NKS-420
ISBN 978-87-7893-509-0

Added Value of uncertainty Estimates of SOurce term and Meteorology (AVESOME)

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February 2019

Abstract

In the early phase of a nuclear accident with possible off-site consequences, e.g. resulting from core melt and breach of containment, accurate prediction of the atmospheric dispersion of radionuclides is of utmost importance. However, two large sources of uncertainty exist: one associated with the meteorological data employed, and one related to the source term, i.e. the amounts of radionuclides released and the temporal evolution of the release.

In the former NKS-B projects MUD, FAUNA, and MESO, the implications of meteorological uncertainties for nuclear emergency preparedness and management were studied, and means for operational real-time assessment of the uncertainties in a nuclear DSS were developed and demonstrated.

In AVESOME, a methodology has been developed for quantitative estimation of the variability of atmospheric dispersion modelling resulting from both sources of uncertainty. With modern supercomputing facilities available e.g. at national meteorological services, the proposed methodology is well suited for real-time assessments and implementation in decision support systems.

The methodology adapts well to the RASTEP system, which provides a set of possible source terms and associated probabilities. In the near future, source terms derived within the EU project FASTNET will also become available, describing different release scenarios.

By employing automatic communication between the DSS and the HPC facility, the methodology developed is applied to selected release scenarios and meteorological situations. Results are presented by the improved graphical user interface adhering to recommendations of the NKS Workshop on the Use of Meteorological Uncertainty Estimates for Decision Making during a Nuclear Emergency in 2015. Based on a given request for dispersion calculation at the HPC facility, the DSS user will be able to either use the probabilistic presentation of all members of the source-term ensemble, or to use the individual source term members.

Key words

nuclear emergency preparedness, atmospheric dispersion model, source term uncertainty, meteorological uncertainty, ensemble prediction

NKS-420
ISBN 978-87-7893-509-0
Electronic report, February 2019
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Added Value of uncertainty Estimates of SOurce term and Meteorology (AVESOME) – final report

Final Report of the NKS-B AVESOME activity

(Contract: AFT/B(18)6)

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Introduction

In the early phase of a nuclear accident with possible off-site consequences, e.g. resulting from core melt and breach of containment, accurate prediction of the atmospheric dispersion of radionuclides is of utmost importance. However, two large sources of uncertainty exist: one associated with the meteorological data employed, and one related to the source term, i.e. the amounts of radionuclides released and the temporal evolution of the release.

In the NKS-B projects MUD (Meteorological Uncertainty of atmospheric Dispersion model results), cf. Sørensen *et al.* (2014), FAUNA (Fukushima Accident: UNcertainty of Atmospheric dispersion modelling), cf. Sørensen *et al.* (2016), and MESO (MEteorological uncertainty of ShOrt-range dispersion, cf. Sørensen *et al.* (2017), the implications of meteorological uncertainties for nuclear emergency preparedness and management have been studied, and means for operational real-time assessment of the uncertainties in a decision-support system (DSS) have been developed and demonstrated.

In the NKS-B project AVESOME (Added Value of uncertainty Estimates of SOurce term and MEteorology), a methodology is developed for quantitative estimation of the variability of atmospheric dispersion modelling resulting from both sources of uncertainty. With modern supercomputing facilities available e.g. at national meteorological services, the proposed methodology is well suited for real-time assessments and implementation in decision support systems (DSSs).

Previously, due to lack of computer power, such methods could not be applied to operational real-time decision support. However, with modern supercomputing facilities, available e.g. at national meteorological services, the proposed methodology is feasible for real-time use, thereby adding value to decision support.

The AVESOME methodology adapts well to the RApid Source TErm Prediction (RASTEP) system (Knochenhauer *et al.*, 2013), which provides a set of possible source terms and associated probabilities. In the near future, source terms derived within the EU project FASTNET will also become available, describing different release scenarios.

The methods developed in AVESOME allow for efficient real-time calculations by making use of scaling properties in the equations governing the release and the atmospheric dispersion of radionuclides.

By employing automatic communication between the nuclear DSS and the HPC facility, the methodology developed is applied to selected release scenarios and meteorological situations. Results are presented by the improved graphical user interface (GUI) adhering to recommendations of the NKS Workshop on the Use of Meteorological Uncertainty Estimates for Decision Making during a Nuclear Emergency in 2015. Based on a given request for dispersion calculation at the HPC facility, the DSS user will be able to either use the probabilistic presentation of all members of the source-term ensemble, or to use the individual source term members.

Source Term Uncertainty

The source term consists of information about the nuclides included in a release from a nuclear power plant (NPP) as well as the activity released per nuclide. The source term also describes the height of the release, the duration of the release phases, and the thermal effect (heat content) of the release.

The Convention on Early Notification of a Nuclear Accident (IAEA, 1986) established a notification system for nuclear accidents which have the potential for international transboundary release that could be of radiological safety significance for another State. It requires States to report the accident's time, location, radiation releases, and other data essential for assessing the situation. Notification is to be made to affected States directly or through the International Atomic Energy Agency (IAEA), and to the IAEA itself. Accordingly, it is a national obligation of the State hosting an accidental nuclear power plant to estimate the source term applying to the accident.

If the plant status is well described, e.g. which valves are open and which are not etc., a given source-term model will produce only a single result. However, it is well known that for the same plant status another source-term model may give a result which differs by up to an order of magnitude. Additionally, certain source term models are known to become numerically unstable after a couple of days of integration into the future. Thus, the obligation to provide the source term is by no means trivial and should be accompanied by an estimate of the inherent uncertainties, i.e. to provide an ensemble of source terms linked to possible release scenarios.

The radionuclides are released in the form of gasses or aerosols of different shapes and sizes; the latter being largely unknown. However, off-site consequences are dominated by the smallest fraction of particle sizes for which gravitational settling can be neglected, and thus the current lack of knowledge on size distributions is not expected to be of any major consequence. The methodology developed in AVESOME can, however, be applied also in case that aerosol size distributions are available.

In AVESOME, we have primarily studied serious accidents with off-site effects such as reactor core-melt scenarios and fuel pond accidents. In the early stage of a serious accident, only the larger plant status parameters can be expected to be available, e.g. the filter efficiency or whether the filter is connected with the reactor or not. As soon as knowledge on plant status is obtained, e.g. on whether the filter is connected or not, the source-term ensemble will be reduced.

Probabilistic Safety Assessment

PSA (probabilistic safety assessment) is a method used to estimate the risk for an incident or accident at a nuclear power plant, i.e. the probability of various scenarios and associated consequences. PSA provides insights into the strengths and weaknesses of the design and operation of a nuclear power plant.

PSA level 1 estimates the total sum of accident frequencies which leads to core damage, also known as the core damage frequency (CDF). The estimation is based on a framework in which initiating events, e.g. system failures such as LOCA (Loss Of Coolant Accident) or transients, internal or external hazards, creating disturbances in the plant are followed by function events where safety functions may fail, eventually escalating to core damage. An event and fault tree analysis describes various plant responses including automatic and manual action of safety functions as well as mitigation systems success or failure.

In PSA level 2, the accident sequences resulting in core damage are further analysed to estimate the potential release magnitude and associated frequencies. The core damage sequences from PSA level 1 are here grouped into plant damage states where each plant damage state is an entry point to the containment event tree. Focus in the analysis is on key phenomena that affect the accident progression and containment response with regard to structures and systems. End states with similar accident progression are combined into a set of release categories. When these end states are characterized, the source term analysis can be performed. Each release category, representing a number of accident sequences, is thus represented by one source term analysis, presumably a conservative analysis to enclose the different scenarios within the category.

Finally, PSA level 3 estimates the consequences to the public health and the environment combined with their respective frequency.

In this study, the source-term ensemble employed consists of a set of release category probabilities and weights derived from a generic BWR (Boiling Water Reactor) PSA level 2 study, and the corresponding set of source terms.

Severe Accident Computer Codes

The source-term analysis can be made with an integral severe accident computer code such as MAAP (Modular Accident Analysis Program), cf. (EPRI, 2006), or MELCOR (Methods for Estimation of Leakages and Consequences Of Releases), cf. Sandia National Laboratories (2001), both developed in US, and ASTEC (Accident Source Term Evaluation Code), developed in Europe (by IRSN and GRS), cf. Chatelard *et al.* (2016).

In MAAP, the thermal hydraulics are modelled for a predetermined set of nodes for the primary circuit (and secondary circuit) systems. Processes and phenomena are described with simplified parametric models which make the code run fast. MELCOR and ASTEC use modules for the thermal hydraulic in different systems and to model different phenomena. The modules are then coupled to solve the thermodynamics. MELCOR is using both mechanistic ("physical") and parametric models where the parametric models are used in case of high phenomenological uncertainties.

The fission-product release models within the different codes include the transport within the fuel, further transport and deposition within the systems and in the containment. The transport depends on the chemistry and speciation, and aerosol physics among other factors. The models are, in general, empirical based on experiments such as PHEBUS (IRSN, 2012). A transport model outside the containment is not always included and instead a direct release to the atmosphere from an aperture in the containment is assumed. For a PSA level 2, this implies that the calculation methodology for containment bypass cases often will differ in principle from that of containment failure cases.

It is important to stress that different versions of a code might have very different approaches/models to different phenomena if new "knowledge" is implemented in a later code version. Also, the difference between different computer codes can vary between different accident sequences and, in particular, if the research of a particular phenomenon in the sequence is less studied. The resulting uncertainties in the source term constituents for a specific accident sequence will affect release time, release duration and release magnitude. Therefore, it is very difficult to estimate the level of uncertainties for a source-term ensemble, since it depends on the code, the models included and the specific accident sequence. The uncertainties consist of both epistemic and aleatory uncertainties, where the epistemic uncertainties per definition would require the exploration of further experimental data to be reduced.

RASTEP

As concluded in the section concerning source term uncertainties, we need to build up knowledge on how source terms may look like and the related uncertainties. An interesting study funded by NKS, RASTEP (RApid Source TErm Prediction), cf. Knochenhauer *et al.* (2013), describes a method which partly touches this area. The main focus is on estimating the state of the Nuclear Power Plant (NPP) when an accident occurs. To do this, an approach called Bayesian Belief Network (BBN) is applied. It uses input (observables) from the NPP to take a probabilistic view on which accident states are possible. For the BBN method to work properly, one needs to reproduce a good network structure and to estimate the probabilities. The output from the BBN algorithm is a list of all states with associated probability numbers given the observables either from sensor readings or manual input.

To produce a source term, the BBN algorithm has to be linked to deterministic reactor state models such as Modular Accident Analysis Program (MAAP), cf. (EPRI, 2006), or Methods for estimation of Leakages and Consequences of Releases (MELCOR), cf. Sandia National Laboratories (2001). Either one can use an approach with pre-calculated fields (produced by MAAP or MELCOR) corresponding to the states, or an iterative solution can be designed. Such a solution is proposed in the study using Modular Accident Response System (MARS), cf. Alonso *et al.* (2005), which is related to MAAP. The iterative solution may run five simultaneous simulations for different accident scenarios and thus produce five source terms. However, these source terms are deterministic, and still we do not have any information on the uncertainties for the particular reactor states.

An interesting question is therefore how large the source term uncertainties are for one reactor state compared to the differences between the scenarios. A comparison between MAAP and MELCOR has been carried out for the same scenario, and it is concluded that the differences are quite large. This indicates that the source term uncertainties for one individual state could be as large as the differences between different scenarios. The conclusion is thus that RASTEP is a good starting point but we have to add information on uncertainties for every individual state. These uncertainties can be studied by MAAP or MELCOR by identifying uncertain parameters and perform a study using a sampling approach. One method suited for this is Latin Hypercube Sampling (LHS), see Rao (2005), which significantly reduces the number of runs compared to a random sampling scheme. The combination of such a study and RASTEP will produce a complete probabilistic view on the source terms both concerning the reactor state and corresponding uncertainties within a reactor state.

FASTNET

The FASTNET project is a four-year European project funded by the Euratom Research and Training Programme 2014–2018.

FASTNET is relevant for the AVESOME NKS project because of the source-term database being developed inside FASTNET.

The objectives of FASTNET are:

- to set up a severe-accident scenarios database
- to qualify a common graduated response methodology that integrates several tools and methods to:
  - evaluate the source term
  - ensure both diagnosis and prognosis of severe accident progression
  - make the connection between the FASTNET tools and other systems that use source-term definition for further assessments in order to implement in any emergency centres the proposed solution for the management of emergency in all the operating nuclear power plant concepts, Pressurized Water Reactors (PWR) of Gen II and III; Boiling Water Reactors (BWR) of Gen II; VVER 440 and 1000; CANDU; and a concept of spent fuel pool facilities in Europe. The International Radiological Information Exchange (IRIX) format will be used for data exchange between FASTNET tools and these systems used for consequence evaluations.

The partners of the project include the Nordic authorities DEMA (Danish Emergency Management Agency), NRPA (Norwegian Radiation Protection Authority), SSM (Swedish Radiation Safety Authority) and STUK (Finnish Radiation and Nuclear Safety Authority). In total 20 partners take part in the project with IAEA as observer. The pre-calculated database developed in FASTNET is directly relevant for AVESOME possibly in connection with the RASTEP tool, which is very interesting for future use.

CONFIDENCE

The EU CONCERT Confidence project performs research focused on uncertainties in the area of emergency management and long term rehabilitation. It concentrates on the early and transition phases of an emergency, but considers also longer-term decisions made during these phases. The work programme of CONFIDENCE is designed to understand, reduce and cope with the uncertainty of meteorological and radiological data and their further propagation in decision-support systems. It goes further than the AVESOME project by also considering social, ethical and communication aspects related to uncertainties. The Confidence project is divided into six work packages addressing uncertainties from the pre- and early release phase (WP1), cancer risk and dosimetry (WP2), radioecological models (WP3), transition phase (WP4), social and ethical issues (WP5) and communication (WP6).

WP1, dealing with uncertainties in the pre- and early release phase, is closest related to the work in the AVESOME project. As with AVESOME, the results of the previous NKS projects MUD and FAUNA are building blocks of this work package. Meteorological uncertainties will be addressed by several meteorological ensemble model systems, namely the ECMWF Ensemble Data, (GLAMEPS), the Met Office Global and Regional Ensemble Prediction System (MOGREPS-G), the Norwegian/Swedish MetCoOp Ensemble Prediction System (MEPS), the Hungarian Arome EPS and the Danish Meteorological Institute

Ensemble Prediction System (DMI-EPS). The uncertainties will be analyzed in three different scenarios: Fukushima Dai-ichi in Japan, Borssele in the Netherlands and emissions from floating nuclear power plants or nuclear icebreakers close to Norway.

Based on (Rao, 2005), the CONFIDENCE project has published guidelines for ranking uncertainties of atmospheric dispersion modelling (Mathieu *et al.*, 2018). In addition, a report addressing the uncertainties related to the source term is written (Bedwell *et al.*, 2018). Preliminary plans for the Norwegian scenario for addressing source-term uncertainties are based on the WASH-1400 reports scenarios with 50% of emissions will happen during the first hour, and just modifying the peak of the timely distribution of release of particles during the first few hours. The inventory of this source-term will be based on NKS-139 (Reistad, 2006).

A future subtask will follow the results from the NKS-MESO project (Sørensen *et al.*, 2017) to reduce the uncertainties of the atmospheric dispersion models by direct use of meteorological measurements, e.g. precipitation intensity as obtained from weather radar systems.

Meteorological Ensemble Prediction

The DMI meteorological Ensemble Prediction System (DMI-EPS), which is based on the HIRLAM numerical weather prediction (NWP) model (Undén *et al.*, 2002; HIRLAM, 2009), involves 25 ensemble members. The horizontal resolution is 0.05°, corresponding to approximately 5.5 km, and vertically the model has 40 layers from the surface up to 10 hPa (approximately 30 km above the sea surface). The ensemble HIRLAM model is nested into ECMWF's global model. For the geographical coverage, see Figure 1.

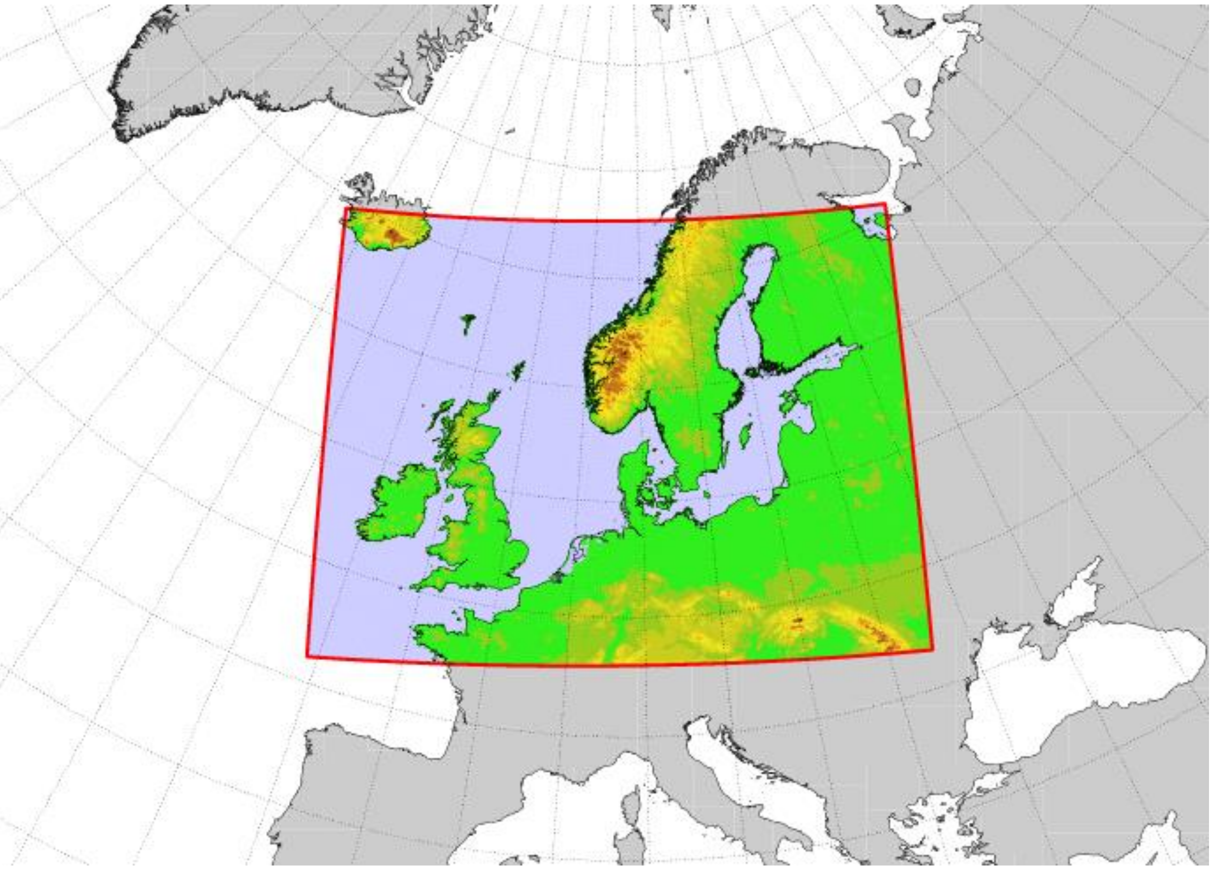


Figure 1 Geographic domain covered by DMI-EPS.

Meteorological forecast uncertainties arise from uncertainties in the initial and lateral boundary conditions and from model short-comings, particularly short-comings associated with parameterization of physical processes that take place on spatial scales that cannot be represented explicitly in the model. The initial condition uncertainty is assumed to be comparable to the forecast error for short (6–18 h) forecasts, and so perturbations proportional to the forecast error are added to or subtracted from the initial conditions (Hou *et al.*, 2001). This approach is easily implemented, it can be generalized to also account for uncertainties in the lateral boundary conditions, it does not require input from a global ensemble prediction system, and the results are satisfactory compared to other, more advanced methods (García-Moya *et al.*, 2011). The main drawback is that the number of perturbations is limited. Therefore, the initial condition perturbations are combined with model perturbations: 13 ensemble members use the STRACO cloud scheme (Sass, 2002), while the remaining 12 members use the Kain-Fritsch/Rasch-Kristjansson scheme (Kain, 2004; Rasch and Kristjansson, 1998), and in 13 members the total contribution from all physical parameterizations is perturbed stochastically (Feddersen, 2009) in order to represent the otherwise unaccounted for uncertainty in the parameterizations, similarly to what has been done for ECMWF's ensemble prediction system for many years (Buizza *et al.*, 1999).

The DMI-EPS has been running operationally from April 2011 till June 2017. For short-range forecasts, i.e. up to two days in advance, the main uncertainties are those associated with clouds and convection, and so the main application of DMI-EPS has been to provide forecasters at DMI with a tool to predict the risk of severe precipitation events (rain or snow) 12 to 36 hours in advance. After an upgrade in 2016, the perturbations were modified in order to increase the spread in wind speed which should reflect uncertainty in wind predictions better.

A new meteorological ensemble prediction model system, COMEPS (Yang *et al.*, 2017), which is based on the Harmonie non-hydrostatic NWP model (Bengtsson *et al.*, 2017), became operational in June 2017 and has substituted the DMI-EPS.

Effective Atmospheric Dispersion Model Calculation

In order to represent the uncertainty of the source term, potentially a large number of atmospheric dispersion calculations are needed. Therefore, effective calculation is required; especially if using Monte Carlo methods involving numerous different source term descriptions. In AVESOME, three different approaches have been developed.

Integrated dispersion model calculation

Since all of the dispersion calculations for a given source-term ensemble are going to use the same meteorological input data, it is advantageous, both with respect to input/output (I/O) and to calculation efficiency, to have the dispersion model treating all of the source terms in one overall calculation. The fact that the tracers, the released radionuclides, are non-interacting should further be utilized. This approach has been implemented in the Danish Emergency Response Model of the Atmosphere (DERMA) (Sørensen *et al.*, 2007; Sørensen, 1998).

Temporally binned continuous release

For dispersion modelling in support of nuclear emergency preparedness and management, one may utilize the fact that the tracers, the released radioactivity, are non-interacting. Therefore, it can be an advantage, in the modelling process involving both the dispersion model and the DSS in use, to split up the release in separate, smaller chunks, a temporally binned release. Additionally, one may utilize the scaling properties of concentration with respect to release rates, and carry out modelling for unit rates only. One will, however, have to treat all radio-nuclides since they decay and deposit differently. This procedure allows the user of the DSS to provide very easily concentration patterns corresponding to any source term within the period covered.

In the following, the source term is denoted by $s_i(t)$, e.g. in units of Bq/s, where i denotes the radionuclide and t the time. The concentration at location $\boldsymbol{r}$ and time t can be written

$$c_i(\boldsymbol{r}, t) = \int_{t_0}^{t} d_i\,(s_i(t'), t')\,\mathrm{d}t'$$

involving time integration from the start of the release t_0 until time t of the model-dependent dispersion function d_i incorporating the effects of the meteorological 3-D parameters in the period.

With a piece-wise constant source term, $s_i(t)$, cf. Figure 2,

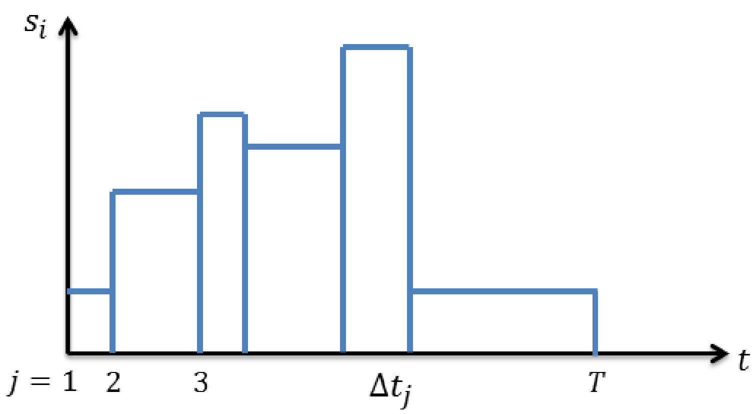


Figure 2 Piece-wise constant source term, $\boldsymbol{s_i(t)}$.

we can employ the scaling properties of concentration with respect to the release rates and write

$$c_i(\boldsymbol{r},t) = \sum_{j=1}^{T} s_{ij}\, D_{ij}(\boldsymbol{r},t)$$

where the 'building blocks' for unit releases of a radionuclide i in the time interval $[t_j, t_{j+1}]$,

$$D_{ij}(\boldsymbol{r},t) = \begin{cases} \int_{t_0}^{t} d_i(1,t')\,\mathrm{d}t' \text{ for } t > t_j \\ 0 \text{ otherwise,} \end{cases}$$

are calculated by the meteorological centre, cf. Figure 3.

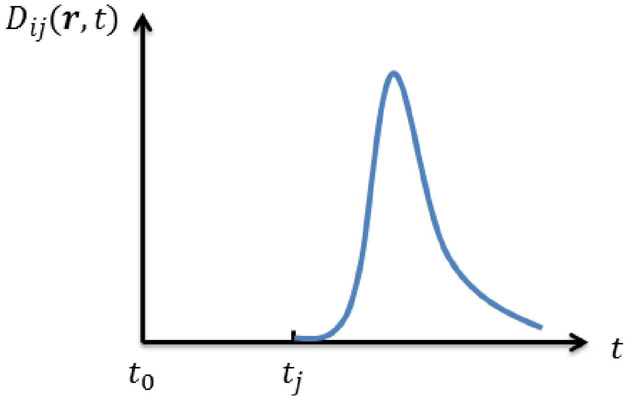


Figure 3 Building blocks $\boldsymbol{D_{ij}(r,t)}$ for unit releases of the radionuclide $\boldsymbol{i}$ in the time interval $[\boldsymbol{t_j}, \boldsymbol{t_{j+1}}]$.

If the time intervals $j = 1, \ \ldots, T$ are well known, then the uncertainty of the source term is expressed by the values of the constants s_{ij}. Thus, it is straightforward to calculate the statistical properties of the concentrations c_i as linear combinations of the set of building blocks, $D_{ij}(\boldsymbol{r},t)$.

It can be suggested that the DSS provides the start of the release, a small constant Δt, e.g. $\Delta t = 1$ h, and an extensive list of possibly released radionuclides to the meteorological centre, which in turn calculates the corresponding building blocks. In fact, by calculating linear combinations of the building blocks, this method allows the user of the DSS to provide very easily concentration patterns corresponding to any source term within the period covered, e.g. 48 hours.

Uncertainties on the heat release, and thereby on the initial plume rise, adds another dimension to the calculations. However, for dispersion models adhering to the assumption of complete mixing in the mixing layer, this is of no consequence as long as the heat is so small that the plume initially stays inside the atmospheric boundary layer (ABL). Otherwise, the proposed method will have to be extended with a discretization of the range of effective release heights thereby adding to the computer resources required.

Effective and efficient combination of weather and source ensembles

A method using post-processing for adding source properties after the dispersion calculations has been developed (Schönfeldt, 2017). This method is suitable for all dispersion models where you can keep track of the particles or puffs. Basically, you need to store information when the particles/puffs are born and the position of these in order to add source properties and radioactive decay in a post-processing mode.

If not having the possibility to apply post-processing the number runs grow fast depending on how large the weather and source ensembles are. For example, having 25 weather ensemble members and 19 source terms generate 475 dispersion runs for every radionuclide or family of radionuclides. With an increasing number of weather and source term ensemble members this number rapidly grows. Therefore, we propose a way of using a sampling method to effectively and efficiently combine weather and source ensembles similar to earlier work done on the local scale (Sigg *et al.*, 2018). The sampling method that we have used is Latin Hypercube Sampling (LHS) and the idea is to use this approach to generate a set of dispersion calculations. Here, all the weather ensemble members are included as well as combinations with other important uncertainties in dispersion model parameters, such as release height, dry deposition velocity and scavenging coefficients.

LHS

The basic approach behind LHS is to divide the probability distributions into a number of bins, an arbitrary value set by the user. This is called stratification. Every stratification can only be used once when combining the parameters included in the uncertainty analysis which means that the number of runs will be equal to the stratification value; see McKay *et al.* (1979).

Given the stratification value the idea is to compute large enough parameter combinations to cover the most important uncertainty features, see Figure 4. After that the dispersion model is run for every combination computed by LHS. The advantage of LHS is that the number of dispersion calculations is significantly reduced compared to Monte-Carlo methods (MCM). In LHS, we typically talk about 50–100 runs while in MCM the number are millions. The selection of the stratification number is dependent on the specific global uncertainty analysis, and typically, with an increased number of parameters with uncertainties the more stratifications you need. Many times you have to study the specific problem in order to understand the proper stratification number.

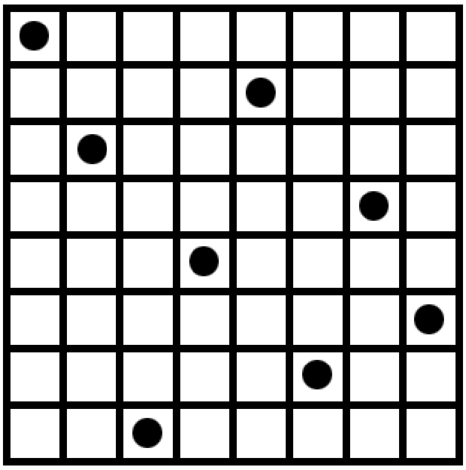


Figure 4 A two-parameter problem with a stratification number set to 8. The total amount of combinations are 64 (MCM) while the LHS method generates 8 combinations (black dots) evenly spaced over all the combinations.

Both LHS and MCM require knowledge of the parameter uncertainties and their probability distributions. These distributions depend on the nature of the physical problem and it is outside the scope of this project to study parameter uncertainties and their distributions. Thus, we are dependent on such knowledge from other studies and one good review paper is Mathieu and Korsakissok (2018). The most used distributions within dispersion modelling are normal, uniform and log-normal. As already mentioned we have chosen the following parameters to illustrate the method: weather ensembles, release height, dry deposition velocity and scavenging coefficients. Here follows a discussion of each parameter and the chosen distribution.

Parameters and distributions

In this study, we work with the European Centre for Medium-range Weather Forecasts (ECMWF) output, and the number of weather ensembles is 50. This means that we have 50 realizations of the weather development for every forecast and it is assumed that every ensemble member is equally probable. The probability distribution of the weather ensembles can therefore be set to uniform. It is also suitable to choose the stratification number to 50 for the whole LHS approach based on that we have this amount of weather ensembles. The weather development (wind speed and direction) is the most important factor to understand where the radioactive cloud is transported.

Another important factor is the release height and it is known from earlier accidents (Fukushima, Chernobyl) that this varies during the release. One estimation is that it should be distributed uniformly and for the Fukushima case the boundaries was set to 0–400 m (Mathieu and Korsakissok, 2018). This is probably dependent on the accident and the type of power plant.

During dispersion there are two important processes to bring down the radioactive material to the ground, dry and wet deposition. Therefore we have included these parameters as well. There are different opinions whether these are distributed log-normally or normally. For simplistic reasons we have chosen normal distributions for these parameters. The dry deposition is dependent on the so-called dry deposition velocity and for the scavenging coefficient we produce a multiplication factor since this coefficient is computed within the dispersion model.

For an overview of the chosen distributions and related values, see Table 1. This is based on Mathieu and Korsakissok (2018).

Parameter	Average (or min)	Standard deviation (or max)
Weather ensemble	1	50
Release height	100 m	300 m
Dry deposition velocity	$8x10^{-3}$ ms^{-1}	$2x10^{-3}$ ms^{-1}
Scavenging coefficient mult.	1	0.3

Table 1 Input to LHS for generation of parameter combinations.

So the first step is to produce a list with every parameter combination that we would like to run, in total 50 combinations. The second step is to perform unit dispersion calculations with input from this this list and the third step is to post-process the result by adding the radioactive properties from the source ensemble. With source ensemble of size 50 a MCM approach renders in $50^5 = 312{,}500{,}000$ traditional dispersion calculations compared to 50 using the LHS approach. From a computer efficiency perspective we are apparently saving quite a lot by this approach. Especially since the post-processing method is fast and takes very little computer power.

Results

Figure 5 shows an example of the deposited field of Cs-137 using the FOI model PELLO for a weather situation in July 2018 (Ensemble 1) using the generic BWR source-term ensemble defined in Section “Source Term Ensembles Employed”. The artificial source is located at the Brokdorf NPP. Four source terms out of 19 are chosen to illustrate the different behaviour using different source terms (added after the dispersion run). Here the result can directly be related to the magnitude and temporal behaviour of the source terms. These results are not equally probable and it is up to the decision maker to judge the most likely valid source term. However, there is a clear difference between the scenarios and here we can have a fast estimation of the potential outcome of the accident.

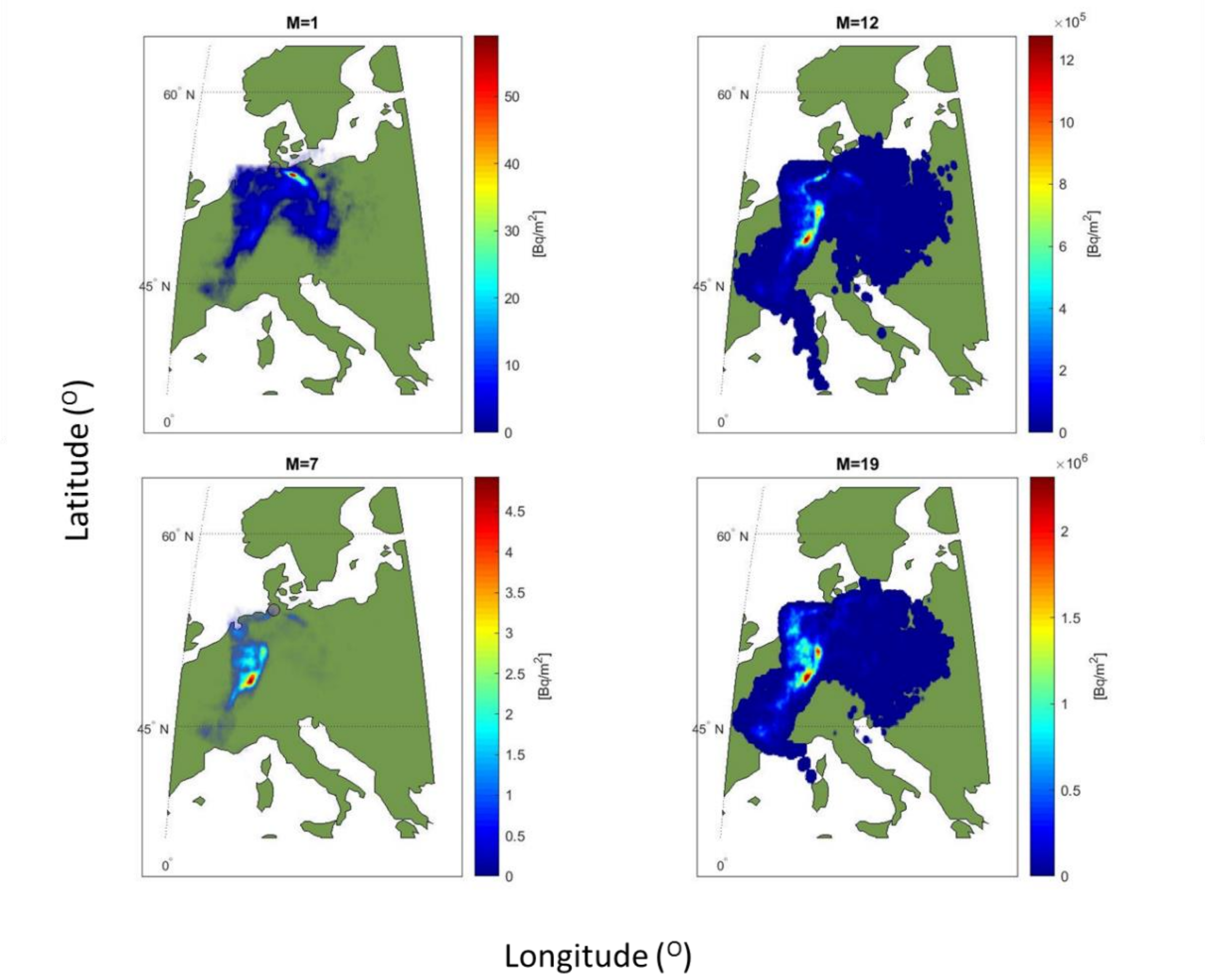


Figure 5 The deposition field after an accident with four different source terms for one weather ensemble.

If we now make an average over several dispersion runs (weather ensembles, in this case 4) we also can study the impact of weather as well as the other defined parameter uncertainties. In this case, we have a stable weather situation with a high pressure region over the European continent so averaging will not give any surprising results, see Figure 6.

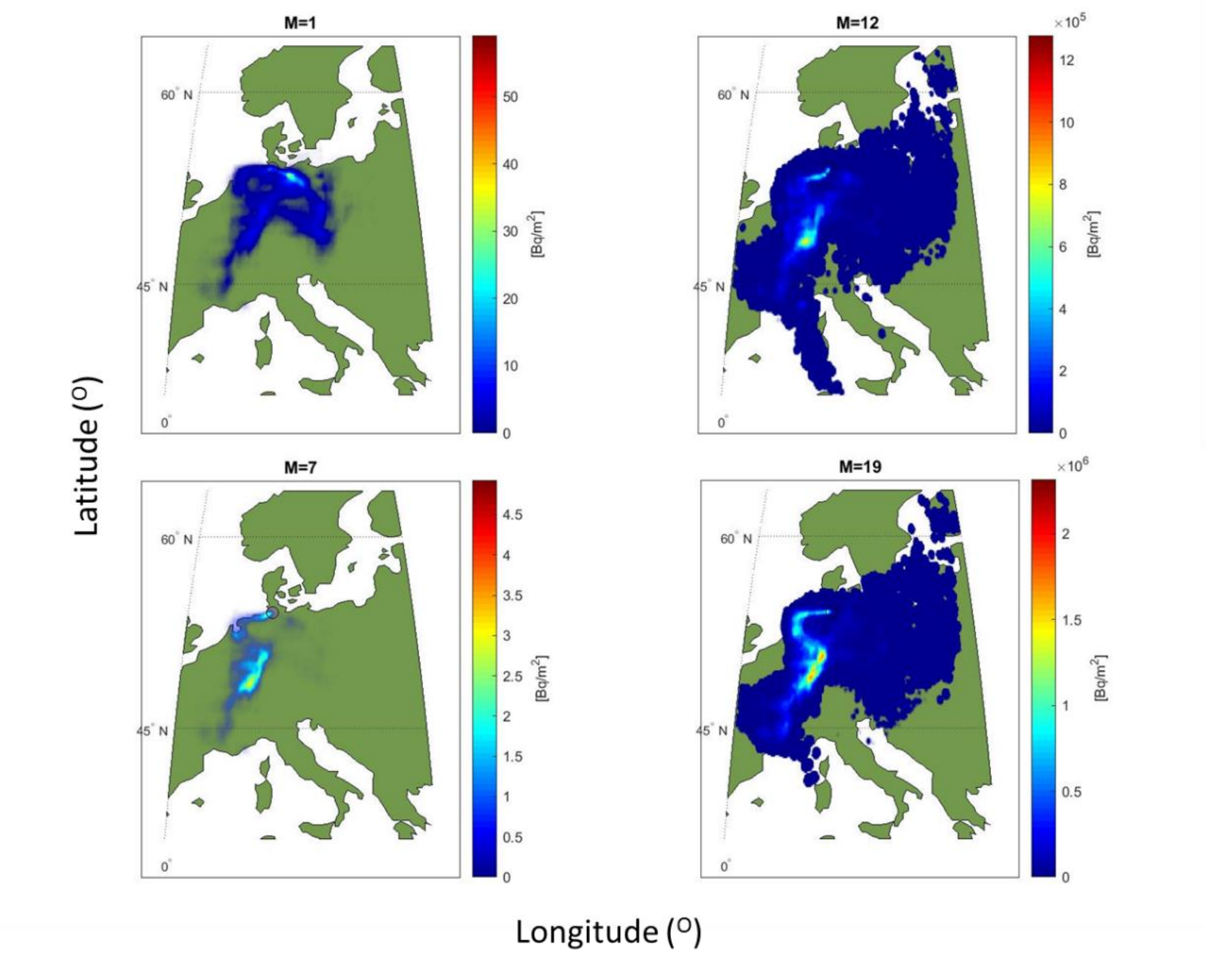


Figure 6 Same as Figure 5 but deposition averaged over four dispersion runs (four different weather ensembles and related parameter uncertainties).

The area affected by the radioactive deposition grows and it is most clear for M12 and M19. With all the 50 dispersion calculations (not done at the moment) we expect to see larger uncertainties.

Conclusions and future work

Post-processing together with LHS generated dispersion calculations is an efficient way of combining the uncertainties (weather, dispersion and source parameters). It allows the end-user to add the most plausible scenario together with its uncertainties after the dispersion runs which can be limited to a reasonable number. Basically, there will be one run per meteorological ensemble member and per radionuclide (or family of radionuclides). At present the number of runs must be multiplied by the number of radionuclides included in the dispersion. At least three families of radionuclides should be included (Mathieu and Korsakissok, 2018).

Future work must address different aspects in the modelling/analysis process. First of all we have to determine which parameters to include in the uncertainty calculations and their probability distributions. Here, much has already been done and the two most important parameters are weather and source characteristics. However, there is an urgent need to better understand the source uncertainties for given scenarios. Work on running reactor state physics models with respect to this area is ongoing (FASTNET) but will not cover all aspects needed for determining the uncertainties.

A relevant question to answer is how representative this LHS uncertainty analysis is compared to a true MCM approach. We have already mentioned that it is important that a proper stratification number is chosen. Since we work with stratified samples there is a risk that we are missing important combinations. However, as mentioned above, the most important parameters are weather and source properties and those are covered by the post-processing approach. So with this in mind we think that we will capture the most important features of the uncertainties.

Atmospheric Dispersion Modelling

Combination of an NWP Model Ensemble and a Source-Term Ensemble

In the MUD, FAUNA and MESO NKS-B projects, cf. Sørensen *et al.* (2014, 2016 and 2017), the atmospheric dispersion model ensembles were based on Numerical Weather Prediction (NWP) model ensembles with N members. In AVESOME, the ensembles involved can be either a Source Term (ST) ensemble with M members applied to a deterministic NWP model, or an ST ensemble combined with an NWP model ensemble. In the latter case, the overall statistical ensemble is larger including $N \times M$ members, cf. Figure 7 below.

	NWP-1	**NWP-2**	**…**	**NWP-N**
ST-1				
ST-2				
…				
ST-M				

Figure 7 Schematic representation of the combination of an $\boldsymbol{N}$-member NWP model ensemble with an $\boldsymbol{M}$-member ST ensemble.

Ensemble Statistics for Atmospheric Dispersion Modelling

The members of a meteorological ensemble are equally likely. However, for a source-term ensemble this is not so; the source-term ensemble members corresponding to serious cases, e.g. core-melt by-pass releases, are very much less likely than other cases. For emergency preparedness purposes taking into account both the meteorological uncertainty and the source-term uncertainty, the analysis applied to an atmospheric dispersion model ensemble should thus be based on weighted statistics. Fortunately, a system such as the RApid Source TErm Prediction (RASTEP) system (Knochenhauer *et al.*, 2013), provides also a-priori probabilities for each source term generated thereby enabling the use of weighted statistics.

Consider an N member ensemble $e_i,\ i = 1, \dots, N$, e.g. a concentration field, $e_i = c_i(\boldsymbol{r}, t)$ where t denotes time and $\boldsymbol{r}$ location for a given radionuclide. With corresponding relative weights, w_i, we can define normalized weight factors ($\sum_i f_i = 1$),

$$f_i = \frac{w_i}{\sum_{j=1,\dots N} w_j}$$

In case of equal weighting, we have $f_i = {}^1\!/_N$.
The ensemble average can now be expressed

$$e_{\text{avg}} = \sum_{i=1,\dots,N} f_i\, e_i$$

The probability for exceeding a threshold value c_{t} is given by

$$P_{\mathrm{t}} = \sum_{i=1,\ldots,N} f_i \, \vartheta(e_i > c_{\mathrm{t}})$$

where ϑ denotes the Heaviside step function.

In general, there is no commonly used definition of a weighted quantile or percentile. Here, we define it as quantiles of the weighted set $\{Nf_i \, e_i \mid i = 1, \ldots, N\}$. The weighted quantiles can be used for risk zoning, i.e. to estimate the geographical area which can be influenced according to the ensemble. However, the quantiles are not solutions to the governing equations and should be seen as statistical measures only.

It is tempting to employ minimum and maximum percentiles to estimate risk zones. However, they are influenced by outliers in the tail of the distributions, and they are therefore in fact often much influenced by few ensemble members. This makes corresponding plots sensitive to the inclusion of more ensemble members and generally uncertain. Instead, a low and a high percentile, e.g. 5% and 95%, together with the mean or median are more appropriate and robust quantities for decision making purposes.

Typically, the no-release scenario is not included in the source-term ensemble. This implies that e.g. the calculated probabilities are conditional, i.e. probabilities given that there will be a release.

The Danish Emergency Response Model of the Atmosphere (DERMA)

The Danish Emergency Response Model of the Atmosphere (DERMA) (Sørensen *et al.*, 2007; Sørensen, 1998) is a comprehensive numerical regional and meso-scale atmospheric dispersion model developed at the Danish Meteorological Institute (DMI). The model is used operationally for the Danish nuclear emergency preparedness, for which the Danish Emergency Management Agency (DEMA) is responsible (Hoe *et al.*, 2002). Besides, the model is employed for veterinary emergency preparedness (Sørensen *et al.*, 2000; 2001; Mikkelsen *et al.*, 2003; Gloster *et al.*, 2010a; 2010b), where it is used for assessment of airborne spread of animal diseases, e.g. foot-and-mouth disease. DERMA may also be used to simulate atmospheric dispersion of chemical substances, biological warfare agents and ashes from volcanic eruptions, and it has been employed for probabilistic nuclear risk assessment (Lauritzen *et al.*, 2006; 2007; Baklanov *et al.*, 2003; Mahura *et al.*, 2003; 2005).

The main objective of DERMA is to predict the dispersion of a radioactive plume and the accompanied deposition. However, the model may also be used in situations where an increased level of radioactivity has been measured but no information is received on radioactive releases. In such cases, inverse (adjoint) modelling may be applied whereby potential sources of radioactivity may be localised and release rates estimated.

The three-dimensional model is of Lagrangian type making use of a hybrid stochastic particle-puff diffusion description, and it is currently capable of describing plumes at downwind distances up to the global scale (Sørensen *et al.*, 1998). The model utilizes aerosol size dependent dry and wet deposition parameterisations as described by Baklanov and Sørensen (2001).

Currently, DERMA makes use of analysed and forecasted meteorological data of various deterministic versions at DMI of the NWP model Harmonie (Bengtsson *et al.*, 2017) covering North-eastern Europe, Greenland and the Faeroes, and from the global model developed and operated by the European Centre for Medium-range Weather Forecasts (ECMWF). Further, DERMA utilizes the COMEPS (Yang *et al*, 2017) ensemble prediction system, which is based on the Harmonie model.

DERMA is interfaced with the Accident Reporting and Guidance Operational System (ARGOS) (Hoe *et al.*, 1999; 2002), a PC based nuclear decision-support system developed by DEMA and the Prolog Development Center (PDC). The integration of DERMA with the ARGOS system is effectuated through automated online digital communication and exchange of data between the ARGOS system and the DMI High Performance Computing (HPC) facility.

Case Studies

Meteorological Cases

A meteorological scenario has been selected, and the DMI ensemble prediction system has been applied to this case with an initial 54 hour forecast series. The numerical weather prediction ensemble data are made available to the DERMA atmospheric dispersion model.

20 May 2011

At the start of the forecast (18 UTC), a low-pressure system is located northwest of Scotland with associated gale force winds south of it. The wind over Scandinavia is mostly from southwest, see Figure 8. Later, a front with relative intense rainfall passes Denmark and southern Scandinavia.**Figure 10** Figure 9 shows that there is little spread in the location of the front, but some spread in the intensity of the rainfall.

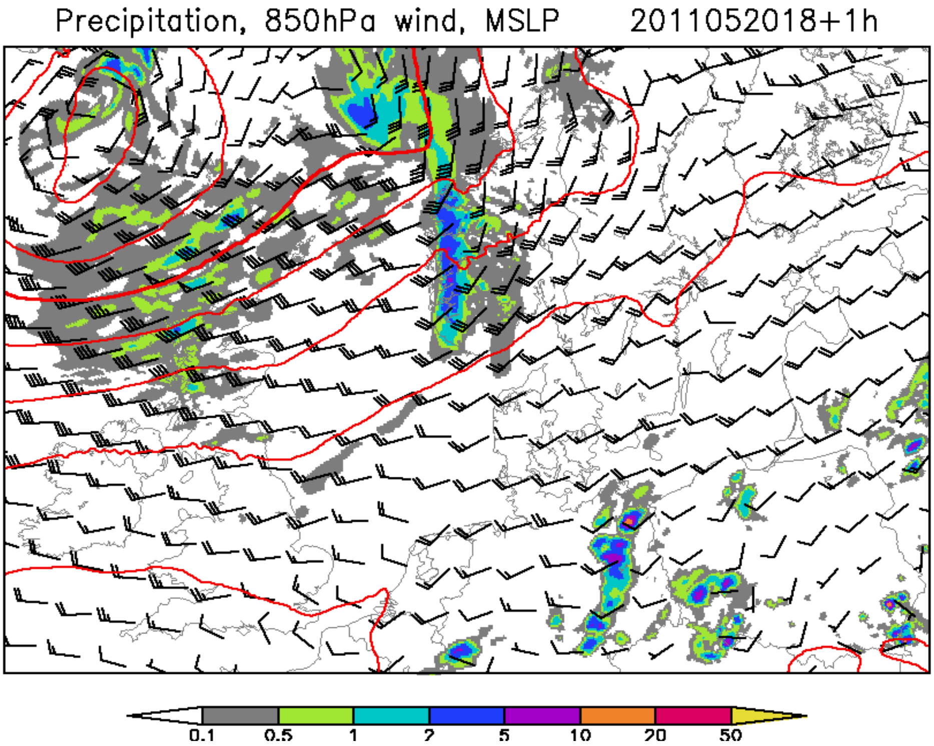


Figure 8 Ensemble mean wind in 850 hPa (wind flags), mean sea level pressure (red contours) and 1-h precipitation in mm (shaded) from forecast initiated at 18 UTC, 20 May 2011.

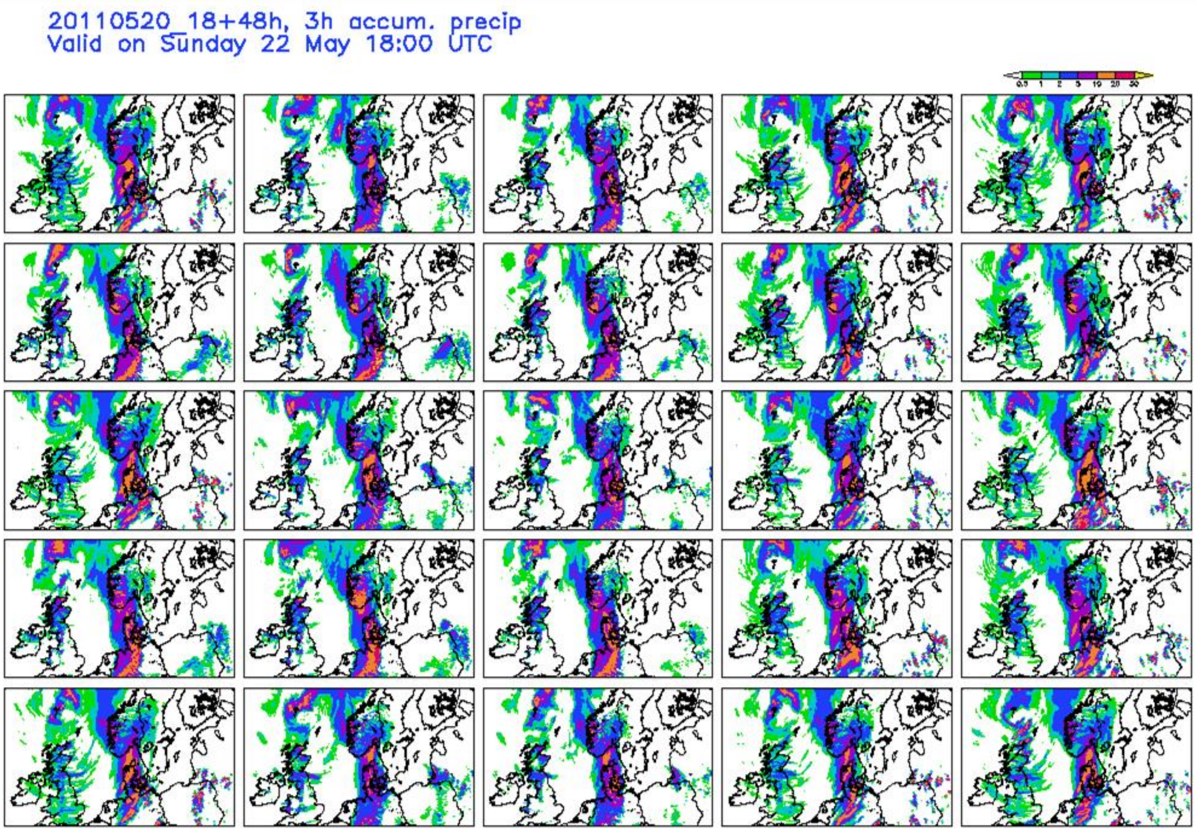


Figure 9 25 ensemble members each showing precipitation accumulated between forecast hours 45 and 48. Contours at 0.5, 1, 2, 5, 10, 20 and 50 mm.

27 April 2016

A low-pressure system is situated over southern Denmark (Figure 10). It is weakened during the forecast, and the wind reduced. There are several rain showers associated with this low. This is also seen in the meteogram for Karup (Figure 11) where the precipitation panel should be interpreted as a risk of rain every hour for the first 30 hours, not as rain continuously every hour.

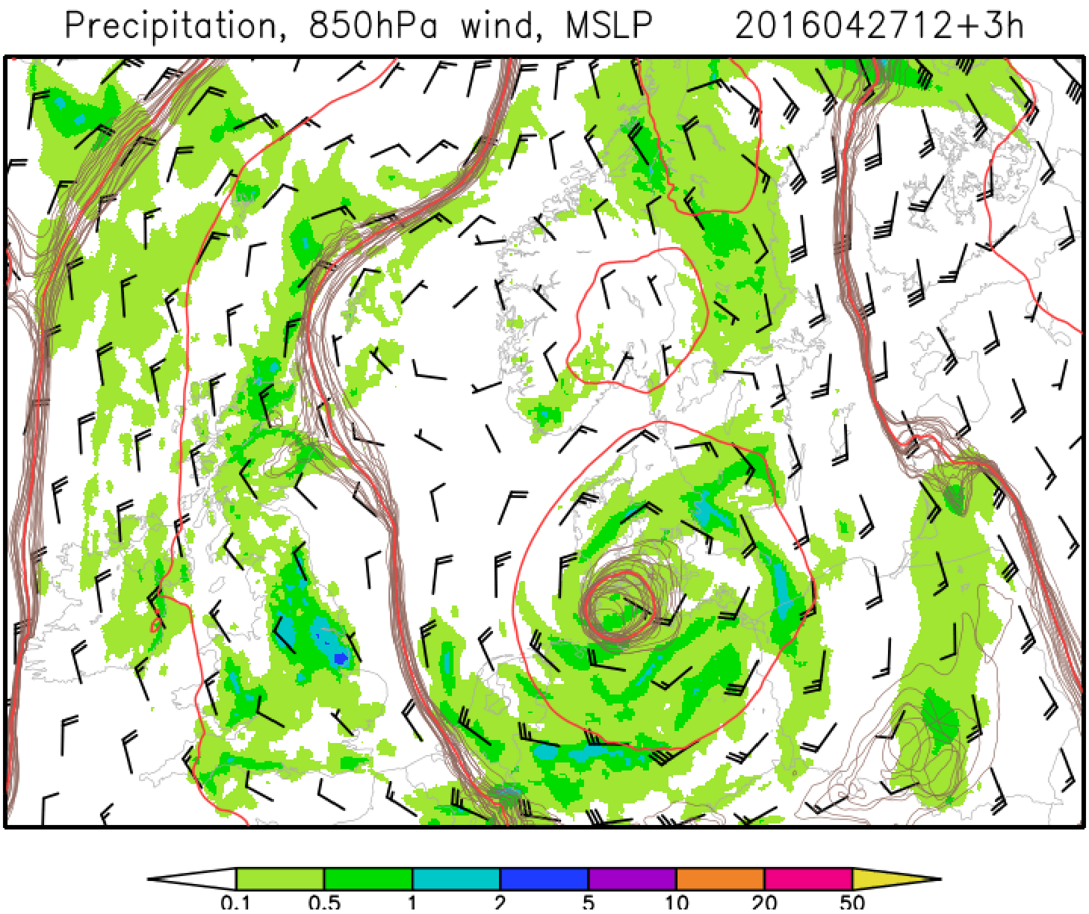


Figure 10 Ensemble mean of 6 hour forecast of hourly precipitation in mm (shaded), wind at 850 hPa (wind barbs) and mean sea level pressure (MSLP; red contours). Individual MSLP ensemble members (brown contours around every other red contour) illustrate the forecast uncertainty.

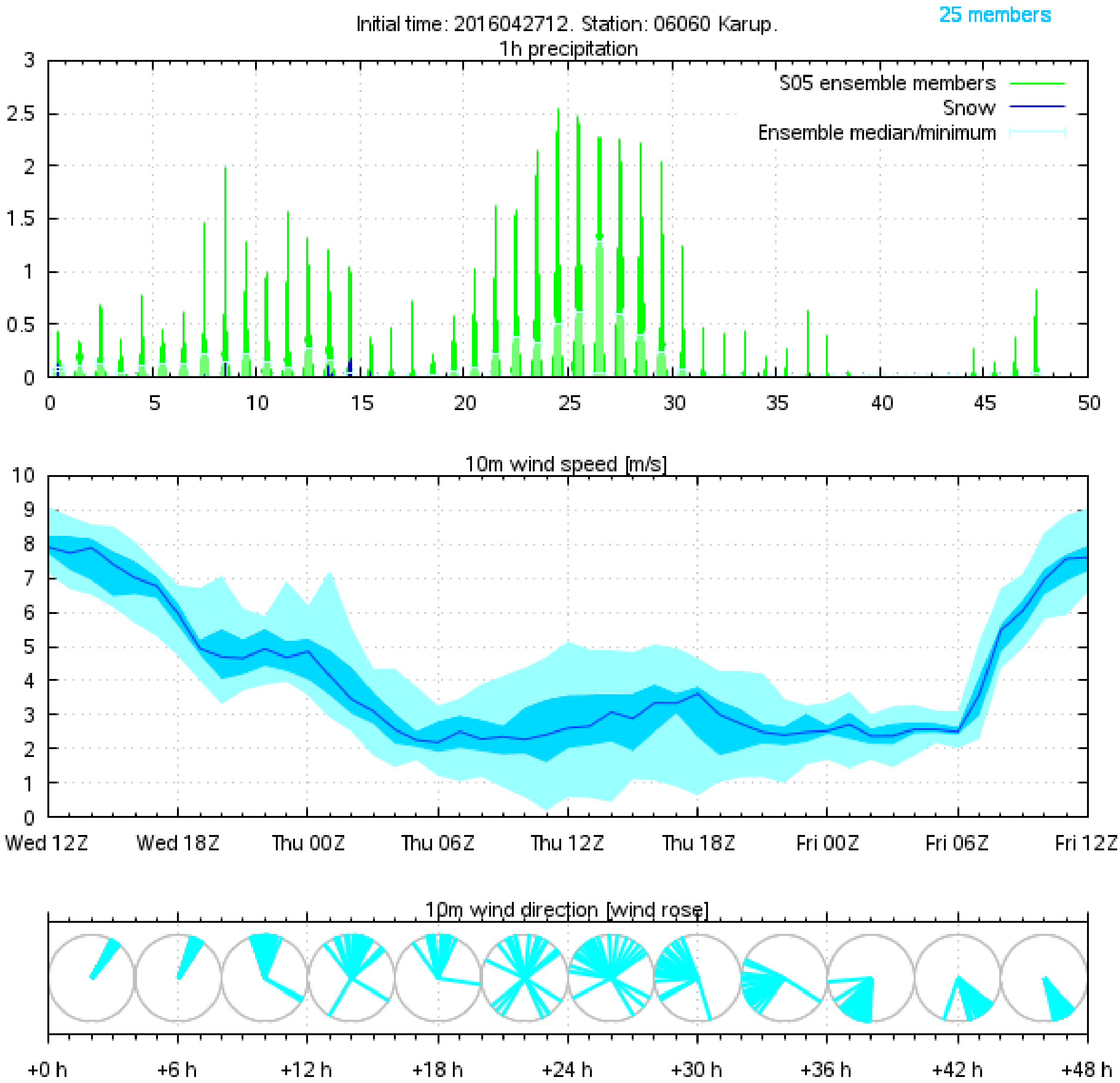


Figure 11 Meteogram showing ensemble forecast for Karup. Top: Precipitation, where each member at every forecast hour is shown as a vertical line (blue for snow, green for total snow + rain). Middle: Wind speed at 10 m above ground (light blue shows "outer half" of the members; darker blue shows "inner half" of the members; darkest blue shows the median). Bottom: Wind roses, indicating the wind direction for each ensemble member.

Source Term Ensembles Employed

The generic BWR source-term ensemble consists of a list of probabilities and source terms for the different release categories from the full power operation cases of a PSA Level 2. The source terms are deduced from an analysis with an estimated time of release, released amount of key radionuclides divided into time intervals, for a particular release path, see Table 2 and Figure 12.

The a-priori probabilities and the associated source-term ensemble for the full power cases are taken from the full-scale PSA model, grouped according to the needs of the Rapid Source Term Prediction (RASTEP) tool. The source-term ensemble weights are the probabilities of the BBN nodes resulting in a release, normalised so that the sum of them is one. The severe cases have large uncertainties, and therefore the associated source terms are assessed by a conservative approach. Thus, if any of them would occur in real life one should expect them to result in less severe consequences than the cases defined by source terms coming from PSA Level 2.

For the example employed in this study, “OT” is a sequence in which the initiating event is a transient, whereas “OL” is a sequence with LOCA as the initiating event. “L-X” indicates a release from diffuse leakage in the containment. “GAP” means a release with the gap inventory in the fuel (no core melt). “L” and “E” indicate late and early containment failure, respectively. The mitigation systems are filtered containment venting “F” and spray “S”. “I” means early core melt with no spray. “BYP” means that the containment integrity is not sustained but bypassed. “RH” and “TH” indicate the reactor and turbine hall release paths, respectively.

Node State	Customised Source Term	Building	Mode
early_failure_spray	OTES	Containment ST2	Transient early/spray
early_failure_no_spray	OTI	Containment ST2	Transient early/no spray
late_failure_spray	OTLS	Containment ST2	Transient late/spray
late_failure_no_spray	OTL	Containment ST2	Transient late/no spray
containment_vent_362_spray	F-ES	Containment ST2	Transient 362 venting/spray
containment_vent_362_no_spray	F-E	Containment ST2	Transient 362 venting/no spray
loca_early_failure_spray	OLES	Containment ST2	LOCA early/spray
loca_early_failure_no_spray	OLI	Containment ST2	LOCA early/no spray
loca_late_failure_spray	OLLS	Containment ST2	LOCA late/spray
loca_late_failure_no_spray	OLL	Containment ST2	LOCA late/no spray
loca_containment_vent_362_spray	F-ES	Containment ST2	LOCA 362 venting/spray
loca_containment_vent_362_no_spray	F-E	Containment ST2	LOCA 362 venting/no spray
loca_gap	GAP	Containment ST1	LOCA gap release (no bypass)
diffuse_leakage	L-X	Containment ST2	Diffuse leakage
melt_bypass_filtered	BYP-RH-F	Reactor Hall	Melt bypass (filtered)
melt_bypass_unfiltered	BYP-RH	Reactor Hall	Melt bypass (unfiltered)
gap_bypass_filtered	BYP-GAP-RH-F	Reactor Hall	Gap bypass (filtered)
melt_TB_overP	BYP-TH	Turbine Hall	Melt bypass
gap_TB_overP	BYP-GAP	Turbine Hall	Gap bypass

Table 2 Generic BWR source-term ensemble.

In total, 19 source terms are obtained containing absolute releases of six key radionuclides divided into 4 release phases. For this ensemble, each source-term member contains the same radionuclei, which does not apply in general. With a meteorological ensemble of 25 members, the combined ensemble consists of 25×19=475 members.

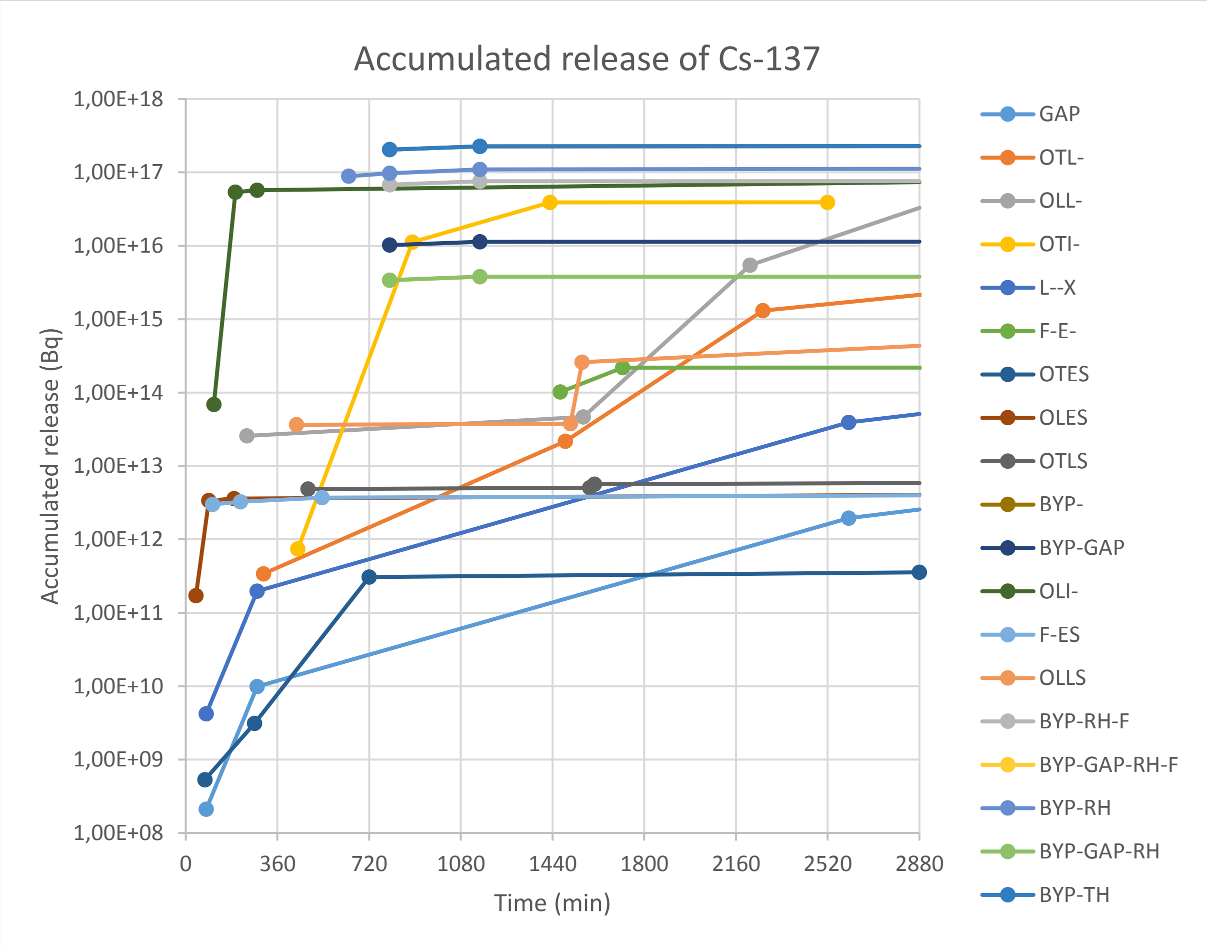


Figure 12 Accumulated release of Cs-137 as function of time since the emergency shutdown of a nuclear reactor (SCRAM) for the source-term ensemble members.

The source-term ensemble and associated a priori probabilities described above are not quality controlled. However, for the sake of illustrating the methodology, the values are very useful.

At the early phase of a serious nuclear accident with hardly any knowledge on the source term, the difference between the ensemble minimum and maximum is very large. Probably, the ensemble shown in Table 2 is too large to be of any practical value. Instead, one may decide to use a scenario-based approach limiting the ensemble members to selected ones. Below, a number of such sub-sets are specified. For each of them, the weighting factors should be re-normalized.

Later, when additional information on the plant status is received, the source-term ensemble will become more focused; in the end probably to a fairly well defined source term or a few. At this point in time, one should probably request new calculations due to the likely appearance of new NWP model forecast available e.g. each three hours. For the present calculations, however, the same NWP model data have been used.

Mitigation source-term ensemble

Few hours after the start of the event, one will likely know if the containment has been successfully isolated and (at least one of) the mitigation systems (containment spraying[1] and filtering[2]) are functioning. In such case, the source-term ensemble is reduced to: (GAP, L-X, OTES, OTLS, F-ES, F-E, OLES, OLLS)

No-mitigation source-term ensemble

In case of a severe accident where the mitigation systems are needed but not working or the containment is bypassed, the source-term ensemble is reduced to: (OTI, OTL, OLL, OLI, BYP, BYP-GAP-RH, BYP-RH-F, BYP-RH, BYP-GAP-RH-F, BYP-TH, BYP-GAP)

Containment source-term

In case the accident involves the containment only, the source-term ensemble is: (OTES, OTI, OTLS, OTL, F-ES, F-E, OLES, OLI, OLLS, OLL, GAP, L-X)

By-pass source-term ensemble

In case the accident is a by-pass scenario, the source-term ensemble is reduced to: (BYP, BYP-GAP-RH, BYP-RH-F, BYP-RH, BYP-GAP-RH-F, BYP-TH, BYP-GAP)

Ambivalent source-term ensemble

The use of a sub-set of the source-term ensemble based on observations entered into the RASTEP model is investigated in the "ambivalent case". In this case, by-pass cases are excluded by an observation on successful containment isolation. Furthermore, an almost minimal set of information is provided by stating that the reactor was at power operation when the initiating event occurred and that the core water level is now observed to be low. In this case, the RASTEP model suggests three possible outcomes with similar probabilities due to the lack of information, hence creating ambivalence in the predicted event and source term.

Customised Source Term	Building	Renormalized weighting factor
OTES	Containment	0.81%
OTI	Containment	3.82%
OTLS	Containment	21.22%
OTL	Containment	2.26%
F-ES	Containment	3.02%
F-E	Containment	28.76%
OLES	Containment	0.03%
OLI	Containment	0.02%
OLLS	Containment	1.06%
OLL	Containment	0.02%
L-X	Containment	38.98%

Table 3 "Ambivalent" BWR source-term ensemble.

The presented values are just examples and should not be taken for representative for a specific reactor. In the above examples, no uncertainties of the release starting time, duration or release magnitude are included. Sequence prediction uncertainty given the lack of detailed accident status information is, however, provided by RASTEP.

[1] Containment spraying implies that the containment is sprayed with water in order to decrease the temperature of the vapour, thereby reducing the containment pressure.

[2] The release to the environment is lead through the containment venting and filtering system.

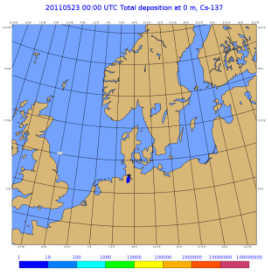
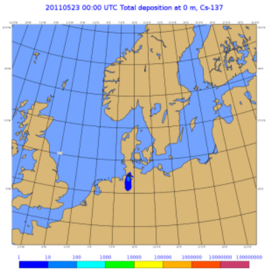
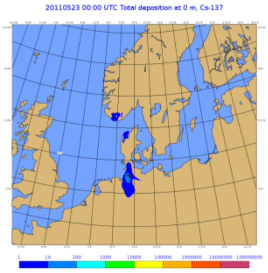
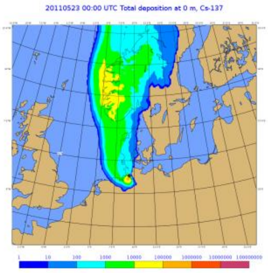
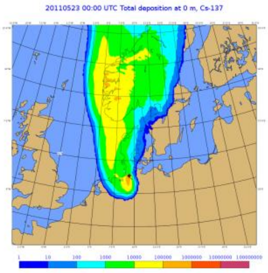
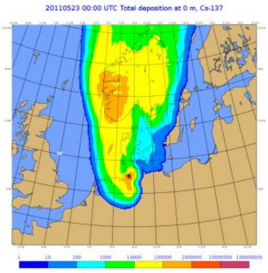
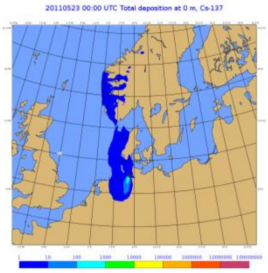
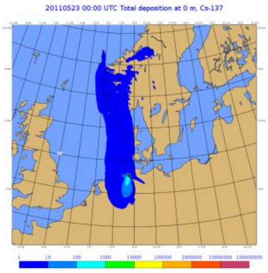
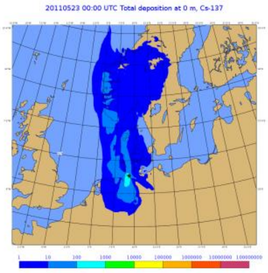
Atmospheric Dispersion Cases

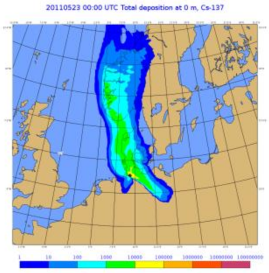
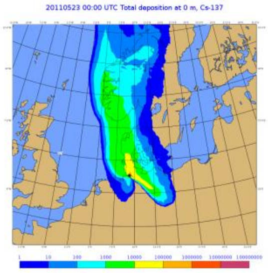
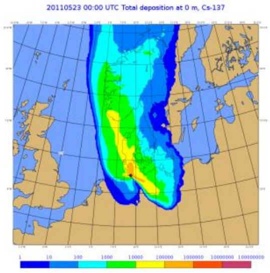
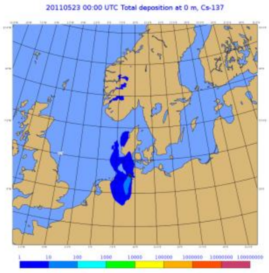
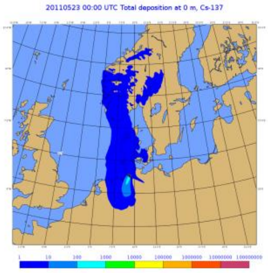
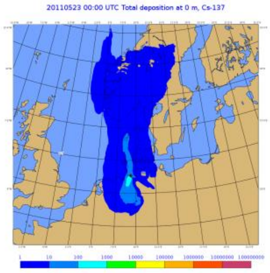
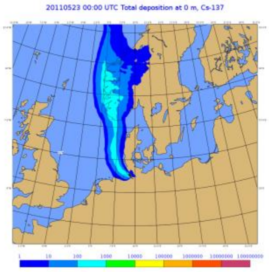
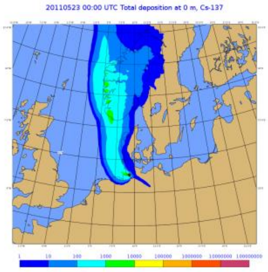
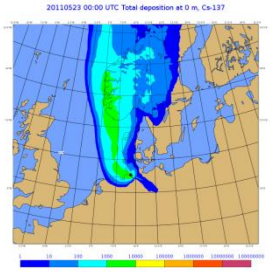
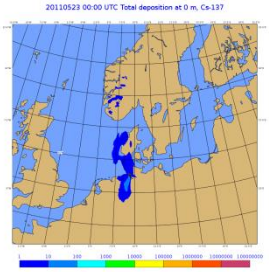
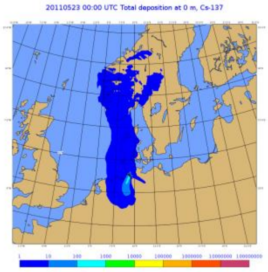
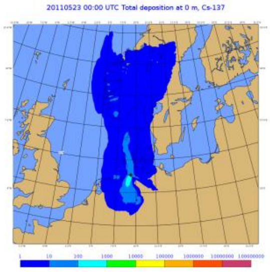
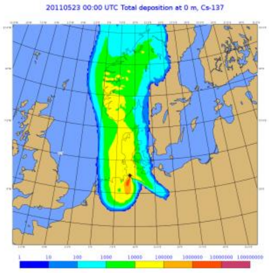
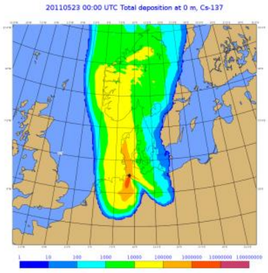
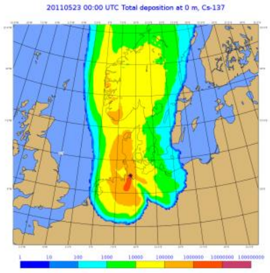
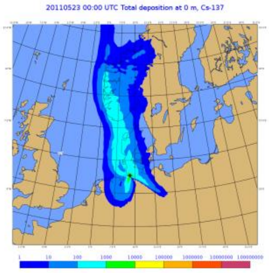
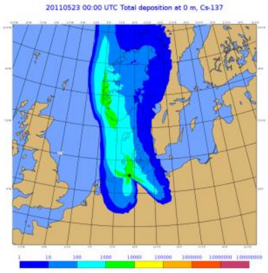
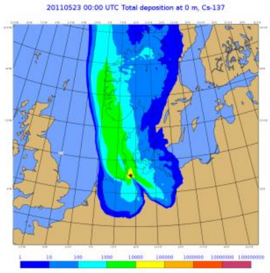
The DERMA model has been applied to each of the above release scenarios, the full generic BWR, the mitigation, the no-mitigation, the containment, the by-pass, and the ambivalent source-term ensembles. Two NPPs have been selected, the Brokdorf NPP using the 20 May 2011 meteorological case, and the Ringhals NPP using the 27 April 2016 meteorological case. In reality, the generic BWR source terms do not apply to the Brokdorf NPP which is a PWR (pressurized water reactor) and not a BWR. However, our objective is to illustrate the methodology, and thus the reactor assumed at the position of the Brokdorf NPP is artificial.

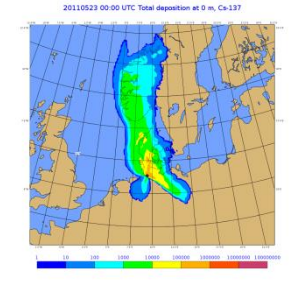
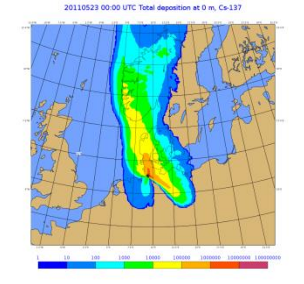
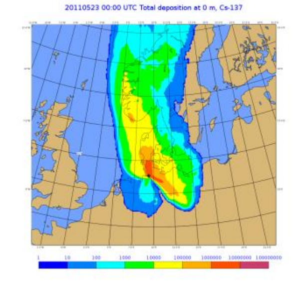
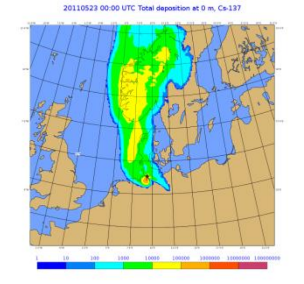
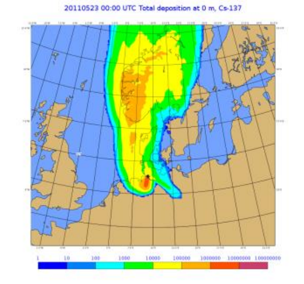
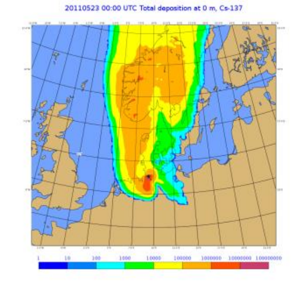
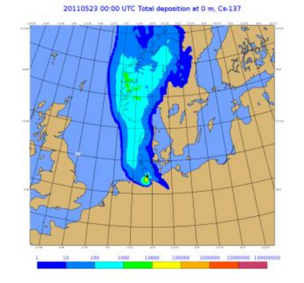
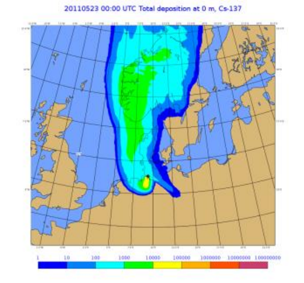
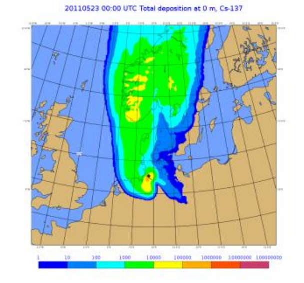
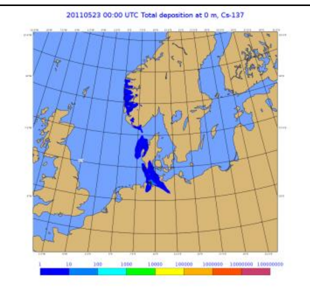
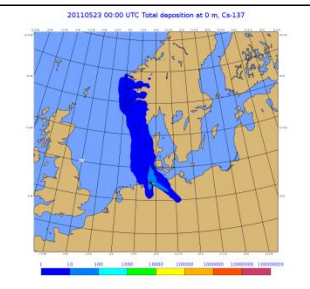
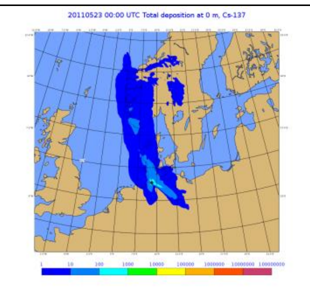
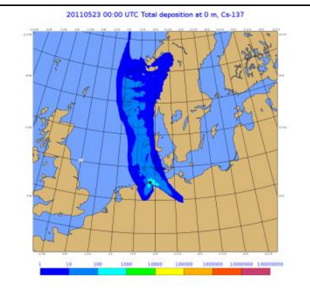
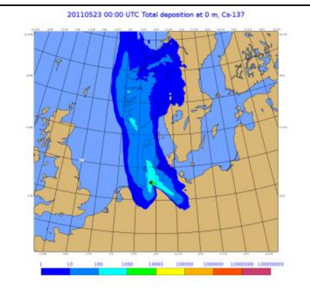
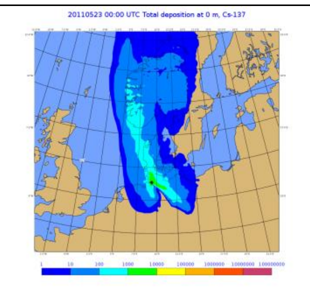
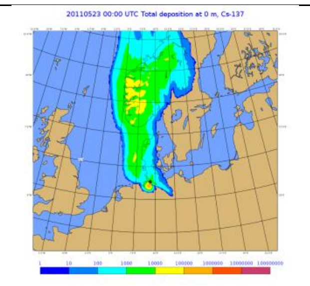
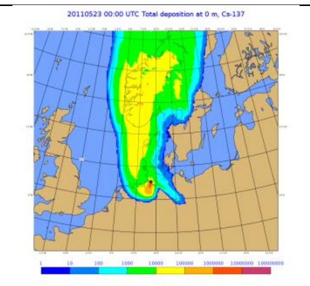
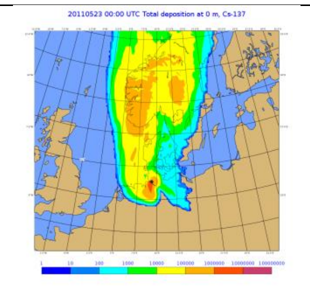
The figures below concern accumulated deposition of Cs-137 based on 54 hour forecast NWP model data from the analysed state.

Brokdorf NPP for the 20 May 2011 meteorological case

Figure 13 below depicts the percentiles of accumulated deposition of Cs-137 for each member of the generic BWR source-term ensemble. Thus, the statistics is here purely meteorological. The calculations are based on 54 hour forecasted NWP model data from the analysed state dated 2016-04-27, 12 UTC. As can be seen in the horizontal, the case-dependent meteorological uncertainty is at the same levels as is seen in the MUD, FAUNA and MESO projects (Sørensen *et al.*, 2014, 2016, 2017). However, in the vertical, the differences between the source-term members are in general much larger.

Source Term	**10th percentile**	**50th percentile**	**90th percentile**	**A priori prob.**
OTES				0.0271%
OTI				0.0074%
OTLS				0.0775%

OTL				0.0127%
F-ES				8.9338%
F-E				6.8910%
OLES				0.0521%
OLI				0.4911%
OLLS				0.0077%

OLL				0.0001%
BYP				0.0423%
BYP-GAP-RH				0.0463%
GAP				1.8334%
L-X				81.4042%
BYP-RH-F				0.0000%

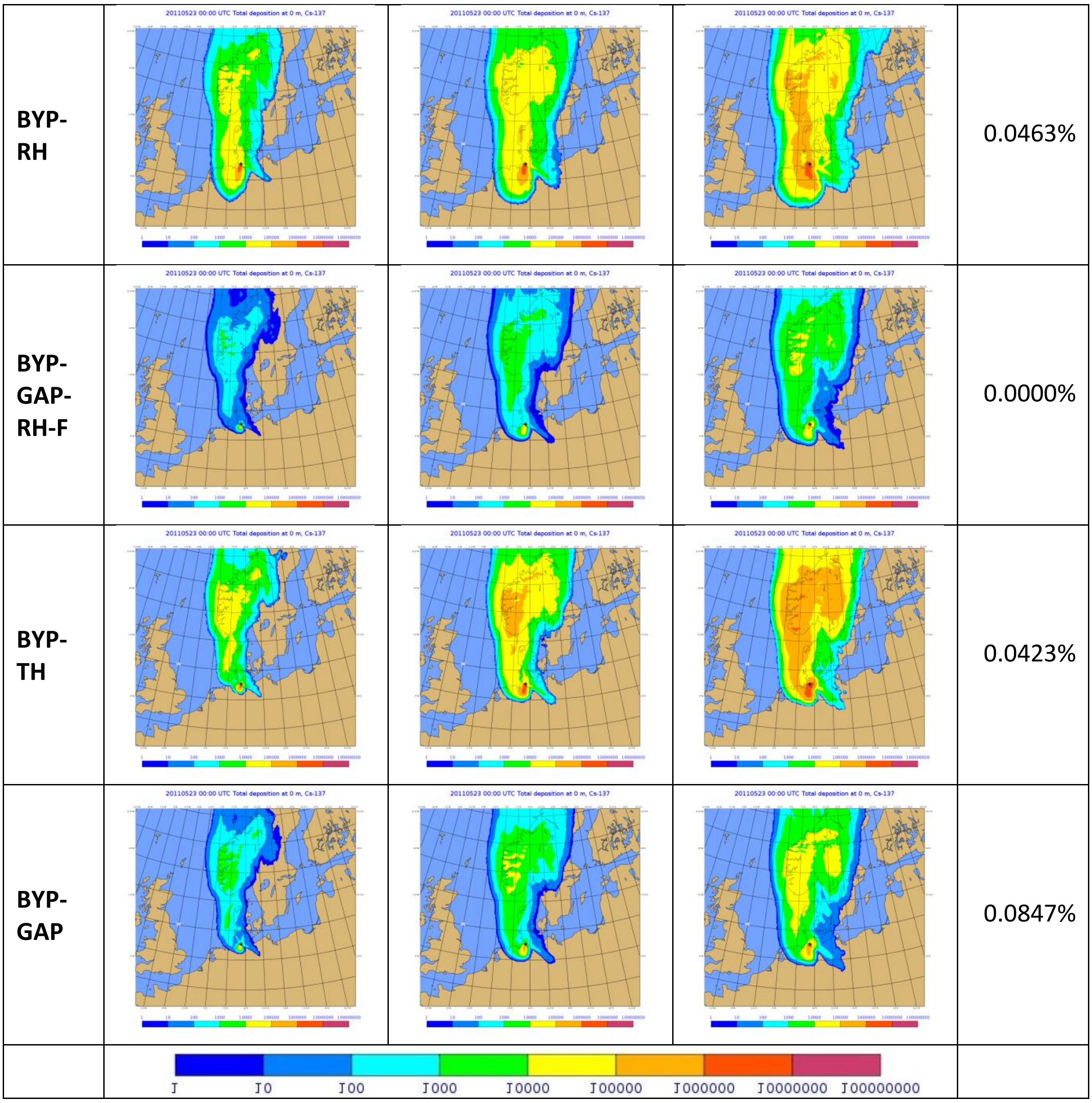


Figure 13 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 for the individual source terms of the generic BWR source-term ensemble. Release start (SCRAM) at 2011-05-20 18:00 UTC.

In Figure 14 are shown percentiles of accumulated deposition of Cs-137 and probabilities for exceeding given threshold values for the entire generic BWR source-term ensemble. This ensemble encompasses more or less all possible releases, and thus there is an enormous difference between a low and a large quantile. Further, it is important to recall that due to the use of weighted ensemble statistics, the severe cases have been suppressed by the weighting factors, the a-priori probabilities. If the ensemble statistical results, e.g. the percentile plots, will be used to assist in estimating risk zones aiming at worst-case scenarios, one should rather use a limited source-term ensemble including the severe scenarios only.

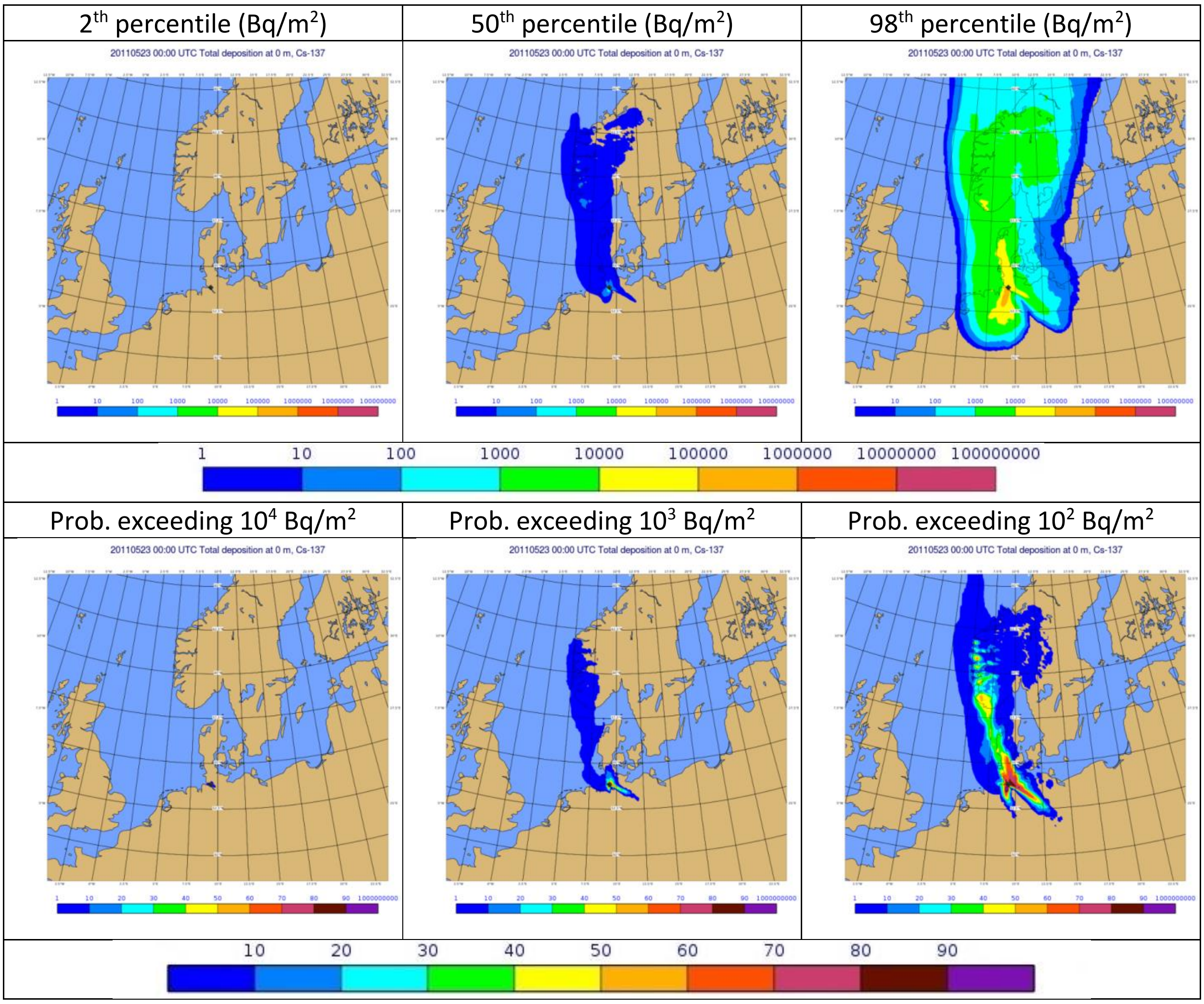


Figure 14 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 and probabilities (%) for exceeding given threhold values for the ***Entire*** generic BWR source-term ensemble. Release start (SCRAM) at 2011-05-20 18:00 UTC.

For practical emergency preparedness, it may be preferable instead to take a scenario-based approach using selected scenarios, e.g. the mitigation, the no-mitigation, the containment, the by-pass and the ambivalent scenarios as described above in Section “Source Term Ensembles Employed”. In this case, the weighting factors should be re-normalized for each of these sub-ensembles, which implies that the sub-ensembles cannot be directly compared regarding absolute magnitudes.

In Figure 15 – Figure 19 are shown percentiles of accumulated deposition of Cs-137 and probabilities for exceeding given threshold values for the the mitigation, no-mitigation, containment, by-pass and ambivalent scenarios.

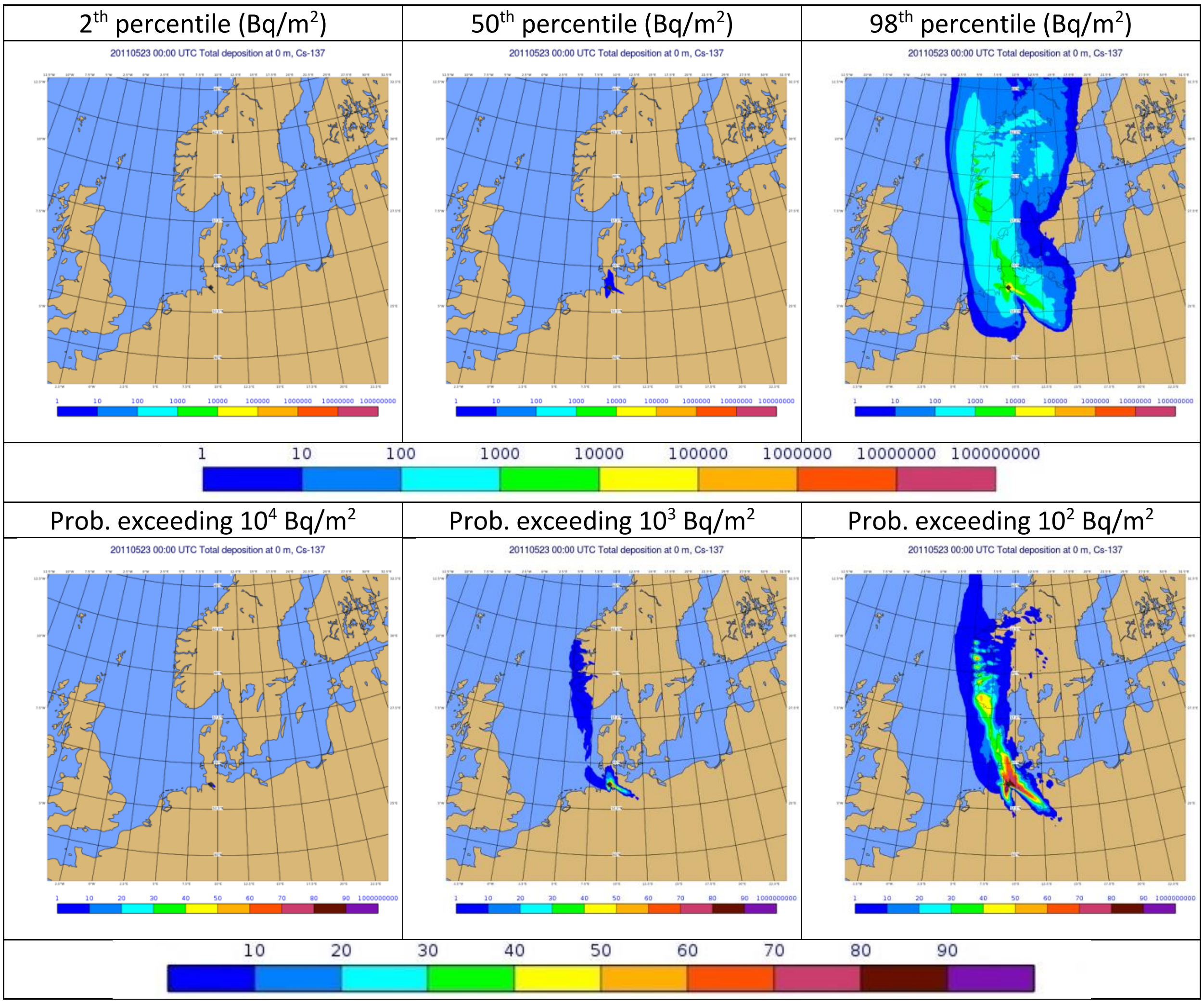


Figure 15 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 and probabilities (%) for exceeding given threhold values for the ***Mitigation*** generic BWR source-term ensemble. Release start (SCRAM) at 2011-05-20 18:00 UTC.

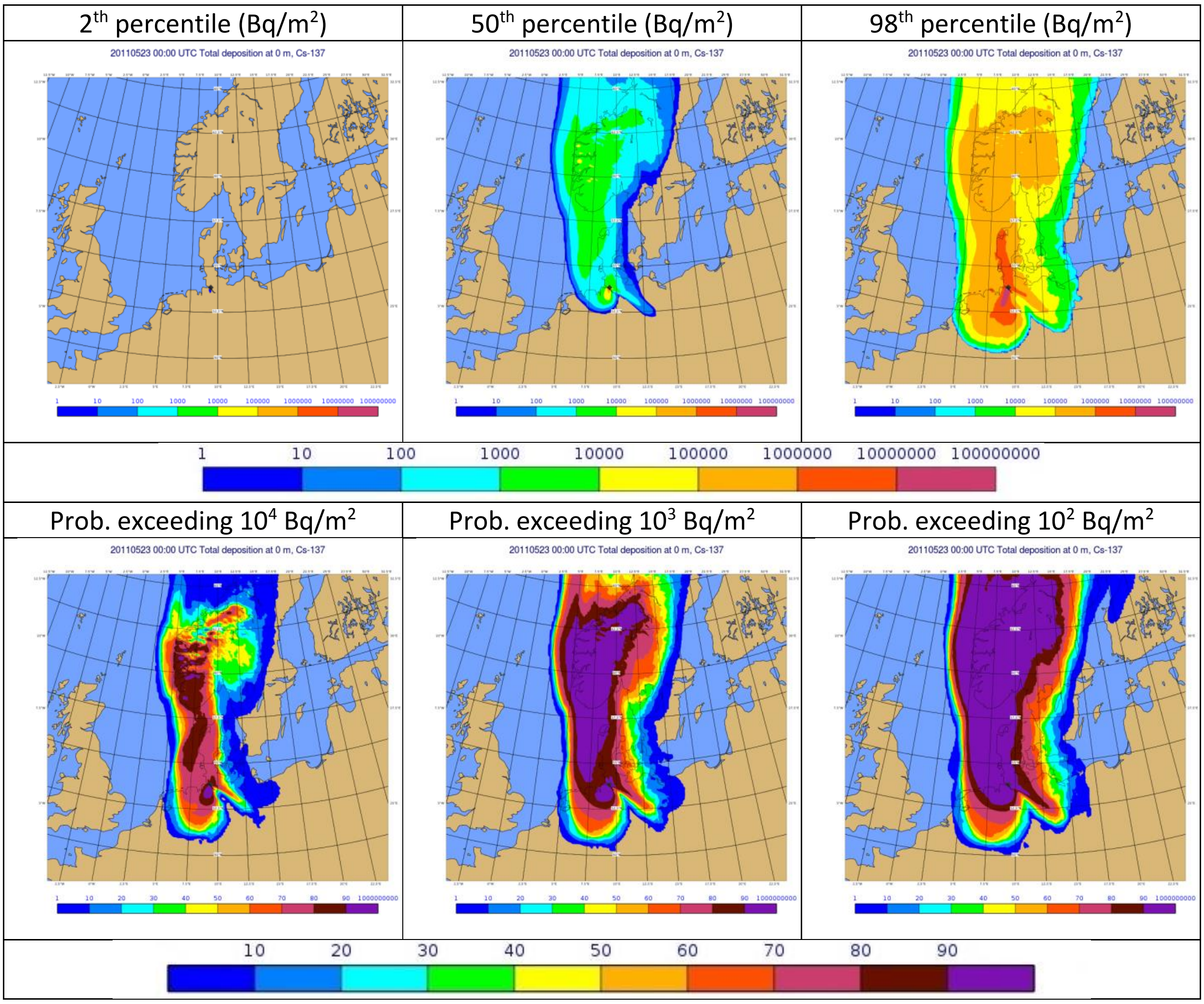


Figure 16 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 and probabilities (%) for exceeding given threhold values for the ***No-mitigation*** generic BWR source-term ensemble. Release start (SCRAM) at 2011-05-20 18:00 UTC.

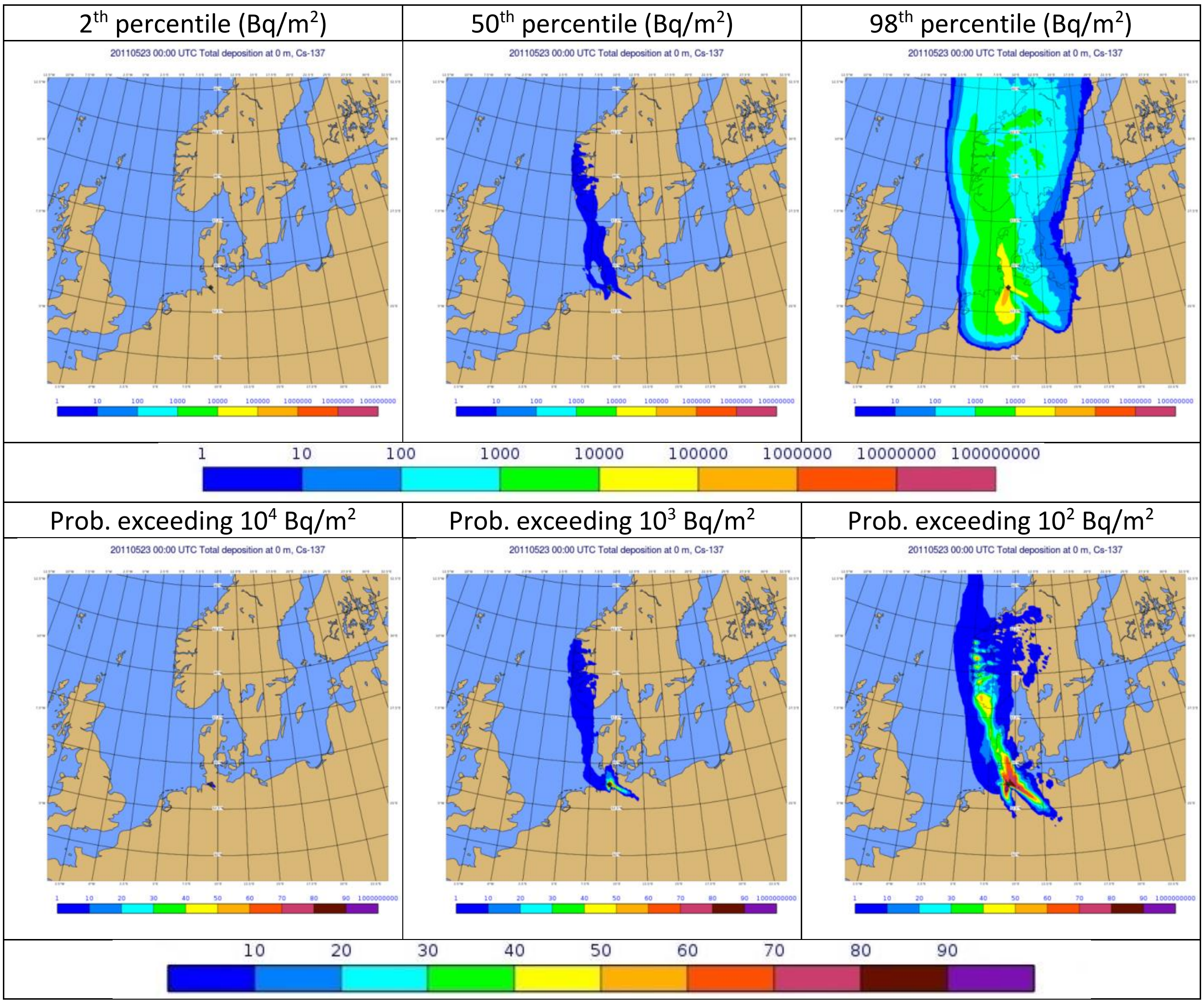


Figure 17 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 and probabilities (%) for exceeding given threhold values for the ***Containment*** generic BWR source-term ensemble. Release start (SCRAM) at 2011-05-20 18:00 UTC.

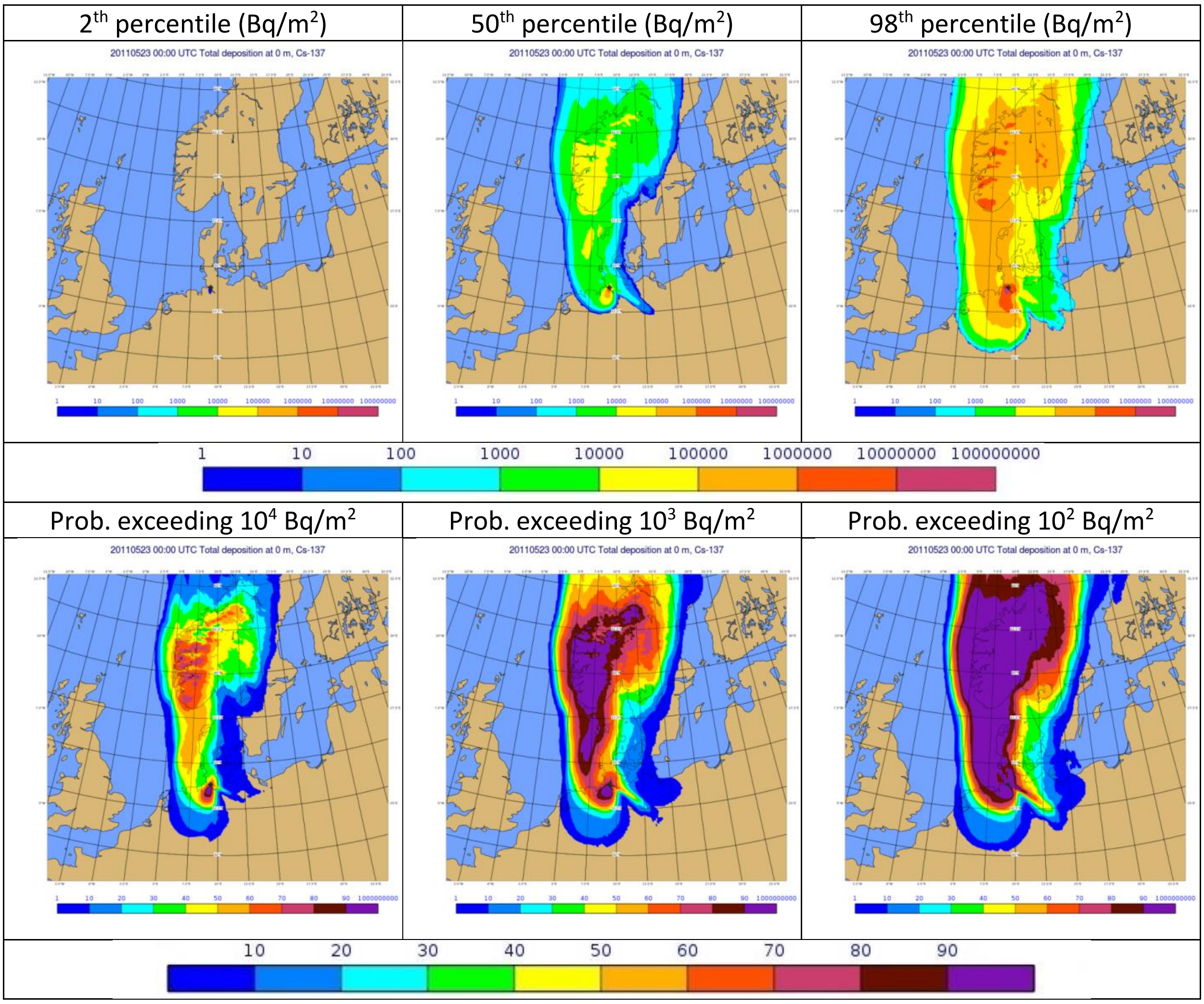


Figure 18 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 and probabilities (%) for exceeding given threhold values for the ***By-pass*** generic BWR source-term ensemble. Release start (SCRAM) at 2011-05-20 18:00 UTC.

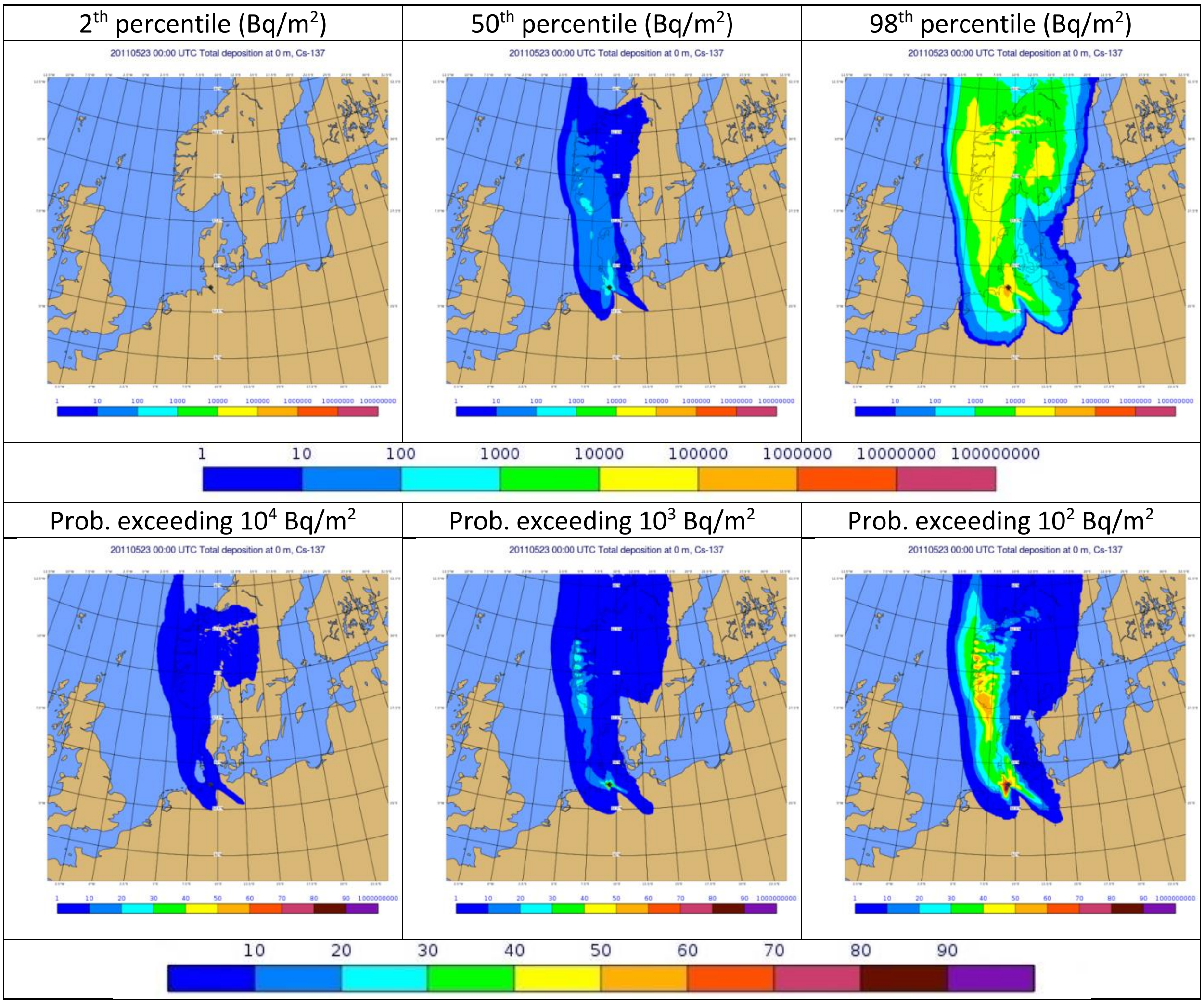
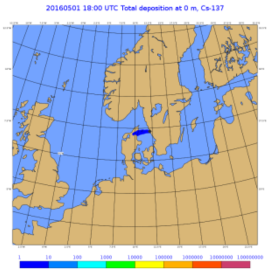
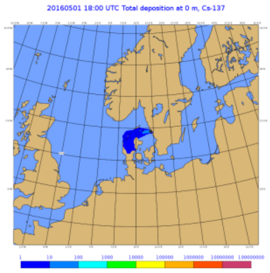
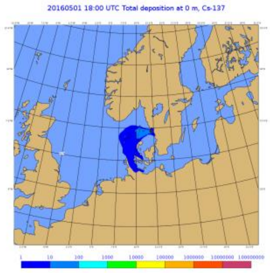
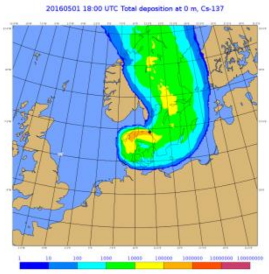
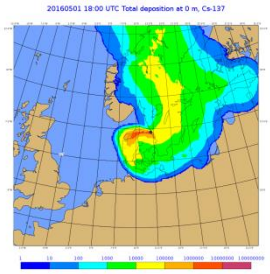
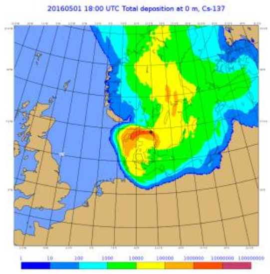
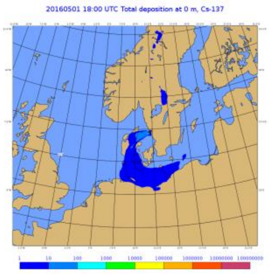
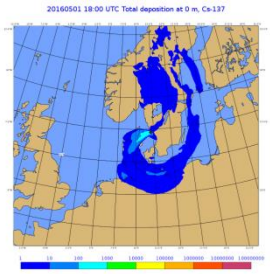
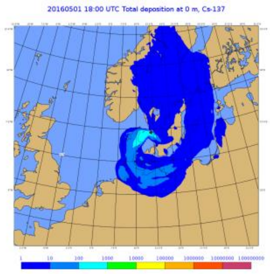
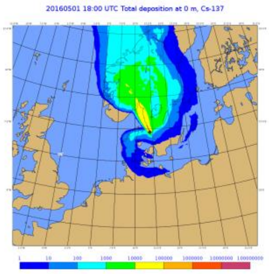
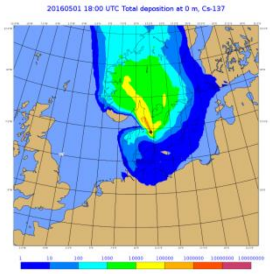
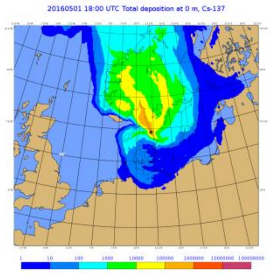
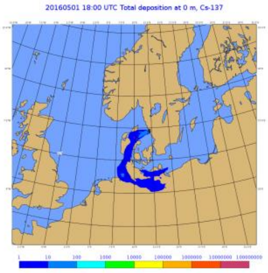
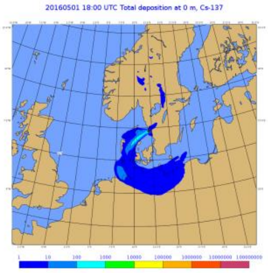
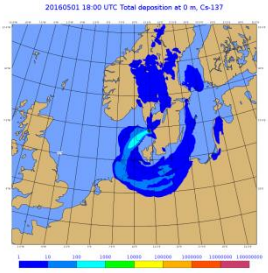
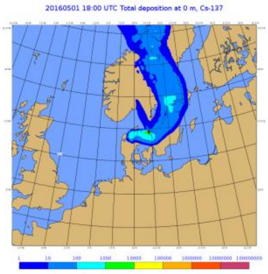
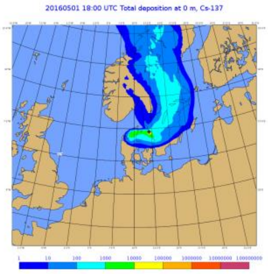
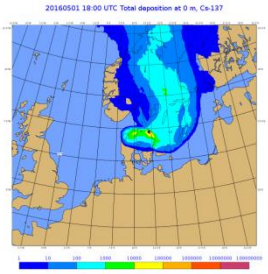
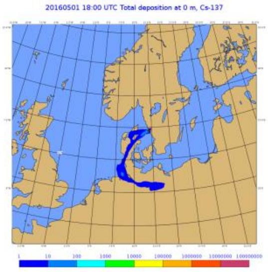
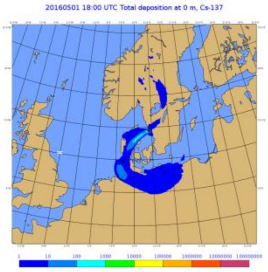
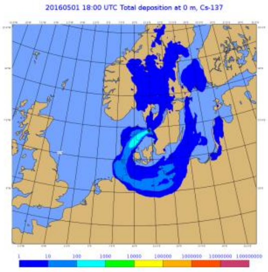
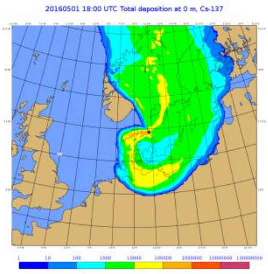
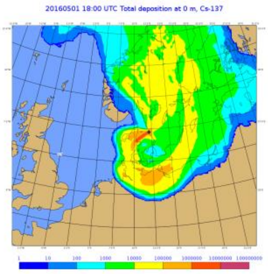
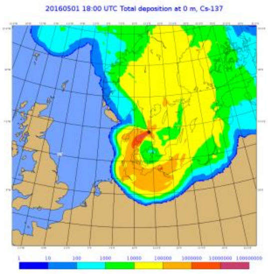
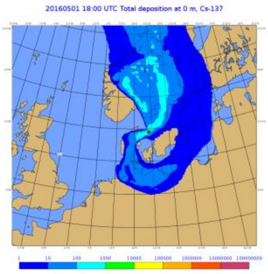
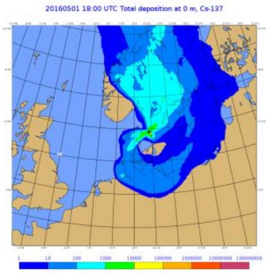
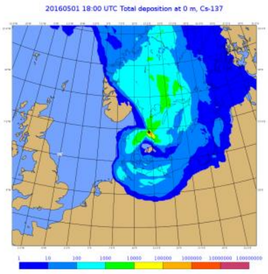
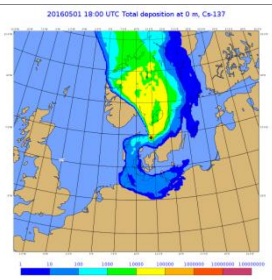
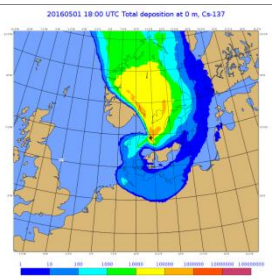
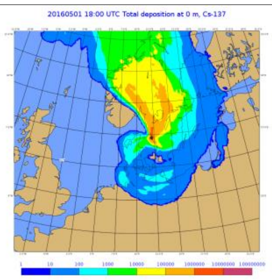


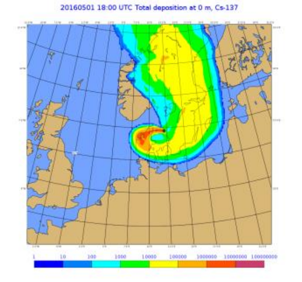
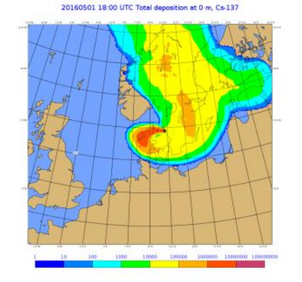
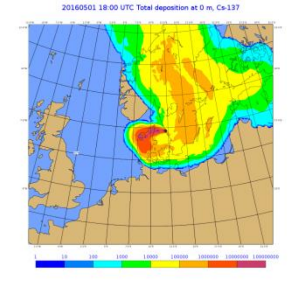
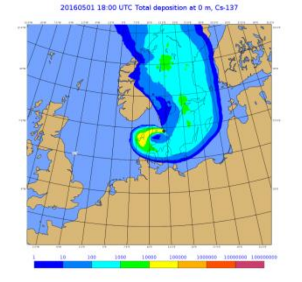
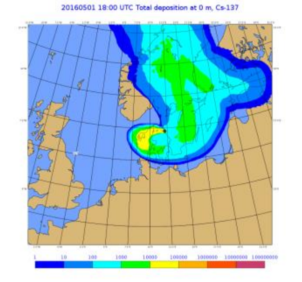
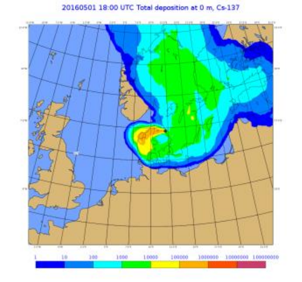
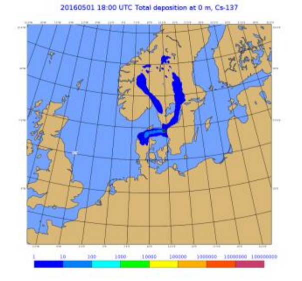
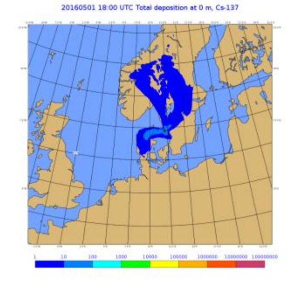
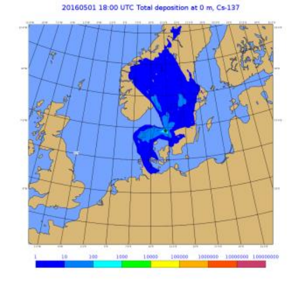
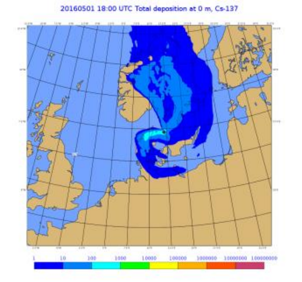
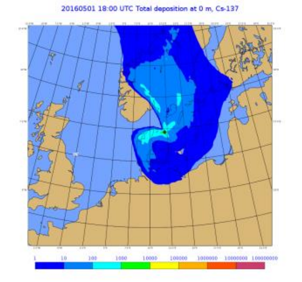
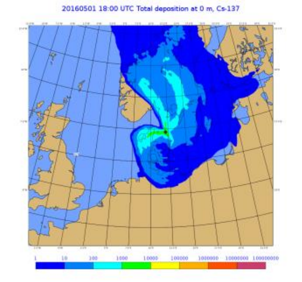
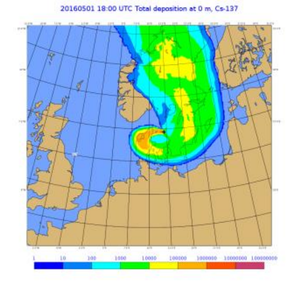
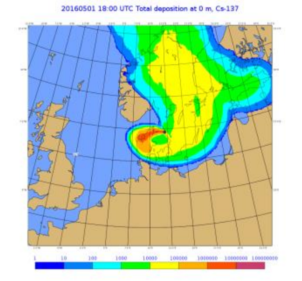
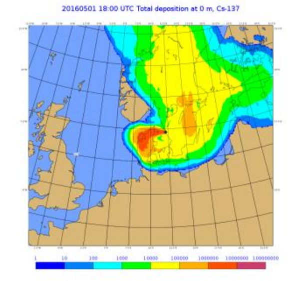
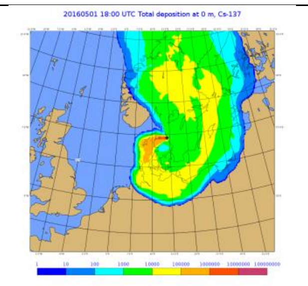
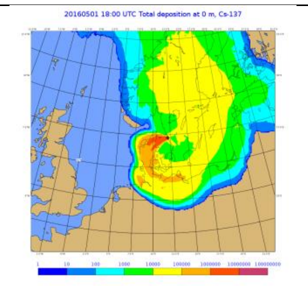
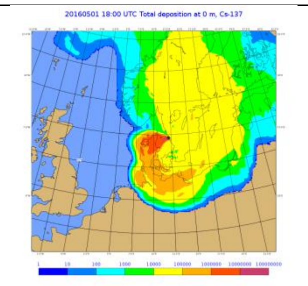
Figure 19 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 and probabilities (%) for exceeding given threhold values for the ***Ambivalent*** generic BWR source-term ensemble. Release start (SCRAM) at 2011-05-20 18:00 UTC.

Ringhals NPP for the 27 April 2016 meteorological case

Figure 20 below depicts the percentiles of accumulated deposition of Cs-137 for each member of the generic BWR source-term ensemble. Thus, the statistics is here purely meteorological. The calculations are based on 54 hour forecasted NWP model data from the analysed state dated 2016-04-27, 12 UTC. As can be seen in the horizontal, the case-dependent meteorological uncertainty is at the same levels as is seen in the MUD, FAUNA and MESO projects (Sørensen *et al.*, 2014, 2016, 2017). However, in the vertical, the differences between the source-term members are in general much larger.

Source Term	10th percentile	50th percentile	90th percentile	A priori prob.
OTES				0.0271%
OTI				0.0074%
OTLS				0.0775%
OTL				0.0127%

F-ES				8.9338%
F-E				6.8910%
OLES				0.0521%
OLI				0.4911%
OLLS				0.0077%
OLL				0.0001%

BYP				0.0423%
BYP-GAP-RH				0.0463%
GAP				1.8334%
L-X				81.4042%
BYP-RH-F				0.0000%
BYP-RH				0.0463%

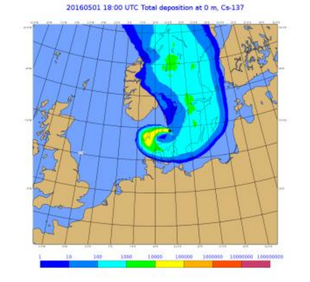
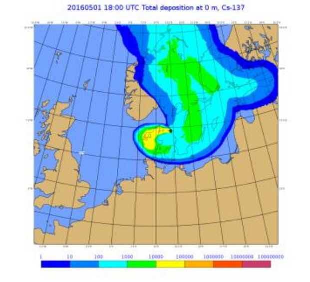
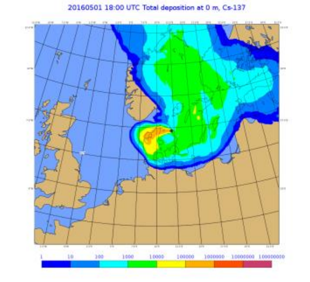
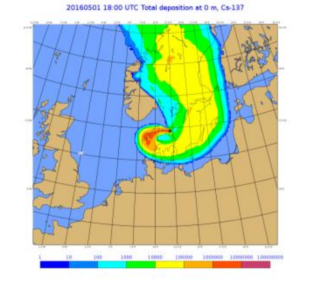
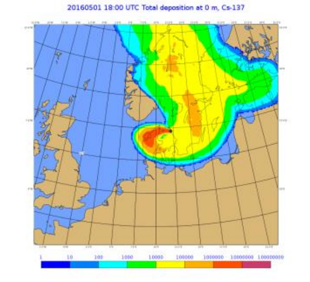
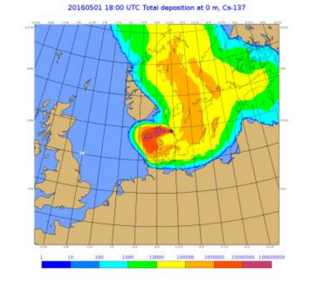
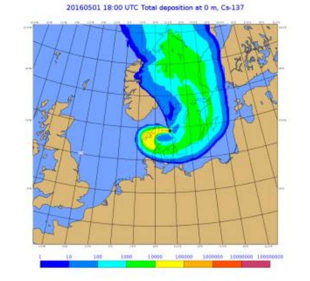
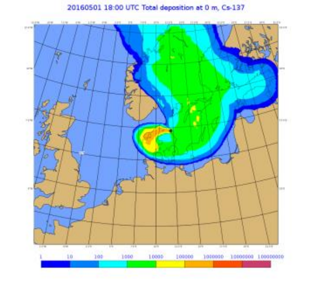
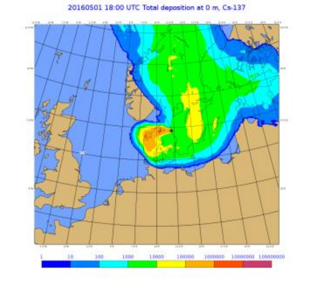
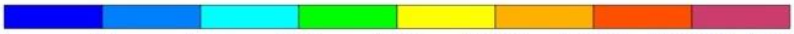
BYP-GAP-RH-F				0.0000%
BYP-TH				0.0423%
BYP-GAP				0.0847%
	 1 10 100 1000 10000 100000 1000000 10000000 100000000			

Figure 20 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 for the individual source terms of the generic BWR source-term ensemble. Release start (SCRAM) at 2016-04-27 12:00 UTC.

In Figure 21 are shown percentiles of accumulated deposition of Cs-137 and probabilities for exceeding given threshold values for the entire generic BWR source-term ensemble. This ensemble encompasses more or less all possible releases, and thus there is an enormous difference between a low and a large quantile. Further, it is important to recall that due to the use of weighted ensemble statistics, the severe cases have been suppressed by the weighting factors, the a-priori probabilities. If the ensemble statistical results, e.g. the percentile plots, will be used to assist in estimating risk zones aiming at worst-case scenarios, one should rather use a limited source-term ensemble including the severe scenarios only.

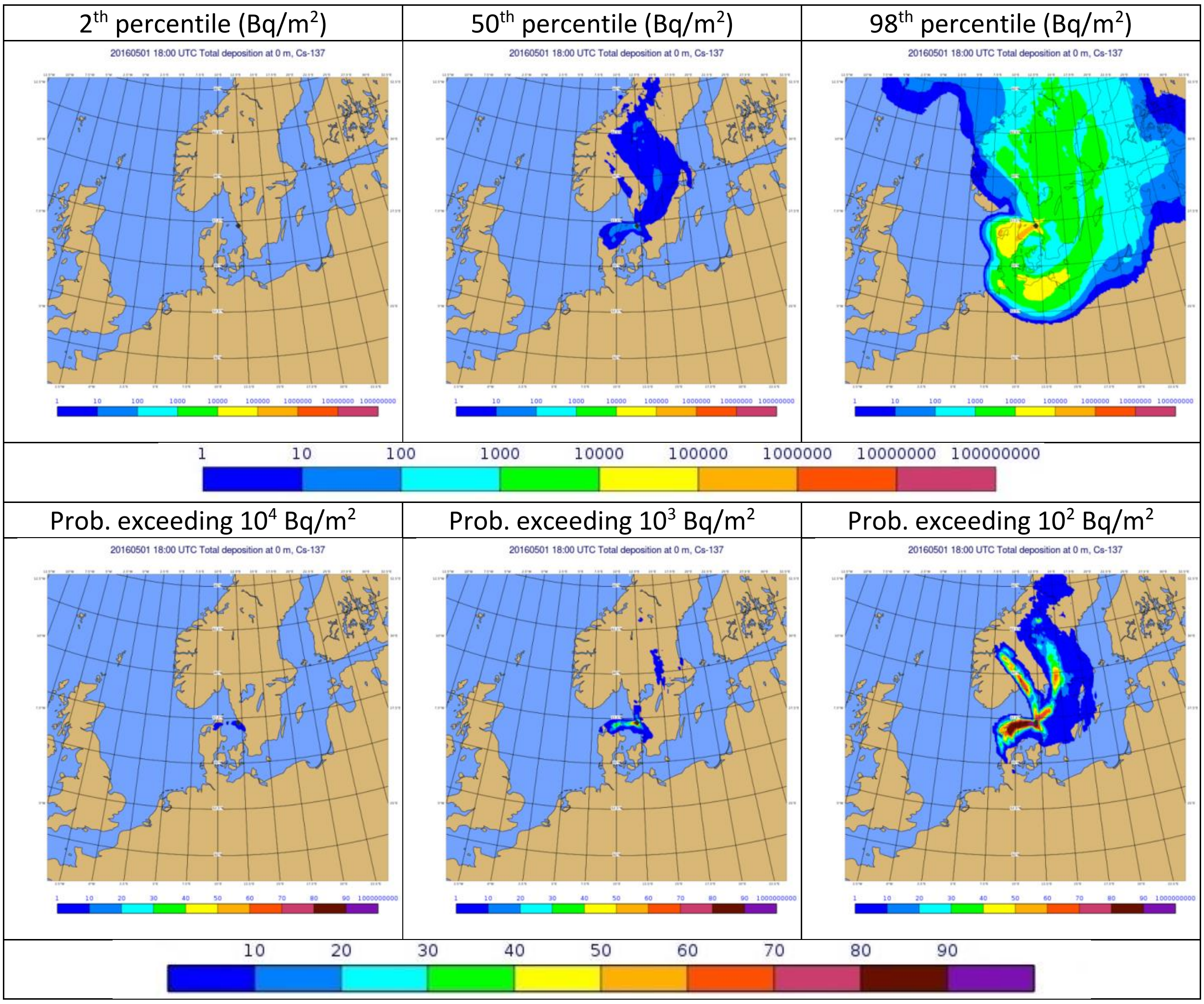


Figure 21 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 and probabilities (%) for exceeding given threhold values for the ***Entire*** generic BWR source-term ensemble. Release start (SCRAM) at 2016-04-27 12:00 UTC.

For practical emergency preparedness, it may be preferable instead to take a scenario-based approach using selected scenarios, e.g. the mitigation, the no-mitigation, the containment, the by-pass and the ambivalent scenarios as described above in Section "Source Term Ensembles Employed". In this case, the weighting factors should be re-normalized for each of these sub-ensembles, which implies that the sub-ensembles cannot be directly compared regarding absolute magnitudes.

In Figure 22–Figure 26 are shown percentiles of accumulated deposition of Cs-137 and probabilities for exceeding given threshold values for the the mitigation, no-mitigation, containment, by-pass and ambivalent scenarios.

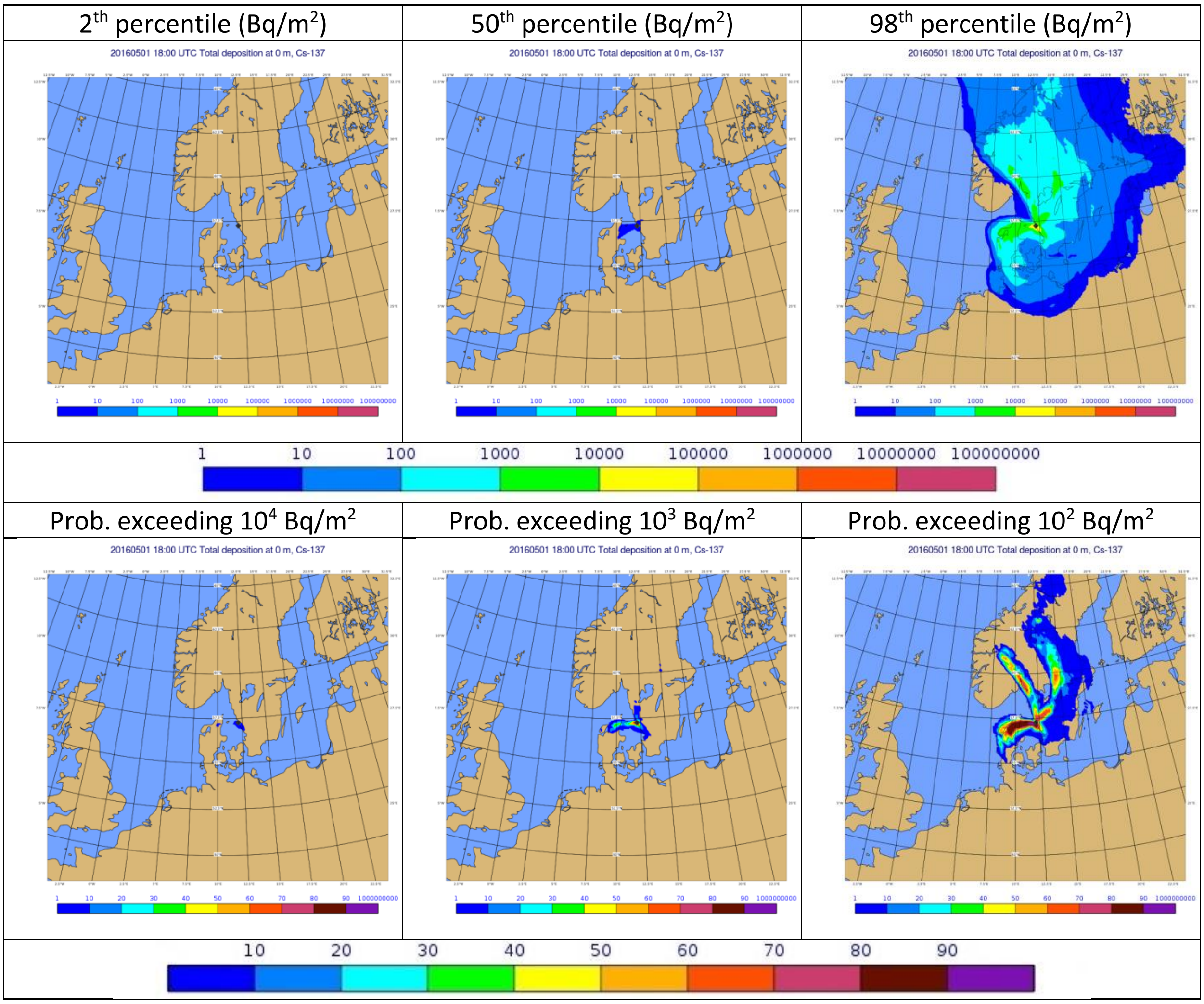


Figure 22 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 and probabilities (%) for exceeding given threhold values for the ***Mitigation*** generic BWR source-term ensemble. Release start (SCRAM) at 2016-04-27 12:00 UTC.

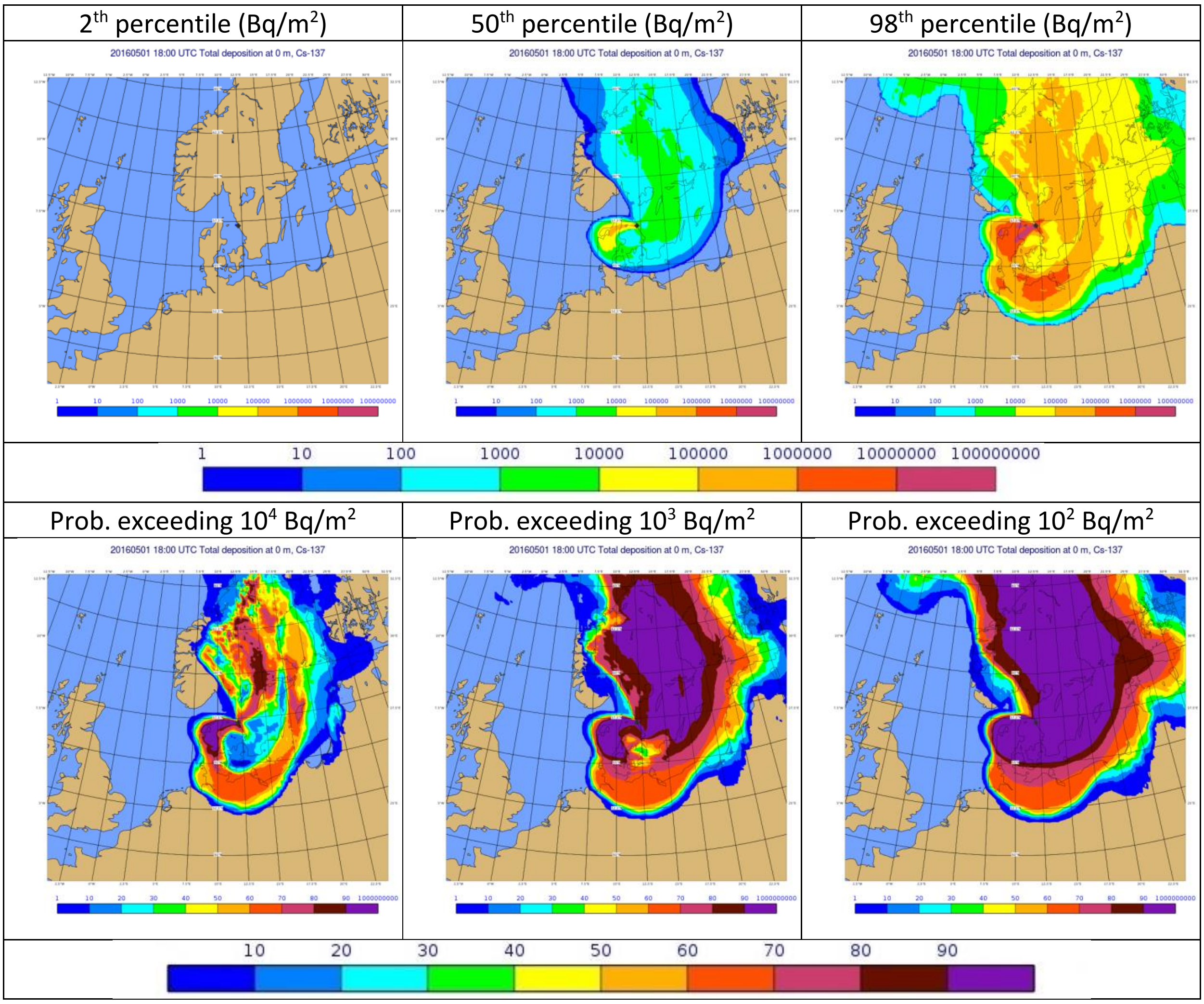


Figure 23 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 and probabilities (%) for exceeding given threhold values for the ***No-mitigation*** generic BWR source-term ensemble. Release start (SCRAM) at 2016-04-27 12:00 UTC.

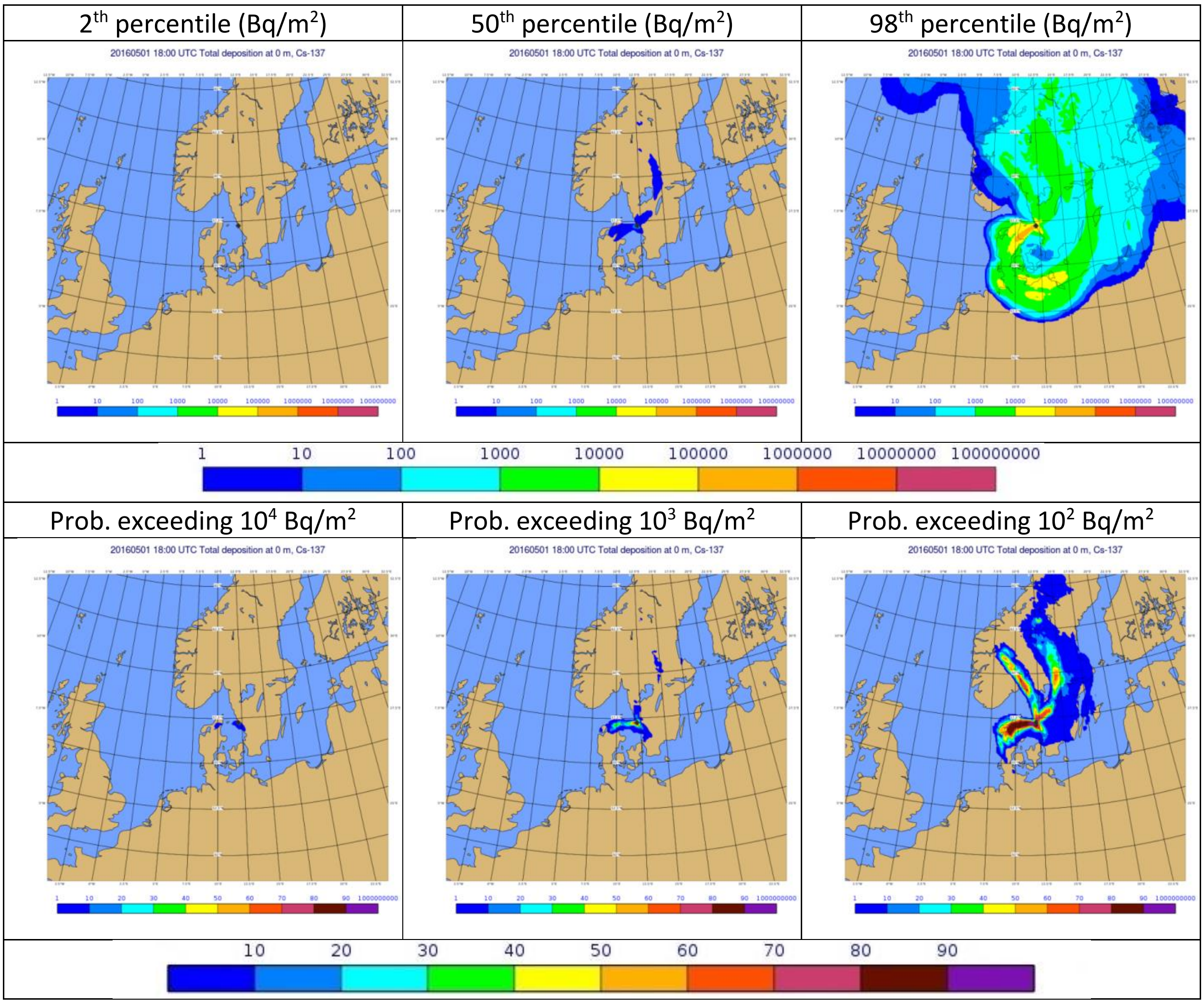


Figure 24 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 and probabilities (%) for exceeding given threhold values for the ***Containment*** generic BWR source-term ensemble. Release start (SCRAM) at 2016-04-27 12:00 UTC.

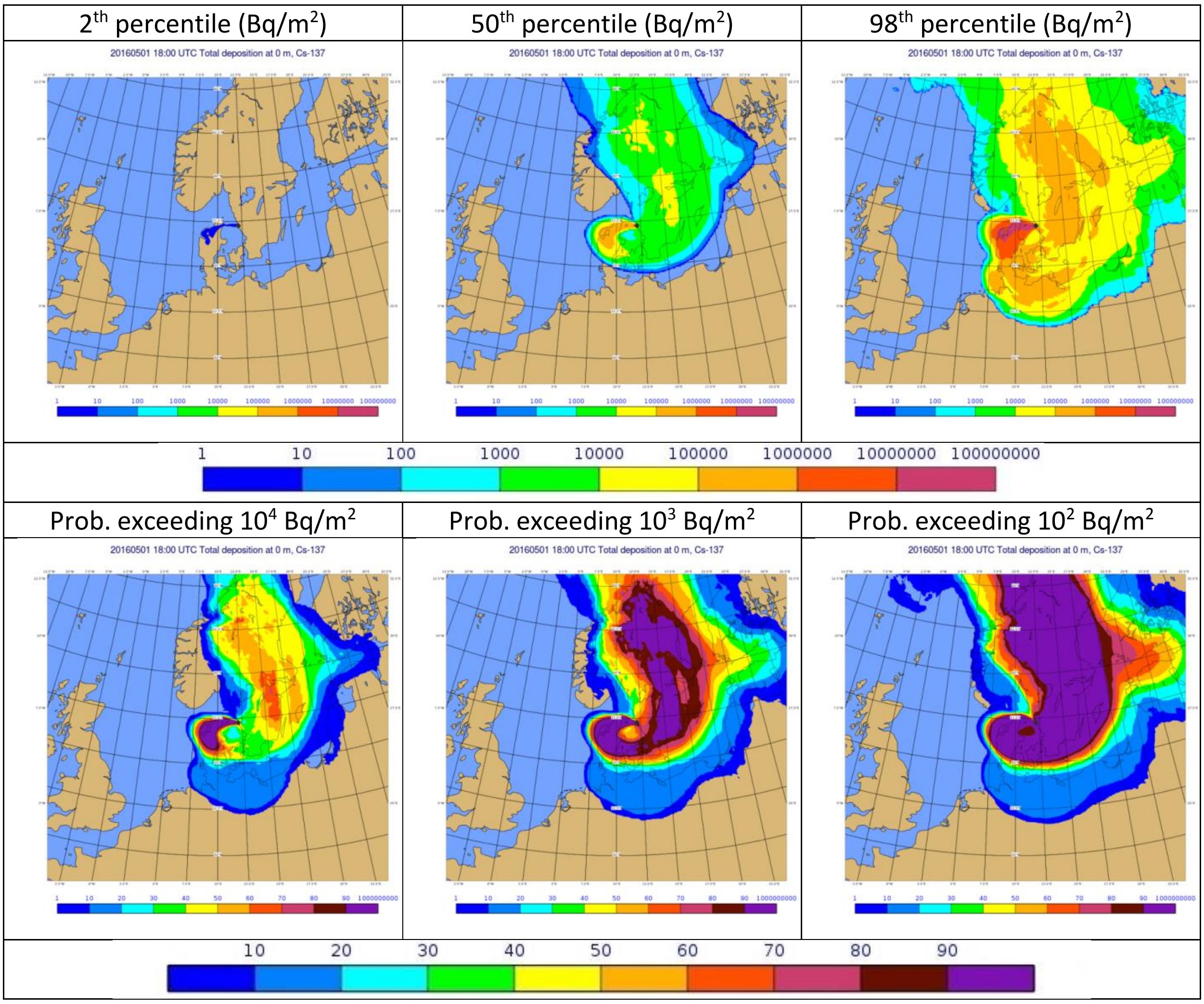


Figure 25 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 and probabilities (%) for exceeding given threhold values for the ***By-pass*** generic BWR source-term ensemble. Release start (SCRAM) at 2016-04-27 12:00 UTC.

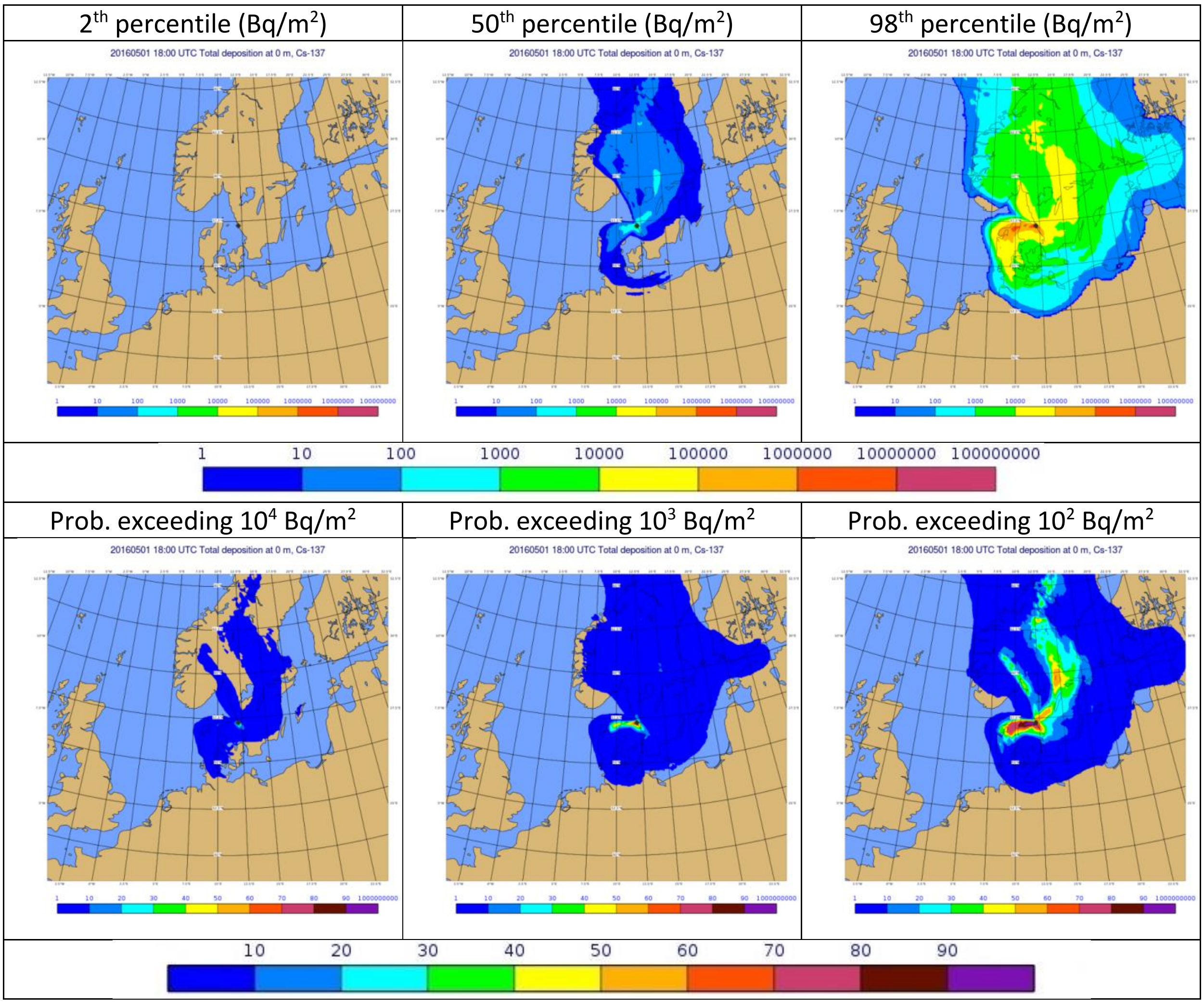


Figure 26 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 and probabilities (%) for exceeding given threhold values for the ***Ambivalent*** generic BWR source-term ensemble. Release start (SCRAM) at 2016-04-27 12:00 UTC.

Selection of percentile values

In many application areas, risk is measured by a p-quantile, with p close to 0 or 1. In safety analyses of NPPs for instance, the U.S. Nuclear Regulatory Commission requires that for an event such as LOCA, the 0.95-quantile of the peak cladding temperature must lie below a given threshold. The stratified sampling technique employed guarantees that also scenarios with small probabilities, but severe consequences, are sampled (Bedford and Cooke, 2016; Nakayama, 2016).

For nuclear emergency preparedness, we recommend using a large and a low percentile of accumulated radionuclide deposition fields and human doses in support of the estimation of risk zones. The reason for not using the absolute minimum and maximum is that these quantities are often influenced by a few outliers. A low and a high percentile, e.g. 5% and 95%, are more robust parameters, and thus appropriate, for decision making.

From a statistical point of view, a meteorological ensemble of around 25 members, and a source-term ensemble of, say, 20 members is fairly small, and the percent value should be balanced against the number of ensemble members. On may select e.g. 10% and 90% for a meteorological ensemble. However, for the much larger combined ensemble of around 500 members, the use of e.g. 2% and 98% is enabled. Due to the large variability between the source-term members, the percentiles are very sensitive to the actual percent value employed. For the above Brokdorf NPP release scenario involving the 475 member combined ensemble, this sensitivity can be seen in Figure 27.

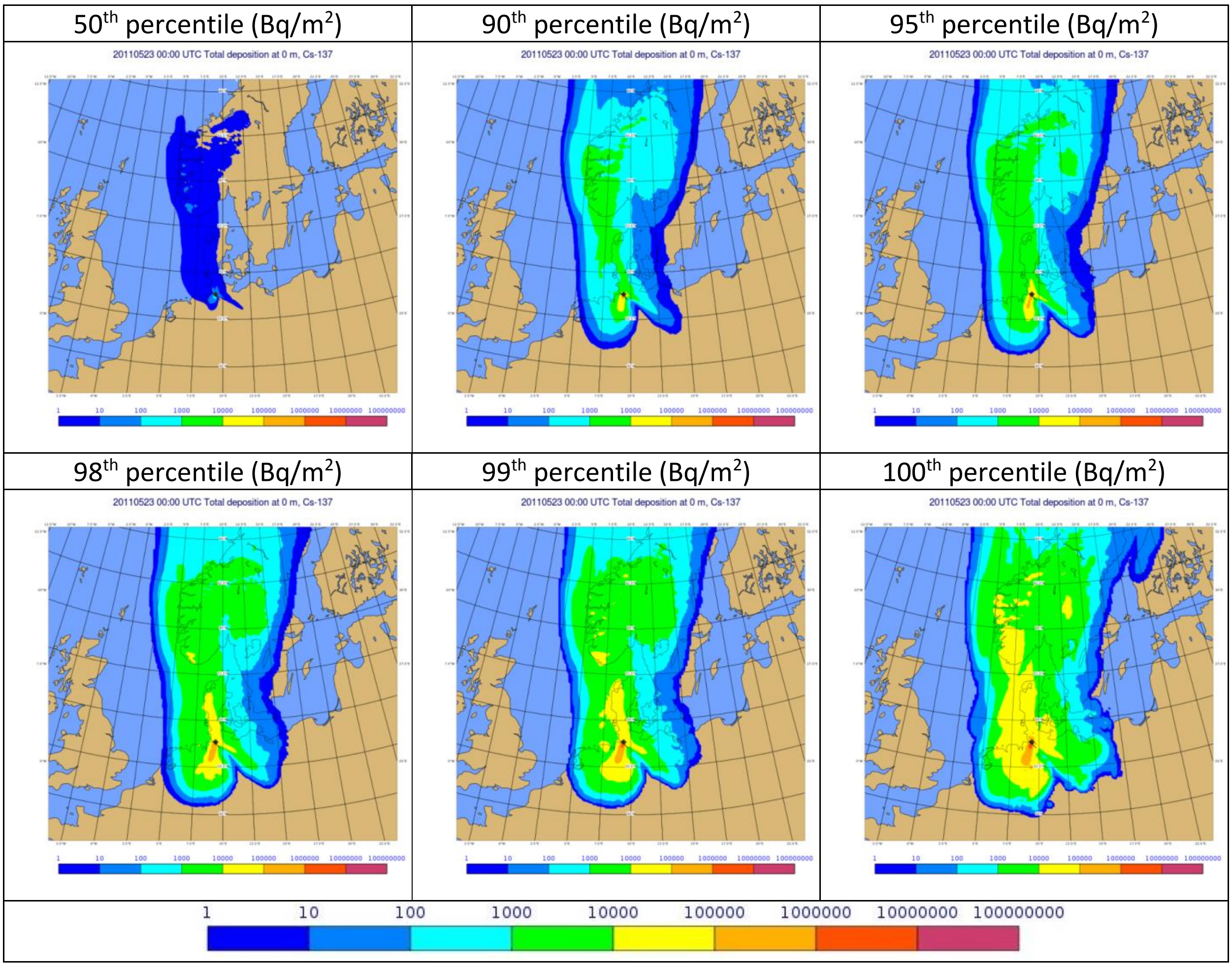


Figure 27 Percentiles of accumulated deposition (Bq/m^2) of Cs-137 for the ***Entire*** generic BWR source-term ensemble. Release start (SCRAM) at 2011-05-20 18:00 UTC.

ARGOS and Ensemble Results

The Long Range dispersion model interface in ARGOS is now capable of providing an ensemble of source terms – a list of possible release descriptions for the same accident type – and to handle multiple results from a single Long Range (LR) request, including a set of statistical results from a so-called ‘Ensemble’ run.

This new feature is implemented in collaboration with the Danish Meteorological Institute (DMI) on whose HPC facility a single model run request from ARGOS in parallel produces a number of deterministic results (each in its own file) and a number of statistical results (all in the same file) – all based on the same input request but with differing source terms – from the ensemble of source terms – and with different versions of NWP model data. Statistical results will be available for the ensemble of NWP model data for each source term and for the total of all source terms and all NWP model data.

Source terms in ARGOS

In ARGOS, a single source term is defined as time-dependent release rates of individual radioactive nuclides combined with additional information on release height, heat flux, iodine distribution and distribution of particle sizes. In Figure 28 is shown an example.

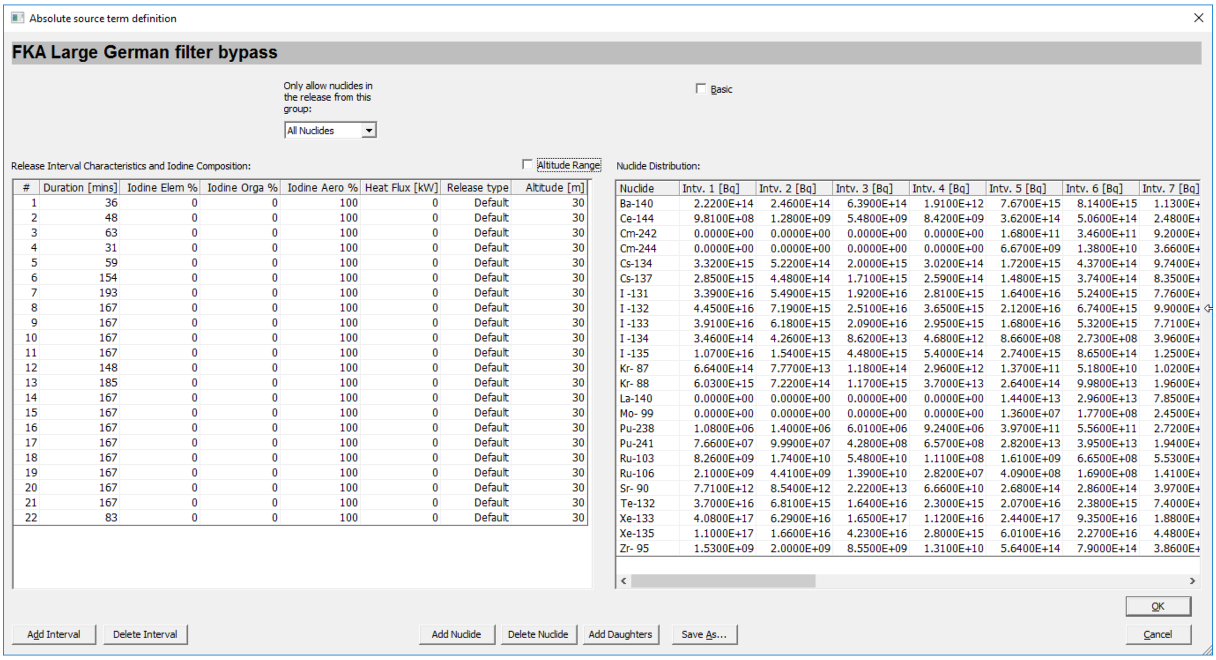


Figure 28 A typical source term in ARGOS.

Now a number of source terms can be combined into an Ensemble of source terms in ARGOS – including their relative probability or weighting factor, cf. Figure 29.

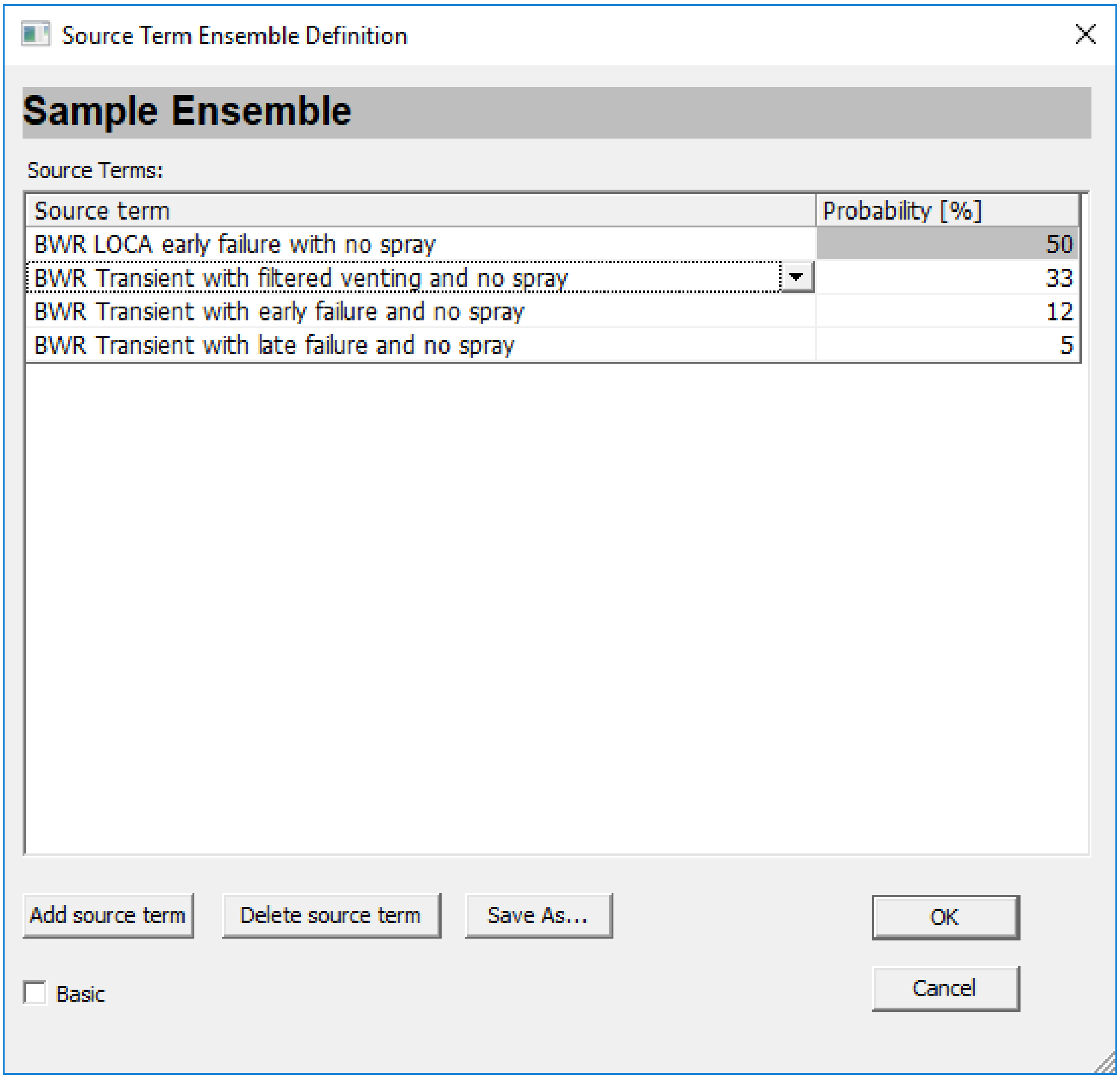


Figure 29 An ensemble of source terms and their probability in ARGOS.

LR request from ARGOS

The Request dialog in ARGOS has been changed in order to provide not only a single source term but rather an ensemble of source terms, cf. Figure 30. When an ensemble of source terms is selected, ARGOS will send a file per source term to the server. The DMI server then simply starts, in parallel, a series of model runs based on the different input information provided in the different request-files.

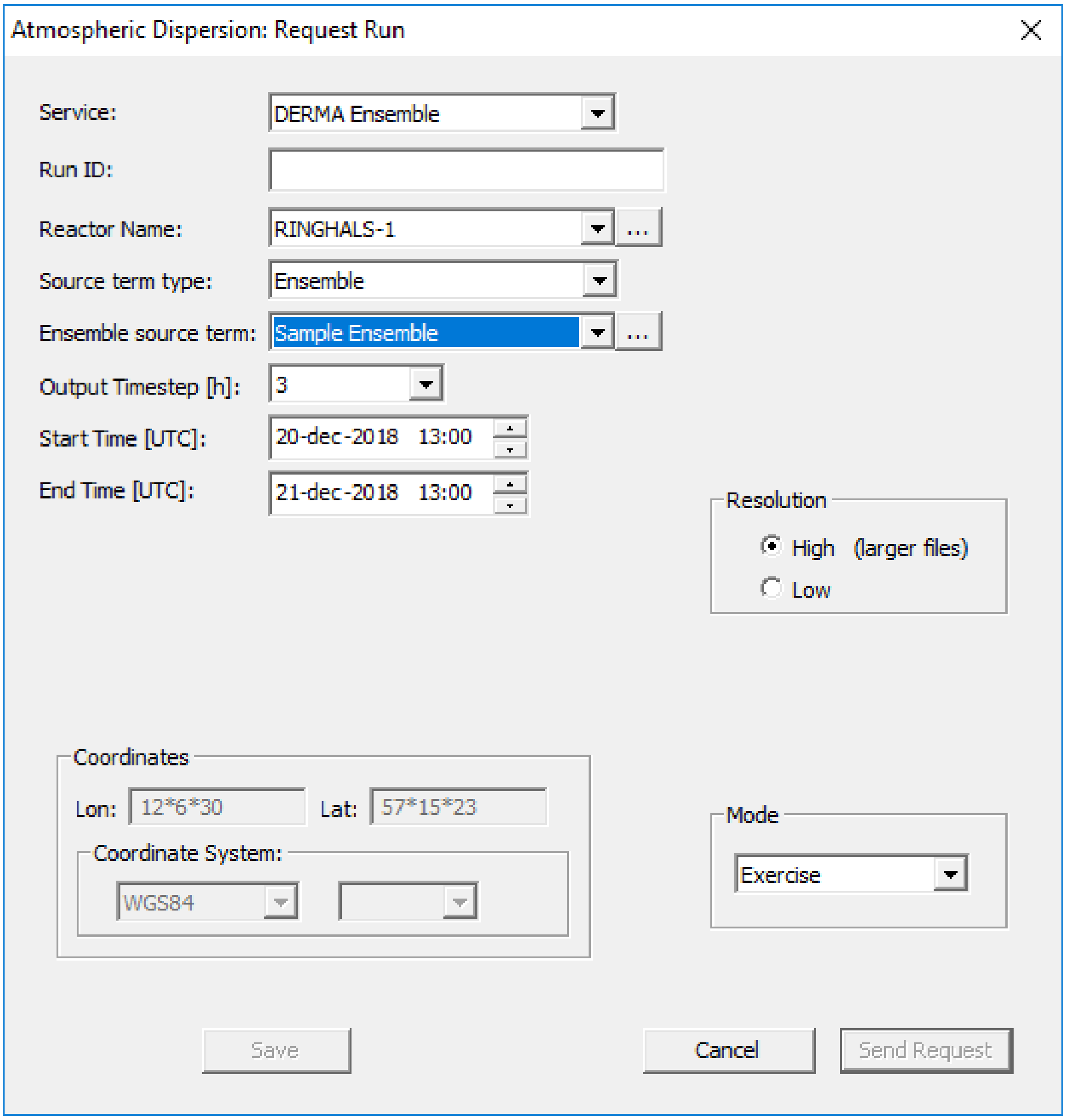


Figure 30 The updated request dialog in ARGOS.

A special result (Versions-xml) file, called <runid>_"Versions.xml", gives information on all the generated results, as these are being started. This Versions-xml file is then downloaded and used in ARGOS to monitor the progress on each version of result data (each 'run version').

Monitoring (for Version file)

When starting a request, a dialog window is displayed that lists the various version results being produced and their run state, see Figure 31.

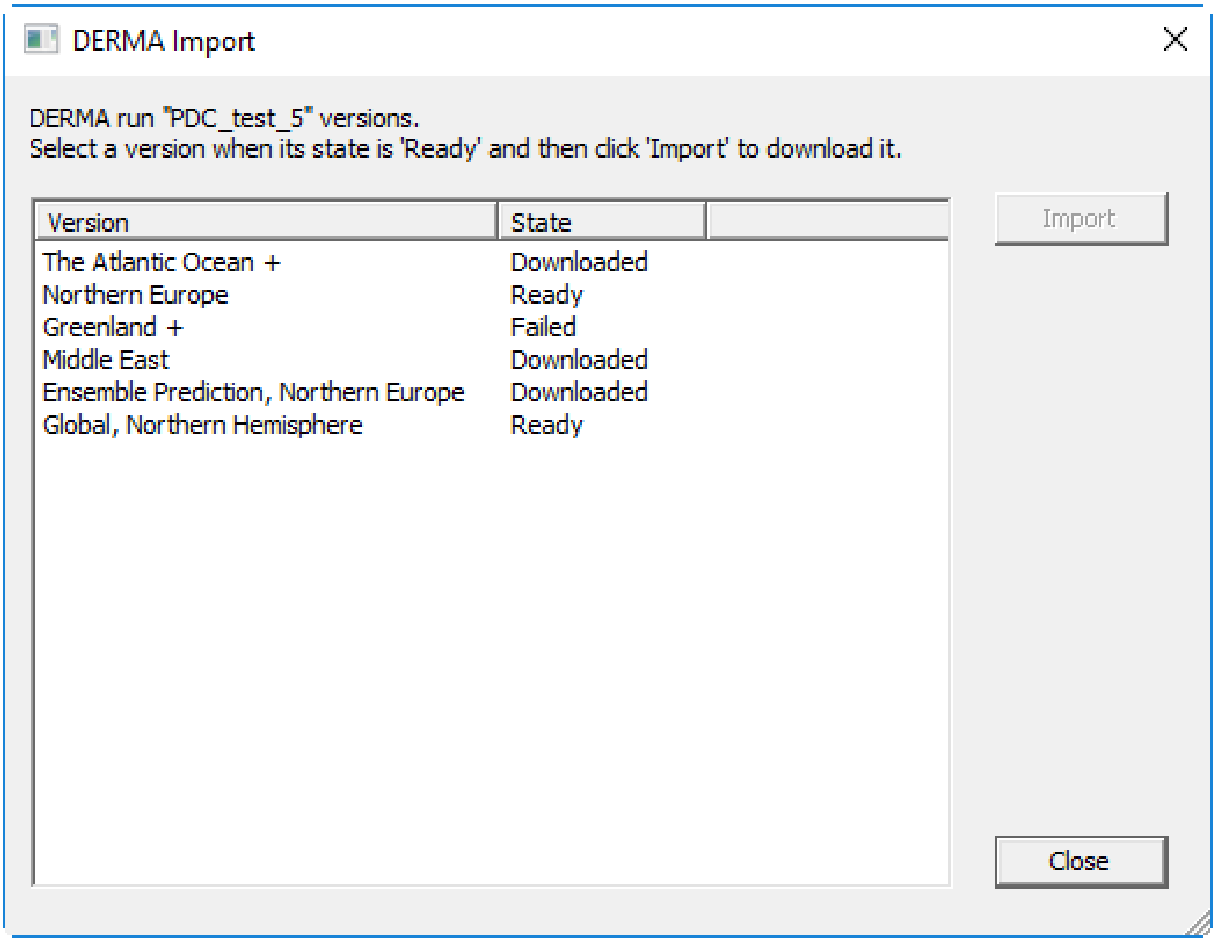


Figure 31 LR monitor.

The ‘State’ for a run version can be either “Not ready”, “Running”, “Ready”, “Failed” or “Downloaded”. The state for a run version is read from the version’s status file by ARGOS after downloading the corresponding status file. The server produces one separate status file per run version.

The user can select a version that has become “Ready” and then click the “Import”-button, which will then open the Import-dialog. Clicking “Import” on this dialog will make ARGOS start downloading the result-file for the selected version.

LR Selection Tree

Once the result for a version has been downloaded, it will be visible in the LR-tree in ARGOS (Figure 32).

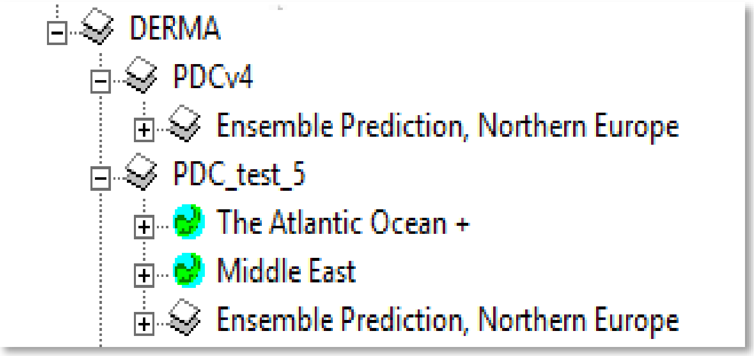


Figure 32 Results in the LR tree.

A new level of tree nodes (below the Run ID) is introduced for LR-results that use a Versions-xml file. This is necessary to separate the results from different versions.
For the statistical results (except Probabilities), all the usual dose calculations are being performed by ARGOS, when the tree-node is being expanded the first time – as these calculations cannot be seen as dose calculations as such from a scientific point of view, they have a special prefix on the presentation of the unit for statistical plots, e.g. “Percentile (Sv)” or “Average (Bq/m^2)”, see Figure 33.

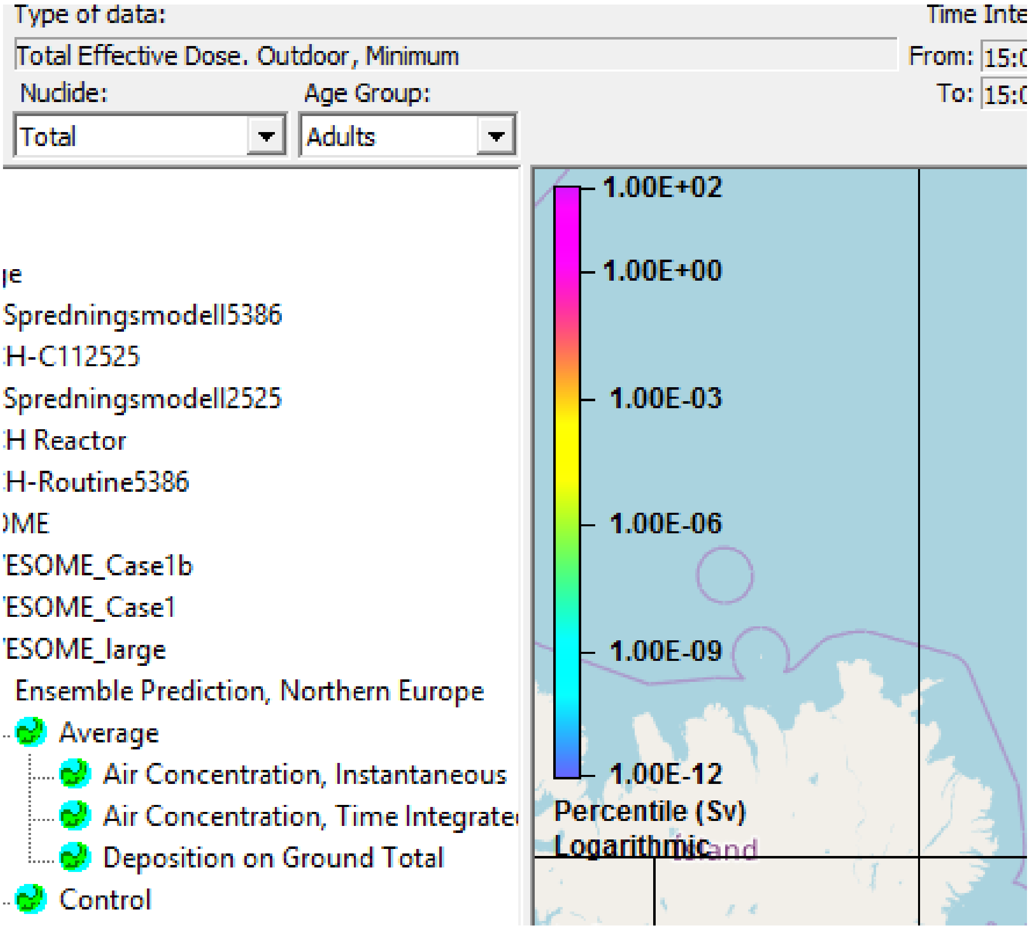


Figure 33 Prefix on the presentation of unit for a percentile plot.

As can be seen in Figure 34 below, all the dose calculations performed on deterministic results are also performed on statistical results.

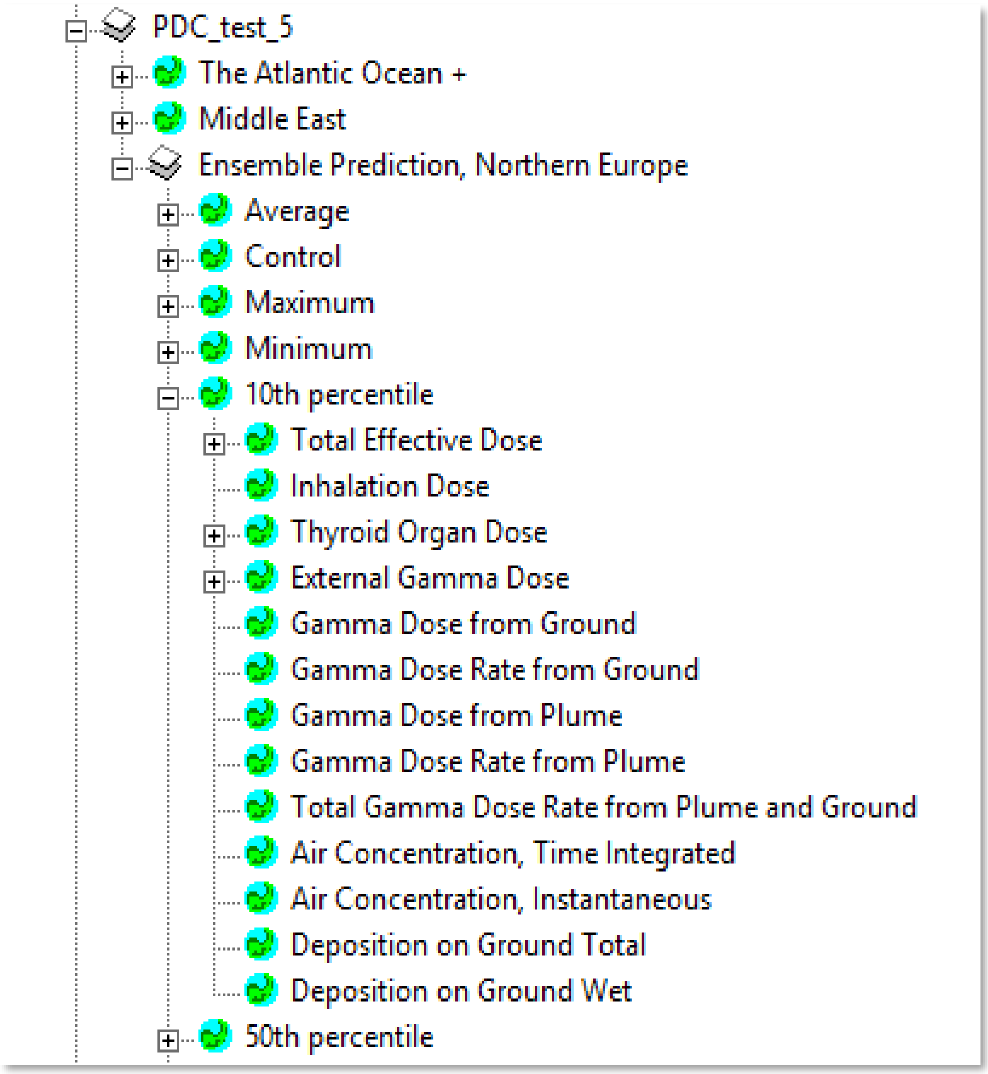


Figure 34 Statistical results with “Dose Calculations”.

In Figure 35 is shown an example of a plot in ARGOS comparing deposition on ground (Cs-137) for three different percentiles.

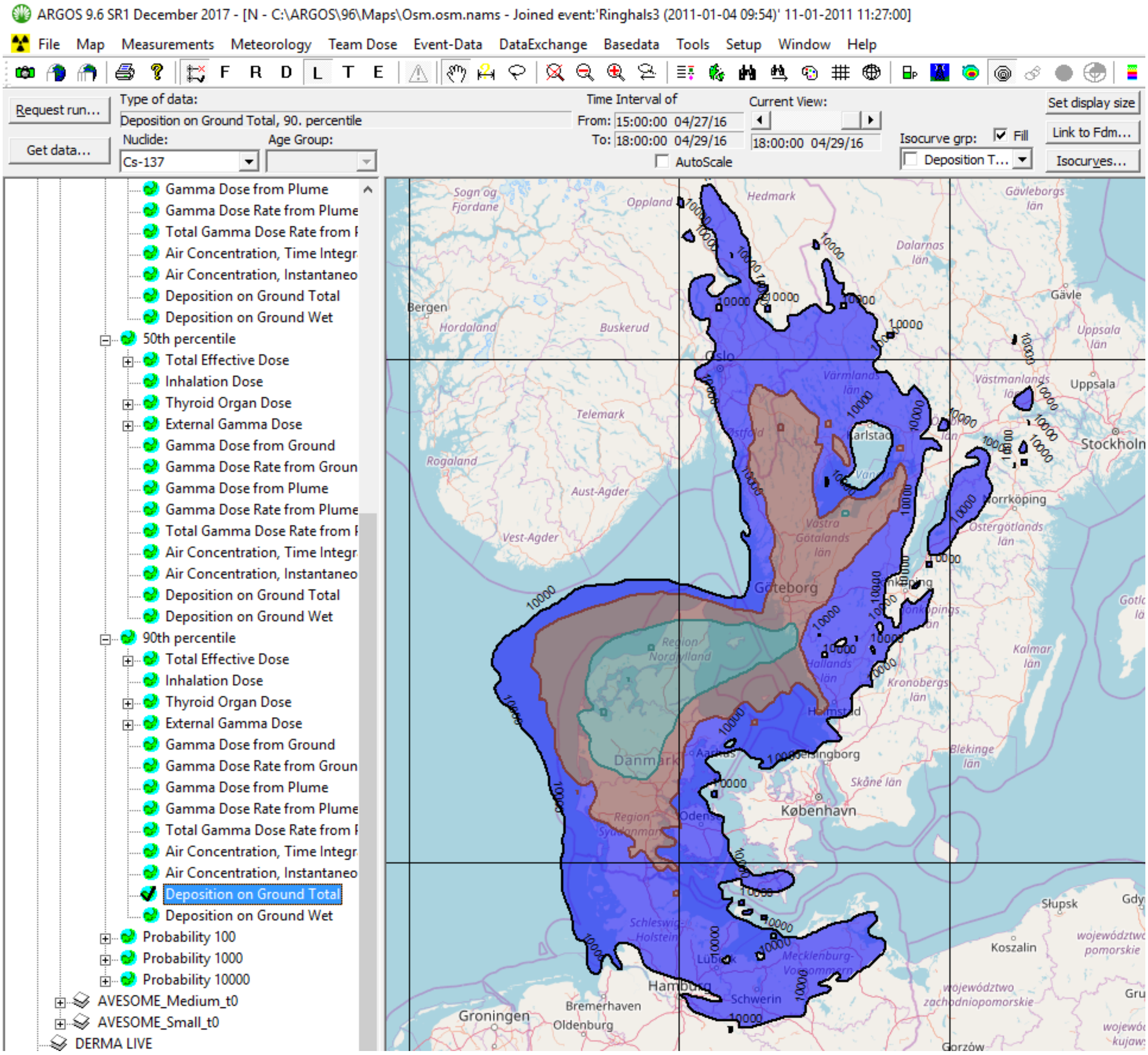


Figure 35 Comparison of 10^{th} (green), 50^{th} (brown) and 90^{th} (blue) percentile for 10 kBq/m^2 deposition of Cs-137 from a simulated release from Ringhals NPP.

In Figure 36 is shown an example of a plot in ARGOS showing three different intervention levels for Total Effective Dose on the Maximum percentile, and in Figure 37 for the Minimum percentile.

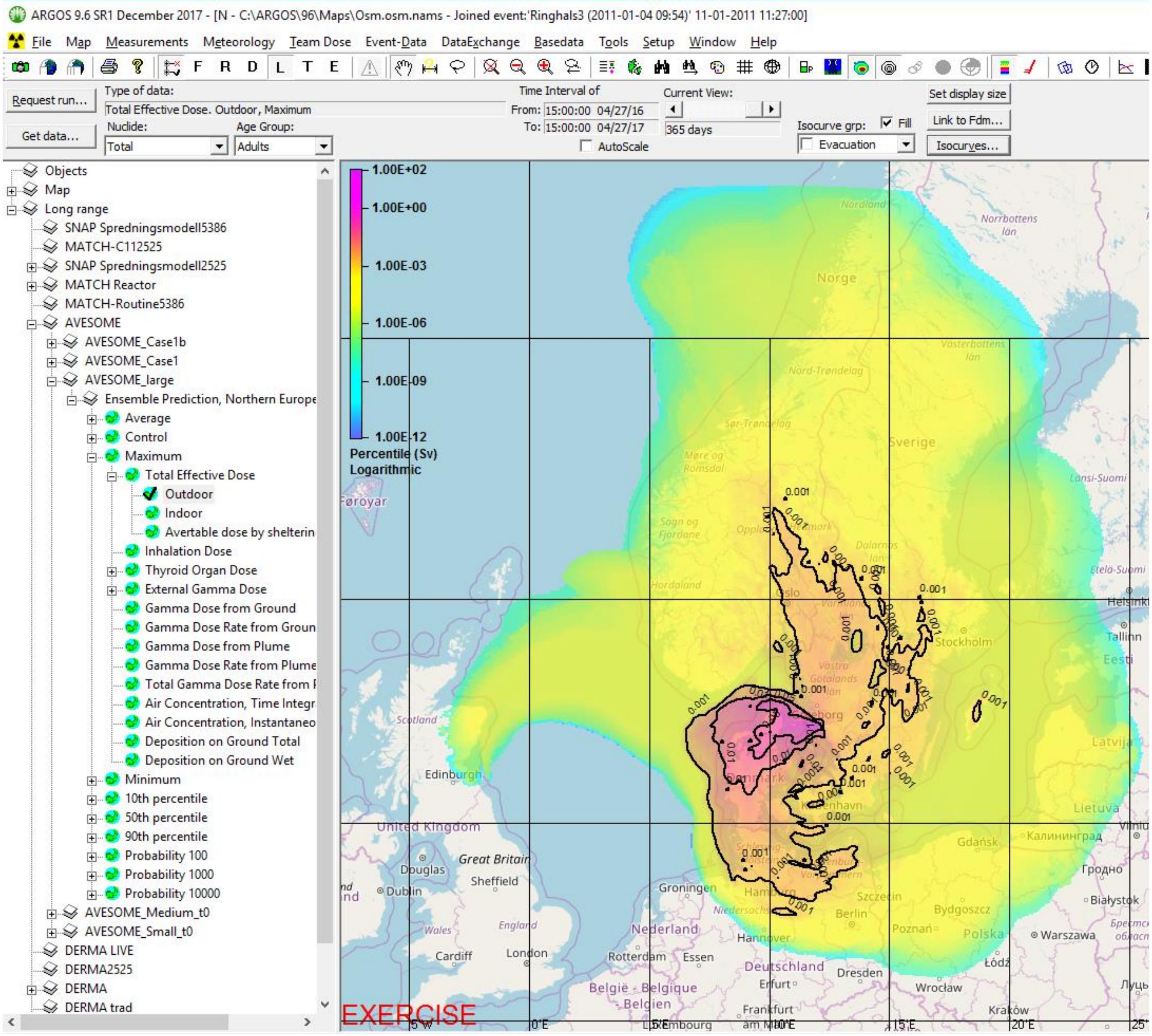


Figure 36 1, 10 and 50 mSv for the Maximum percentile (100%) of Total Effective Dose from a simulated release from Ringhals NPP.

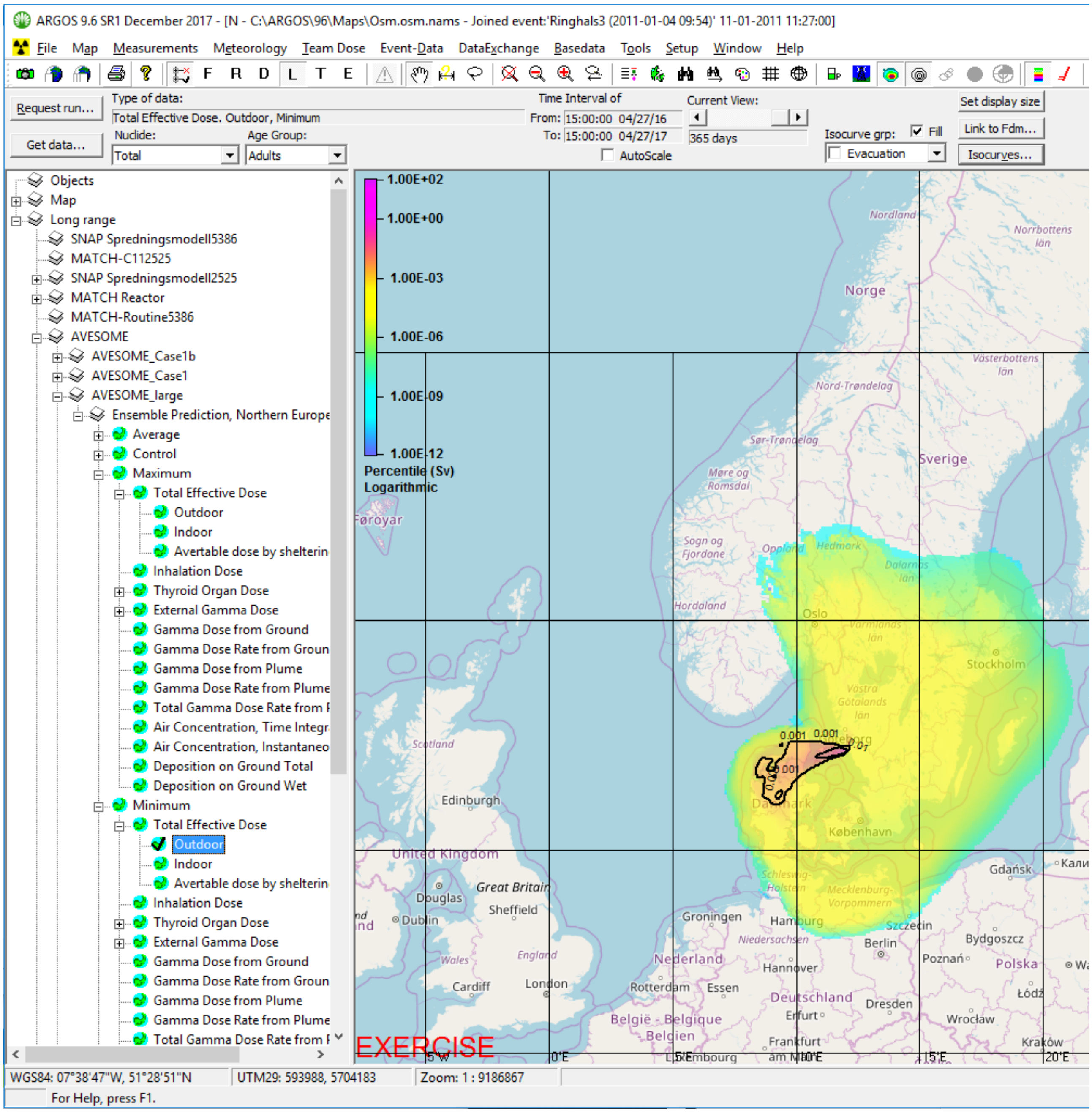


Figure 37 1 and 10 mSv (no values over 50) for the Minimum percentile (0%) of the same simulated release from Ringhals.

For Probability results, only the results delivered by the model are shown as it does not make sense to perform “dose calculations” on the probability results, see Figure 38.

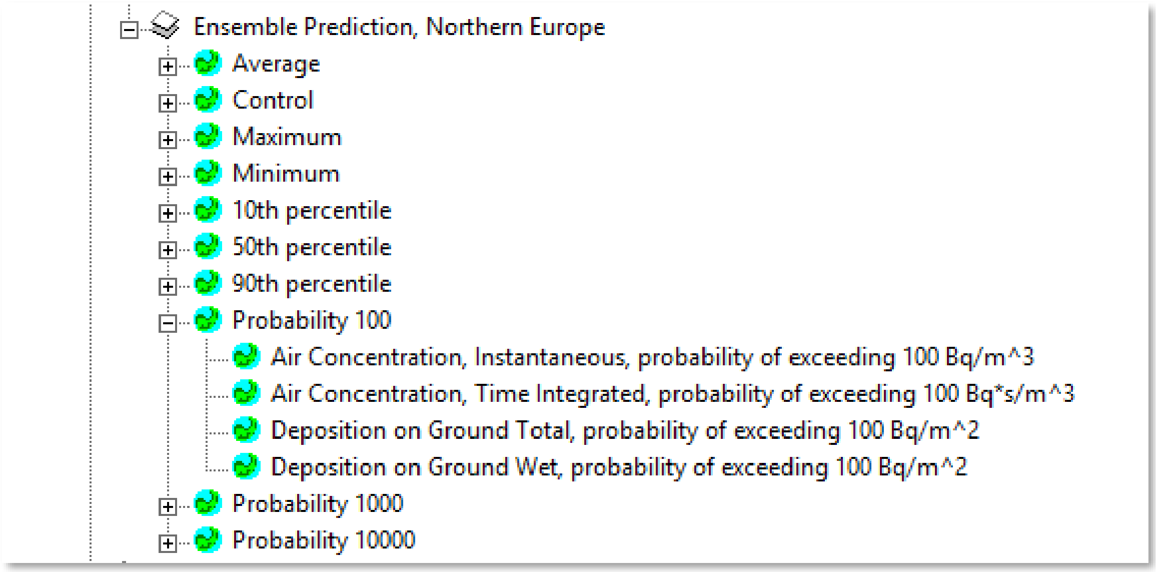


Figure 38 Statistical results with probabilities.

In Figure 39 is given an example of showing probability for exceeding 10 kBq/m^2 deposition of Cs-137.

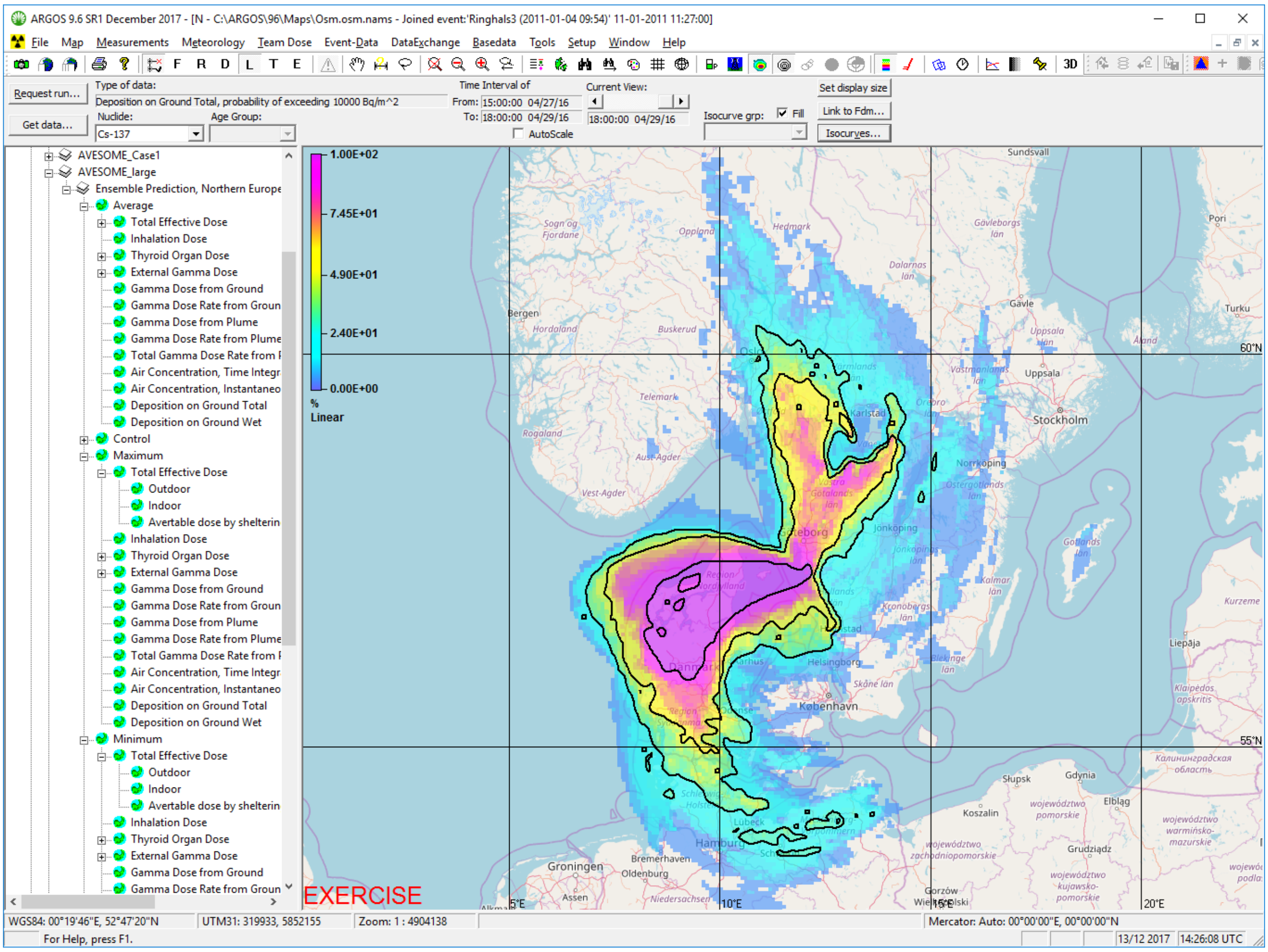


Figure 39 Probability of exceeding 10 kBq/m^2 deposition of Cs-137, lines for 100, 50 and 25% inserted.

Interface Changes between ARGOS and Long Range Model (DERMA)

Request-interface

For the final implementation of the AVESOME project in ARGOS, the request-interface has been updated in order to reflect the need for requesting calculations with ensembles of source terms. If an Ensemble-run (of source terms) is requested, ARGOS simply provides a zip-file containing a release description file per source term in the ensemble.

Result-interface

As mentioned earlier, the Result interface between ARGOS and DERMA was enhanced in order to cope with the extra level of results coming from the delivery of statistical results. For this purpose, a new file produced by the DERMA-model – the version-file - in XML-format has been introduced.

The Versions-xml file describes all the run versions on the server. This XML file has the Schema as described below in Figure 40.

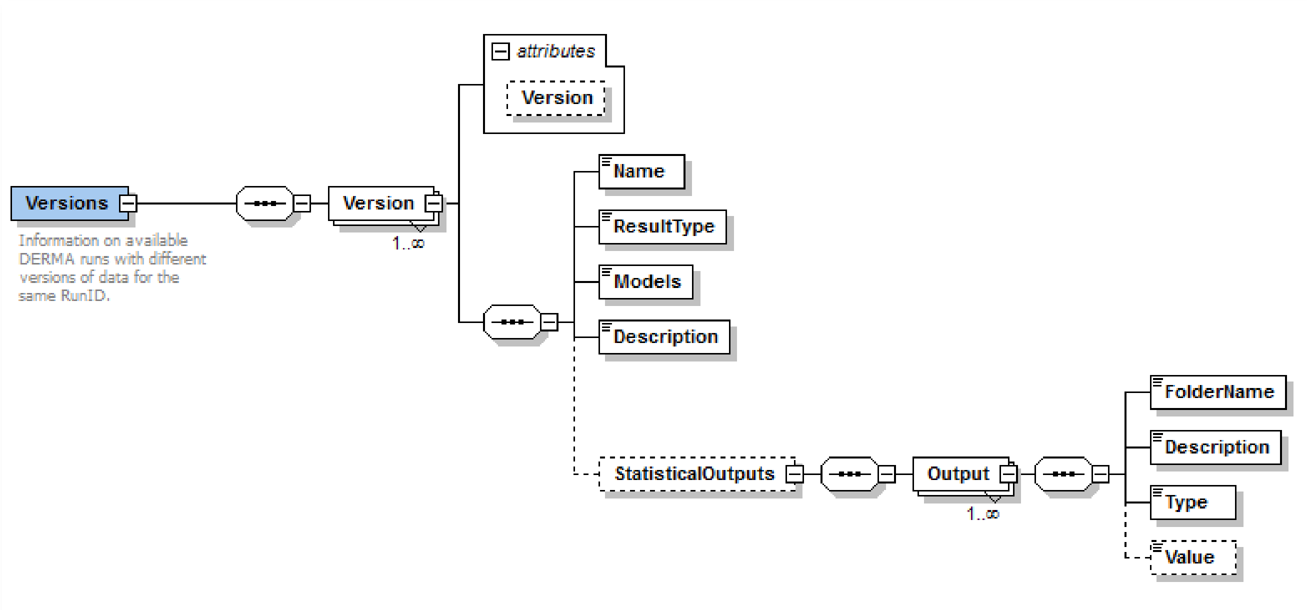


Figure 40 Versions-xml schema.

The two "Description" elements are used for the Monitoring dialog and the LR selection-tree.

The elements "Name" and "FolderName" are used to name subfolders below the Run ID folder.

The optional "Value" element shall be present for "Probability" outputs and contain the given probability. It shall also be present for "Percentile" output and contain the given percentile as a number.

The "ResultType" element shall be either "deterministic" or "statistical".

The "Type" element shall be either "Normal", "Percentile" or "Probability".

Protocol for Interactive Communication

The nuclear DSS and the long-range dispersion model are implemented in different computers. Typically, the DSS is implemented in a personal computer, e.g. a lap-top computer, whereas the dispersion model runs at a High Performance Computing (HPC) facility at the national meteorological centre where the vast amount of meteorological model data, including meteorological ensembles, are present in full spatial and temporal resolution. Thus, a protocol is required for interactive communication between the DSS and the HPC facility enabling the requests by the DSS user for long-range atmospheric dispersion model calculations. The following is an extension of such an already existing operational protocol, in this case ARGOS, extended with the capability of simultaneous handling of a number of source term descriptions.

If the request from the DSS, contains more than one source file, then dispersion model predictions will be carried out for each source, and results will become available for the DSS. Additionally, the request is considered as a request for source-term ensemble modelling. By requesting simultaneous calculation for more than one source term, calculations can organised effectively at the national meteorological service. If the set of source terms can be considered an ensemble spanning the possible realisations of the release, also the generated statistical output can be used to describe the related uncertainty of atmospheric dispersion.

The resulting statistical parameters are the same as for the NWP ensemble dispersion results (percentiles, probabilities etc.).

The ARGOS request zip-archive contains the following files:

ST000_DERMA_src, ST001_DERMA_src, …, STMMM_DERMA_src
ST000_DERMA_iso, ST001_DERMA_iso, …, STMMM_DERMA_iso
DERMA_input

The file DERMA_input is common for the different sources, holding among other data the geographical coordinates of the source and the start of the scenario. Weighting factors for each of the source-term ensemble members are supplied in a separate file denoted Weighting_factors.

The resulting data for ARGOS are organised as <ID> / <NWPmodel> / <src>; cf. also Figure 41.

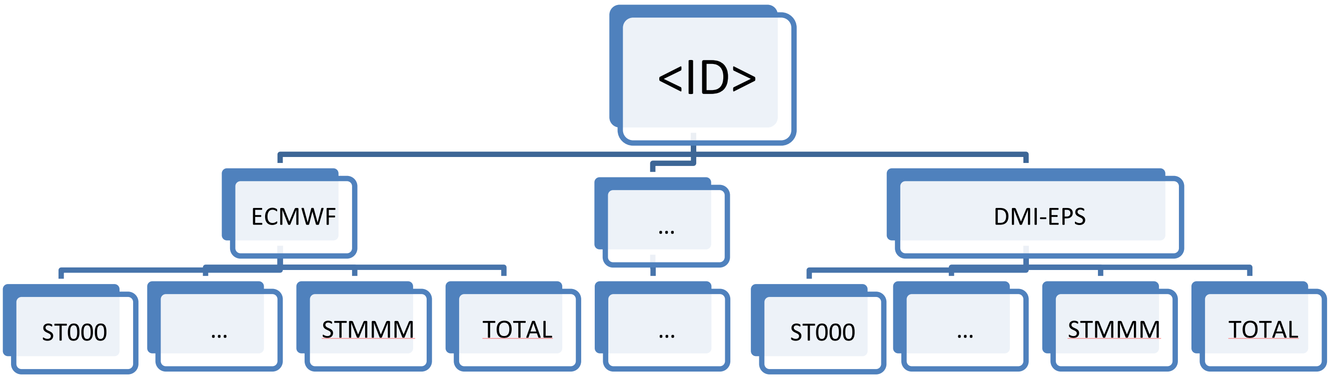


Figure 41 Structure of the content of the resulting data from DERMA to ARGOS.

The content of each src-block is as of today for deterministic and meteorological ensemble models, except for the TOTAL block which holds the source-term ensemble statistical results in terms of percentiles, probabilities etc.

The tree structure represents both the content of the zip archive holding the results of the atmospheric dispersion model for the DSS, and the presentation hereof in the DSS.

Conclusions and Outlook

Implications have been addressed of the inherent uncertainties of the radionuclide source term on the prediction of atmospheric dispersion of radioactivity from a release. Such uncertainties involve both the amounts of radionuclides released and the temporal evolution of the release. Furthermore, the combined uncertainties of atmospheric dispersion model forecasting stemming from both the source term and the meteorological data are examined. Impacts on real-time emergency preparedness and management are further examined.

The seminar "Uncertainties in Decision Support – on the use of meteorological and source-term data in nuclear emergency management" was organized on 12 September 2018. The seminar attracted 40 persons from research institutions and governmental authorities, and included ten presentations. Representatives of the EU projects FASTNET and CONFIDENCE took part. The collaboration between AVESOME, FASTNET and CONFIDENCE, which was initiated during the first year of AVESOME, was continued, especially with respect to source-term model calculation and generation of source-term ensembles describing the inherent uncertainty. In the future, e.g. as a result of FASTNET, it is expected that radiation protection authorities will have available databases of ensembles of source terms describing the possible releases. The AVESOME methodology will also work well with the Rapid Source Term Prediction (RASTEP) system, which provides a set of possible source terms with associated probabilities based on pre-calculated source terms.

The methods developed in AVESOME allow for efficient real-time calculations by making use of scaling properties in the equations governing the release and the atmospheric dispersion of radionuclides. Accordingly, the computer-resource demanding calculations should be carried out at HPC facilities available e.g. at national meteorological services, whereas less demanding post-processing can be carried out at the computer hosting the DSS. The former tasks include atmospheric dispersion model calculations; the latter include interactive communication with the supercomputer as well as presentation of final results in the form of distributions of radionuclide concentrations, depositions and human doses.

For the source-term ensembles used, each member is in fact associated with an individual uncertainty. This is e.g. seen when applying different source-term models to the same scenario; it is well-known that such results may differ substantially. There is a need for future research in this area providing a better understanding of source-term uncertainties and their effects on atmospheric dispersion of radionuclides from nuclear accidents.

The methodology developed is applied to six source-term ensembles for the Ringhals and the Brokdorf NPPs and to two meteorological situations represented by weather ensembles. The methodology developed can be applied to any source-term ensemble and is thus prepared for future integration with e.g. RASTEP or the FASTNET source-term database.

The nuclear DSS ARGOS has been extended with a facility to handle multiple results from a single request for long-range prediction, including a set of statistical results from an ensemble run from either a meteorological ensemble or a source-term ensemble, or the two combined. A protocol is described for interactive communication between the DSS and the HPC facility enabling requests from the DSS user for long-range atmospheric dispersion model calculations. It is based on an existing operational protocol extended with the capability of simultaneous handling of a source-term ensemble.

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Acknowledgements

The AVESOME team is grateful to Dr. Leif Persson, FOI CBRN Defence and Security, and Department of Mathematics and Mathematical Statistics, Umeå University, Sweden, for sharing his thoughts on probabilistic risk analysis with us.

We are grateful to Drs. Anders Riber Marklund and Elisabeth Tengborn, Lloyd's Register Consulting – Energy AB, Sundbyberg, Sweden, for providing us with source-term ensembles and associated a-priori probabilities as well as for helpful discussions and comments.

NKS conveys its gratitude to all organizations and persons who by means of financial support or contributions in kind have made the work presented in this report possible.

Title	Added Value of uncertainty Estimates of SOurce term and Meteorology (AVESOME)
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ISBN	978-87-7893-509-0
Date	February 2019
Project	NKS-B / AVESOME
No. of pages	72
No. of tables	3
No. of illustrations	41
No. of references	48

Abstract
max. 2000 characters

In the early phase of a nuclear accident with possible off-site consequences, e.g. resulting from core melt and breach of containment, accurate prediction of the atmospheric dispersion of radionuclides is of utmost importance. However, two large sources of uncertainty exist: one associated with the meteorological data employed, and one related to the source term, i.e. the amounts of radionuclides released and the temporal evolution of the release.

In the former NKS-B projects MUD, FAUNA, and MESO, the implications of meteorological uncertainties for nuclear emergency preparedness and management were studied, and means for operational real-time assessment of the uncertainties in a nuclear DSS were developed and demonstrated.

In AVESOME, a methodology has been developed for quantitative estimation of the variability of atmospheric dispersion modelling resulting from both sources of uncertainty. With modern supercomputing facilities available e.g. at national meteorological services, the proposed methodology is well suited for real-time assessments and implementation in decision support systems.

The methodology adapts well to the RASTEP system, which provides a set of possible source terms and associated probabilities. In the near future, source terms derived within the EU project FASTNET will also become available, describing different release scenarios.

By employing automatic communication between the DSS and the HPC facility, the methodology developed is applied to selected release scenarios and meteorological situations. Results are presented by the improved graphical user interface adhering to recommendations of the NKS Workshop on the Use of Meteorological Uncertainty Estimates for Decision Making during a Nuclear Emergency in 2015. Based on a given request for dispersion calculation at the HPC facility, the DSS user will be able to either use the probabilistic presentation of all members of the source-term ensemble, or to use the individual source term members.

Key words

nuclear emergency preparedness, atmospheric dispersion model, source term uncertainty, meteorological uncertainty, ensemble prediction