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

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Abstract

In the early phase of a nuclear accident, two large sources of uncertainty exist: one related to the source term and one associated with the meteorological data. Operational methods are being developed in AVESOME for quantitative estimation of uncertainties in atmospheric dispersion prediction resulting from uncertainties in assessments of both the release of radionuclides from the accident and their dispersion.

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.

In the recent NKS-B projects MUD, FAUNA and MESO, 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 nuclear DSS have been described and demonstrated. In AVESOME, we address the uncertainty of the radionuclide source term, i.e. the amounts of radionuclides released and the temporal evolution of the release. Furthermore, the combined uncertainty in atmospheric dispersion model forecasting stemming from both the source term and the meteorological data is examined. Ways to implement the uncertainties of forecasting in DSSs, and the impacts on real-time emergency management are described.

The proposed methodology allows for efficient real-time calculations. Accordingly, the computer-resource demanding calculations should be carried out at the high-performance computing facilities available e.g. at the national meteorological services, whereas less demanding post-processing could be carried out at the computer hosting the DSS. The former tasks include the atmospheric dispersion model calculations; the latter includes interactive communication with the supercomputer as well as presentation of final results.

Key words

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

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Added Value of uncertainty Estimates of SOurce term and Meteorology (AVESOME) – first-year report

First Year Report of the NKS-B AVESOME activity

(Contract: AFT/B(17)7)

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Introduction

In the early phase of a nuclear accident with off-site consequences, e.g. resulting from a core-melt scenario, two large sources of uncertainty exist: one related to the source term and one associated with the meteorological data. In the NKS-B project AVESOME (Added Value of uncertainty Estimates of SOurce term and Meteorology), operational methods are being developed for quantitative estimation of uncertainties in atmospheric dispersion modelling resulting from uncertainties in assessments of both the release of radionuclides and of their atmospheric dispersion.

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.

In the recent 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 ongoing project, we address the implications for dispersion of the uncertainty of the radionuclide source term, i.e. the amounts of radionuclides released and the temporal evolution of the release. Furthermore, the combined uncertainty in atmospheric dispersion model forecasting stemming from both the source term and the meteorological data is examined. Implementation of the forecasting uncertainties in DSSs, and the impacts on real-time emergency management are being described.

Collaboration has been initiated with the EU projects FASTNET and the Concert programme project CONFIDENCE, especially with respect to source-term model calculation and generation of source-term ensembles describing the inherent uncertainty. Today, employing current operational methods based on a given source-term model, e.g. MELCOR, and available data, one should expect only a few categories of source terms for a core-melt scenario. However, it is well-known that different source-term models may give source terms differing by up to an order of magnitude. In the future, e.g. as a result of FASTNET, one will have available an ensemble of source terms describing the possible releases. In AVESOME, we develop a methodology which can handle both a few-member source-term ensemble and a large ensemble spanning all possible releases. The AVESOME methodology will 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.

One of the methods, which are being developed in AVESOME, allows 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 the high-performance computing (HPC) facilities available e.g. at the national meteorological services, whereas less demanding post-processing could be carried out at the computer hosting the DSS. The former tasks include atmospheric

dispersion model calculations; the latter includes interactive communication with the super-computer as well as presentation of final results in the form of distributions of radionuclide concentrations, depositions and human doses.

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 optionally 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

In AVESOME, we are primarily studying 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. Thus, the radiation protection authority will probably at the most have a few representative core-melt source terms available for a given reactor. In the present report, we have limited ourselves to three source terms, namely two describing filtered releases (optimum filtering, and filtering with limited performance), and a worst-case scenario in which the filter is not connected with the reactor. As soon as knowledge is obtained on whether the filter is connected or not, the three-member ensemble will be reduced to either a two- or a one-member ensemble.

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

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, Knochenhauer 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, EPRI 2006) or Methods for estimation of Leakages and Consequences of Releases (MELCOR, 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, 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 done 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, 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 others 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, but for future use the RASTEP tool (an existing Bayesian Belief Network (BBN) tool, developed for SSM) is extremely interesting, with the possibility of ranking source terms from a pre-computed database of European reference accident scenarios.

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 6 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 models, 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 plant or nuclear icebreaker close to Norway.

By 2018, guidelines for ranking uncertainties of atmospheric dispersion modelling in these cases, based on (Rao, 2005) will be published. In addition, a report addressing the uncertainties related to the source term will be written. Preliminary plans for the Norwegian scenario for addressing source-term uncertainties are based on the WASH1400 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).

One future subtask will follow the results from the NKS-MESO project (Sørensen *et al.*, 2017) to reduce the uncertainties of the models by using meteorological measurements, e.g. by using precipitation radar.

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.

Since all of these dispersion calculations 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.

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 1,

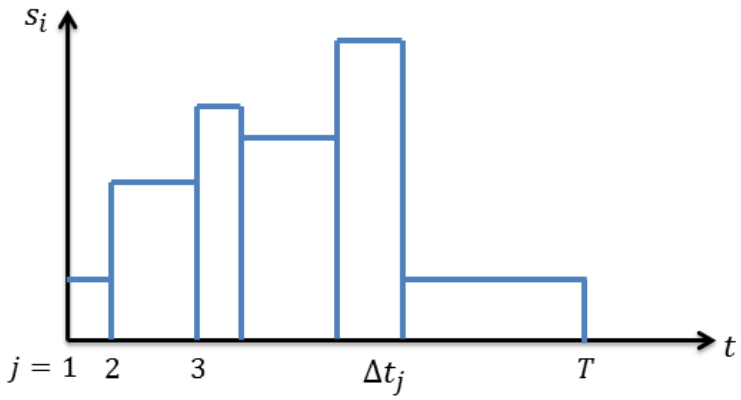


Figure 1 Piece-wise constant source term, $\boldsymbol{s_i(t)}$.

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 2.

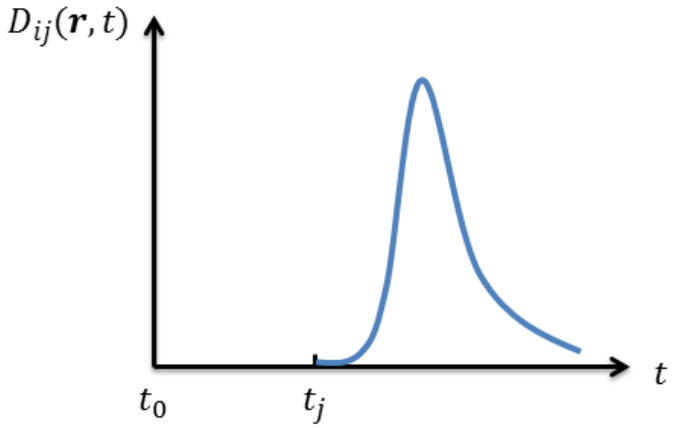


Figure 2 Building blocks $\boldsymbol{D_{ij}(r,t)}$ for unit releases of the radionuclide $\boldsymbol{i}$ in the time interval $[\boldsymbol{t_j}, \boldsymbol{t_{j+1}}]$.

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.

If the source-term uncertainty is expressed in terms of only up to around ten different sources, then probably it is not worthwhile to employ the above method due to the computational overhead involved.

Methods for Source Uncertainty

With the aim to present a computationally efficient method for the study of source term uncertainties, a work was done to show that it is possible to post-process the properties of the source term onto the output from a particle dispersion model. From this, the suggested source ensemble method was developed, which can be used to study the impact of uncertainties in the temporal variation of radioactive emissions.

Examples with a fictitious setup of the source term and its temporal distribution were made to demonstrate some of the added information that the source ensemble method can give. This method is straightforward to merge with a weather ensemble system. For the full report, see Appendix A.

Meteorological Ensemble Prediction

The DMI meteorological Ensemble Prediction System (DMI-EPS), which is currently 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 3.

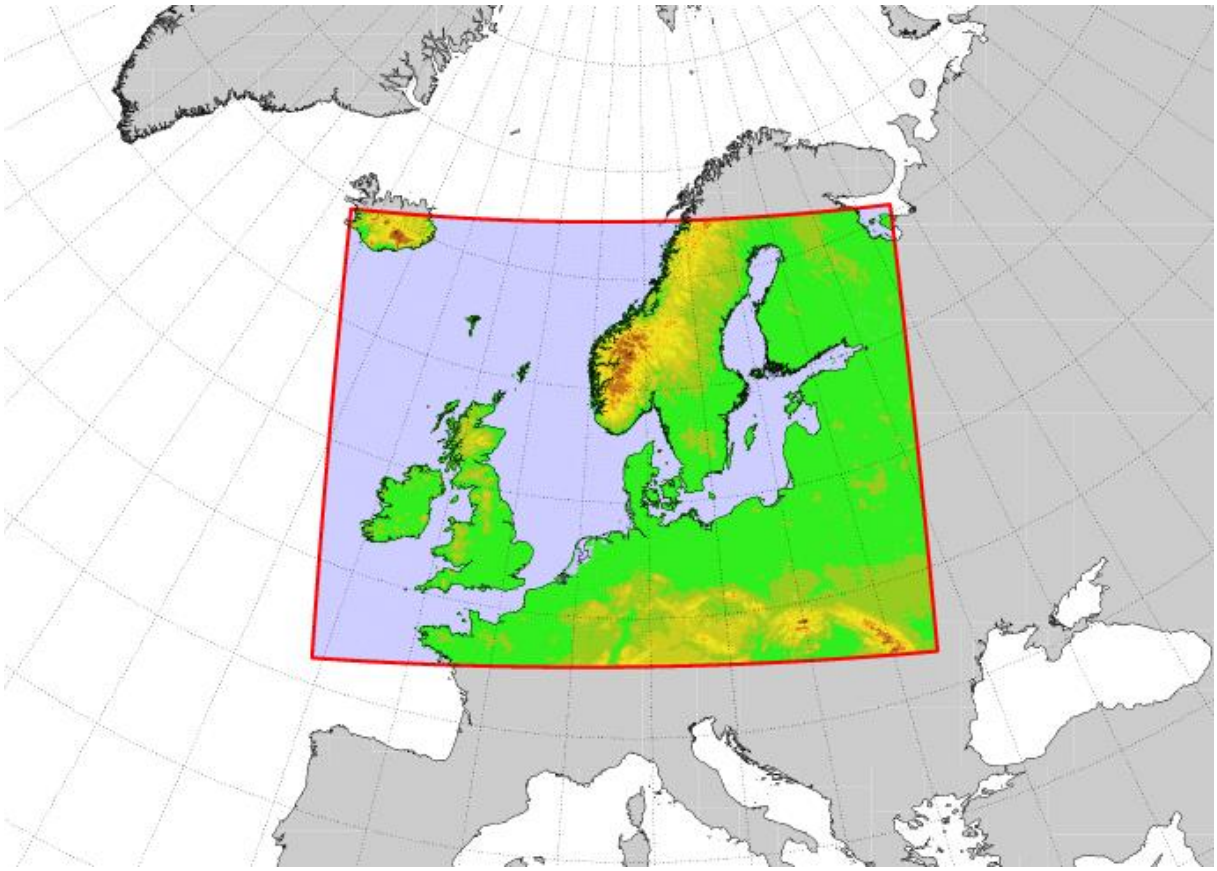


Figure 3 Geographic domain covered by DMI-EPS.

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).

DMI's ensemble prediction system has been running operationally since April 2011. 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.

Atmospheric Dispersion Modelling

Ensemble Statistics for Atmospheric Dispersion Modelling

The calculation and display of probabilities for exceeding a threshold level constitutes a means for presenting uncertainties associated with atmospheric dispersion modelling. For simplicity consider e.g. the total deposition of a single radionuclide a given time after the start of the release. The probabilities (also known as the ATL, cf. Galmarini *et al.* (2004)) are obtained from the ensemble of atmospheric dispersion calculations as

$$P_T(\boldsymbol{r},t) = \frac{1}{N}\sum_{i=1,\ldots,N} \vartheta\{c_i(\boldsymbol{r},t) - c_T\},$$

where i denotes ensemble members, c the physical quantity (here total deposition), $\boldsymbol{r}$ the geographical location and t the time. The function ϑ denotes the Heaviside step function, and c_T is the threshold value for the physical quantity.

The method may readily be expanded to include not only atmospheric dispersion uncertainties but also uncertainties associated with e.g. source term variations, in which case the parameters are drawn from statistical ensembles associated with these variables.

A different approach to presenting the uncertainties associated with atmospheric dispersion modelling is to display the maximum, minimum and average influence areas. The maximum deposition is given by

$$c_{\max}(\boldsymbol{r},t) = \max_{i=1,\ldots,N} c_i(\boldsymbol{r},t),$$

Similarly, the average is given by

$$c_{\mathrm{avr}}(\boldsymbol{r},t) = \frac{1}{N}\sum_{i=1,\ldots,N} c_i(\boldsymbol{r},t).$$

This maximum, $c_{\max}$, can be used to estimate the geographical area which could possibly be influenced according to the ensemble. However, it is not a solution to governing equations, e.g. it is not conserving mass. Therefore, the quantity should be seen as a statistical measure.

Maximum plots are influenced by outliers in the tail of the distributions, and they are therefore in fact often based on only few ensemble members. This makes these plots sensitive to the inclusion of more ensemble members and generally uncertain. Instead, a low and a high percentile, e.g. 10% and 90%, together with the mean or median are more appropriate for decision making purposes. The percentiles are more robust than e.g. maximum values.

Combination of a Numerical Weather Prediction 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 having $N \times M$ members, cf. Figure 4 below.

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

Figure 4 Schematic representation of the combination of an ***N*** member NWP model ensemble with an ***M*** member ST ensemble.

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 from the numerical weather prediction model DMI-HIRLAM covering Denmark, Greenland and the Faeroes (Sass *et al.*, 2002) and from the global model developed and operated by the European Centre for Medium-range Weather Forecasts (ECMWF).

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 Study

Meteorological Case

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.

27 April 2016

A low is situated over southern Denmark (Figure 5). It is filled during the forecast, and the wind weakens. There are several showers associated with this low. This is also seen in the meteogram for Karup (Figure 6) 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.

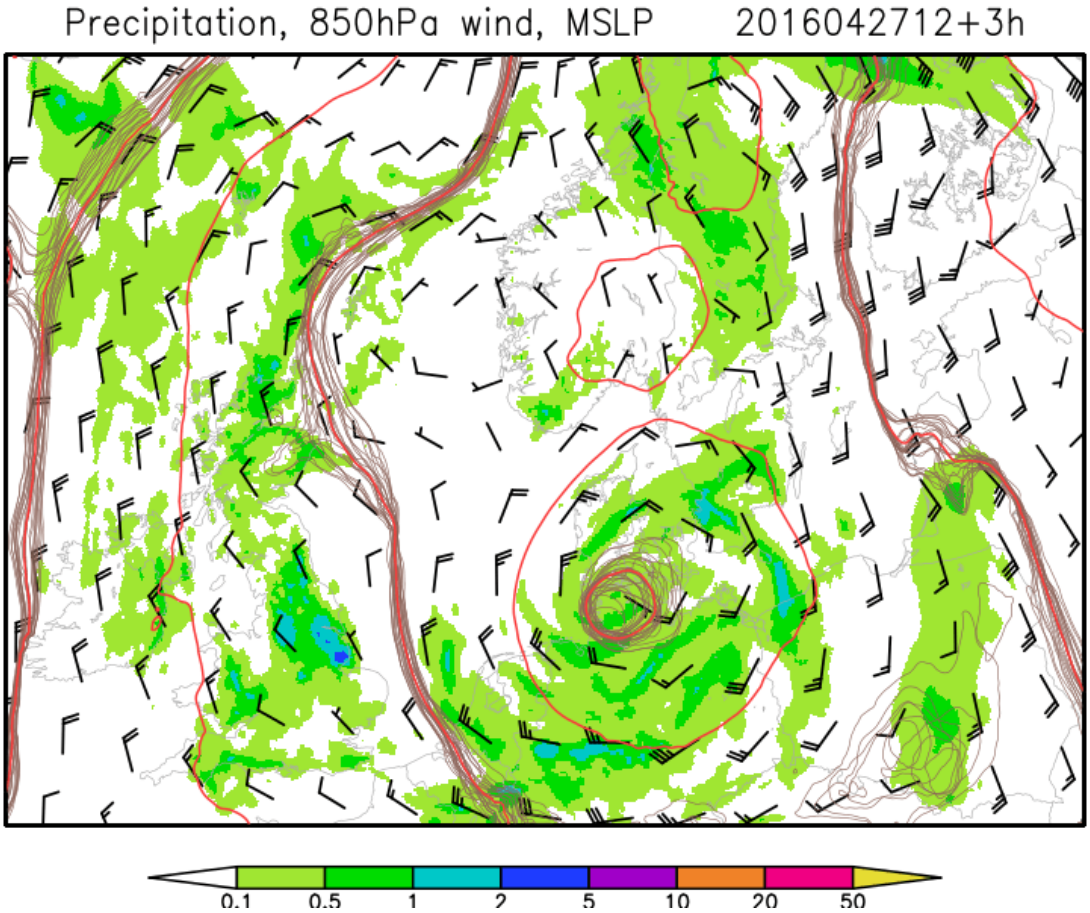


Figure 5 Ensemble mean of 6 hour forecast of hourly precipitation in mm (shaded), wind at 850 hPa (barbs) and mean sea level pressure (MSLP; red contours). Individual MSLP ensemble members (brown contours around every other red contour) illustrate the forecast uncertainty.

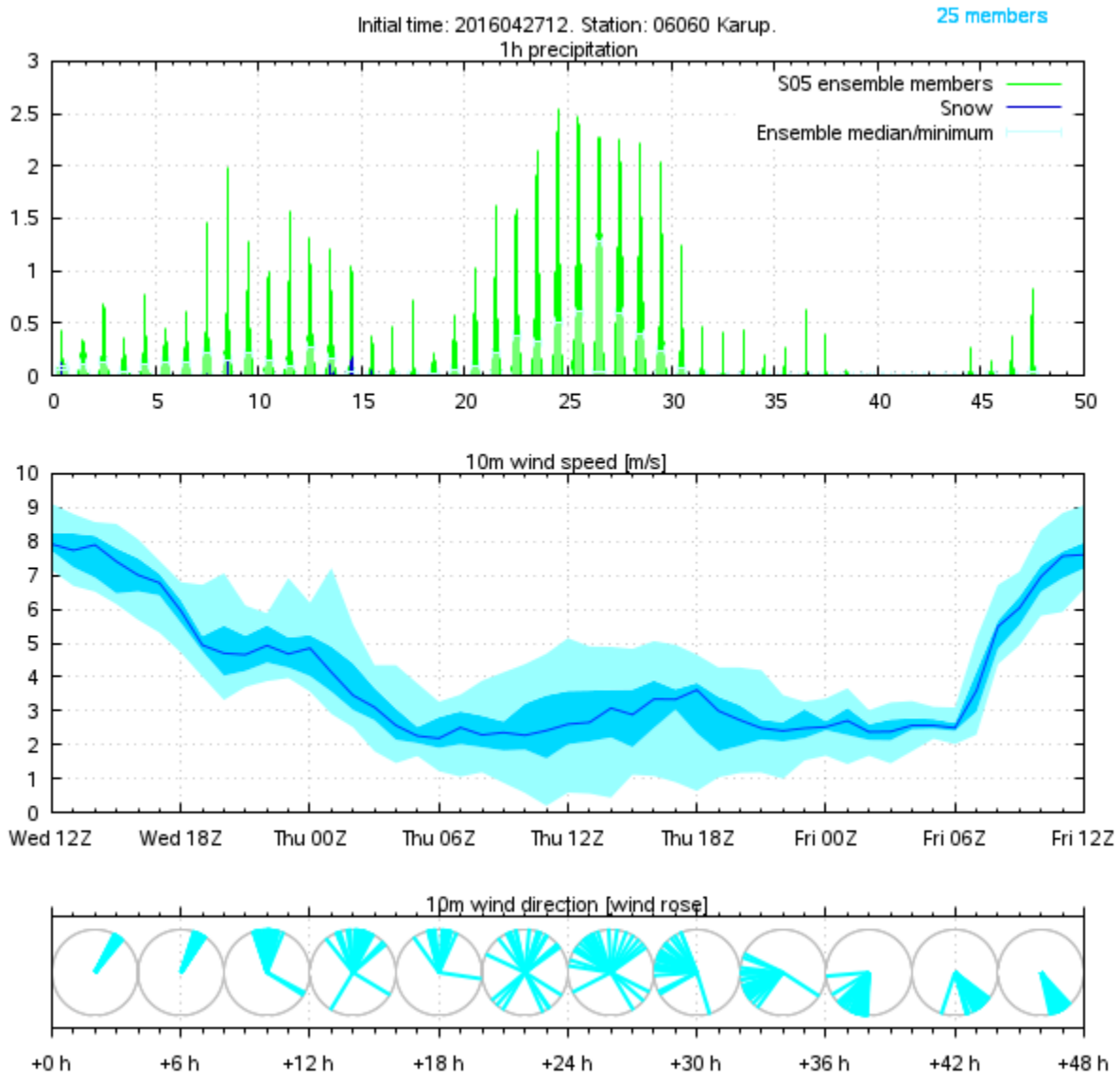


Figure 6 Meteogram showing ensemble forecast for Karup. Top: Precipitation, where each member at every forecast hour is shown as a vertical line (blue for snow, green for total snow + rain). Middle: Wind speed at 10 m above ground (light blue shows "outer half" of the members; darker blue shows "inner half" of the members; darkest blue shows the median). Bottom: Wind roses, indicating the wind direction for each ensemble member.

Source Terms Employed

The source term provides information about the nuclides included in the release as well as the activity released per nuclide. The source term also describes the height of the release, duration of the release phases, and the thermal effect (heat content) of the release.

In this study, three source terms have been introduced. The source terms are intended to represent examples of possible releases to the environment following a severe accident in a PWR type reactor with an approximate thermal effect of 3250 MW.

The three source terms, hereafter denoted VFF, FF and NFF, all stem from the same initiating event, namely a serious accident leading to a core meltdown followed by a reactor pressure vessel core melt-through. The three scenarios thereafter diverge as a function of availability and performance of consequence-mitigating systems. In the VFF scenario ("Small"), the containment spray system[1] is activated after two hours and the release to the environment is lead through the containment filtered venting system, assuming a filter factor of 1500. In the FF scenario ("Medium"), containment spraying is activated only after 8 hours, whereas the filter factor of the containment venting system is assumed to be 500. The third and most severe scenario with respect to environmental impact, NFF ("Large"), represents a case where the containment spray system is unavailable and where the integrity of the containment is compromised in connection with the reactor pressure vessel core melt-through, leading to an unfiltered release where the cross-section of the release path corresponds to the cross-section of the tube connecting the containment with the filtered venting system.

The different assumptions regarding availability and performance of consequence-mitigating systems leads to source terms that are varying in magnitude and relative composition with respect to nuclides released, as well as in timing and in altitude of release. This includes, in particular, the relative composition of the iodine released to the environment (elementary, organic or aerosol form). All those factors will impact the subsequent atmospheric dispersion and dose calculations.

The origin of the source terms described above is analyses performed within another project at SSM using the MELCOR source term code. From these analyses, yielding high temporal resolution releases (50 s) of some 200 nuclides in terms of fractions of mass of the core inventory, some 30 key nuclides have been extracted and converted to releases in absolute terms for 48 one-hour intervals following the initial event.

The release height for the source terms with functioning consequence-mitigating systems has been set to 48 m, whereas the release height for the NFF source term has been set to 27 m. No heat content is assumed.

Figure 7, Figure 8 and Figure 9 show the cumulative releases for selected key nuclides as a function of time from the initial event and in terms of fractions of an assumed core inventory for the three selected source terms, "Small", "Medium" and "Large". In particular it should be noted that, in the absence of functioning consequence-mitigating systems (NFF source term), significant release to the environment will occur within less than 4 hours after the initiating event, whereas well-functioning consequence-mitigating systems (VFF source term) in this

[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.

example delay the initial release by some 26 hours. Figure 10 depicts the release rate of Cs-137 for the three selected source terms.

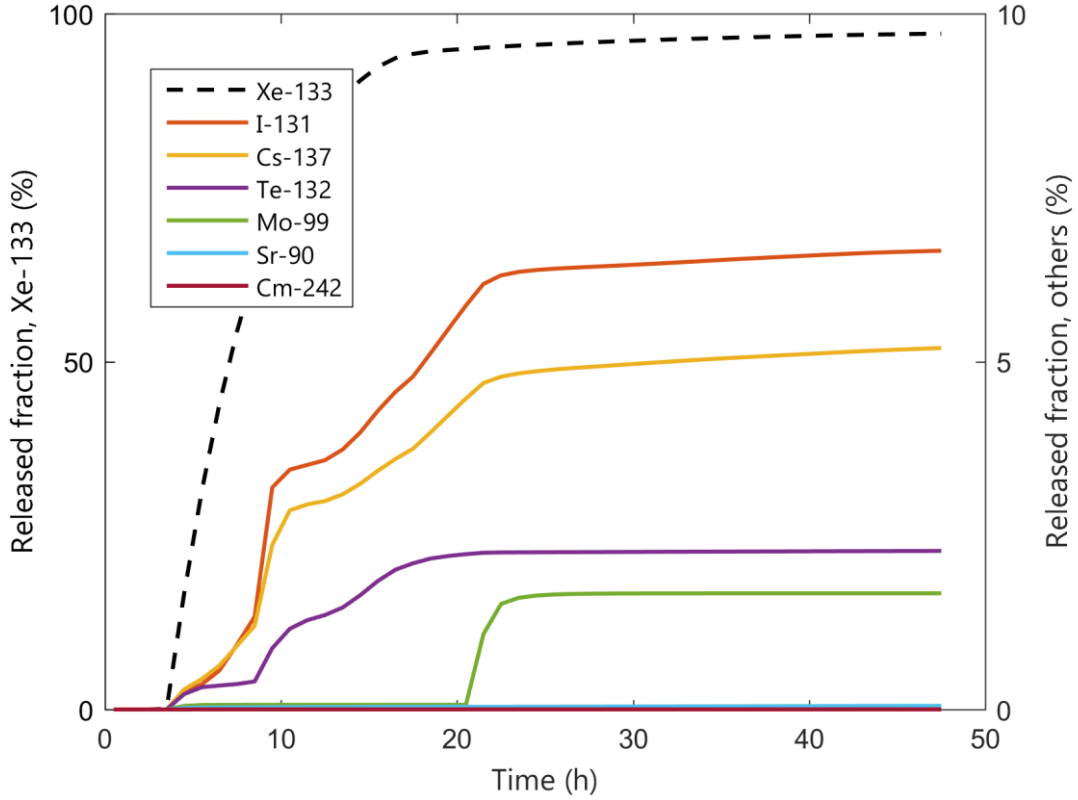


Figure 7 Source Term NFF ("Large").

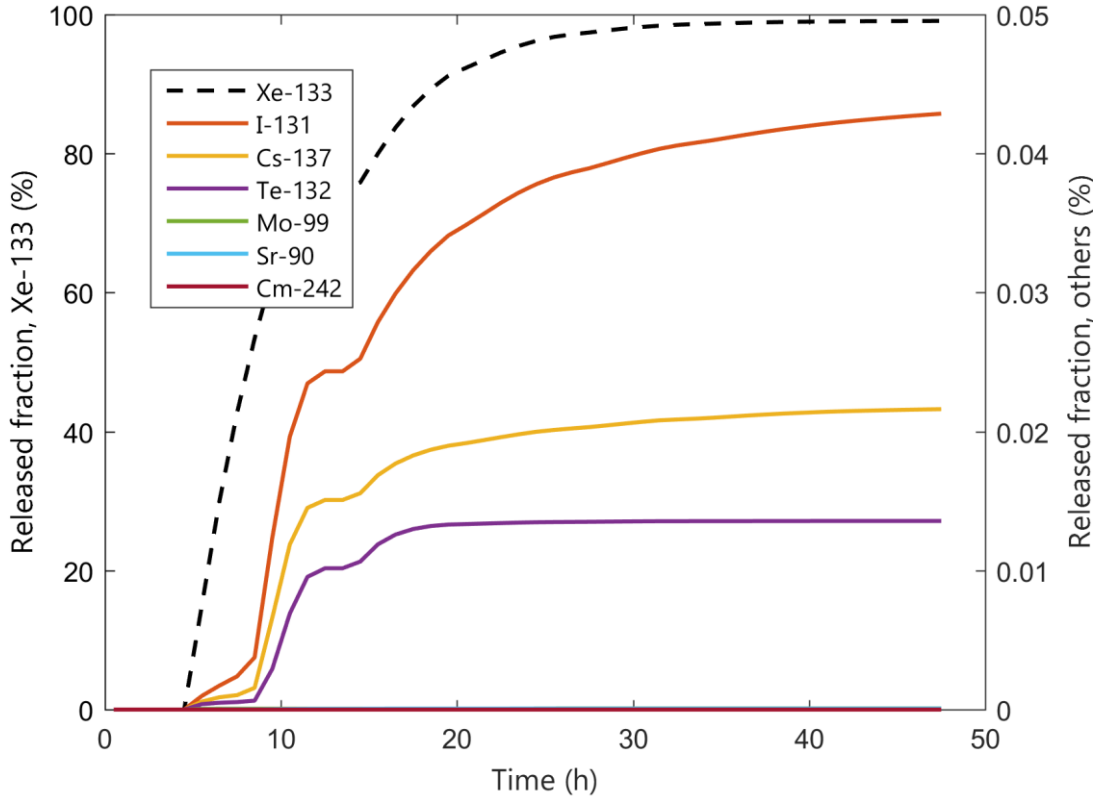


Figure 8 Source Term FF ("Medium").

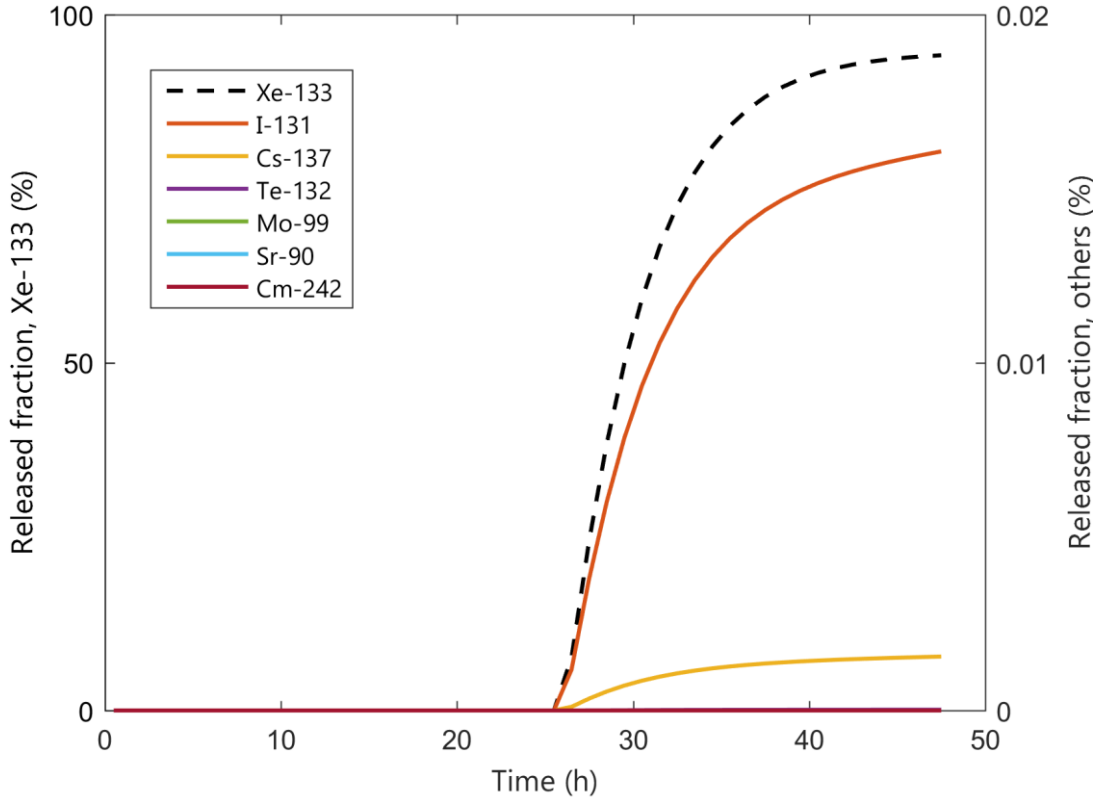


Figure 9 Source Term VFF ("Small").

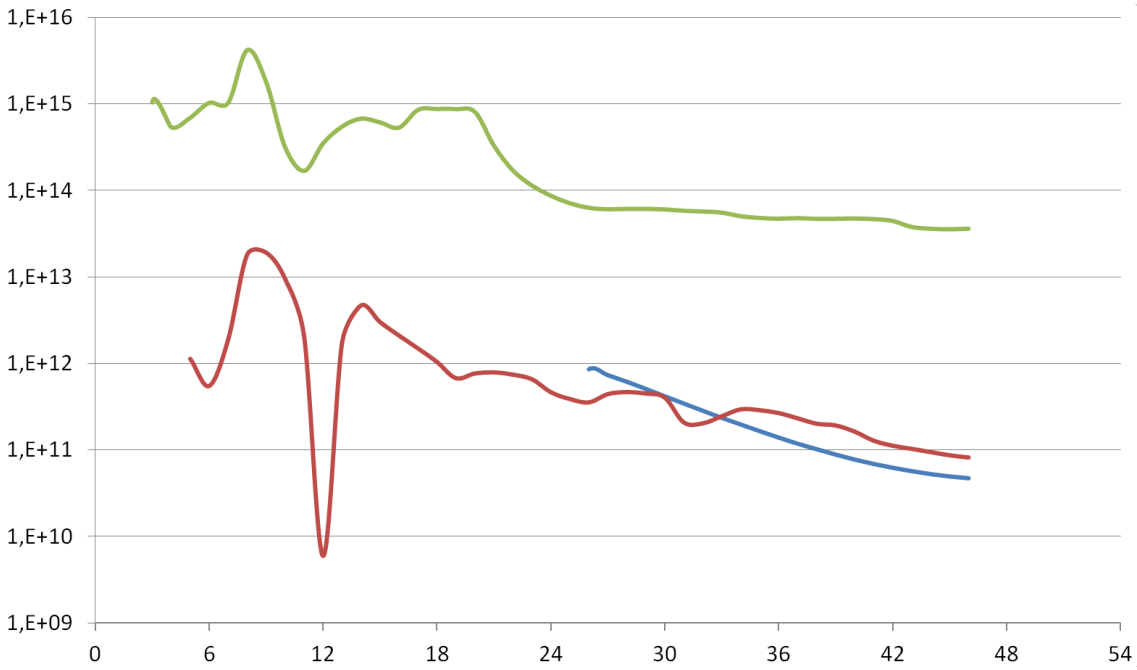


Figure 10 Time-dependent release of Cs-137 for the three selected source terms named "Small", "Medium" and "Large" depicted by blue, red and green curves, respectively. The release rates are given in units of Bq/h, and the time in hours since SCRAM.

Atmospheric Dispersion Case

The DERMA model has been applied to each of the three release scenarios, “Small”, “Medium” and “Large” for a hypothetical accident at the Ringhals NPP. For each release scenario, DERMA has been run for each member of the meteorological ensemble corresponding to the selected meteorological case. The methodology of calculating and presenting uncertainties, developed in course of the NKS-B projects MUD and FAUNA, has been applied to the dispersion model results. The figures below depict the accumulated deposition of Cs-137 based on 54 hour forecast NWP model data from the analysed state dated 2016-04-27, 12 UTC.

Figure 11 below concern the release scenario “Small”, Figure 12 concern “Medium”, and Figure 13 concern “Large”. In Figure 14 are shown results of the three release scenarios combined as a source-term ensemble.

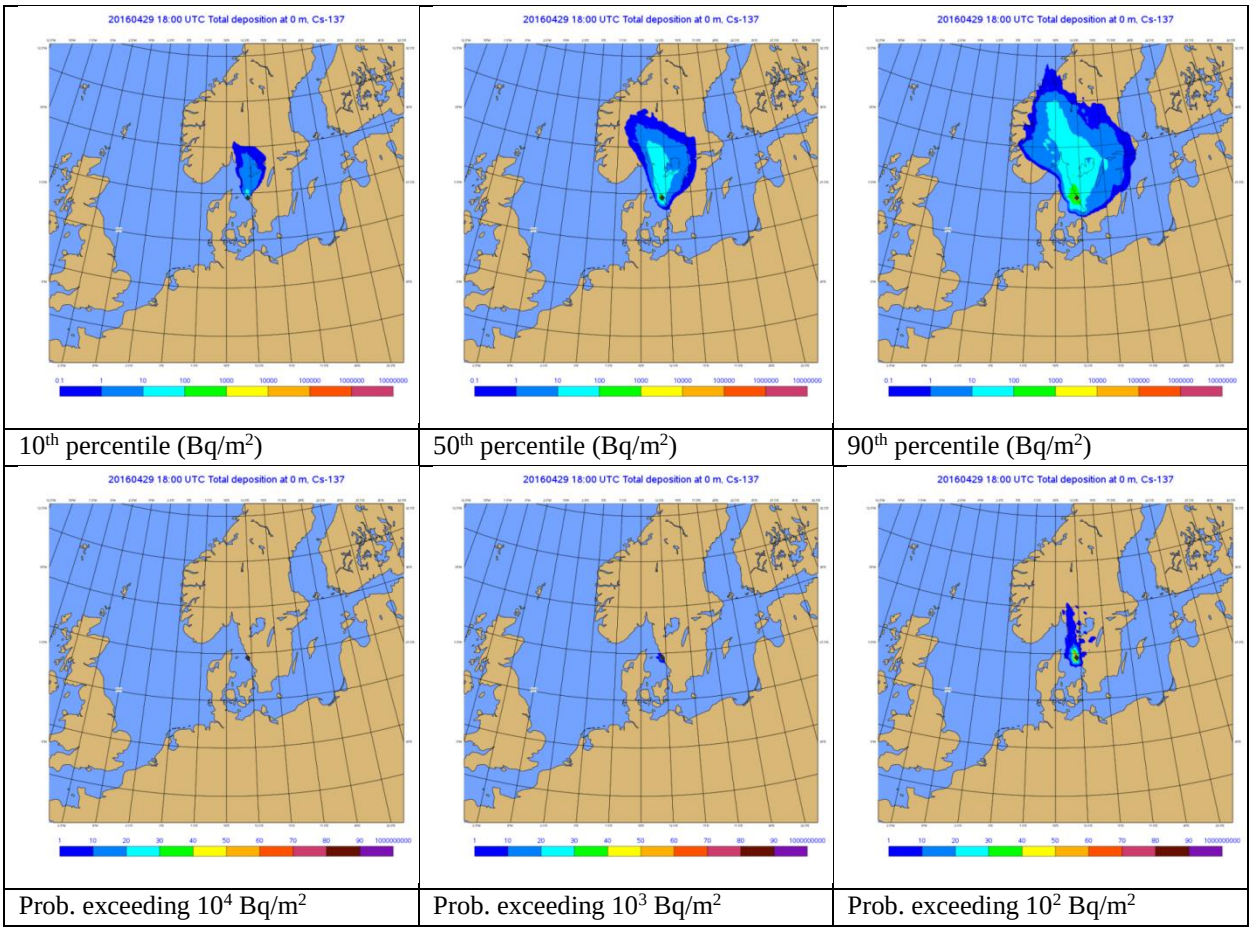


Figure 11 Release scenario “Small”. DERMA ensemble prediction of accumulated deposition of Cs-137 based on 54 hour forecast NWP model data from the analysed state dated 2016-04-27, 12 UTC.

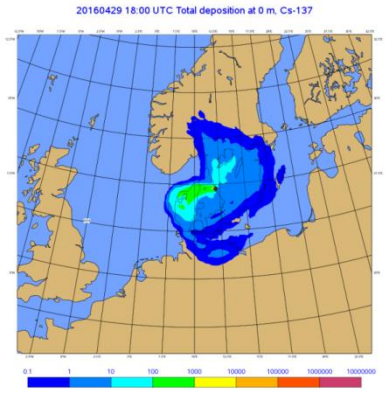
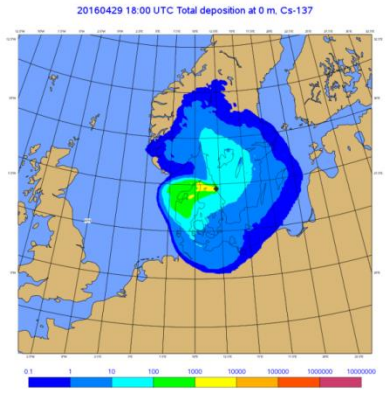
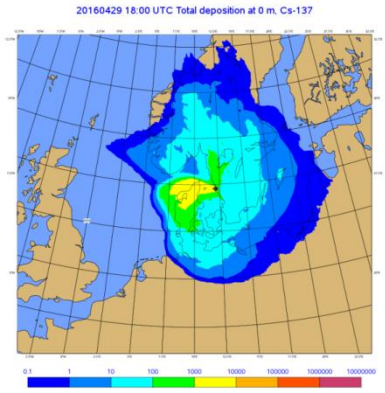
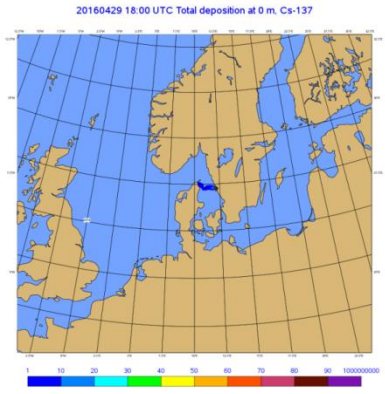
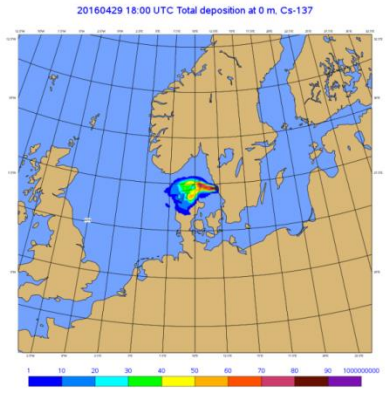
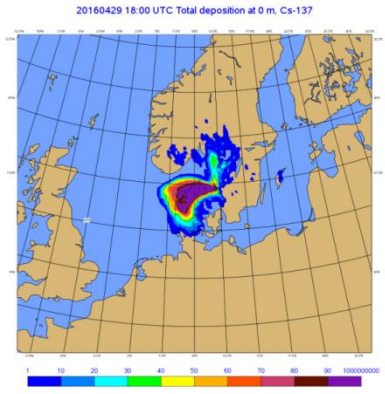
		
10^{th} percentile (Bq/m^2)	50^{th} percentile (Bq/m^2)	90^{th} percentile (Bq/m^2)
		
Prob. exceeding 10^4 Bq/m^2	Prob. exceeding 10^3 Bq/m^2	Prob. exceeding 10^2 Bq/m^2

Figure 12 Release scenario "Medium". DERMA ensemble prediction of accumulated deposition of Cs-137 based on 54 hour forecast NWP model data from the analysed state dated 2016-04-27, 12 UTC.

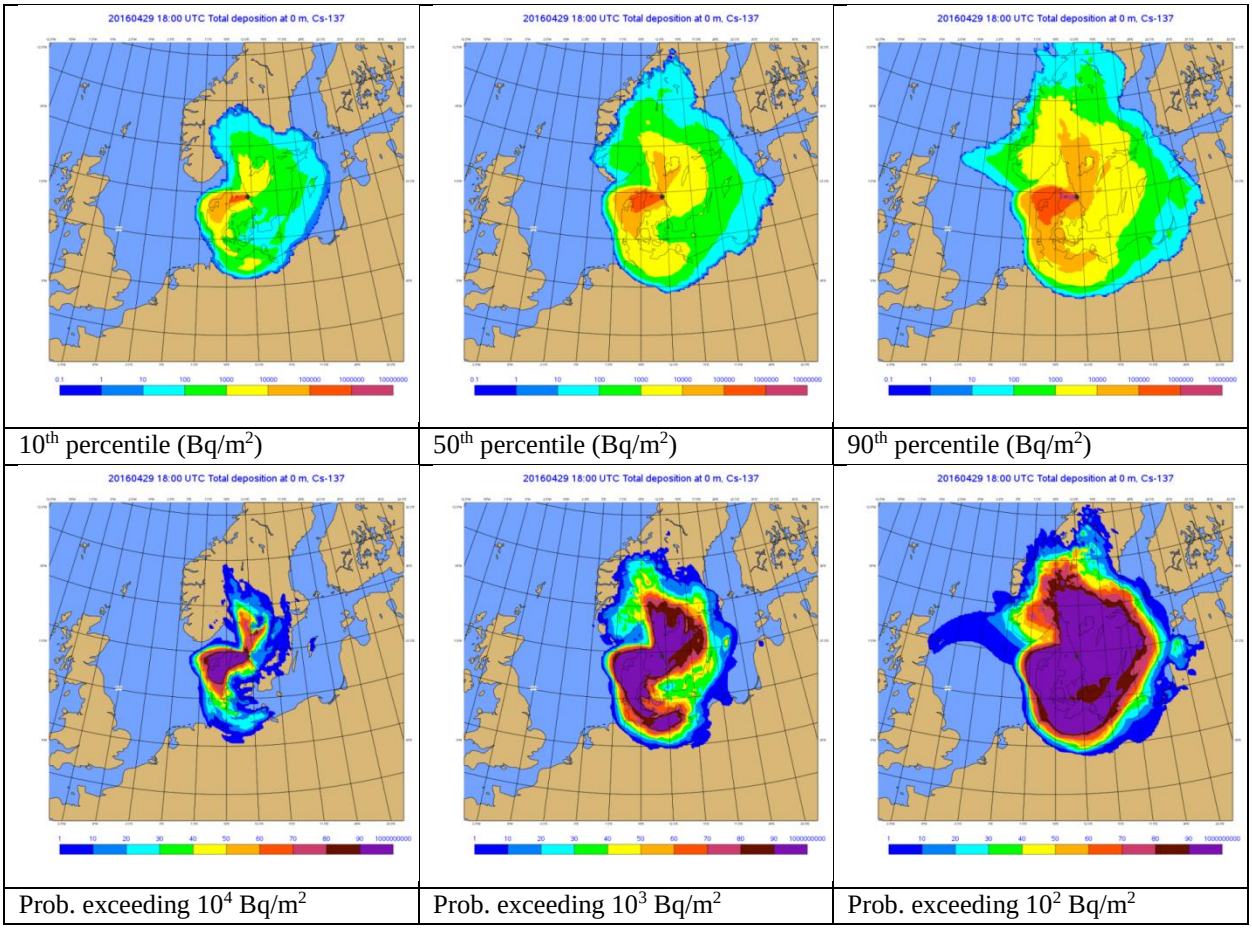


Figure 13 Release scenario "Large". DERMA ensemble prediction of accumulated deposition of Cs-137 based on 54 hour forecast NWP model data from the analysed state dated 2016-04-27, 12 UTC.

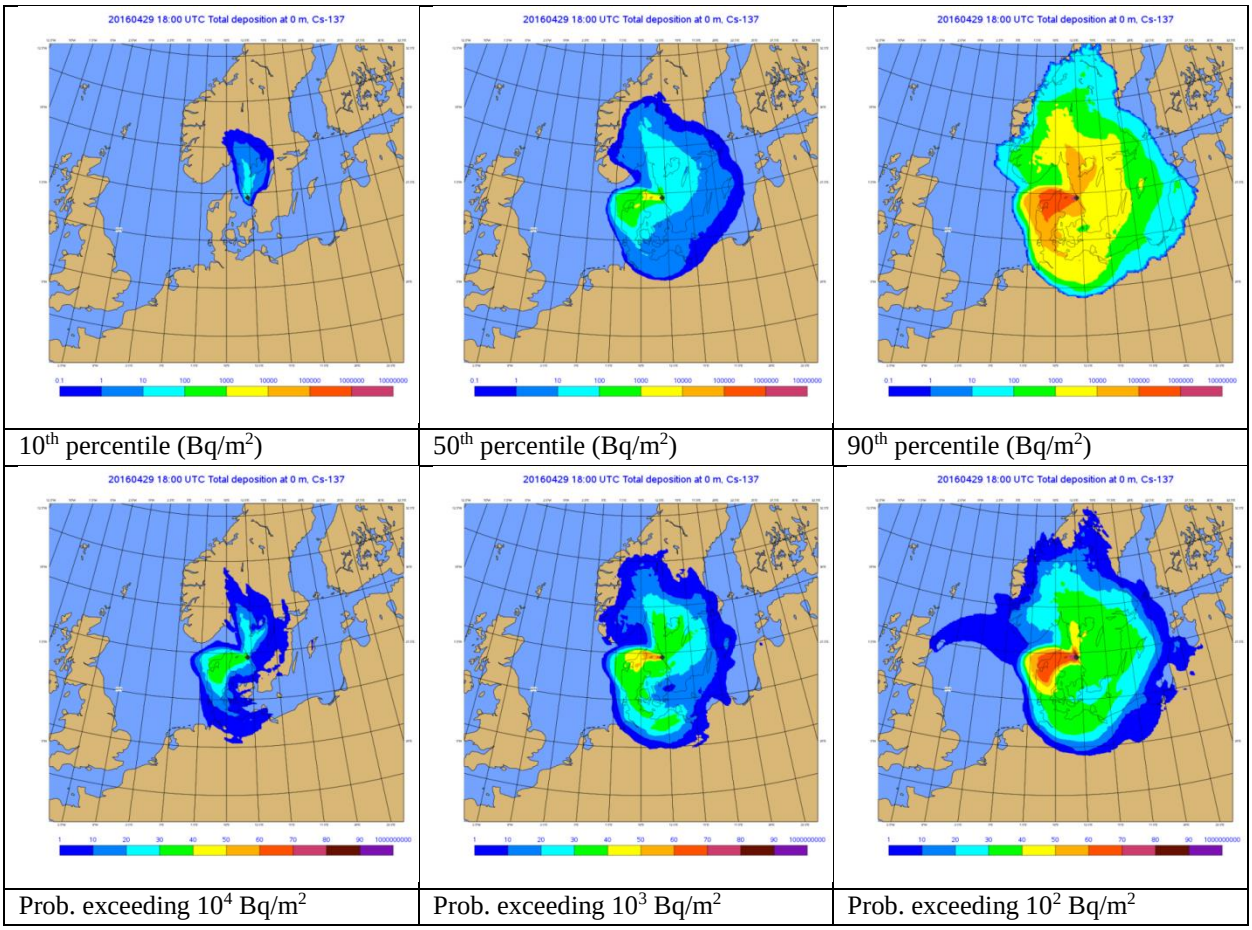


Figure 14 The three release scenarios "Small", "Medium" and "Large" combined. DERMA ensemble prediction of accumulated deposition of Cs-137 based on 54 hour forecast NWP model data from the analysed state dated 2016-04-27, 12 UTC.

Note that the one day later start of the release in case of the "Small" release scenario has a dramatic effect on the deposition in Denmark due to the turning of the wind in this period.

From three to five hours after the start of the scenario, either the "Large" source has been realized, or the release is expected to be the "Small" or the "Medium". In Figure 15, an ensemble calculation for the latter scenario involving these two source-term members is presented.

In a real situation, one should at this point in time in fact request new calculations due to the likely appearance of new NWP model forecast. For the present calculations, however, the same NWP model data have been used.

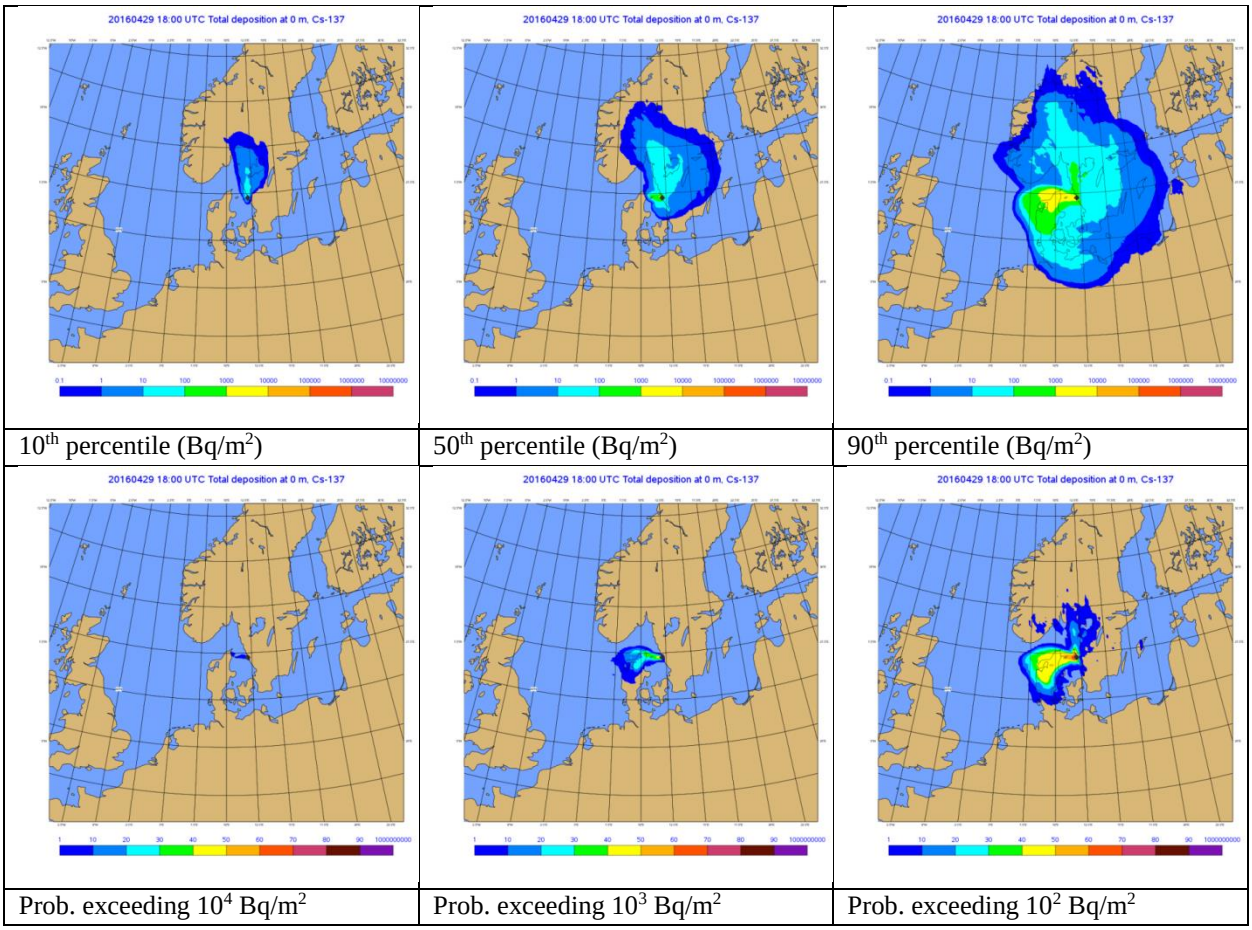


Figure 15 The two release scenarios "Small" and "Medium" combined. DERMA ensemble prediction of accumulated deposition of Cs-137 based on 54 hour forecast NWP model data from the analysed state dated 2016-04-27, 12 UTC.

ARGOS and Ensemble Results

The Long Range dispersion model interface in ARGOS is now able 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 result (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 different versions of NWP model data.

LR request from ARGOS

The Request dialog in ARGOS has not changed since no new input data needs to be given to the server. The DMI server simply starts, in parallel, a series of model runs based on the same input information provided by the request.

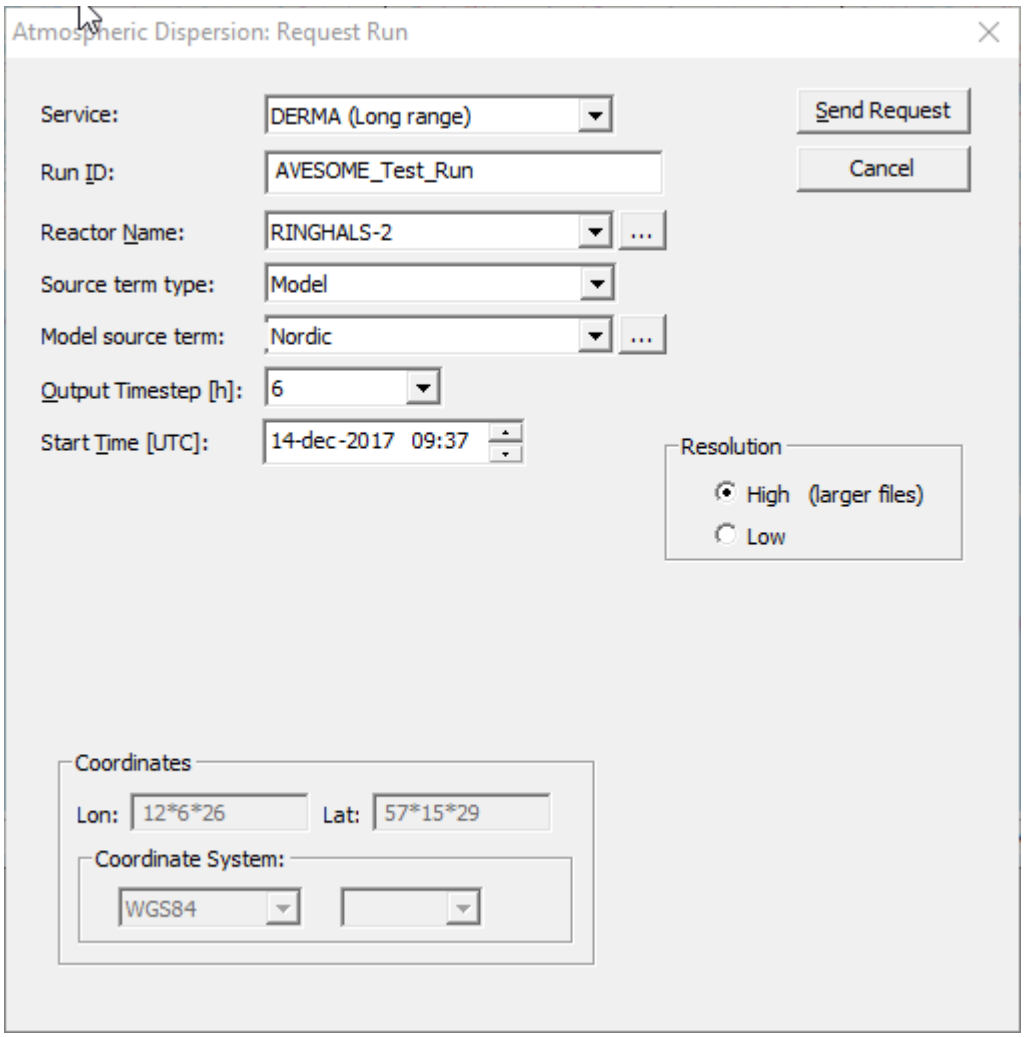


Figure 16 The "usual" request dialog in ARGOS.

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:

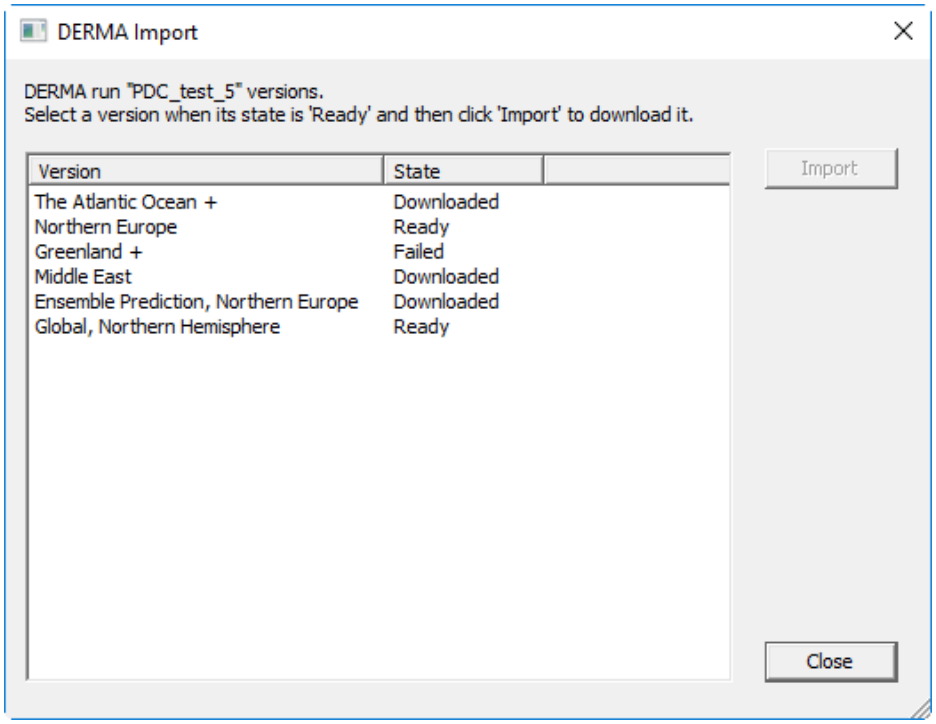


Figure 17 LR monitor.

The 'State' for a run version can be either "Not ready", "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.

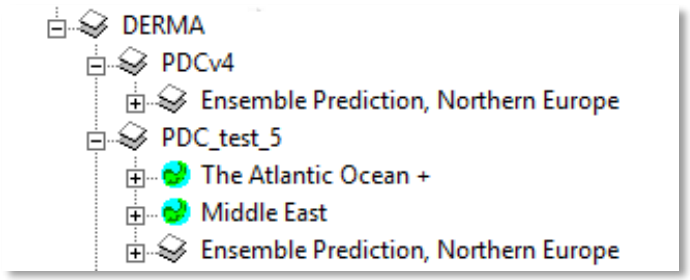


Figure 18 Results in the LR tree.

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)”.

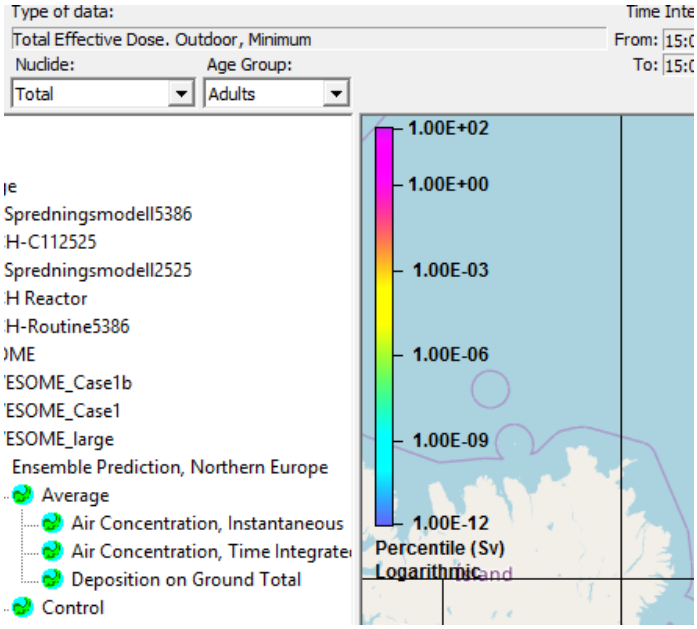


Figure 19 Prefix on the presentation of unit for a percentile plot.

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

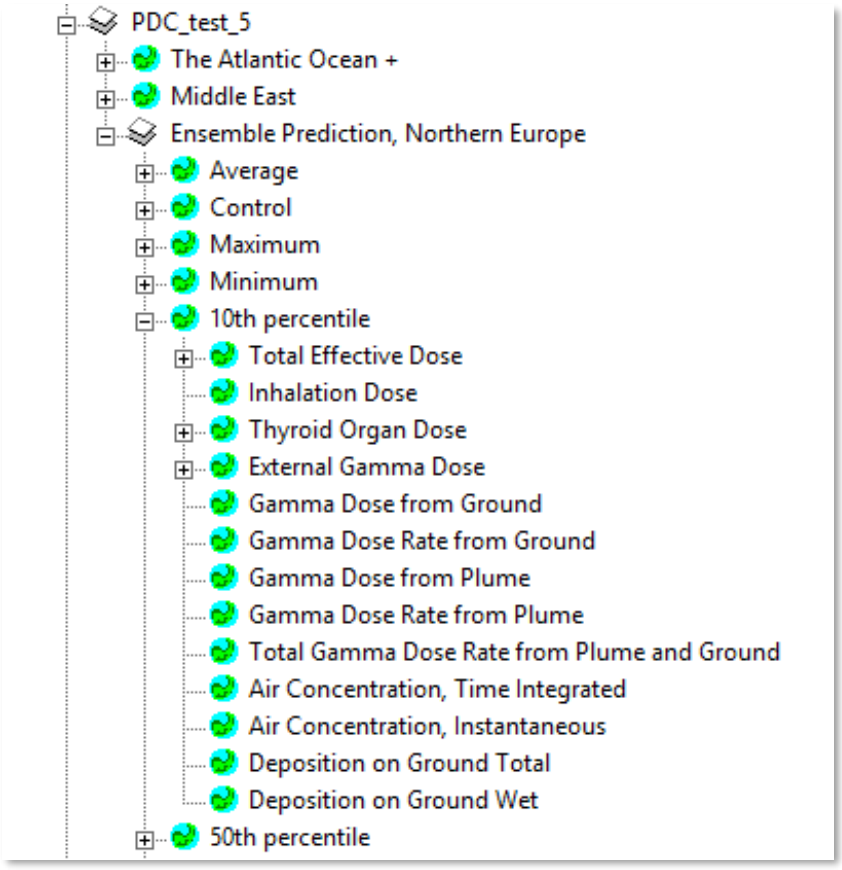


Figure 20 Statistical results w/ "Dose Calculations".

Example of a plot in ARGOS comparing deposition on ground (Cs-137) for 3 different percentiles:

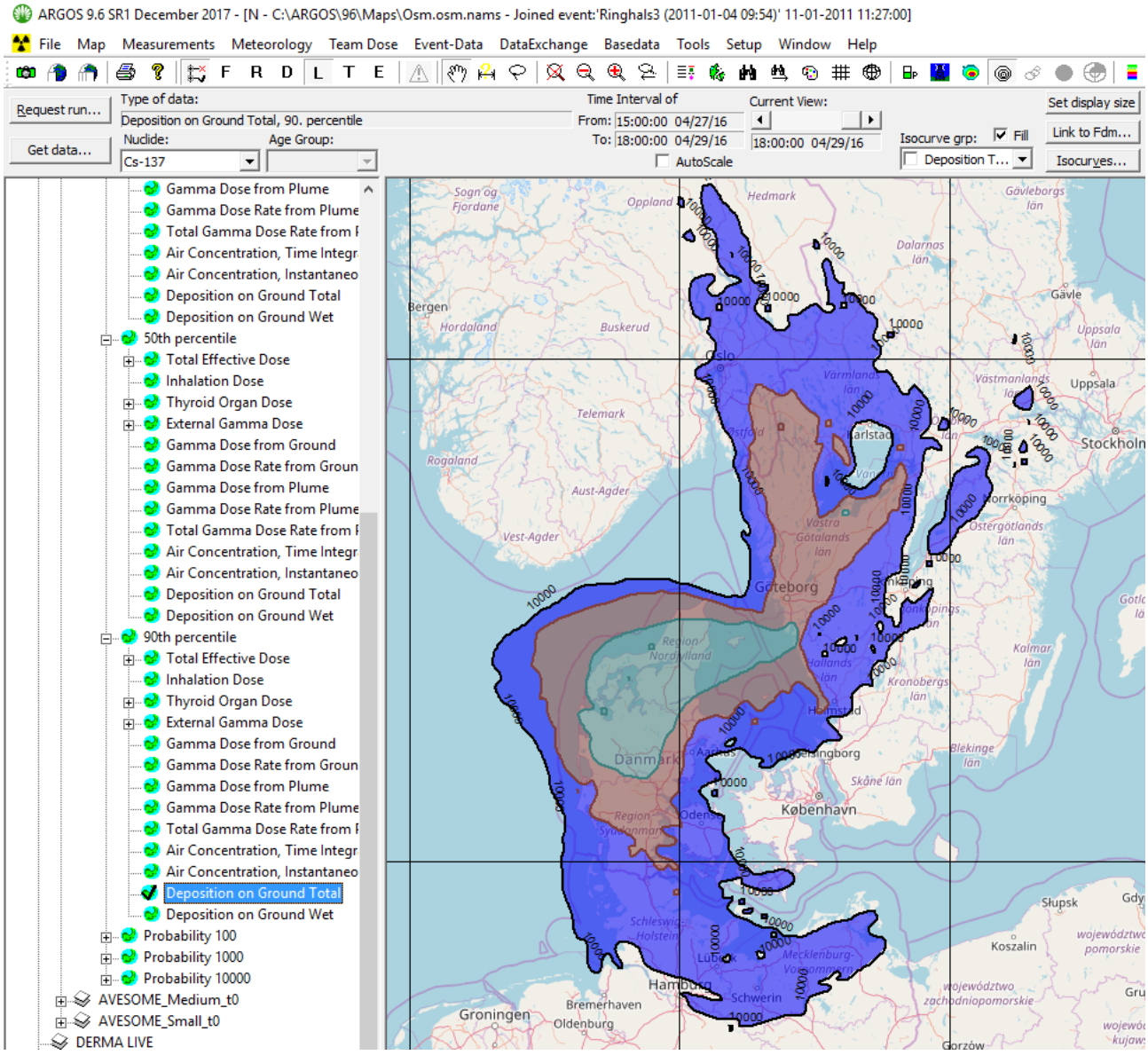


Figure 21 Comparison of 10th (green), 50th (brown) and 90th (blue) percentile for 10 kBq/m^2 deposition of Cs-137 from a simulated release from Ringhals.

Example of a plot in ARGOS showing three different intervention levels for Total Effective Dose on the Maximum percentile:

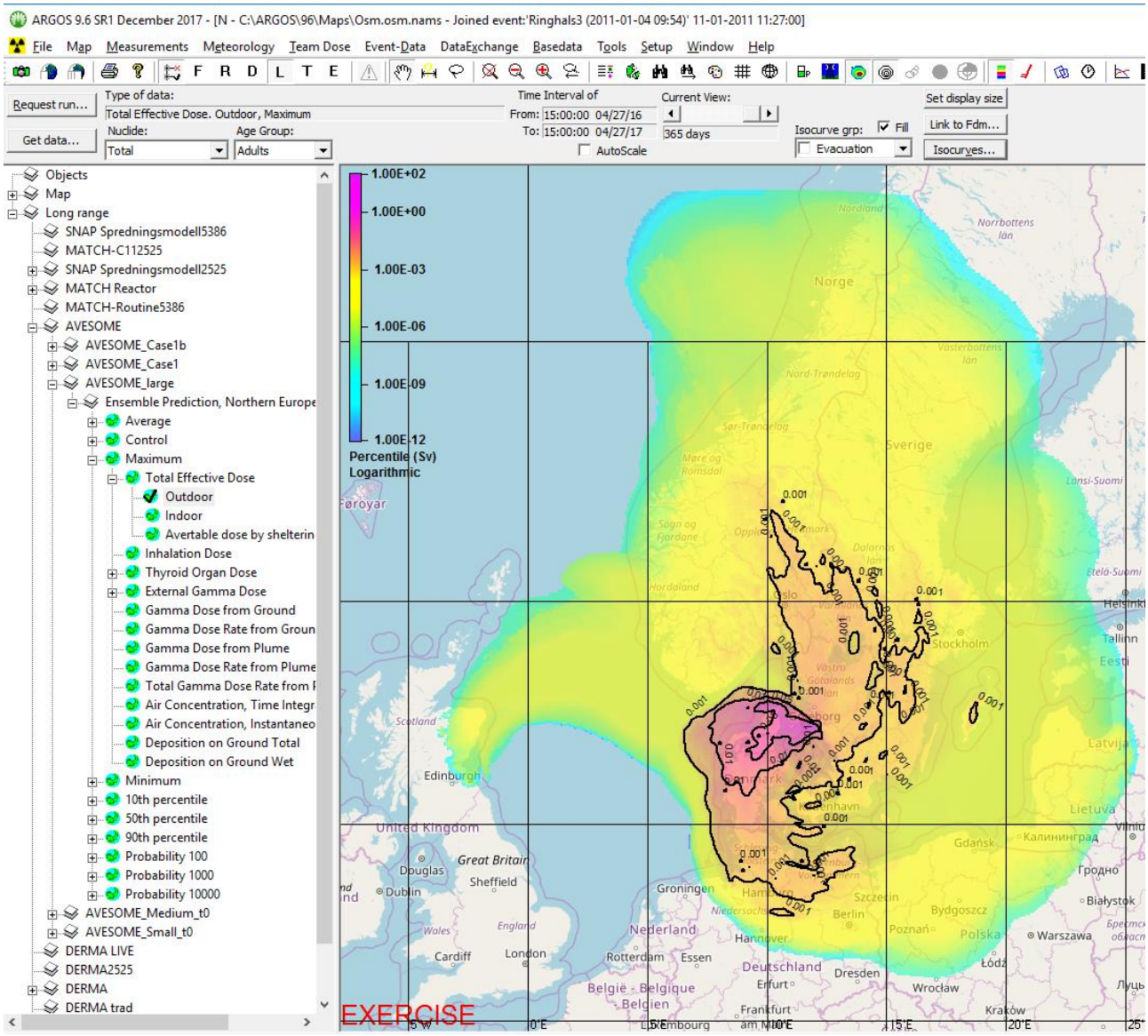


Figure 22 1, 10 and 50 mSv for the Maximum percentile (100%) of Total Effective Dose from a simulated release from Ringhals.

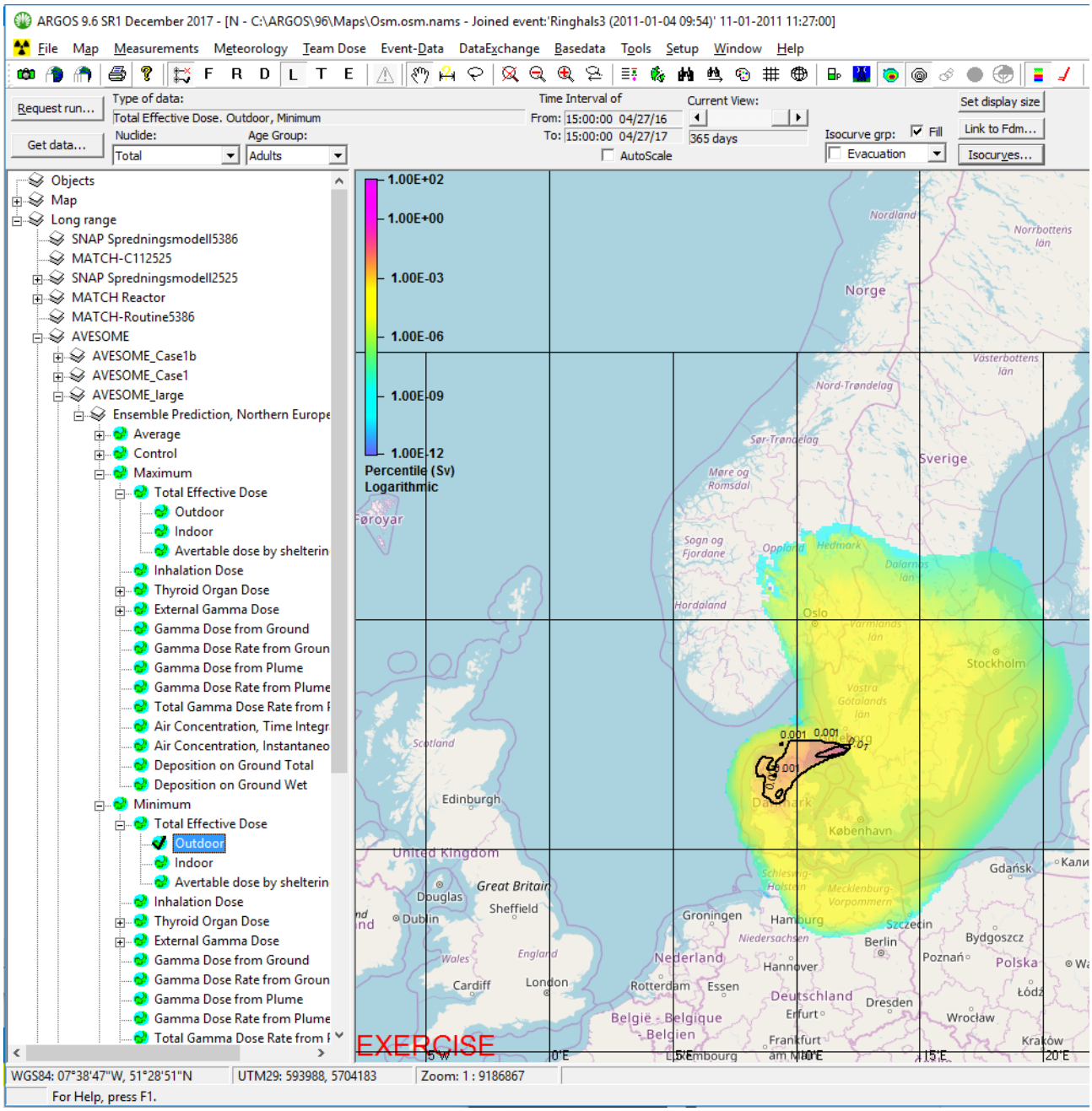


Figure 23 1 and 10 mSv (no values over 50) for the Minimum percentile (0%) of the same simulated release from Ringhals.

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.

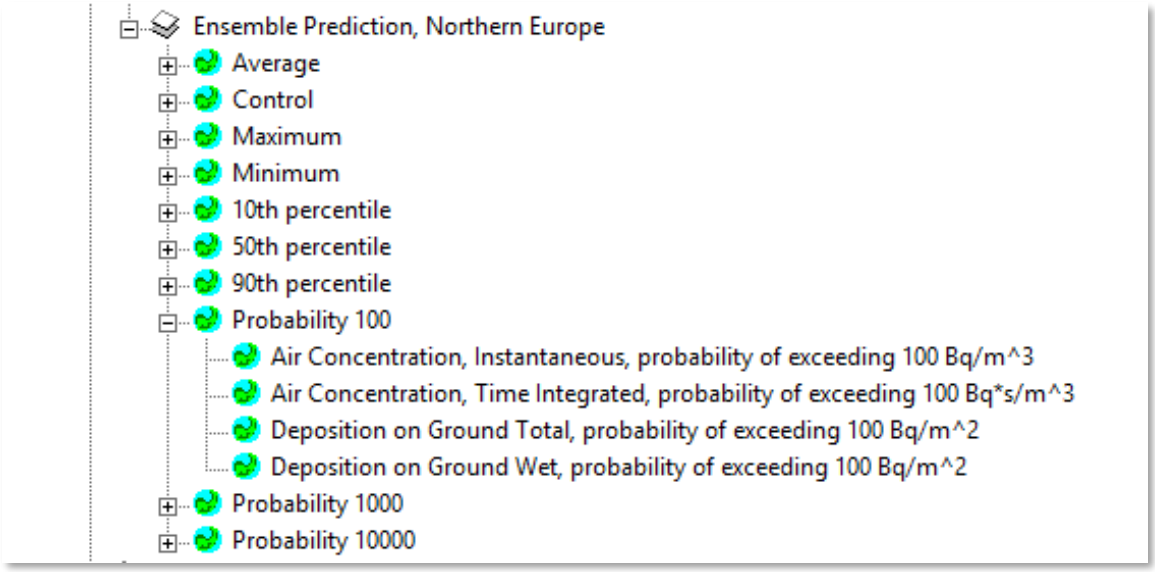


Figure 24 Statistical results with probabilities.

Example of showing probability for exceeding 10 kBq/m^2 deposition of Cs-137:

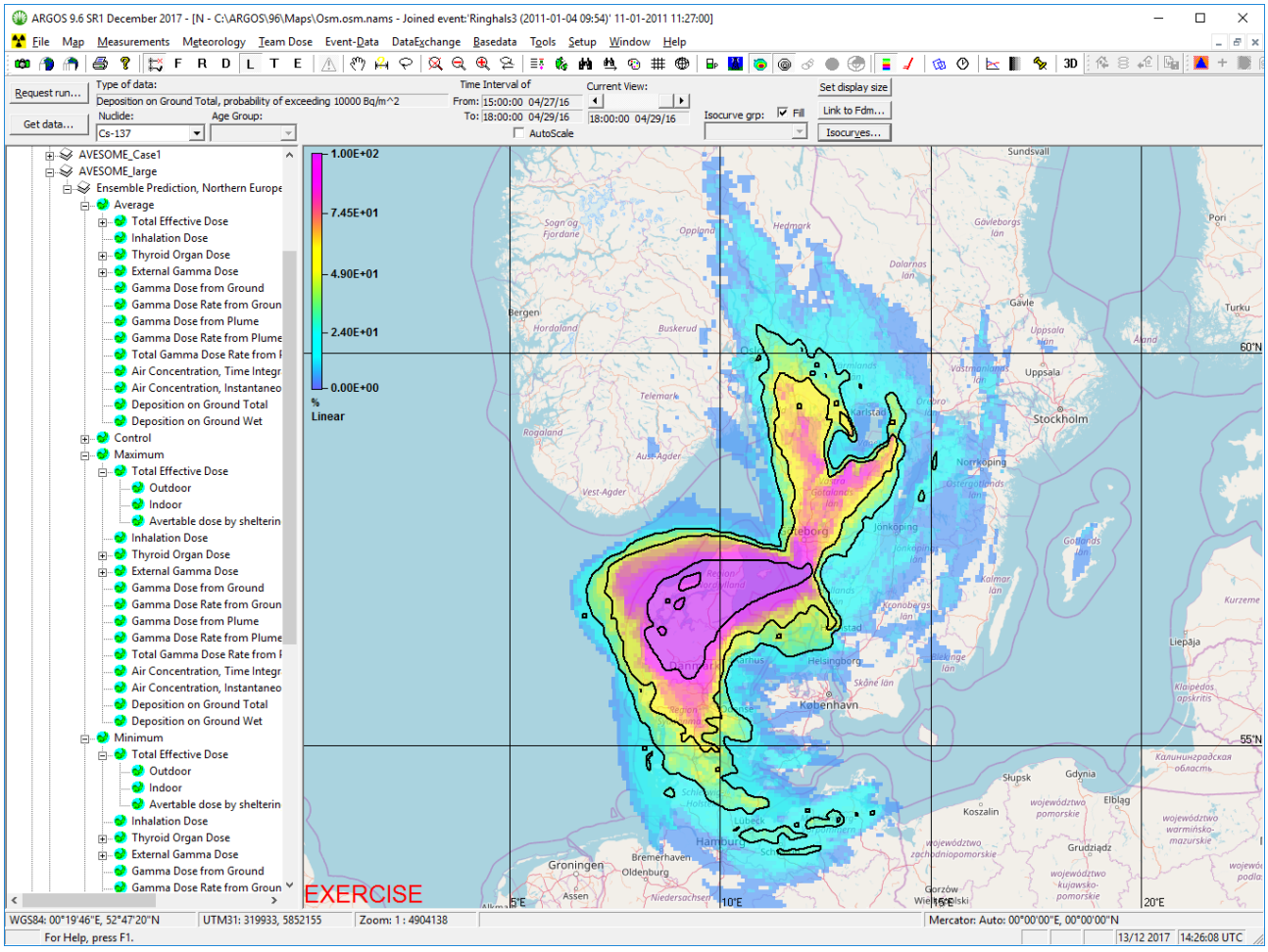


Figure 25 Probability of exceeding 10 kBq/m^2 deposition of Cs-137, lines for 100, 50 and 25% inserted.

Interface Changes between ARGOS and Long Range Model (DERMA)

Request-interface

For the first implementation of the AVESOME-project in ARGOS, the request-interface has remained unchanged.

Result-interface

As mentioned earlier, the Result-interface between ARGOS and DERMA has been 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:

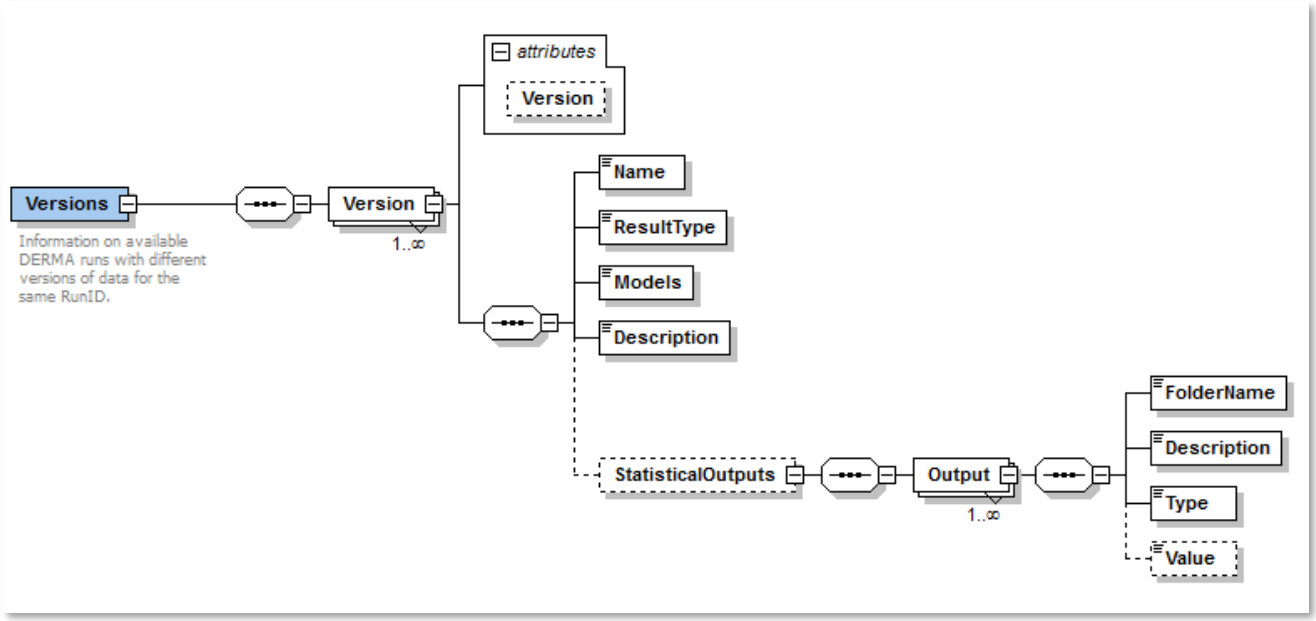


Figure 26 Versions-xml schema.

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 at different computers. Typically, the DSS is implemented at a personal computer, e.g. a laptop 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:
<ID>_DERMA_src000, <ID>_DERMA_src001, …, <ID>_DERMA_srcMMM
<ID>_DERMA_iso000, <ID>_DERMA_iso001, …, <ID>_DERMA_isoMMM
<ID>_DERMA_input
The file <ID>_DERMA_input is common for the different sources, holding among other data the geographical coordinates of the source and the start of the scenario.

If necessary, one could supply a weighting factor for each of the source-term ensemble members. However, since this is not known, and since as of today there are no means of describing this, it is suggested to employ an even distribution, i.e. to assume that each source term is equally likely.

The resulting data for ARGOS are organised as <ID> / <NWPmodel> / <src>; cf. also Figure 27.

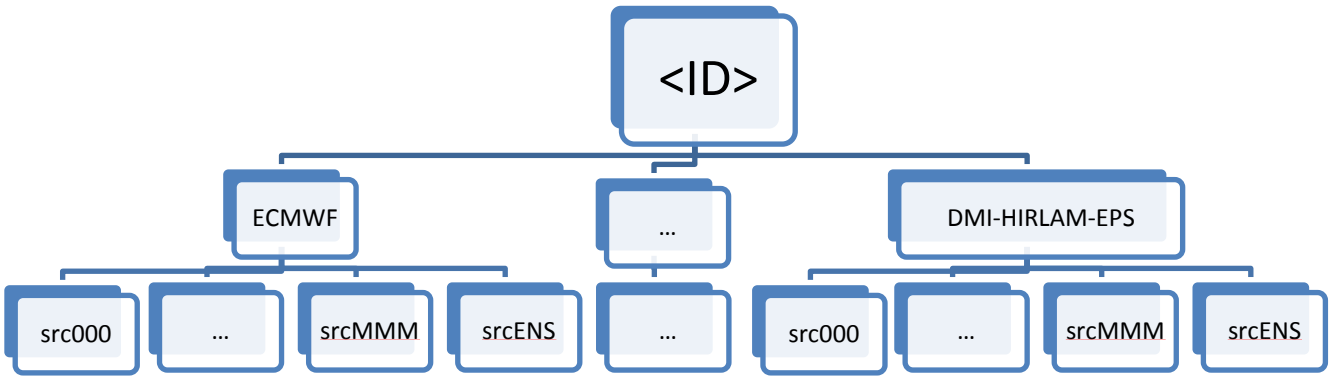


Figure 27 Structure of the content of the resulting data from DERMA to ARGOS.

The content of each src-block is as of today for deterministic and meteorological ensemble models, except for the srcENS 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

The implications have been addressed of the inherent uncertainties of the radionuclide source term on the prediction of atmospheric dispersion of radioactivity from a release. These 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. The impacts on real-time emergency management are being examined.

Collaboration has been initiated with the EU projects FASTNET and the Concert programme project CONFIDENCE, especially with respect to source-term model calculation and generation of source-term ensembles describing the inherent uncertainty. With current knowledge and existing operational source term models for real-time use in the early phase of an accident, one should expect that only a few source terms for a core-melt scenario will be available in real time. In the future, e.g. as a result of FASTNET, it is expected that one will have available a whole ensemble of source terms describing the possible releases. In AVESOME, a methodology is developed which can handle both a few-member source-term ensemble and a large ensemble spanning all possible releases. The AVESOME methodology will 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, which are being developed in AVESOME, allows 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 the high-performance computing (HPC) facilities available e.g. at national meteorological services, whereas less demanding post-processing should be carried out at the computer hosting the DSS. The former tasks include atmospheric dispersion model calculations; the latter include interactive communication with the super-computer as well as presentation of final results in the form of distributions of radionuclide concentrations, depositions and human doses.

The methodology developed is applied to three available release scenarios for the Ringhals NPP and to one meteorological situation represented by a 25-member weather ensemble. Based on a request for dispersion calculation at the HPC facility, the DSS user will optionally be able to either use the probabilistic presentation of all members of the source-term ensemble, or to use the individual source term members. The source-term ensembles employed here are very small. However, the methodology developed can be applied to any source-term ensemble, and thus the methodology is prepared for future integration with e.g. the RASTEP formalism 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 suggested for interactive communication between the DSS and the HPC facility enabling the 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 number of source-term descriptions, including a full source-term ensemble.

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Appendix A: Methods for Source Uncertainty

FOI-R--4534--SE

Fredrik Schönfeldt

Method for Source Uncertainty

Titel	Metod för källosäkerhet
Title	Method for Source Uncertainty
Rapportnr/Report no	FOI-R--4534--SE
Månad/Month	December
Utgivningsår/Year	2017
Sidor/Pages	25 p
Kund/Customer	Försvarsdepartementet
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FoT-område	
Projektnr/Project no	A403317
Godkänd av/Approved by	Mats Strömqvist
Ansvarig avdelning	CBRN-skydd och säkerhet

Sammanfattning

Detta arbete visar att det är möjligt att lägga till källtermens egenskaper i efterhand (postprocessering) på ett givet utdata från en partikelspridningsmodell. Den framtagna källensemblemetoden gör det möjligt att på ett effektivt sätt kunna studera effekten av osäkerheten i den temporala variationen hos ett radioaktivt utsläpp. De givna exemplen visar att metoden ger resultat som överensstämmer med förväntningarna, och ger en försmak av det ökade informationsvärde som den kan tillföra en spridningsprognos. Källensemblemetoden är enkel att kombinera med ett väderensemblesystem.

Nyckelord: Postprocesseringsmetod, ensembleprognoser, atmosfärisk spridning, partikelmodell

Summary

In this work the ability to post-process the properties of the source term onto the output from a particle dispersion model has been investigated and established. The aim is to present an efficient source ensemble method that can be used to study the impact of uncertainties in the temporal variation of radioactive emissions. The given examples of the method align with intuition and give a taste of the added information that the source ensemble method can give to dispersion forecasts. It is straightforward to merge the source ensemble method with a weather ensemble system.

Keywords: Post-processing method, ensemble prediction, atmospheric dispersion, particle model

Content

1 Introduction

There are many sources of uncertainty in modelling the dispersion of radioactive substances in the atmosphere. The meteorological uncertainties have had some recent attention with the use of *weather ensemble* techniques, see e.g. Sørensen, Amstrup, Feddersen, Korsholm, et al., (2014), Sørensen, Amstrup, Feddersen, Bartnicki, et al., (2016), and Sørensen, Amstrup, Bøvith, et al., (2017).

Another source of uncertainty is the source term: variations in the strength and temporal variation of the emission of the radioactive substance will largely impact the dispersion calculation. Until now the standard approach has been to set up of the source term in a pre-processing step to a dispersion model, which means that all properties of the source term have to be decided and set in advance to each model run.

In this work the idea is to remove the treatment of the source term from the pre-processing step and instead apply the properties of the source term in *post-processing*. This has a great practical advantage since the run-time of the more advanced dispersion models typically is in the order of hours. With post-processing, the properties of the source term can be replaced without having to re-run the model, now to a computational cost that can be expressed in seconds or minutes. These savings make it practically possible to develop the *source ensemble* method that is presented in this report.

2 Particle dispersion modeling

2.1 In general

In a random displacement particle dispersion model, in each time step of the iteration, each particle is moved by adding a mean wind contribution and a stochastic contribution, where the latter simulates the turbulence of the atmospheric flow. The PELLO particle dispersion model uses a random displacement formulation where the mean wind fields are given by the input from a numerical weather prediction model. Thomson, (1987) describes particle dispersion models in more detail.

2.2 Radioactive source term treatment

The emission rate at the source, the *source strength*, is in the radioactive case given in activity per second [Bq/s]. Conceptually this can be thought of as emitting a certain amount of radioactive Cesium per second from the source. In the dispersion model the source strength is constant between the start time t_s and the finish time t_f of the source. Therefore if n_p is the number of particles emitted during the interval $[t_s, t_f]$, the *emission rate* will be

$$r_p = \frac{n_p}{t_f - t_s} \quad [1/\mathrm{s}] \tag{1}$$

Thereby each particle is given a value v [Bq] that correlates to the emissions through

$$v = \frac{S}{r_p}. \tag{2}$$

Events where the source strength changes during the emission are simulated by using several sources in sequence after one another and with different source strengths. The source strength function $S(t)$ used by the model will therefore effectively be a staircase function.

2.3 Concentration and deposition

The concentration [Bq/m^3] or deposition [Bq/m^2] from the model is simply obtained by summing up the activities of the particles in a given air volume, or on a given area of ground respectively. The data from PELLO is smoothed by *Kernel density estimation* (KDE) (Björnham et al., 2015) while doing these conversions. Concentrations are calculated in the lowest 1000 m, which should give good statistics at some distance from the source, even for few particles.

3 The post-processing method

The post-processing method assumes that the effect of transformation processes can be ignored: this is often a good approximation regarding radioactive particles.

3.1 Basics

The activity that a particle has upon leaving the source unambiguously decides its activity at a later time, provided that the function for the radioactive decay is known. This is the fundamental assumption used for this method.

Let the *time-stamp* $t_\xi \geq 0$ label the time when the particle p leaves the source, $t > t_\xi$ some later point in time, usually the *forecast time*, and t_a the age of the particle. These are related through

$$t_a = t - t_\xi. \tag{3}$$

Time units will be in seconds unless stated otherwise.

If there is no radioactive decay present, the activity of the particle will remain constant:

$$\upsilon(t) = \upsilon(t_\xi). \tag{4}$$

If the particle rate from the model is constant, then (2) can be used to give

$$\upsilon(t) = \frac{S(t_\xi)}{r_p}. \tag{5}$$

The radioactive decay $\mathrm{RD}\,[\mathrm{non-dimensional}]$ can be expressed in terms of the half-life time $t_{1/2}$ by

$$\mathrm{RD}(t_a) = 2^{-t_a/t_{1/2}} \tag{6}$$

(Nordling and Österman, 1996). This can then be used together with (4) and (5) to give

$$\upsilon(t) = \upsilon(t_\xi) \cdot \mathrm{RD}(t_a) = \frac{S(t_\xi)}{r_p} \cdot \mathrm{RD}(t_a) = \frac{S(t_\xi)}{r_p} \cdot \mathrm{RD}(t - t_\xi). \tag{7}$$

This is the fundamental relation between the state of the particle when leaving the source and its state at some later time.

3.2 Unit source and post-processing

Let T be the total time interval where there are any emissions from a source to be simulated. The source strength $S : T \mapsto \mathbb{R}$ can be split up into a multiplication between a *unit source* S_I and a *source-factor function* $\Phi : \mathbb{R} \mapsto \mathbb{R}$ according to

$$S(t) = S_I \cdot \Phi(t). \tag{8}$$

The unit source is defined through

$$S_I = 1 \quad [\text{Bq/s}] \tag{9}$$

and the source-factor function by

$$\Phi(t) = \begin{cases} S(t)/S_I, & t \in T, \\ 0, & t \notin T. \end{cases} \qquad [\text{non} - \text{dimensional}] \tag{10}$$

Using (8) relation (7) can be written

$$\upsilon(t) = \frac{S_I \Phi(t_\xi)}{r_p} \cdot \text{RD}(t - t_\xi) = \upsilon_I \cdot \Phi(t_\xi) \cdot \text{RD}(t - t_\xi), \tag{11}$$

where $\upsilon_I := S_I/r_p$ is the activity that each particle emitted from a unit source gets. This shows that it is possible to calculate a particle's activity at any time t from a *unit run* provided that the functions Φ and RD are known.

The unit run is a central concept of the method: it is a particle dispersion model run where the source strength is set to S_I and where the the emission interval T_I covers the interval T: $T_I \supseteq T$. The unit run makes it possible to experiment with any properties of $S(t)$ and $\text{RD}(t)$ by post-processing on the interval T, *without* having to re-run the computationally expensive particle model.

Notice from (11) that in a unit run the activities of the particles will not be of unit value. This might seem odd, but by letting S_I have unit value and υ_I vary according to the particle rate, there is no need to keep track of how many particles there are in the simulation: There will be a direct relation between S_I, Φ and the resulting concentrations and depositions.

3.3 Variable source start

Last section described how the source properties can be applied in post-processing onto a unit run. This section will show how to construct new time-shifted sources from a given source and unit run; from a meteorologist's viewpoint it is of much interest to study the effects of the uncertainties in the source start time since this can potentially have a big impact on the forecast in relation to e.g. wind shifts, precipitation (particle washout) etc.

Let thus S be a source strength function that represents an emission that starts at time $t = 0\,\mathrm{h}$, and $\Phi(t)$ the corresponding source factor function. A new function, S', that is shifted by the delay[1] $t_\omega \geq 0$ can then be constructed by

$$S' = S_I \cdot \Phi(t - t_\omega). \tag{12}$$

Figure 1 illustrates an example with S depicted in blue and S' in red. In this particular case $t_\omega = 7\,\mathrm{h}$.

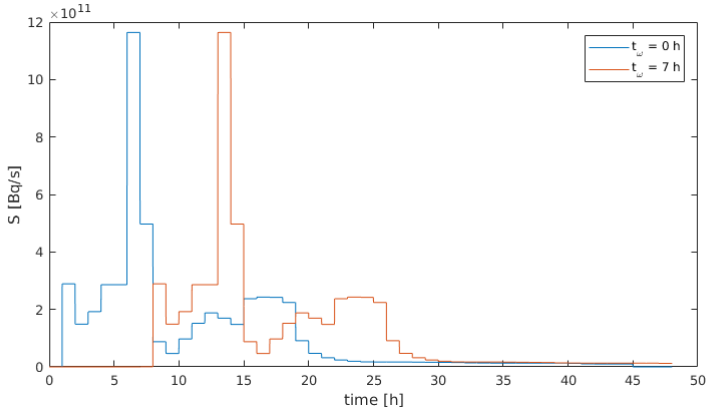

Figure 1: Using $S_I \cdot \Phi(t - t_\omega)$ to create a new source strength function that is shifted in time by the delay $t_\omega = 7\,\mathrm{h}$(red). Notice that the linear vertical scale does not resolve that the emission during the first hour is $4.5 \cdot 10^8$ Bq/s.

Equation (11) shows how the activity of a particle can be calculated from the unit run at forecast time t for a source represented by S and Φ. Referring again to Figure 1 it is now easy to see that the activity for a particle originating from a source S' delayed by t_ω can be calculated from

$$v(t) = v_I \cdot \Phi(t_\xi - t_\omega) \cdot \mathrm{RD}(t - t_\xi). \tag{13}$$

Now all is set to start building source start time dependent statistics from a single unit run.

[1] Outside this section t_ω will be called the *source start time*.

3.4 Constructing the source ensemble

A collection of forecasts where the source start times has been offset in time will be called a *source ensemble*. Two distinct approaches has been identified:

- *time-distribution* - the probability distribution of the source start times are given by the start times themselves: A time-interval where a source start is less likely has few ensemble members, a more likely interval has more. Each ensemble member will be as likely as all the others. One way of constructing the ensemble could be to draw the source start times as random samples from a known distribution.
- *weighted distribution* - the source start times are evenly distributed in the start time interval and the probability distribution is instead described by adding a weight to each ensemble member.

The weather ensemble members from a numerical forecast model does not use any weights for probabilities and therefore the first approach is more straightforward to merge with such a system. The latter approach will, on the other hand, give a cheaper way to span the probability space of the output.

Using Equation (13) the source ensemble can be constructed according to Algorithm 1. This algorithm keeps all particles and just zeroes out the activities of the particles that does not belong to a particular ensemble member: see Equation (10). An actual implementation could also remove particles with zero activity if one wishes to save memory. This will also save computation time when later using the source ensemble.

Input: P - the particle state (struct) from the unit run at forecast time t, Φ - the source-factor function, RD - the radioactive decay, $\mathbf{t}_\omega \in \mathbb{R}^m$ - source start times, and $\mathbf{w} \in \mathbb{R}^m$ - weights.
Output: The struct PE containing the source ensemble for forecast time t.

1 Allocate memory for PE;
2 **for** *every source ensemble member* i **do**
3 **for** *every particle* j **do**
4 $(PE_i).x_j \leftarrow P.x_j$;
5 $(PE_i).y_j \leftarrow P.y_j$;
6 $(PE_i).z_j \leftarrow P.z_j$;
7 $(PE_i).v_j \leftarrow P.v_j \cdot \Phi(P.t_{\xi,j} - t_{\omega,i}) \cdot \mathrm{RD}(t - t_{\xi,j})$;
8 $(PE_i).w \leftarrow w_i$;
  `/* plus any additional parameters */`
9 **end**
10 **end**
11 OUTPUT PE;
12 STOP;

Algorithm 1: Algorithm for building the source ensemble PE. Here $\leftarrow$ is the assignment operator.

3.5 Source ensemble statistics

Section 2.3 describes how concentration and deposition is calculated from a single forecast from the dispersion model. The report from the MESO project (Sørensen, Amstrup, Bøvith, et al., 2017) has some suggestions how the result from a weather ensemble forecast can be presented.

Here, besides being able to present the result from each separate source ensemble member, three different statistic measures will be used. The *maximum* will be calculated by

$$\theta_{max}(\mathbf{r},t) = \max_{i=1,\ldots,m} \theta_i(\mathbf{r},t), \tag{14}$$

the *mean* by

$$\theta_{mean}(\mathbf{r},t) = \sum_{i=1}^{m} w_i \cdot \theta_i(\mathbf{r},t), \tag{15}$$

and the *standard deviation*[2] by

$$\theta_{sd}(\mathbf{r},t) = \left(\frac{\sum_{i=1}^{m} w_i \left(\theta_i(\mathbf{r},t) - \theta_{mean}(\mathbf{r})\right)^2}{1 - \sum_{i=1}^{m} w_i^2} \right)^{\frac{1}{2}}. \tag{16}$$

Here i labels the source ensemble members, θ concentration or deposition, $\mathbf{r}$ the geographical location and t the forecast time. Notice that the mean and the standard deviation are weighted to be able to handle both approaches given in Section 3.4, and that the weights are assumed to be normalized ($\sum_{i=1}^{m} w_i = 1$). The maximum only looks for the maximum value that any ensemble member has at a particular location: consequently the calculation does not contain any weights.

[2] Unbiased.

4 Post-processing method examples

The method outlined in Section 3 was implemented in Matlab together with routines for plotting. This section shows some basic examples using the method with a weighted distribution and then a time-distribution. The same meteorological case is used.

4.1 Source term

In describing the source term there are mainly two issues to consider: (1) How does the source strength vary in time, i.e. what $S(t) = S_I \cdot \Phi(t)$ to use, and (2) what does the distribution of the source start time t_ω look like? Unfortunately there is no suitable data available for either of these, hence they will be fictitious.

The temporal behaviour of the source strength, which will be used for all ensemble members, is described in Figure 2

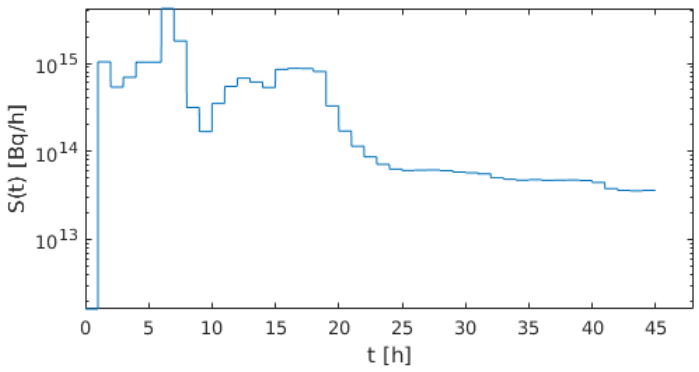

Figure 2: The source strength as a function of time. This was used to build up the source ensemble in the examples. The release, which is assumed to consist of only Cs-137, starts at $t = 0$ h and stops at $t = 45$ h. Notice that the vertical axis (and the release) begins at the value $1 \cdot 10^{-12}$ Bq/h.

For the distribution of the source start time it is assumed that the release to the atmosphere will start within 10 hours of the actual incident and most likely after 5 hours. It is reasonable to assume that it is approximately normal-distributed. The details will be given in the examples.

The simulation will be done using about 100 000 particles and the source for the release will be the nuclear power plant in Brokdorf, Schleswig-Holstein, Germany.

4.2 Meteorological case 1 march 2016

The examples use the same meteorological case reaching from 1 March 2016 until 3 March 2016. Figure 3 shows an overview of the synoptic situation. At the start of the release from Brokdorf there is a fresh southerly wind and a front with precipitation passes to the east during the first 24 hours. Then the wind weakens and becomes westerly at first and then southerly again. This is one of the cases used in Sørensen, Amstrup, Bøvith, et al., (2017). In all examples PELLO will be run using meteorological fields from the ECMWF model with base-time 2016-03-01, 00 UTC. The source start times will be in a 10 hour time window between 2016-03-01, 12 UTC and 2016-03-01, 22 UTC, i.e. centered on 2016-03-01, 17 UTC.

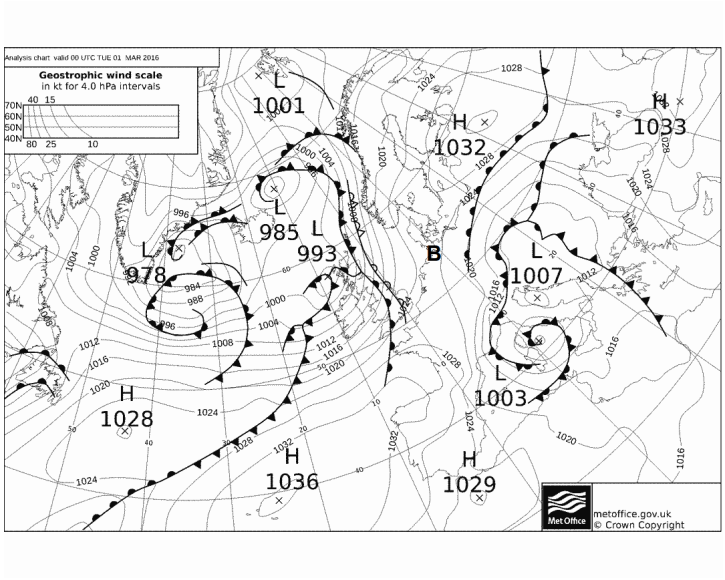

Figure 3: Synoptic situation on 2016-03-01, 00 UTC. The source used in the examples is the nuclear power plant in Brokdorf, Schleswig-Holstein, Germany. It is marked by the letter B.

4.3 Distribution by weights

This example shows how source term uncertainties can be treated by the method with weights. Presented will be the prediction of concentrations and deposition of Cs-137 valid at 2016-03-03, 12 UTC. This will be a 60 hour forecast counting from the dispersion model base-time at 2016-03-01, 00 UTC. This example uses 10 different source start times linearly distributed between 2016-03-01, 12:30 UTC and 2016-03-01, 21:30 UTC, with weights

$$\mathbf{w} = (0.02, 0.04, 0.1, 0.14, 0.2, 0.2, 0.14, 0.1, 0.04, 0.02)$$

This will simulate a normal-distribution for the source start centered on 2016-03-01, 17 UTC, with a sample standard deviation of 2 hours.

A value of 30 years was used for the half life time of the Cs-137, which means that the activities of the particles are approximately constant during the simulation.

4.3.1 Air concentrations

Figure 4 shows that there are clear differences in the concentration fields between the ten source ensemble members: The first member shows dispersion over a larger area than the last; this is since during the first 10 hours of the scenario, from 12 to 22 UTC on the 2016-03-01, the wind is coming from between south-west and west, while during the rest of the period the wind is rather straight from the south. In the last member neither the southern parts of Sweden nor Poland are affected, but on the other hand there are higher concentrations over Jutland.

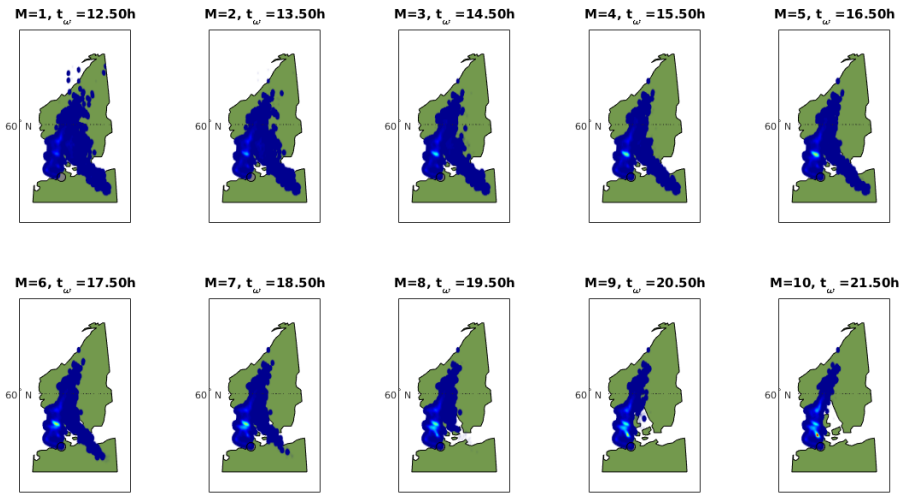

Figure 4: Prediction of concentrations [Bq/m^3] of Cs-137 valid at 2016-03-03, 12 UTC. The ten source starts are linearly distributed between 2016-03-01, 12:30 UTC and 2016-03-01, 21:30 UTC. The same scale as in Figure 5 applies.

Figure 5 shows the result from applying the statistical measures from Section 3.5. In in the maximum concentration plot the ten members are equally important: this kind of product might e.g. be used to make conservative judgments of risk areas. In the mean and standard deviations plots the weights has been applied: The mean plot can typically be used to asses the most likely scenario, while the standard deviation can give compiled information on the uncertainty.

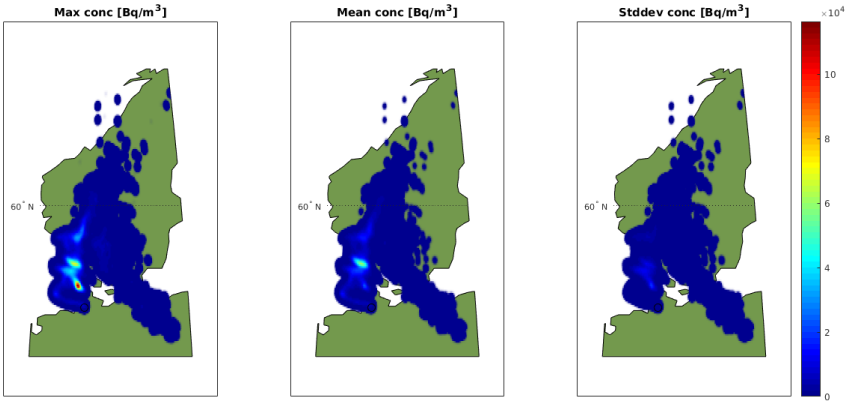

Figure 5: Prediction of max, mean and standard deviation of concentrations [Bq/m^3] of Cs-137 valid at 2016-03-03, 12 UTC. This uses the weighted method with ten source starts linearly distributed between 2016-03-01, 12:30 UTC and 2016-03-01, 21:30 UTC.

4.3.2 Deposition concentrations

Figure 6 shows that there are distinct differences between the ten members also in the deposition fields: They can be explained by, as in the previous section, that the wind had a westerly component during the first ten hours of the scenario, while then being mainly from the south.

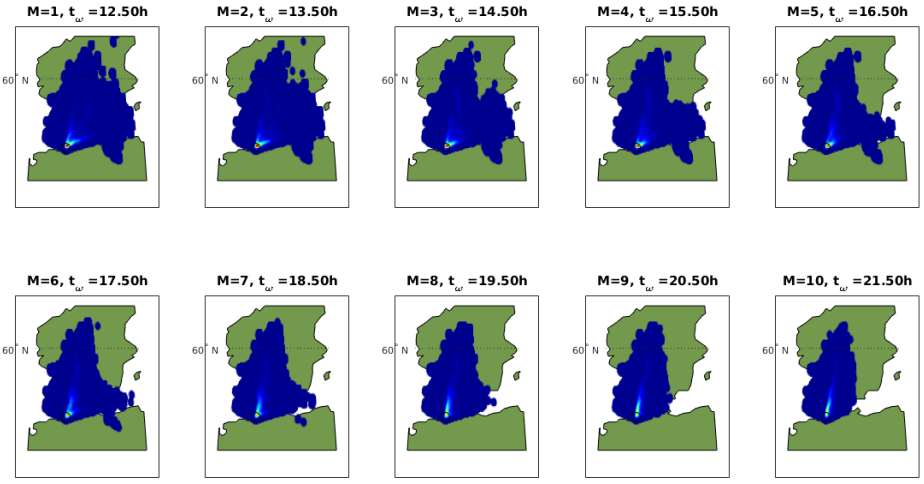

Figure 6: Prediction of deposition [Bq/m^2] of Cs-137 valid at 2016-03-03, 12 UTC. The ten source starts are linearly distributed between 2016-03-01, 12:30 UTC and 2016-03-01, 21:30 UTC. The same scale as in Figure 7 applies.

Looking at the statistical fields in Figure 7 there seems to be little difference between the maximum and mean plot. This is likely due to that the linear scale badly resolves the smaller values of deposited activity.

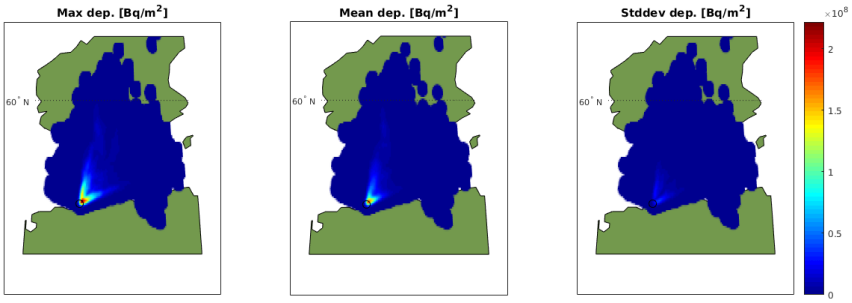

Figure 7: Prediction of max, mean and standard deviation of deposition [Bq/m^2] of Cs-137 valid at 2016-03-03, 12 UTC. This uses the weighted method with ten source starts linearly distributed between 2016-03-01, 12:30 UTC and 2016-03-01, 21:30 UTC.

4.4 Distribution by time

This example shows how source term uncertainties can be treated by time-distribution. Just as in the weighted case, concentrations and deposition of Cs-137 will be shown at 2016-03-03, 12 UTC (2016-03-01, 00 UTC + 60 hrs). This example uses 50 different source start times distributed on the 10 hour interval from 2016-03-01, 12 UTC to 2016-03-01, 22 UTC according to Figure 8. This simulates a normal distribution centered on 2016-03-01, 17 UTC, with a sample standard deviation of 2 hours.

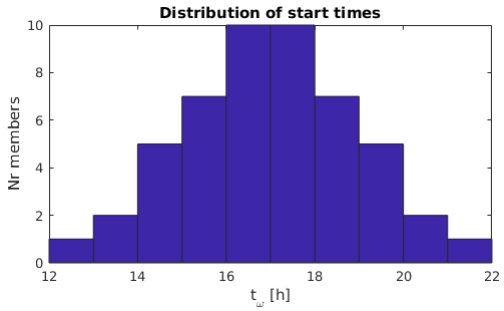

Figure 8: Histogram showing how many source starts there were in each one-hour interval.

4.4.1 Air concentrations

Plotting all 50 members from the 10 hour interval source start times will qualitatively give the same information as the 10 members in the weighted case: therefore they will not be shown. For the statistical measures Figure 9 shows close to identical results as in the weighted case. This is expected.

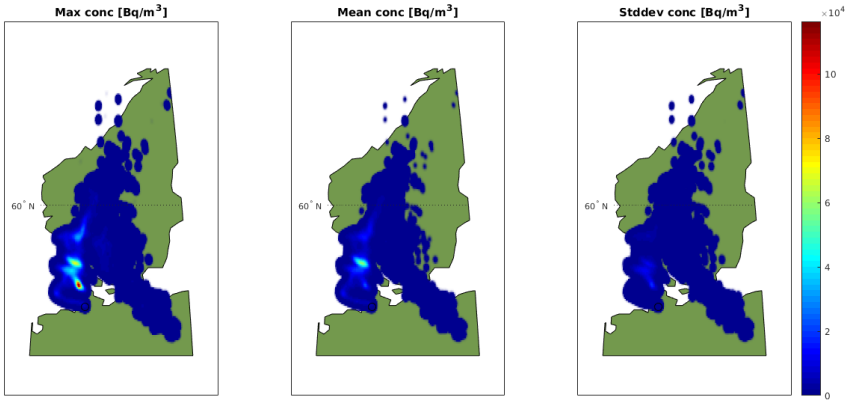

Figure 9: Prediction of max, mean and standard deviation of concentrations [Bq/m^3] of Cs-137 valid at 2016-03-03, 12 UTC. This uses the time-distribution with 50 source starts normal distributed between 2016-03-01, 12 UTC and 2016-03-01, 20 UTC.

Since each ensemble member can be regarded as equally likely in this method, and since there are now quite a few of them, it is straightforward to look at the data in other ways. To give an example of what one could do, Figure 10 shows a histogram over the air concentrations at latitude 56.4°N and longitude 8.3°E: the location of the maximum in the source ensemble mean over northwestern Jutland. Since more than 30 of the 50 members has calculated probabilities of concentrations between $6{\cdot}10^4$ and $7{\cdot}10^4$ Bq/m^3, the risk of obtaining these values can be judged as high. From this kind of product the form of the distribution might also add some value.

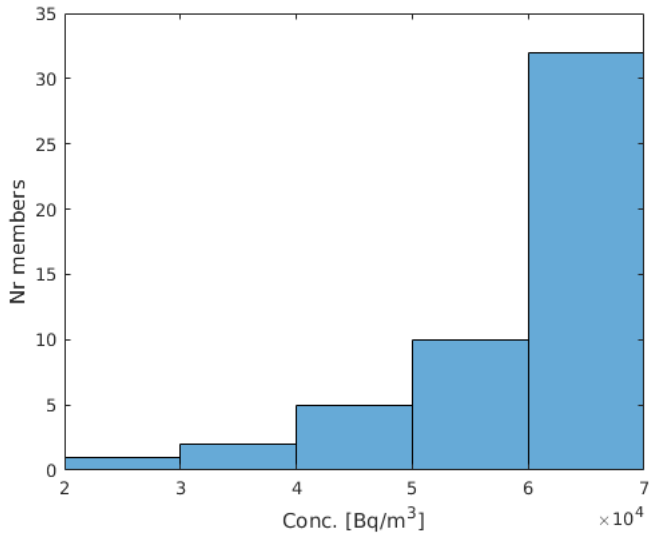

Figure 10: Histogram of air concentrations at the maximum in the source ensemble mean. This is located at 56.4°N; 8.3°E. The valid time is 2016-03-03, 12 UTC.

4.4.2 Deposition concentrations

For the 50 member time-distribution ensemble, Figure 11 shows the statistical measures. Yet again the result is just about identical to the corresponding weighted case.

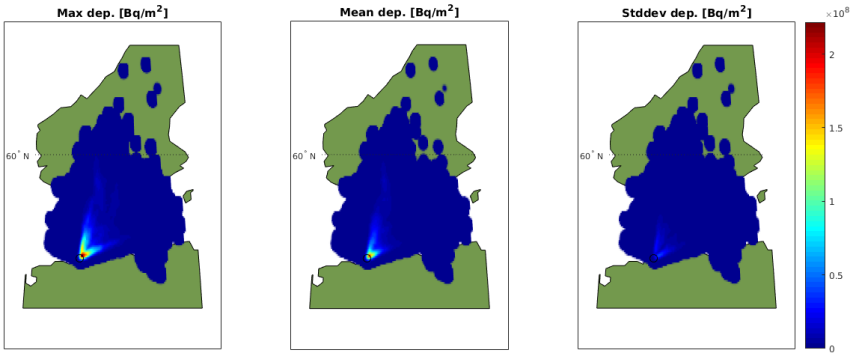

Figure 11: Prediction of max, mean and standard deviation of deposition [Bq/m^2] of Cs-137 valid at 2016-03-03, 12 UTC. This uses the time-distribution with 50 source starts normal distributed between 2016-03-01, 12 UTC and 2016-03-01, 22 UTC.

Figure 12 shows a histogram over the deposition concentrations at latitude 53.9°N and longitude 9.5°E: the location of the maximum in the source ensemble mean just to the northeast of Brokdorf. This distribution looks different than in the corresponding product for air concentrations; it looks more like a normal-distribution. There are more than 20 members with deposited concentrations between $1.5 \cdot 10^8$ and $1.8 \cdot 10^8$ Bq/m^2.

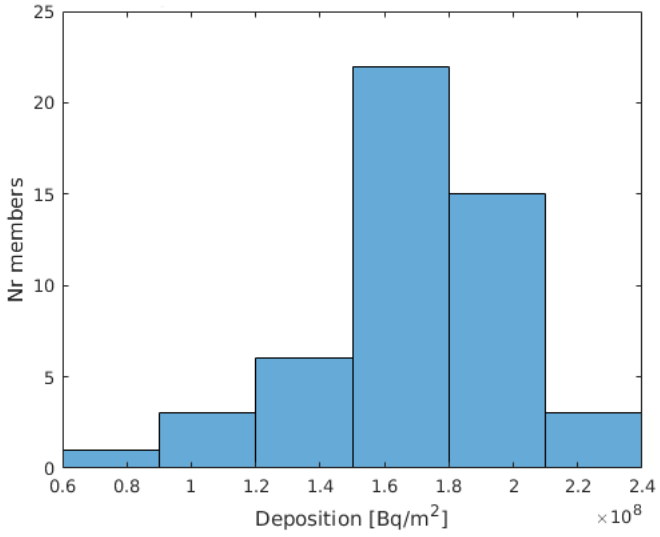

Figure 12: Histogram of deposition concentrations at the maximum in the source ensemble mean. This is located at 56.4°N; 8.3°E. The valid time is 2016-03-03, 12 UTC.

4.5 Performance

On an Intel Core I5 laptop, using one core, building the source ensemble (Matlab implementation of Algorithm 1) typically takes a couple of fractions of a second. The calculation of the concentrations/depositions and the statistical measures typically take a couple of minutes. This figures are based on a problem size of approximately 100 000 particles.

Looking at the complexity of the method, Algorithm 1 has one for-loop over the ensemble members and one for-loop over the number of particles. Keeping the number of ensemble members constant, this means that the complexity of the method is linear, $O(n)$, in regard to the number of particles. This is a pleasing property.

5 Discussion

In this work the ability to post-process the properties of the source term has been investigated and established. This has made it possible to develop the suggested source ensemble method which can be used to study the impact of uncertainties in the temporal variation of radioactive emissions. This method is above all characterized by a high computational efficiency. The source ensemble should be straightforward to merge with a weather ensemble system.

The given examples, with the fictitious source term and source start distribution, demonstrates some of the preliminary features of what one could expect to get in terms of added information to support decisions in the case of a nuclear accident. More investigation could be spent in this regard; different questions might be easier answered by looking at the statistics in a different way.

There are plans to extend this method to handle several source strength functions. This will add flexibility to study other uncertainties than just temporal ones. This feature should be straightforward to add: one way could be to pass a vector of function pointers to source strength functions as an argument to the source ensemble algorithm.

Another line of development could be to treat the splitting of nuclides in post-processing. This would then make up for a really flexible and efficient post-processing method.

6 Acknowledgement

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A Test of algorithm

The most critical part in the post-processing method is the algorithm that builds the source ensemble. Here it is checked that the results from the post-processing method are comparable to those obtained from using the model with pre-processed source behaviour, and in addition it is checked that the time shifting functionality works as expected. The test is performed using the Matlab implementation.

The simple but distinct test function will be

$$\Phi(t) = \begin{cases} 2, & t \in [0,1), \\ 4, & t \in [1,2), \\ 3, & t \in [2,48), \\ 0, & \text{otherwise}, \end{cases} \tag{17}$$

where the units for t is in hours and Φ is dimensionless. This function is shown in Figure 13.

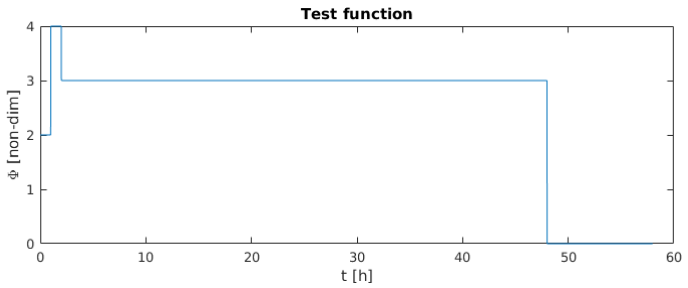

Figure 13: The source-factor-function Φ used in the test.

From this test function and the unit run used in Section 4, a two member source ensemble is constructed with source start times $t_\omega = 0$ h and $t_\omega = 7$ h. Next the test function is prescribed as input to the model (pre-processed source behaviour) to create two reference runs corresponding to the same source start times and using the same meteorological fields from ECMWF as in the unit run. Comparing the activities of the particles between the source ensemble and the reference runs Figure 14 shows that the results are practically identical. The forecast time is $t = 60$h, but this could have been chosen arbitrarily from within the length of the forecast.

At a closer study, the difference in mean on each step interval between the ensemble members and the reference runs is no greater than $\Delta v < 2 \cdot 10^{-6}$ and the relative difference $\Delta v / v < 4 \cdot 10^{-8}$. This shows that the post-processing approach and that the Matlab implementation works.

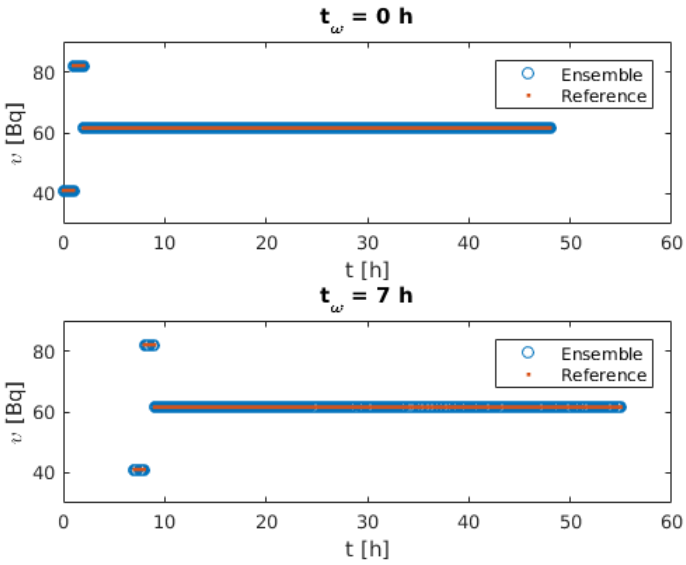

Figure 14: Comparison between the particle activities from the source ensemble (circles) and the two reference runs (dots). The source start times were $t_\omega = 0$ h and $t_\omega = 7$ h.

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Abstract
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In the early phase of a nuclear accident, two large sources of uncertainty exist: one related to the source term and one associated with the meteorological data. Operational methods are being developed in AVESOME for quantitative estimation of uncertainties in atmospheric dispersion prediction resulting from uncertainties in assessments of both the release of radionuclides from the accident and their dispersion.

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.

In the recent NKS-B projects MUD, FAUNA and MESO, 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 nuclear DSS have been described and demonstrated. In AVESOME, we address the uncertainty of the radionuclide source term, i.e. the amounts of radionuclides released and the temporal evolution of the release. Furthermore, the combined uncertainty in atmospheric dispersion model forecasting stemming from both the source term and the meteorological data is examined. Ways to implement the uncertainties of forecasting in DSSs, and the impacts on real-time emergency management are described.

The proposed methodology allows for efficient real-time calculations. Accordingly, the computer-resource demanding calculations should be carried out at the high-performance computing facilities available e.g. at the national meteorological services, whereas less demanding post-processing could be carried out at the computer hosting the DSS. The former tasks include the atmospheric dispersion model calculations; the latter includes interactive communication with the supercomputer as well as presentation of final results.

Key words

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