

Surface area, direction and aperture above threshold

Given a variable of interest (e.g. deposition or dose) and a threshold, several indicators can be determined for a given simulation. The maximum distance was already defined earlier. To that indicator, we may add the following:

- **Surface area**: determine the area where the given threshold is exceeded (given by the number of grid points over threshold and the area of each grid cell);
- **Direction**: we compute the “general direction” as the average direction from the source in degrees over all grid points above the given threshold;
- **Lateral spread**: it corresponds to four times the standard deviation of the grid points’ directions.

Each of these endpoints may be computed for each member of the ensemble. Then, the mean and standard deviation may be used as endpoints (as in Figure 6 for the maximum distance). Alternatively, the extrema of the ensemble may be preferred.

Table 4 : Area (in number of cells) of the threshold exceedance averaged over the ensemble members, for the Borssele case study (short release) and several variables of interest. (*) indicates that some (or all) members reach the end of the modelling domain. The green values are the minimum and maximum value over the ensemble members.

	Cs-137 Deposition	Inhalation thyroid dose	
	37 kBq/m^2	10 mSv	50 mSv
BfS	589 (*)(203—1068)	151	17
DTU	189 (*) (92—422)	86	18
EEAE	20 (*) (2—44)	27	5
IRSN	324 (164—474)	614	111
MetOffice/PHE	1103 (652—1463)	232	35

Table 5 shows the surface area above the threshold for the Cs-137 deposition threshold of 37 kBq/m^2 and the inhalation thyroid dose (10 and 50 mSv). The effective dose is not shown, since values were too small. The rank between the participants’ results is globally the same as in Table 4 (those giving the highest distance also give the highest surface above threshold). Although it can be noted that sometimes, the distance is high but the surface is small (e.g. EEAE results for deposition). This is typical of deposition by rain in the form of a few spots (see Figure 8).

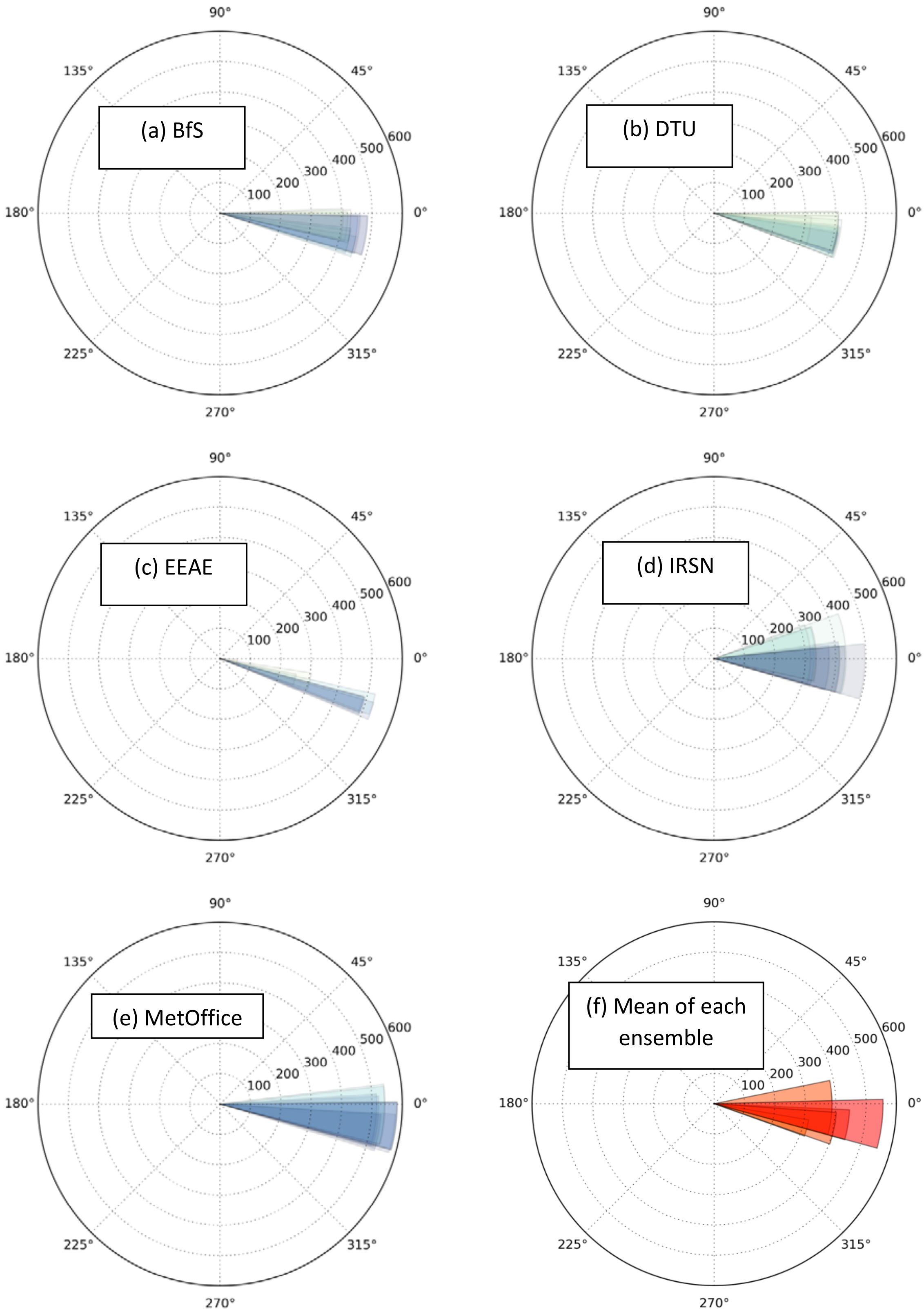

Figure 7 : Maximum distance, surface, direction and lateral spread of Cs-137 deposition for 37 kBq/m², for all ensemble members of 5 participants (a—e), and for the ensemble mean of each participant (f). It reads as follows: each blue "pie slice" corresponds to an ensemble member. Its direction corresponds to the direction of the ensemble, the distance (in km) is the maximum distance, the width corresponds to the lateral spread and the color represents the area above threshold (the darker the color, the larger the area). Each red "pie slice" corresponds to the average of these parameters over each ensemble.

Figure 7 is an example of a possible operational output. Its aim is to summarize the characteristics of the simulations (distance, surface, direction and aperture), in a way that may be useful to decision makers. Alternatively, more realistic contamination patterns may be used, for instance in the form of percentile maps, or maps of probability of threshold exceedance. The usefulness and relevance of such figures will be further discussed in the course of the project.

Percentiles of threshold exceedance

Figure 8 shows the 50th and 75th percentiles of several participants threshold exceedance of Cs-137 deposition (10 kBq/m^2) and 50th percentile of several participants threshold exceedance of Cs-137 deposition (37 kBq/m^2). Those percentiles correspond to the limit where 50% (resp. 75%) of the ensemble members are above the given threshold. These maps confirm the patchy pattern, typical of wet deposition, which may lead to high distances but not necessary large surfaces. When the chosen percentile is higher, the contours are smaller and this patchy characteristic is more visible. It is all the more the case when looking at a higher threshold.

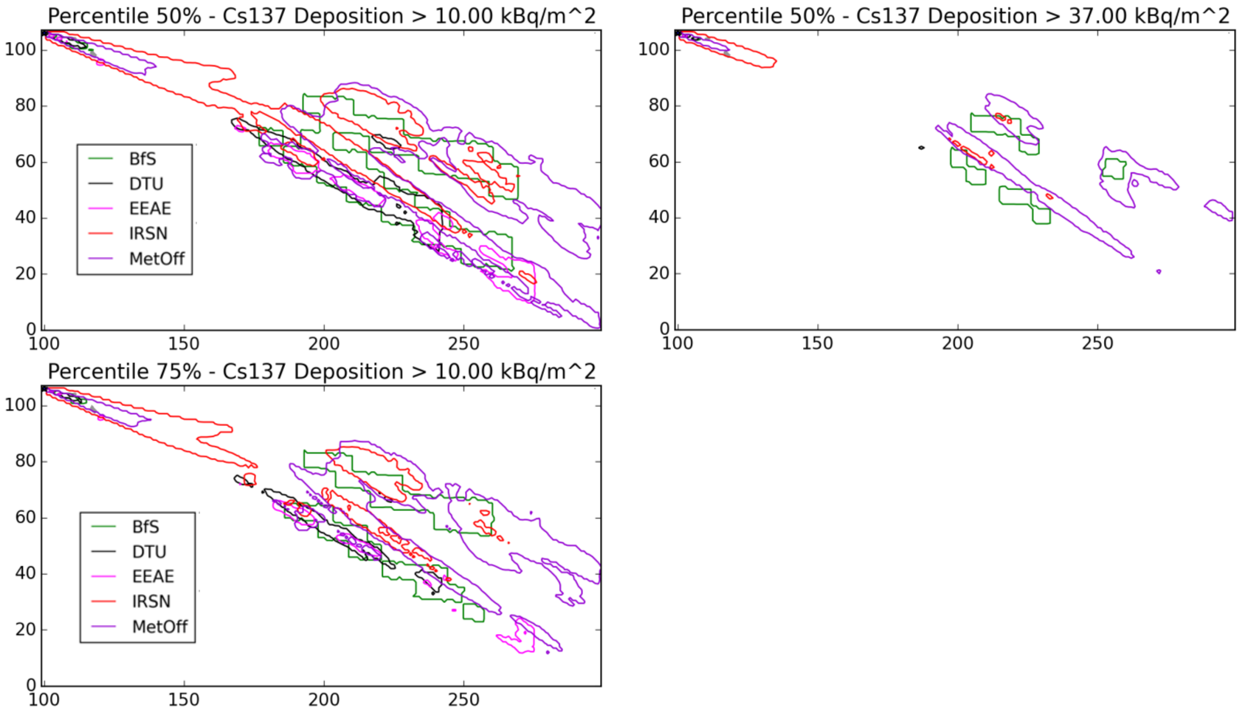

Figure 8 : 50th percentile for the threshold exceedance of 10 kBq/m^2 (upper left) and 37 kBq/m^2 (upper right) of Cs-137 deposition. 75th percentile for the threshold exceedance of 10 kBq/m^2 of Cs-137 deposition (lower left). The abscissa and ordinate correspond to the cell indices: cell (100,105) contains the source.

Probability maps of threshold exceedance

The probability maps of thresholds exceedance can be drawn for each ensemble, given an output variable and a threshold (Figure 9 and Figure 10). The percentiles shown in Figure 8 are particular contours of these probability maps, which show the whole range of percentiles. In Figure 9, the variability between the deposition of Cs-137 given by the participants is clear. The pattern induced by scavenging, showing “hot spots” of deposition, is clearer in IRSN and MetOffice maps, while the others show a more continuous plume. Figure 10, representing the threshold exceedance of 10 mSv thyroid dose, shows a more continuous plume but still a large variability between the participants. These differences will be further discussed at a later stage.

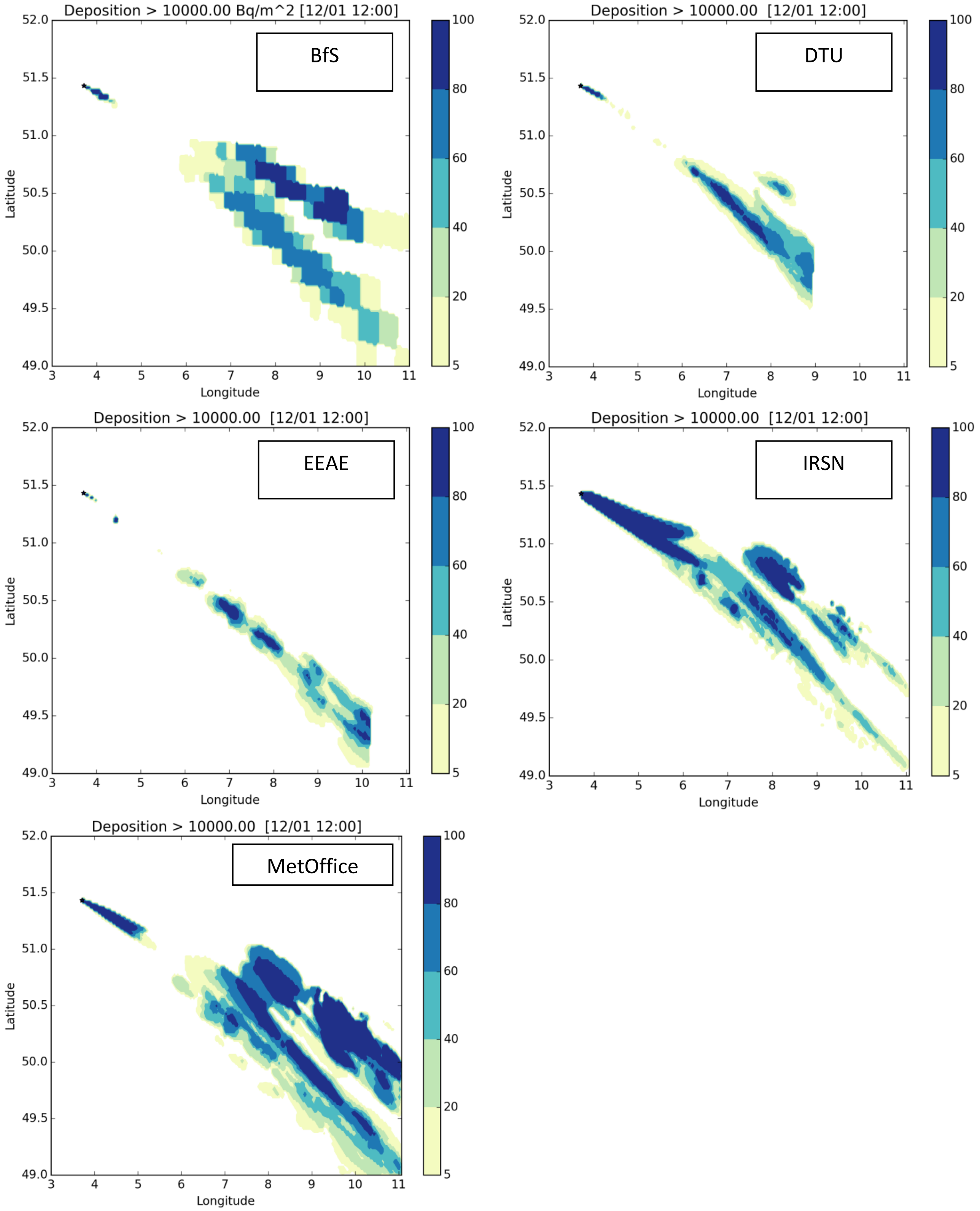

Figure 9 : Probability maps of a threshold exceedance of 10 kBq/m² for Cs-137 deposition, for a number of discrete bands of percentiles, for several participants.

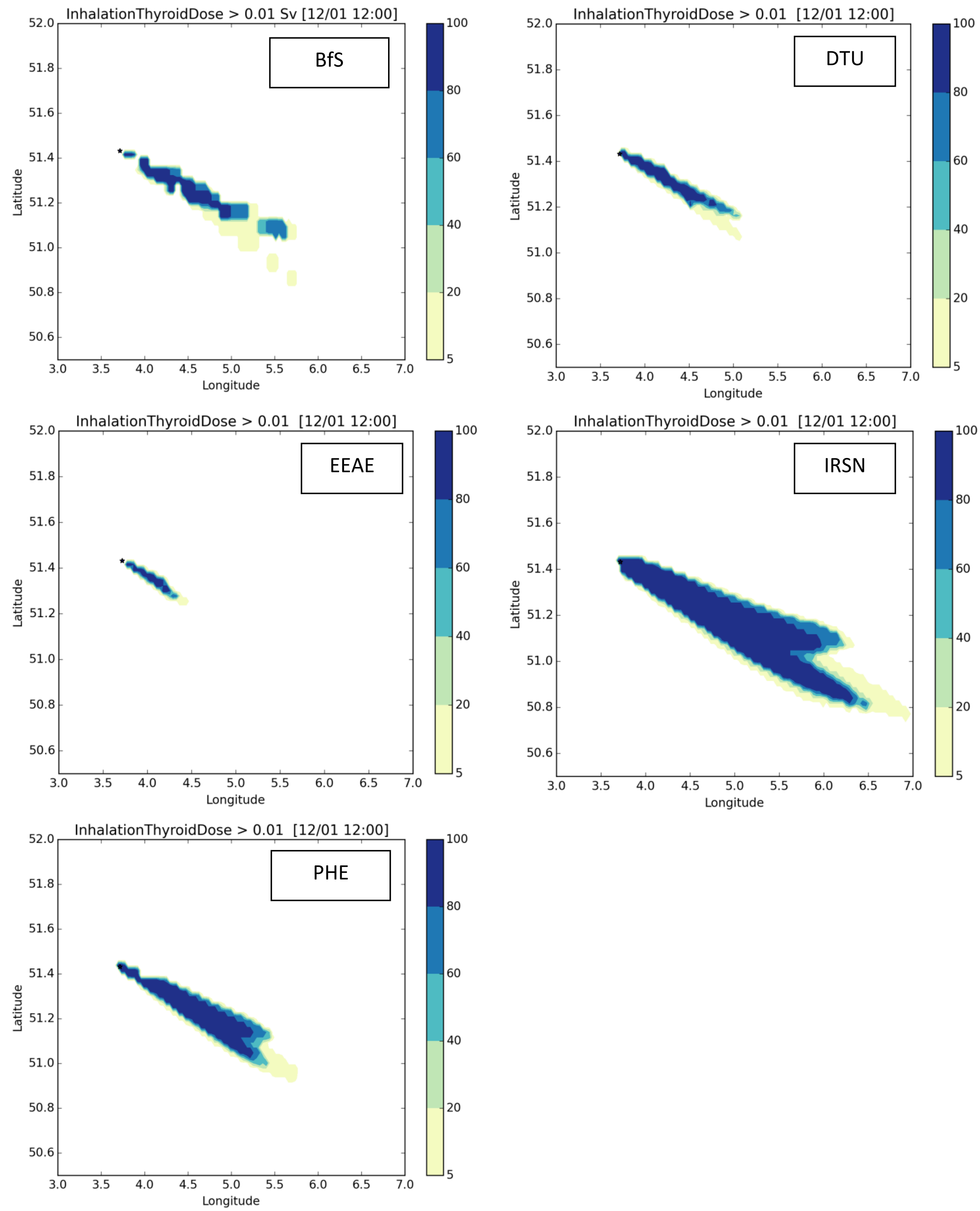

Figure 10 : Probability maps of a threshold exceedance of 10mSv for the inhalation thyroid dose, for a number of discrete bands of percentiles, for several participants.

Ensemble results with the meteorological ensemble and additional perturbations

Uncertainties related to the source term were defined for the short release scenario (given in Table 1). These were taken into account differently by the participants, as shown in Table 6. IRSN carried out Monte Carlo simulations, including perturbations in deposition velocities, scavenging coefficients and vertical diffusion, in addition to the source perturbations listed in the table and the meteorological ensemble. All other participants did “cross simulations”, that is, the number of simulations is equal to [number of source terms] X [number of meteorological members].

Table 5 : source perturbations used with the 10 meteorological members by each participant.

Participant	Number of simulations	Source perturbations		
		Release height	Release time	Released quantity
IRSN	100 (Monte Carlo)	[0, 100m] uniform	[-6h, 6h] uniform	[1/3, 3] uniform
BfS	150	[0m, 50m, 100m]	T0 + [-6h, -3h, 0h, +3h, +6h]	
MetOffice/ PHE	90	[50m]	T0 + [-6h, 0h, +6h]	[x1/3, x1, x3]
EEAE	50	[50m]	T0 + [-6h, -3h, 0h, +3h, +6h]	
MTA EK	250	[0m, 25m, 50m, 75m, 100m]	T0 + [-6h, -3h, 0h, +3h, +6h]	

Maximum distance of threshold exceedance

Maximum distances of threshold exceedance, averaged over the ensemble members, are given for the perturbed simulations in Figure 11 and Table 7. It can be noted that these distances are generally lower than those in Table 4, meaning that the source perturbations tend to decrease *on average* the deposition distance. It may be that the meteorological conditions for the perturbed release times lead to lower ground deposition (lower or no rain) than the initial release time. On the other hand, the distance for inhalation thyroid dose and effective dose tends to be similar or higher than the results without perturbation. If wet deposition is lower, then the plume is less depleted and it is consistent with a higher inhalation dose. These differences will be further investigated. In particular, the study of iodine activity concentrations in air and deposition would be useful for the comprehension of inhalation dose. For effective dose greater than 50 mSv, they were previously zero for IRSN and PHE/MetOffice with the non-perturbed source term (in Table 4), while some perturbed simulations (for instance when multiplying the source term by 3) lead to non-zero distances, which explains the results in Table 7.

Table 6: Distance (in km from the source) of the threshold exceedance averaged over the ensemble members, for the Borssele case study (short release) and several variables of interest.

	Cs-137 Deposition		Inhalation thyroid dose		Effective dose	
	10 kBq/m²	37 kBq/m²	10 mSv	50 mSv	10 mSv	50 mSv
BfS	503 km	413 km	160 km	35 km	14 km	4 km
EEAE	467 km	237 km	45 km	18 km	6 km	0 km
IRSN	408 km	179 km	227 km	89 km	34 km	6 km
MetOffice/PHE	482 km	360 km	129 km	54 km	27 km	4 km

Figure 11 shows that the variability in the perturbed ensembles is much higher than with the ensemble solely based on meteorological uncertainties (note: DTU is represented here with the “unperturbed” ensemble). It confirms the importance of taking into account the source uncertainties. Interestingly, the spread of IRSN’s ensemble including model uncertainties is not larger than that of other ensembles. It may tend to confirm that uncertainties linked to physical parameterizations are of second order compared to source term and meteorology. However, inter-model variability is still large and not quite represented by the ensemble’s spread.

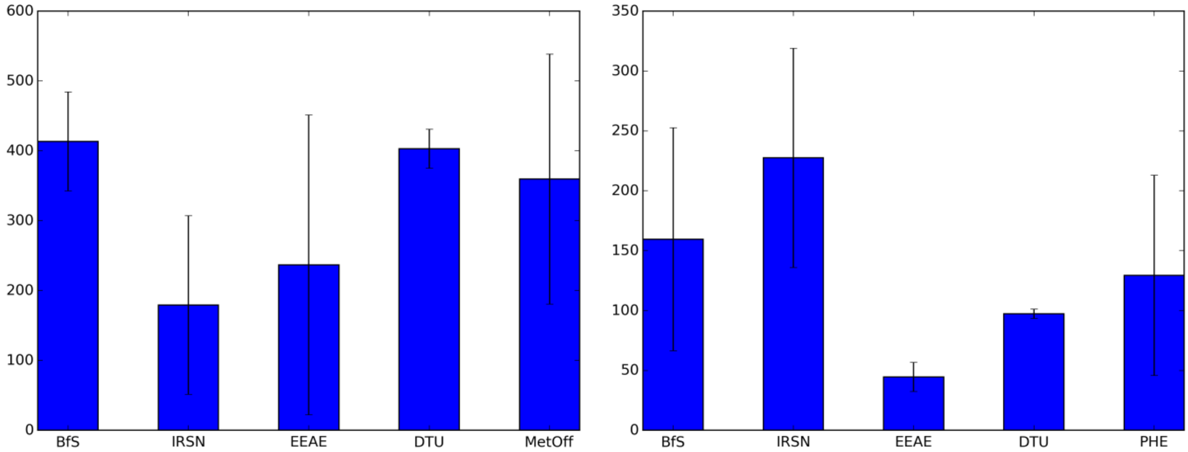

Figure 11 : Ensemble mean of the maximum distance for the threshold exceedance of 37 kBq/m² of Cs-137 deposition (left) and for a threshold exceedance of 10 mSv for inhalation thyroid dose (right) for five participants, 24 hours after the beginning of the release, and associated standard deviations.

Probability maps of threshold exceedance

The probability maps for two participants are shown for illustration, with the 10-members simulation (left) and with the additional source perturbations (right). For these two participants, the maximum distance of threshold exceedance is lower with the perturbed simulations (503 km for BfS and 482 km for MetOffice) than without (542 km and 578 km respectively). Figure 12 clearly shows that, although the area of highest probabilities is much smaller, the overall contaminated surface (above the 5th percentile) is much larger with the perturbed simulations. When taking into account different release times, different plume directions are taken into account, which leads to a larger spread. These results will be further investigated.

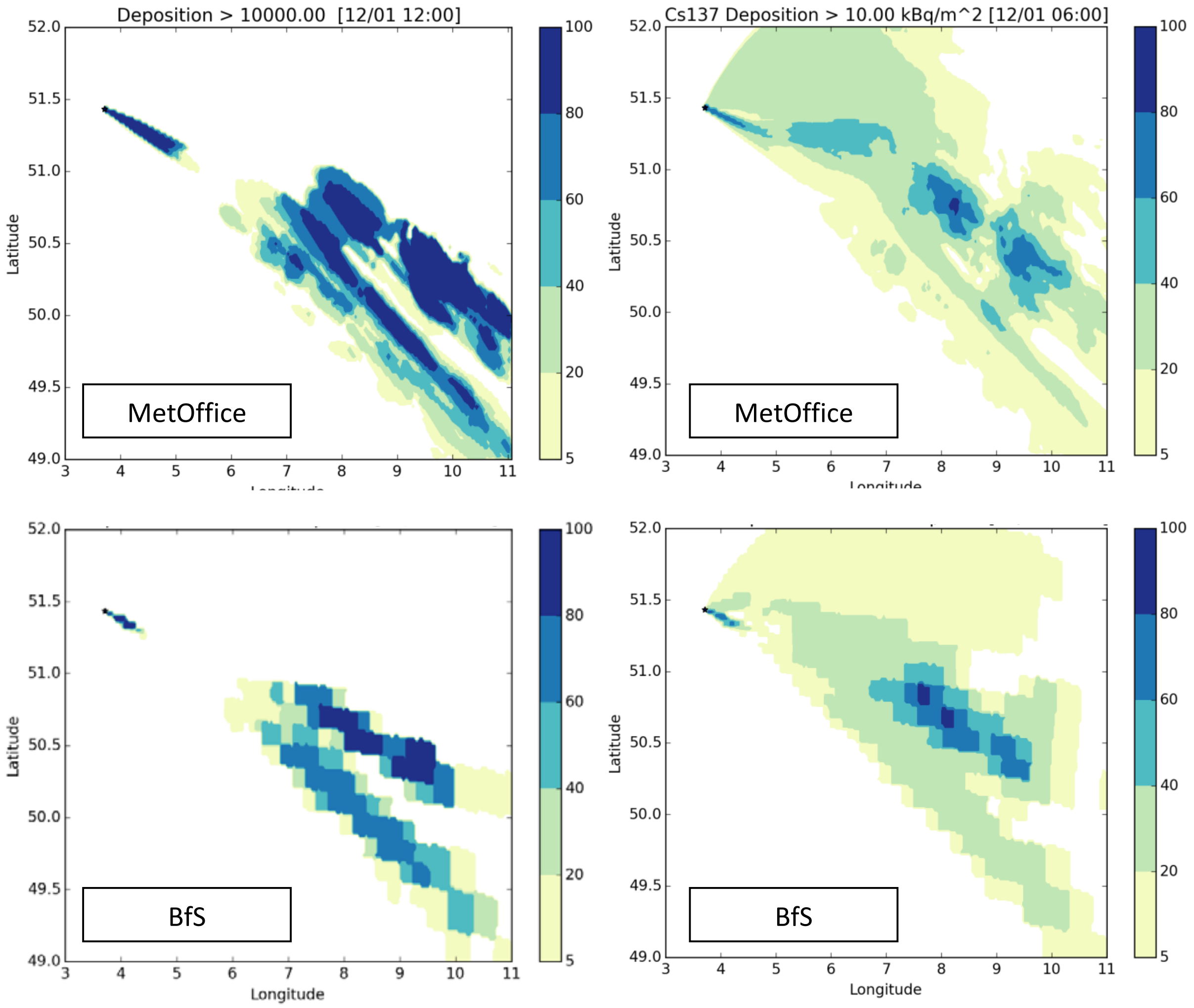

Figure 12 : Probability maps of a threshold exceedance of 10 kBq/m² for Cs-137 deposition, for a number of discrete bands of percentiles, without (left) and with (right) additional perturbations on the source term combined with the application of a meteorological ensemble.

Conclusions

The maps will be provided to other participants, especially WP5 and WP6, for discussion about visualisation and decision making. In addition, shapefiles may be provided upon request so that the contamination pattern can be localized on other European nuclear sites, to trigger consequences in the countries of interest.

The simulation outputs presented here have been based on the reference levels for dose and deposition discussed with participants from other work packages. Other reference levels, adapted to the countries of interest, can be provided upon request. Outputs other than maps of probability threshold exceedance will also be discussed, in terms of variables (e.g. surface areas, maximum distances) or statistical indicators (e.g. percentiles, median, minimum and maximum values).

The next steps will consist of using different meteorological scenarios (sea breeze, storm front), different meteorological ensembles (ECMWF and/or other national meteorological models), and different case studies. In particular, the Fukushima case will provide a benchmark for uncertainty validation against radiological observations. In parallel, these uncertainties will also be propagated along the calculation chain and linked with food contamination assessment.

References

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