

NKS-307
ISBN 978-87-7893-385-0

Meteorological Uncertainty of atmospheric Dispersion model results (MUD)

Jens Havskov Sørensen¹
Bjarne Amstrup¹
Henrik Feddersen¹
Ulrik Smith Korsholm¹
Jerzy Bartnicki²
Heiko Klein²
Peter Wind²
Bent Lauritzen³
Steen Cordt Hoe⁴
Carsten Israelson⁴
Jonas Lindgren⁵

¹Danish Meteorological Institute

²Norwegian Meteorological Institute

³Technical University of Denmark

⁴Danish Emergency Management Agency

⁵Swedish Radiation Safety Authority

May 2014

Abstract

The MUD project addresses assessment of uncertainties of atmospheric dispersion model predictions, as well as optimum presentation to decision makers. Previously, it has not been possible to estimate such uncertainties quantitatively, but merely to calculate the 'most likely' dispersion scenario. However, recent developments in numerical weather prediction (NWP) include probabilistic forecasting techniques, which can be utilised also for atmospheric dispersion models.

The ensemble statistical methods developed and applied to NWP models aim at describing the inherent uncertainties of the meteorological model results. These uncertainties stem from e.g. limits in meteorological observations used to initialise meteorological forecast series. By perturbing the initial state of an NWP model run in agreement with the available observational data, an ensemble of meteorological forecasts is produced. In MUD, corresponding ensembles of atmospheric dispersion are computed from which uncertainties of predicted radionuclide concentration and deposition patterns are derived.

Key words

nuclear emergency preparedness, atmospheric dispersion model, meteorology, uncertainty, ensemble prediction

NKS-307
ISBN 978-87-7893-385-0

Electronic report, May 2014
NKS Secretariat
P.O. Box 49
DK - 4000 Roskilde, Denmark
Phone +45 4677 4041
www.nks.org
e-mail nks@nks.org

Meteorological Uncertainty of atmospheric Dispersion model results MUD

Final Report of the NKS-B MUD activity

Contract: AFT/B(13)2

Jens Havskov Sørensen¹ (co-ordinator), Bjarne Amstrup¹, Henrik Feddersen¹,
Ulrik Smith Korsholm¹,

Jerzy Bartnicki², Heiko Klein², Peter Wind²

Bent Lauritzen³

Steen Cordt Hoe⁴, Carsten Israelson⁴

Jonas Lindgren⁵

¹Research and Development Department, Danish Meteorological Institute

²Norwegian Meteorological Institute

³Center for Nuclear Technologies, Technical University of Denmark

⁴Nuclear Division, Danish Emergency Management Agency

⁵Swedish Radiation Safety Authority

Table of contents

1. Introduction	1
2. Atmospheric ensemble prediction and uncertainties in DSSs	2
3. Dose calculations	4
4. Presentation of meteorological uncertainties of atmospheric dispersion model calculations	6
5. Selection of release scenarios	7
6. Selection of meteorological scenarios	8
7. Description of the DMI meteorological EPS	9
<i>7.1 DMI EPS runs for MUD</i>	<i>10</i>
7.1.1 20 May 2011 case	10
7.1.2 14 August 2011 case	11
7.1.3 8 January 2012 case	13
7.1.4 7 March 2012 case	15
8. Description of the GLAMEPS meteorological EPS	17
9. Description of the DMI atmospheric dispersion model DERMA	19
<i>9.1 DERMA runs for MUD</i>	<i>20</i>
10. Description of the MET Norway atmospheric dispersion model EEMEP	21
<i>10.1 EEMEP runs for MUD</i>	<i>22</i>
11 Results on dispersion model uncertainties	23
12. EPS for DSS	30
<i>12.1 Interactive automatic communication between NMS and DSS</i>	<i>30</i>
<i>12.2 MUD – an End User Perspective</i>	<i>30</i>
13. Conclusions	33
Acknowledgements	34
Disclaimer	34
14. References	35

1. Introduction

The NKS-B project Meteorological Uncertainty of atmospheric Dispersion model results (MUD) addresses assessment of uncertainties of atmospheric dispersion model predictions, as well as means for presentation of uncertainties to decision makers.

Atmospheric dispersion model calculations of anticipated radionuclide releases from a nuclear accident should assist decision makers in assessing contamination levels, to provide information on the radiation hazards, and possibly to facilitate decisions on protective actions. This is implemented in emergency management through Decision Support Systems (DSSs) such as the ARGOS or RODOS systems.

Current DSSs, however, do not include uncertainties in presentations of atmospheric dispersion and deposition patterns, but merely present a 'most likely' dispersion scenario. However, recent developments in numerical weather prediction (NWP) include probabilistic forecasting techniques, which can be utilised also for atmospheric dispersion models and allows incorporation in DSSs.

The ensemble statistical methods developed and applied to NWP models aim at describing the inherent uncertainties of the meteorological model predictions. These uncertainties stem from e.g. limitations in meteorological observations used to initialise meteorological forecast series. By perturbing the initial state of an NWP model run in agreement with the available observational data, an ensemble of meteorological forecasts is produced from which uncertainties in the various meteorological parameters are estimated, such as probabilities for rain. By running an atmospheric dispersion model describing an accidental release of hazardous matter for each of the meteorological ensemble members, corresponding ensembles of atmospheric dispersion can now be computed from which air concentration and deposition patterns can be obtained, including estimates of the uncertainty in the model calculations.

In the NKS/MUD project, meteorological scenarios have been selected involving windy cyclonic and low-wind anti-cyclonic conditions as well as convective summer precipitation, resulting in large uncertainties in the deposition patterns. The DMI operational meteorological ensemble prediction system has been applied to these cases providing input for the atmospheric dispersion models DERMA and EEMEP. Four nuclear power plants in the vicinity of the Nordic countries have been selected and a common release scenario described, and the dispersion models have been executed for these scenarios.

There is a variety of different statistical parameters which can be calculated from an ensemble. However, in a time-critical and stressful situation associated with an accidental release of hazardous material, it is considered important to have available only few predefined parameters which the decision makers are acquainted with and which can readily be comprehended. Accordingly, the use of uncertainties for nuclear decision support, including presentation, has been discussed thoroughly, and a selection of methods has been made.

Interactive communication between national meteorological services and nuclear decision-support systems, using the Accident Reporting and Guidance Operational System (ARGOS) (Hoe *et al.*, 2002; Hoe *et al.*, 1999), as an example, has been examined as well as use of automatic procedures. And the numerical results of MUD have been made available in a format which can be imported in ARGOS, which will thereby host the demonstration of MUD results.

2. Atmospheric ensemble prediction and uncertainties in DSSs

The first Ensemble Prediction System (EPS) system for NWP became operational in 1992 Molteni *et al.* (1996) considering dynamically defined perturbations in initial conditions. Since then, the concept of meteorological ensembles has become an essential part of NWP at a number of meteorological institutes in Europe. The availability of meteorological EPS output together with substantial increases in computer power has made possible the usage of operational ensemble based atmospheric dispersion model systems for emergency preparedness.

In an emergency situation there are several sources of dispersion uncertainty which must be considered before decisions on counter measures can be taken. The strength, composition and position of the source, release height and uncertainties related to meteorological input data and boundary conditions, intrinsic model uncertainties due to model formulations and stochastic variations in the atmosphere, cf. e.g. Rao (2005) and Burman *et al.* (2013). A basic question is: How large are the uncertainties associated with the meteorological input driving the dispersion models? The individual members of the meteorological ensemble system may be considered as probing the probability density function (PDF) of possible forecasts. Assuming that the PDF is well represented by the ensemble system, both the meteorological uncertainties and the most likely weather development may be calculated. By using the meteorological ensemble to force the dispersion models, thereby generating an EPS based dispersion ensemble, the influence of uncertainties of the meteorological input may be addressed.

A dispersion ensemble may be obtained following different types of methodologies which in some cases probe different types of uncertainty. Perturbing the initial conditions or intrinsic model process descriptions of either the dispersion or the meteorological model, or using different combinations of meteorological and dispersion models, are examples of methodologies resulting in a dispersion ensemble. In practise, most dispersion ensembles are based on the availability of operational meteorological ensemble systems and therefore uses only one dispersion model (Straume, 2000; Warner, 2002; Lee *et al.*, 2009) although examples of multi-model ensembles do exist (Galmarini *et al.*, 2010; Potempski *et al.*, 2010). For specific investigations into e.g. the representativeness of ensemble spread in describing forecast error, more idealized ensemble methodologies based on statistical quantities have also been considered (Kolczynski, 2009; Draxler, 2002).

The usage of different types of ensemble methodologies has previously been investigated (Galmarini *et al.*, 2010). However, due to the strict time requirements for operational emergency preparedness models, timely computation of an ensemble of dispersion models may not be possible and it therefore seems sensible to rely on the readily available meteorological ensembles for dispersion calculations.

The execution of a dispersion model for a whole NWP ensemble is easily parallelized since there is no data exchange between ensemble members during the model runs. Assuming sufficient computing power, the forecast time is only minimally affected, due to the calculation of dispersion statistics for presentation and further processing in the DSS, when using the ensemble methodology instead of a single deterministic realization of the dispersion model.

Previously, in projects such as ETEx (Graziani *et al.*, 1998), analytical tools for model inter-comparison as well as comparison with observations have been considered. However, tools

for interpretation and presentation for decision makers could be further developed. The EU project ENSEMBLE (Galmarini *et al.*, 2001; Bianconi *et al.*, 2004) considered a web-based platform presenting dispersion model ensemble results aiming at supporting decision making. They considered presentations from the point of view of a decision maker who is not necessarily trained in statistics and suggested that inter-comparison of model-ensemble member agreement would provide valuable information for decision makers. A main conclusion from the ENSEMBLE project was that in emergency situations simultaneous consultation of several model results is a convenient asset that allows a decision maker to take a more complete spectrum of scenarios into account. This may be particularly true in emergency situations where there is a lack of observations. However, the time constraint is of central importance in emergency situations, and it may be more appropriate to present a few statistical measures summarising information from ensemble simulations than to include a large set of individual forecasts.

The statistical quantity called the Agreement in Threshold Level (ATL), which represents the agreement in the geographical distribution of all ensemble dispersion model members with predicted values above a pre-defined threshold value, has previously been suggested as an indicator of the geographical distribution of the models' agreement (Galmarini *et al.*, 2004) for usage in DSSs. Likewise, the use of threshold values was suggested by Straume (2001) calculating the probability that concentration values exceed a certain threshold value. This approach has also been followed in other publications, e.g. Warner *et al.* (2002), Galmarini *et al.* (2010).

Precautionary protective actions in anticipation of a large release or in acute phases of an imminent or ongoing release, where the source term can more reasonably be estimated, the scale and duration of the countermeasures should be optimized to reduce the radiation exposures while avoiding unnecessary interventions. Decision on possible interventions should therefore be based on an assessment of the avertable radiation dose ΔE .

Reference levels for optimized intervention levels are provided by e.g. IAEA (IAEA, 2011), and a countermeasure is justified provided the expected avertable dose exceeds the reference level, i.e.

$$\langle \Delta E \rangle = \frac{1}{N} \sum \Delta E = \Delta E_{IL} .$$

Here, the expectation value $\langle \Delta E \rangle$ is determined as the average value over a set of N independent estimates of the avoidable dose. In case of atmospheric dispersion model calculations, this amounts to estimating the ensemble average over the set of such calculations. The reference level, ΔE_{IL} , constitutes a threshold level for the specific countermeasure.

The ensemble mean value of avoidable dose will allow for optimizing the area (other factors not considered) for implementing the countermeasure while the high value of avoidable dose provides an estimate of the maximum influence area. The reference values for intervention become threshold values for decision on countermeasures, as shown schematically in Fig. 1 below, where also an isocurve (10%) for exceeding the threshold level is shown.

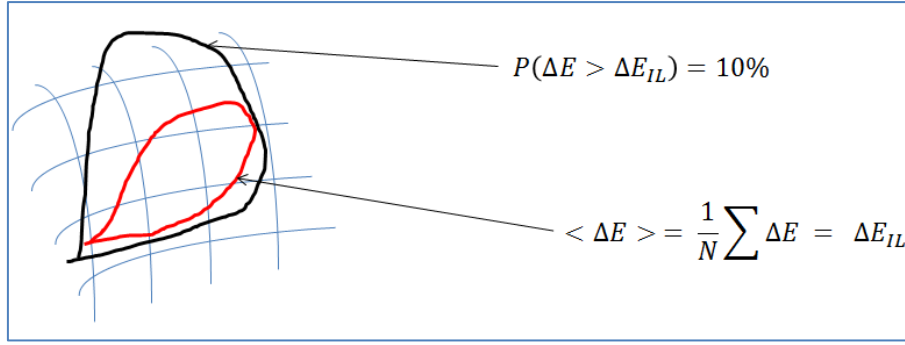


Figure 1. Schematic illustration of envelopes of the ensemble mean and the 10% probability of exceeding an intervention level.

A practical issue arises in implementation into DSSs, since dose calculations typically are an integral part of the DSS, while calculation within the DSS for each ensemble member individually followed by a calculation of statistical dose indicators would be very time consuming. Instead, it might be more efficient to carry out dose model calculations on the same server running the dispersion model, i.e. outside the DSS.

While the threshold level is expressed in terms of an avertable dose, from a practical point of view, order of magnitude estimates of threshold values for air concentration and deposition may suffice. However, such threshold values depend on the type of radionuclide, and it is noteworthy that the sizes of estimated risk zones depend critically on those values.

3. Dose calculations

The atmospheric dispersion model calculations yield time-dependent radionuclide activity concentrations in air, ρ_i , and on the ground, c_i , stemming from dry and wet depositions during plume passage. In addition, from the radionuclide concentrations in air the time-integrated (surface) air concentration and the total, accumulated deposition can be inferred,

$$\chi_i = \int_0^\infty dt' \rho_i$$

$$c_{i,\infty} = \int_0^\infty dt' \left(\frac{dc_i}{dt} \right)_{dep},$$

where $\left(\frac{dc_i}{dt} \right)_{dep}$ is the removal rate from the plume due to deposition and the time integration extends over the plume passage time.

Considering sheltering and evacuation countermeasures, three different pathways contribute to the avertable radiation doses: external radiation from the plume, from the ground, and inhalation doses. These radiation doses depend linearly on the radionuclide concentrations in the air and on the ground. For sheltering, the avertable dose can be written as

$$\Delta E = \Delta E_{plume} + \Delta E_{ground} + \Delta E_{inh}$$

$$\Delta E = \sum_i \{ (1 - L_{plume}) e_{plume,i} + (1 - F) B e_{inh,i} \} \chi_i$$

$$+ \sum_i (1 - L_{ground}) e_{ground,i} \int_0^t dt' \left(\frac{dc_i}{dt} \right)_{dep} (t - t')$$

where the applied dose and dose reduction factors are provided in tables 1 and 2, and where the sums are over the contributing radionuclides. Similarly, for evacuation the avertable dose is given by

$$\begin{aligned}\Delta E &= \Delta E_{plume} + \Delta E_{ground} + \Delta E_{inh} \\ &= \sum_i \{e_{plume,i} + B e_{inh,i}\} \chi_i \\ &+ \sum_i e_{ground,i} \int_0^t dt' \left(\frac{dc_i}{dt} \right)_{dep} (t - t')\end{aligned}$$

The radiation doses from radioactive materials deposited on the ground may be simplified by employing

$$\int_0^t dt' \left(\frac{dc_i}{dt} \right)_{dep} (t - t') \approx (t - \frac{1}{2}T) c_{i,\infty},$$

where T is the plume passage time and t is the duration of the intervention, assumed to be longer than the plume passage time. With this approximation, the avertable doses from sheltering and evacuation become

Sheltering

$$\begin{aligned}\Delta E &= \Delta E_{plume} + \Delta E_{ground} + \Delta E_{inh} \\ \Delta E &= \sum_i \{(1 - L_{plume})e_{plume,i} + (1 - F)B e_{inh,i}\} \chi_i \\ &+ \sum_i (1 - L_{ground})e_{ground,i} (t - \frac{1}{2}T) c_{i,\infty}\end{aligned}$$

Evacuation

$$\begin{aligned}\Delta E &= \Delta E_{plume} + \Delta E_{ground} + \Delta E_{inh} \\ &= \sum_i \{e_{plume,i} + B e_{inh,i}\} \chi_i \\ &+ \sum_i e_{ground,i} (t - \frac{1}{2}T) c_{i,\infty}\end{aligned}$$

Table 1. Quantities used for dose calculations.

Field	Symbol	Unit
Surface air concentration	ρ_s	Bq m ⁻³
Time-integrated surface air concentration	χ	Bq m ⁻³ s
Deposition (dry+wet)	$c = c_D + c_W$	Bq m ⁻²
Building location factor	L	-
Building filtration factor	F	-
Breathing rate	B	m ³ s ⁻¹

Table 2. Effective dose conversion factors for external gamma radiation from a semi-infinite plume and an infinite plane surface, and for inhalation.

Radionuclide	$e_{\gamma,plume}$ [Sv m ³ Bq ⁻¹ s ⁻¹]	$e_{\gamma,ground}$ [Sv m ² Bq ⁻¹ s ⁻¹]	$e_{inh(50)}$ [Sv Bq ⁻¹]
⁸⁵ Kr	1.4·10 ⁻¹⁶	-	-
⁸⁷ Kr	2.0·10 ⁻¹⁴	-	-
⁸⁸ Kr	5.7·10 ⁻¹⁴	-	-
⁹⁰ Sr	-	-	1.6·10 ⁻⁷
¹⁰³ Ru	2.7·10 ⁻¹⁴	3.1·10 ⁻¹⁶	3.0·10 ⁻⁹
¹⁰⁶ Ru	1.1·10 ⁻¹⁴	1.4·10 ⁻¹⁶	6.6·10 ⁻⁸
¹³¹ I	2.1·10 ⁻¹⁴	2.6·10 ⁻¹⁶	7.4·10 ⁻⁹
¹³² Te	1.1·10 ⁻¹⁴	1.6·10 ⁻¹⁵	2.0·10 ⁻⁹
¹³³ Xe	1.9·10 ⁻¹⁵	-	-
¹³⁵ Xe	1.3·10 ⁻¹⁴	-	-
¹³⁴ Cs	8.5·10 ⁻¹⁴	1.0·10 ⁻¹⁵	2.0·10 ⁻⁸
¹³⁶ Cs	1.1·10 ⁻¹³	3.0·10 ⁻⁹	2.8·10 ⁻⁹
¹³⁷ Cs	3.1·10 ⁻¹⁴	3.9·10 ⁻¹⁶	3.9·10 ⁻⁸
²³⁹ Pu	-	-	1.6·10 ⁻⁵

4. Presentation of meteorological uncertainties of atmospheric dispersion model calculations

The calculation and display of probabilities for exceeding a threshold level, cf. Fig. 1, in itself constitutes a means for presenting uncertainties associated with atmospheric dispersion modelling. For simplicity consider 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

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

where i denotes ensemble members, c the physical quantity (here total deposition), \mathbf{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 source term variations and plume characteristics, in which case the parameters (e.g. source strengths and plume rise) 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

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

Similarly, the average is given by

$$c_{\text{avr}}(\mathbf{r}, t) = \frac{1}{N} \sum_{i=1, \dots, N} c_i(\mathbf{r}, t).$$

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 merely be seen as a practical measure.

Maximum plots are influenced by outliers in the tail of the distributions and therefore are 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 mean or median are more appropriate for decision making purposes, e.g. as base for the deployment of portable measurement equipment in an emergency situation.

The percentiles are more robust than e.g. maximum values, and the approach could also be expanded to include uncertainties of e.g. source term variation.

Two different quantities have been considered within the MUD project: The coefficient of variation, which is defined as the ratio of the standard deviation to the mean,

$$c_v(\mathbf{r}, t) = \frac{\sigma}{\mu},$$

is also known as the relative uncertainty or the inverse of the signal-to-noise ratio. This, however, puts emphasis on low concentration values. Also it may not be a good measure of variability for skewed distributions.

From the avertable dose equations in section 3 it can be seen that quantiles of the dose distributions can be readily calculated from the corresponding quantiles of the distributions of time-integrated concentration and deposition for each radionuclide. This is convenient for use in DSSs like ARGOS for which the dose calculations are carried out on the ARGOS server itself rather than at the high-performance computer (HPC) at which the long-range dispersion calculations are performed. Thus, the ensemble statistics on time-integrated concentration and deposition results may be calculated on the HPC and transferred to the DSS where they may be directly used also for dose calculations.

5. Selection of release scenarios

A selection of four nuclear power plants (NPPs) and the release scenario to be employed in MUD has been made. The following NPPs, which are all located in, or in vicinity of, the Nordic countries, were selected as hypothetical release points for the atmospheric dispersion model calculations:

- Ringhals
- Brokdorf
- Sellafield
- The future NPP in Kaliningrad

The same release scenario will be used for the selected NPPs. It is defined by: low heat release, 40 m release height, and 6-hour emission of the radionuclides Cs-134, I-131, Xe-135 and Pu-239. The detailed release scenario was prepared by DEMA.

6. Selection of meteorological scenarios

Four meteorological scenarios involving full forecast series of 54 hours and fulfilling the needs for variability have been found by examining archived data several years back in time. The scenarios involve windy cyclonic and low-wind anti-cyclonic conditions, as well as convective summer precipitation influencing the wet deposition, and thereby potentially producing large uncertainties in the resulting deposition patterns, cf. Table 3.

Table 3. Meteorological scenarios. The date and time indicate the start of the 54 hour forecast series (the meteorological analysis time), which is here identical with the start of the 6-hours release.

Date and time (UTC)	Comment
2011-05-20 18:00	Brokdorf affecting Denmark (frontal precipitation over Jutland), Sellafield Norway, Ringhals Sweden and Finland
2011-08-14 00:00	Brokdorf affecting Denmark (frontal precipitation over south Jutland), Sellafield Denmark, Ringhals Norway, Kaliningrad Sweden
2012-01-08 00:00	Ringhals affecting Denmark (low wind, no precipitation)
2012-03-07 00:00	Brokdorf affecting Denmark, Sellafield southern Norway, Ringhals Sweden and Norway, Kaliningrad Sweden and partly Finland

7. Description of the DMI meteorological EPS

The DMI meteorological Ensemble Prediction System (EPS), which is currently based on the HIRLAM model (Sass *et al.*, 2002) numerical weather prediction model, 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 to 10 hPa (approximately 30 km above the sea surface). The ensemble HIRLAM model is nested into ECMWF's global model. The geographic domain is displayed in Fig. 2.

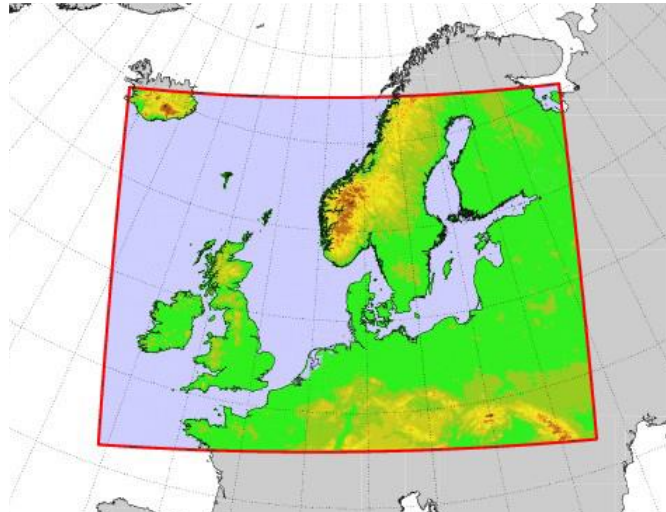


Figure 2. Geographic domain covered by the DMI EPS.

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 a short (6 or 12 h) forecast, 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 (Garcia-Moya *et al.*, 2011). The main drawback is that the number of perturbations is limited to four, if the estimated forecast errors are based on the two most recent deterministic ECMWF forecasts. 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); 12 members use the HIRLAM-version of the ISBA surface scheme (Rodriguez *et al.*, 2003), and 13 members use a modified version, referred to as “Newsnow” (Gollvik and Samuelsson, 2010). Finally, 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 was made operational during 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. Occasionally, there is also uncertainty associated with the wind field, typically in relation to passing weather fronts.

7.1 DMI EPS runs for MUD

The DMI EPS has been run for the four selected scenarios for 54 hour forecast periods. The corresponding weather situations are described in detail, and corresponding ensemble-statistical results calculated.

We note that in general the meteorological uncertainty increases with the forecast lead time. Hence, the plots that illustrate the ensemble spread in the following typically refer to the later parts of the forecast.

7.1.1 20 May 2011 case

At the start of the forecast (18 UTC), a low-pressure system is located northwest of Scotland with associated gale force winds south of it. The wind over Scandinavia is mostly from southwest, see Fig. 3. Later, a front with relative intense rainfall passes Denmark and southern Scandinavia. Figure 4 shows that there is little spread in the location of the front, but some spread in the intensity of the rainfall.

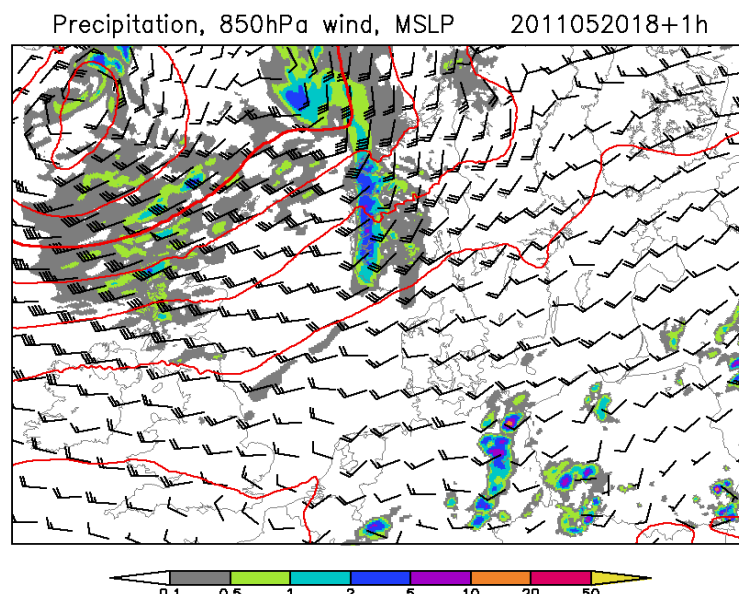


Figure 3. Ensemble mean wind in 850 hPa, mean sea level pressure and 1-h precipitation from forecast initiated 18 UTC, 20 May 2011.

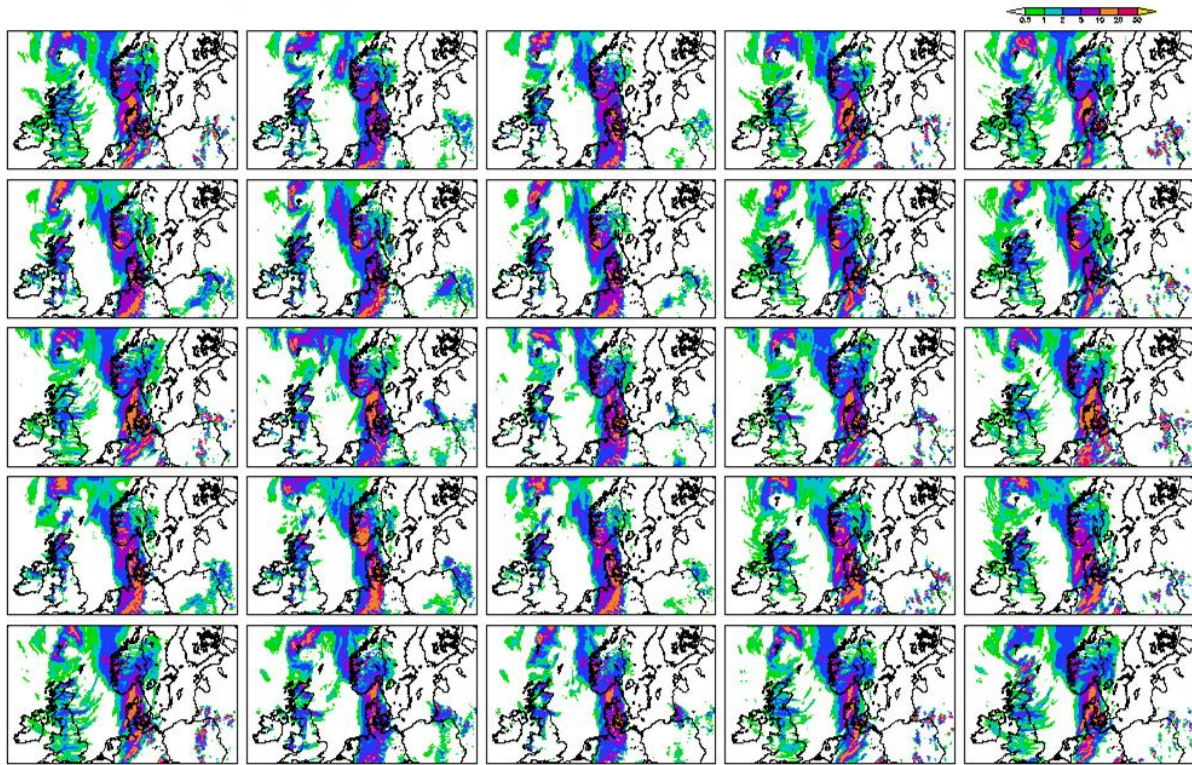


Figure 4. 25 ensemble members each showing precipitation accumulated between forecast hours 45 and 48. Contours at 0.5, 1, 2, 5, 10, 20 and 50 mm.

7.1.2 14 August 2011 case

A low pressure system is located west of the Faroe Islands, and a front is approaching Denmark and southern Scandinavia from the west. The flow over Scandinavia is south and southeasterly (Fig. 5). About 18 hours into the forecast, a secondary low and a quite intense rainfall develop just south of Denmark. The development varies between the members of the ensemble, affecting the spread in both rainfall and wind direction, particularly in the western part of the Baltic Sea (Figs. 6 and 7).

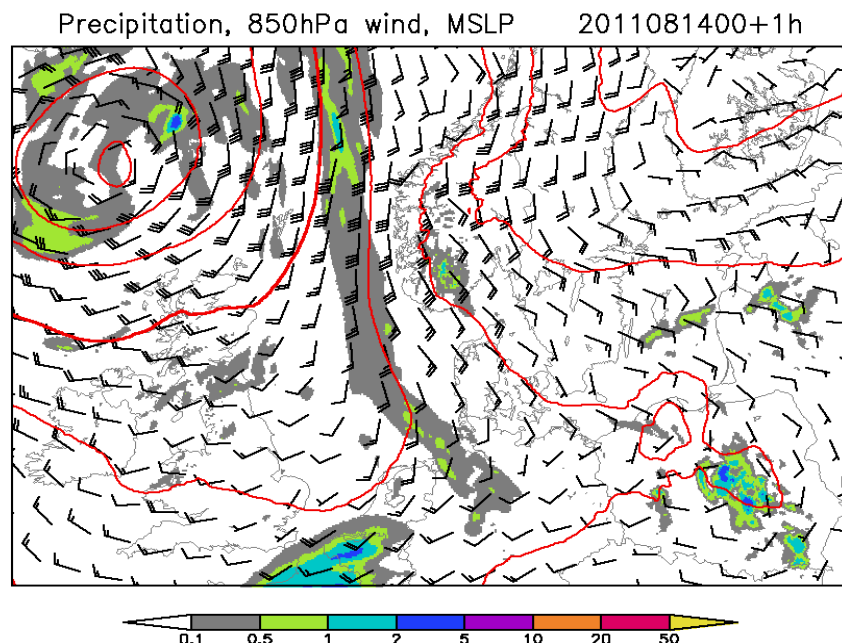


Figure 5. Ensemble mean wind in 850 hPa, mean sea level pressure and 1-h precipitation from forecast initiated 0 UTC, 14 Aug 2011.

20110814_00+24h, 10m wind speed
Valid on Monday 15 Aug 00:00 UTC

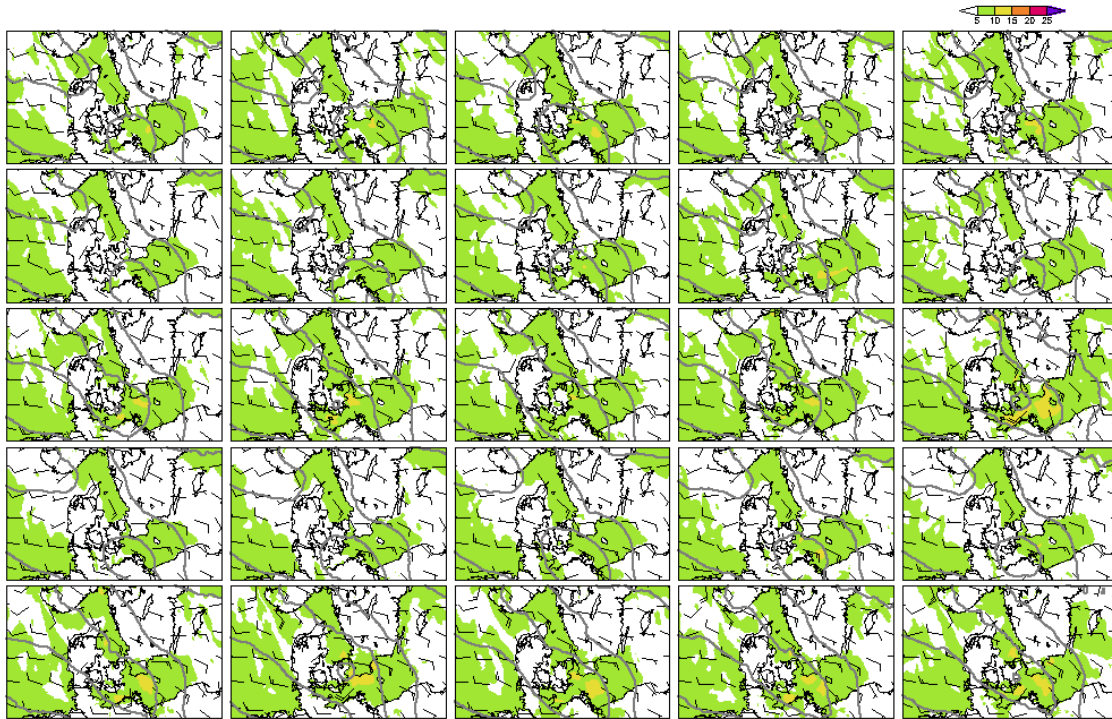


Figure 6. Wind speed (colours), wind direction (barbs) and mean sea level pressure (grey contours) ensemble.

20110814 00+24h, 3h accum. precip
Valid on Monday 15 Aug 00:00 UTC

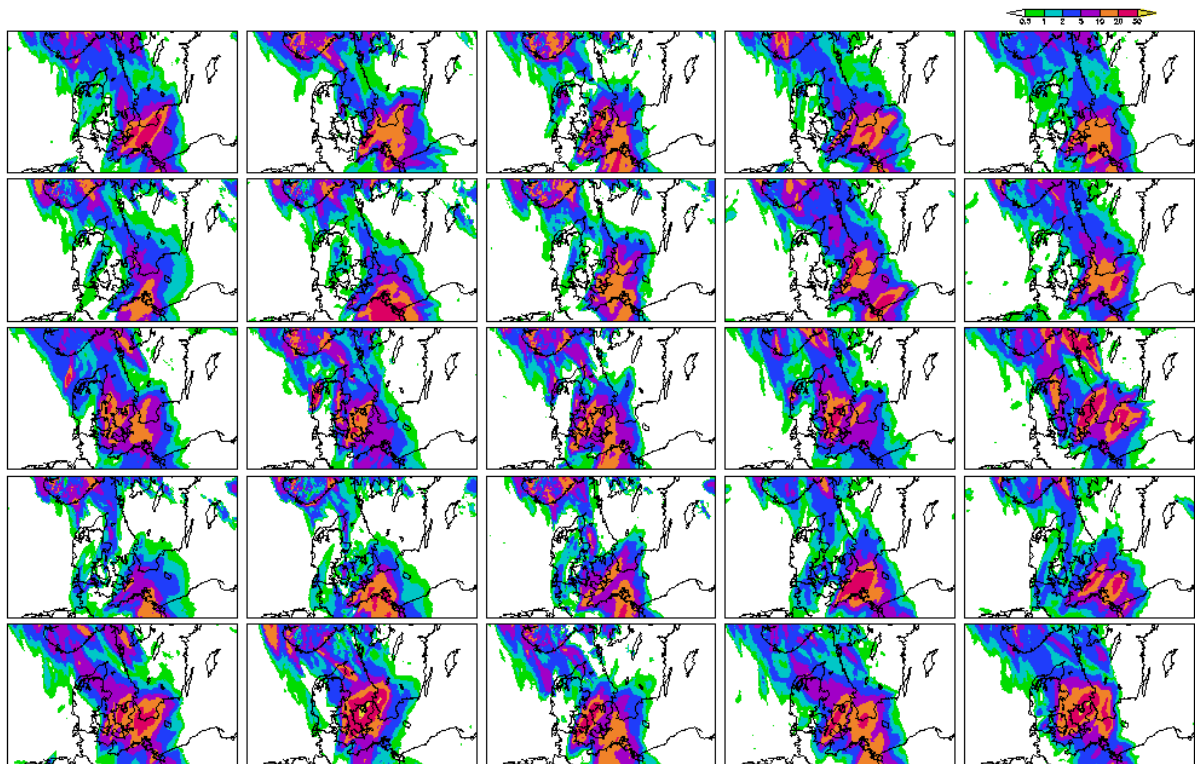


Figure 7. 25 ensemble members each showing precipitation accumulated between forecast hours 21 and 24. Contours at 0.5, 1, 2, 5, 10, 20 and 50 mm.

7.1.3 8 January 2012 case

In this case the wind over southern Scandinavia is relatively weak from directions between west and north. Figure 9 shows some spread in the 10 m wind field in southern Scandinavia 42 hours into the forecast. The spread results from uncertainty about the low located over Kattegat as illustrated in Fig. 10. There is also some precipitation associated with this low – rain in Denmark, snow in Sweden.

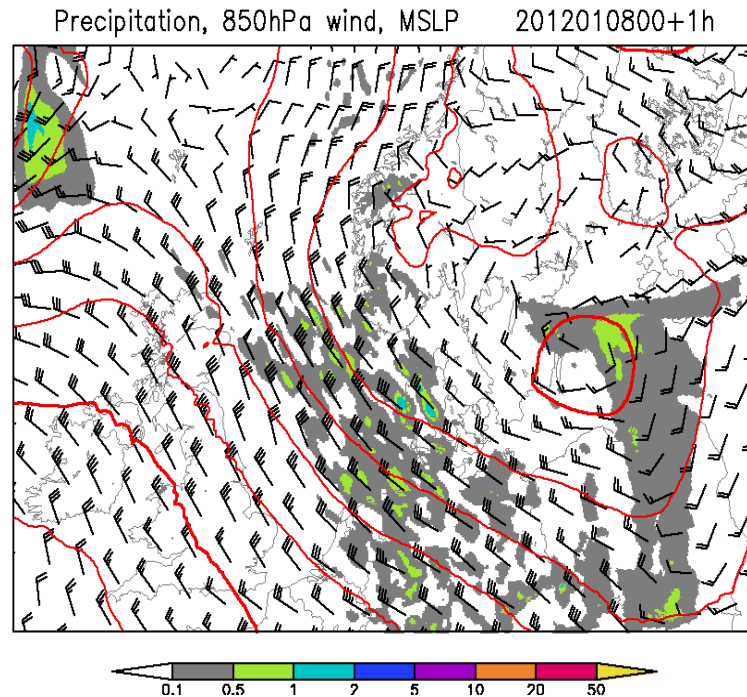


Figure 8. Ensemble mean wind in 850 hPa, mean sea level pressure and 1-h precipitation from forecast initiated 0 UTC, 8 Jan 2012.

20120108 00+42h, 10m wind speed
Valid on Monday 9 Jan 18:00 UTC

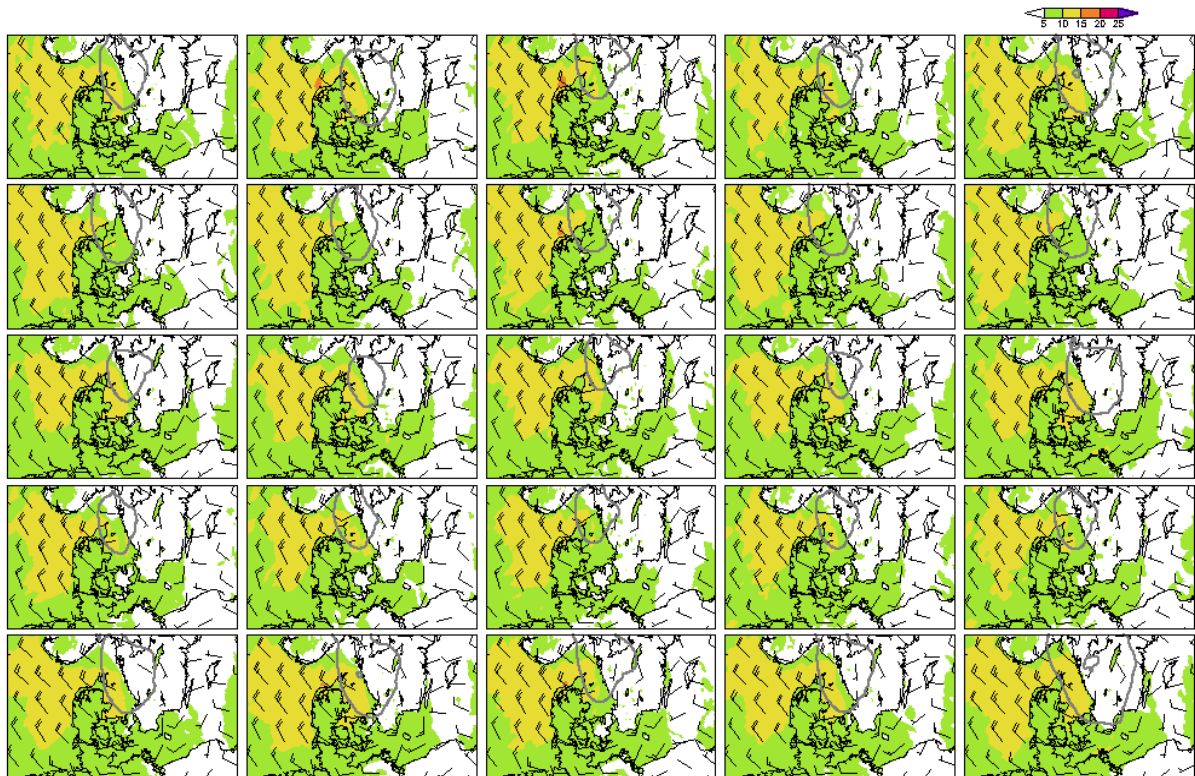


Figure 9. Wind speed (colours), wind direction (barbs) and mean sea level pressure (grey contours) ensemble.

20120108_00+42h, MSLP
Valid on Monday 9 Jan 18:00 UTC

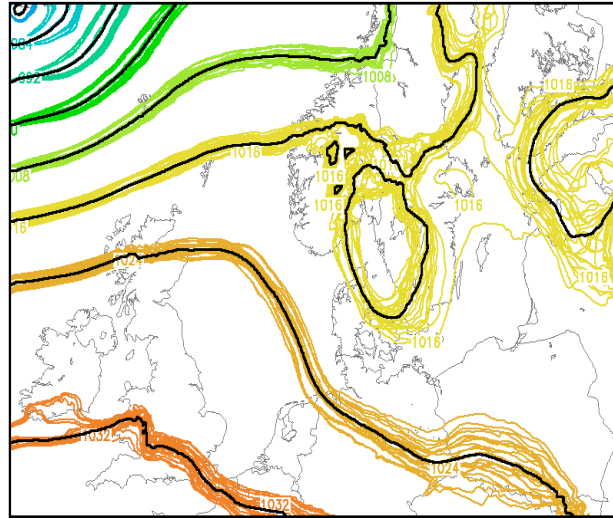


Figure 10. “Spaghetti map” showing mean sea level pressure for all members. Ensemble mean is shown as black contours.

7.1.4 7 March 2012 case

In the North Atlantic north of the Faroe Islands stormy conditions prevail. Over the British Isles and the North Sea the wind direction is southwesterly, while over Scandinavia the wind direction is mostly from the south (Fig. 11). Further east, over the Baltic States, the wind is weak and from a northerly direction. One day into the forecast the wind direction over Denmark and southern Norway changes to northeast following the passing of a cold front, while the wind direction over the rest of Scandinavia remains southerly for several hours. The ensemble spread remains remarkably small during the first day of the forecast (Fig. 12). It is not until the last hours of the forecast, when the wind is generally weak over southern Scandinavia, that we notice some spread between the ensemble members (Figs. 13 and 14).

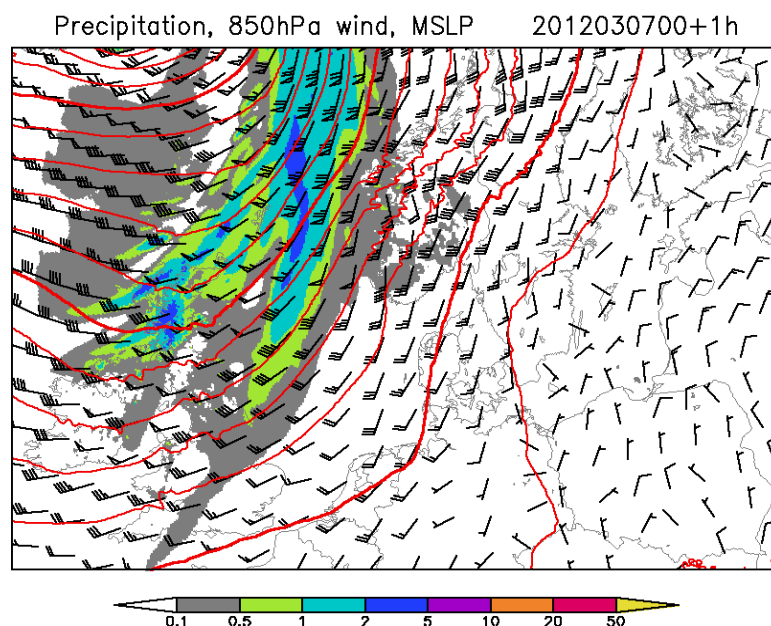


Figure 11. Ensemble mean wind in 850 hPa, mean sea level pressure and 1-h precipitation from forecast initiated 0 UTC, 7 Mar 2012.

20120307_00+27h, 10m wind speed
Valid on Thursday 8 Mar 03:00 UTC

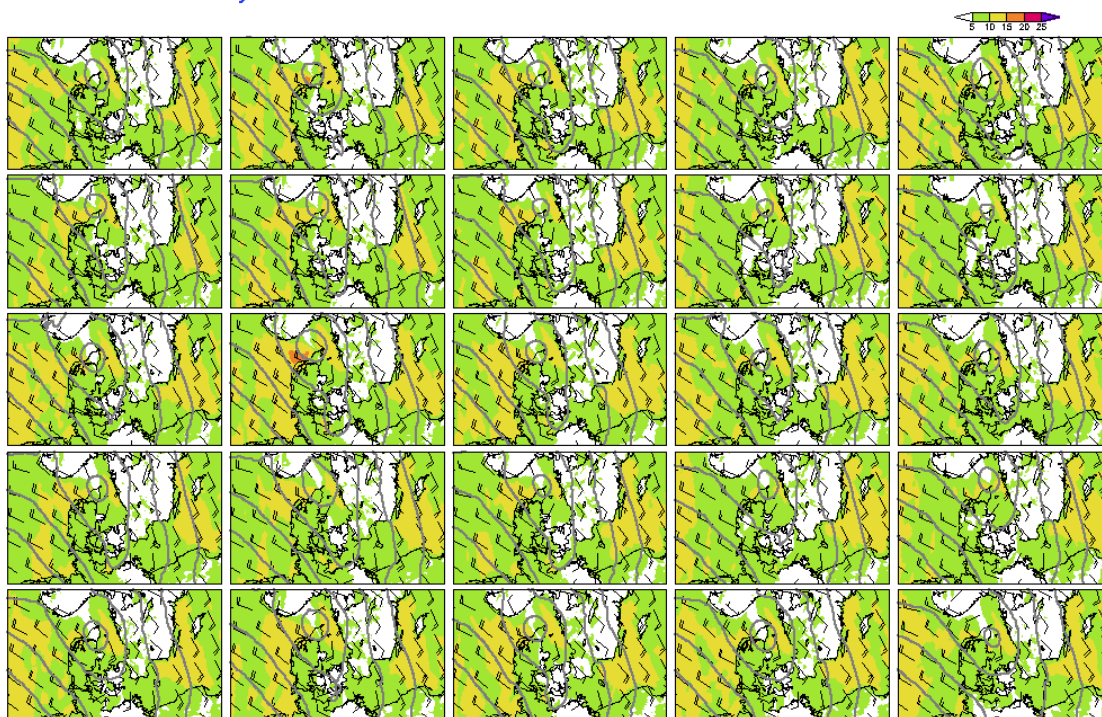


Figure 12. Wind speed (colours), wind direction (barbs) and mean sea level pressure (grey contours) ensemble of 27 hour forecasts from 0 UTC, 7 Mar 2012.

20120307_00+45h, 10m wind speed
Valid on Thursday 8 Mar 21:00 UTC

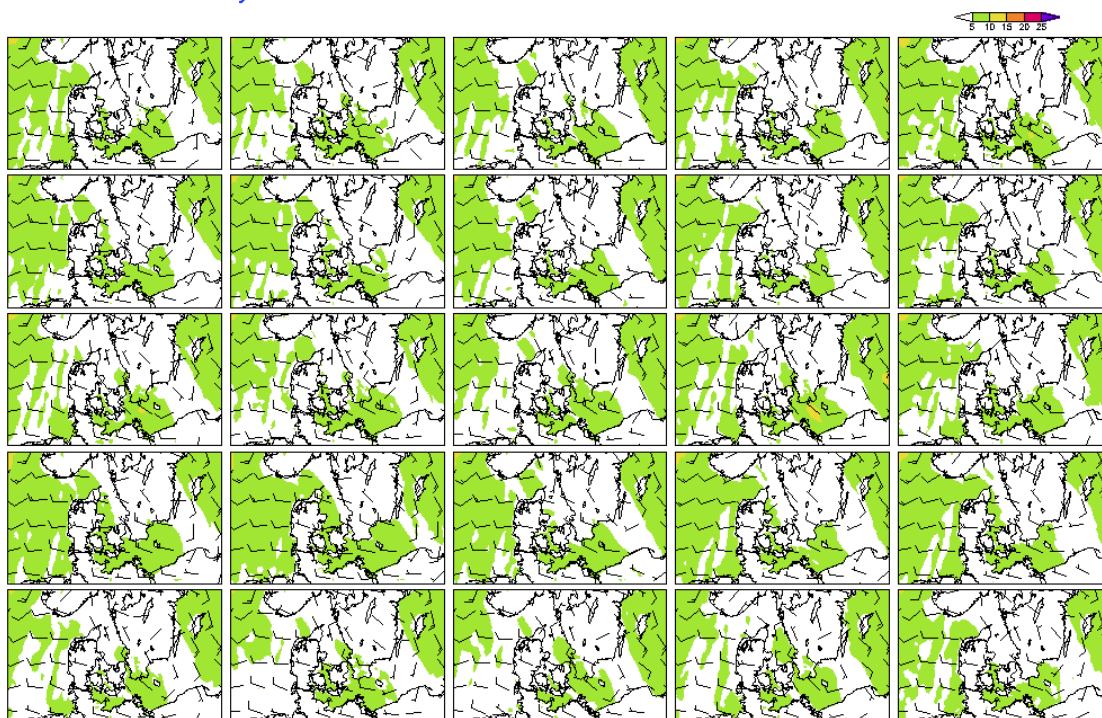


Figure 13. As Fig. 11, but for 45 hour forecasts from 0 UTC, 7 Mar 2012.

20120307_00+45h, MSLP
Valid on Thursday 8 Mar 21:00 UTC

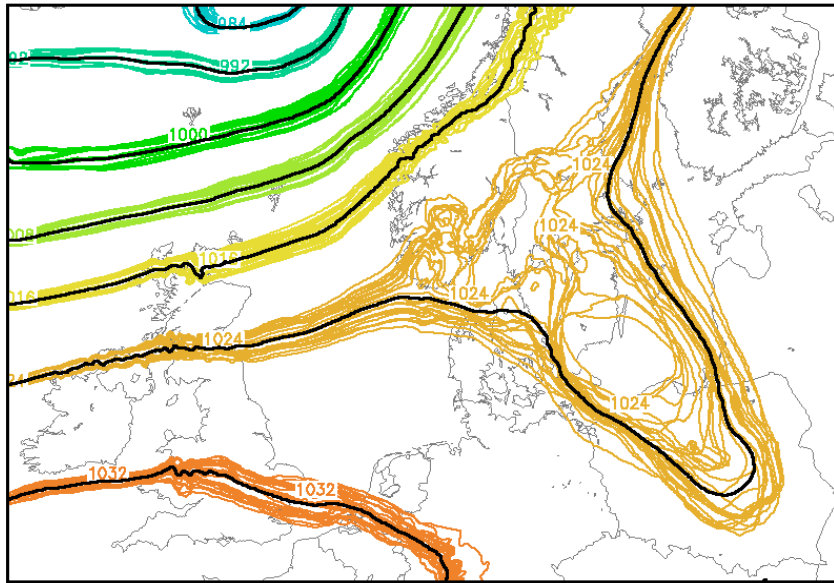


Figure 14. “Spaghetti map” showing mean sea level pressure for all members. Ensemble mean is shown as black contours.

8. Description of the GLAMEPS meteorological EPS

Glameps is the current operational ensemble prediction system at the Norwegian Meteorological Institute (MET Norway) in Oslo. The basic idea behind GLAMEPS is to account for all major sources of forecast inaccuracy up to 2.5 days using a multi model approach. GLAMEPS consists of several sub-ensembles as well as the deterministic run from the European Centre for Medium-Range Weather Forecasts (ECMWF) as shown in Fig. 15. There are two versions of HIRLAM, denoted as HirEPS_S and HirEPS_K where HirEPS_S employs the stratiform and convective cloud and precipitation scheme STRACO (Sass *et al.*, 1999; Unden *et al.*, 2002), and HirEPS_K uses the Kain-Fritsch schemes for deep cumulus (Kain and Fritsch, 1990; Kain, 2004; Calvo, 2007) and Rasch and Kristjansson (1998) for stratiform clouds and precipitation (Ivarsson, 2007). There is also one sub-ensemble based on Alaro. Both the Hirlam sub-ensembles and the Alaro sub-ensemble have an approximate resolution of 11 km and are nested in EPS from ECMWF. Also initial condition perturbations are taken from EPS, from ECMWF (perturbation = EPS member – EPS control, then added to the appropriate LAM control member). The control members for the HIRLAM sub-ensembles have 6-hourly 3D-Var assimilation, while the Alaro control member is a downscaling of the EPS control member. However, all members (Hirlam and Alaro) have their own surface assimilation. With each of the three sub-ensembles with Hirlam and Alaro having 12 + 1 members, the first 36 of 50 members from ECMWF EPS are used as boundary conditions for GLAMEPS. The remaining 14 members are added to GLAMEPS as they are, we call this sub-ensemble ECEPS. This gives a total of 54 members, so quite comparable in ensemble size to EPS from ECMWF. GLAMEPS is run every day at ECMWF at 06 and 18 UTC, using initial conditions and lateral boundary conditions from 6 hours before. The main output products are probability forecasts in grib2 displayed at the website glameps.org. 3D fields can be downloaded from ECMWF, but this needs to be done regularly as the 3D fields are not stored but are available only for a few days. This pure model output is presently in grib1-format.

The main challenge for a regional EPS is to produce significantly better forecast in the short range than the best available global forecast. GLAMEPS is therefor compared against EPS from ECMWF. Different probabilistic scores are computed for GLAMEPS and compared to EPS with one example given in Fig. 16. Figure 16 shows the CRPSS (Continuous Ranked Probability Skill Score) for GLAMEPS (red) and EPS (black) for 10 m wind speed over Europe from February 2012 to September 2012. EPS is used as reference, hence it lies on the zero line. Positive values for GLAMEPS means that it scores better than EPS from ECMWF, and negative values that it scores worse. As can be seen from this figure, the improvement for GLAMEPS is between 0 to ~25%, compared to EPS for all period except some strange behavior in February/March. Looking closer at this period it turned out that also EPS showed big fluctuations in quality during this period (not shown), so this was not something specific for GLAMEPS. Also other weather parameters show similar scores as wind (not shown). Therefore it can be concluded that GLAMEPS with its present set-up is able to produce significantly better forecasts than EPS from ECMWF on the desirable forecast length of up to 2.5 days for Europe.

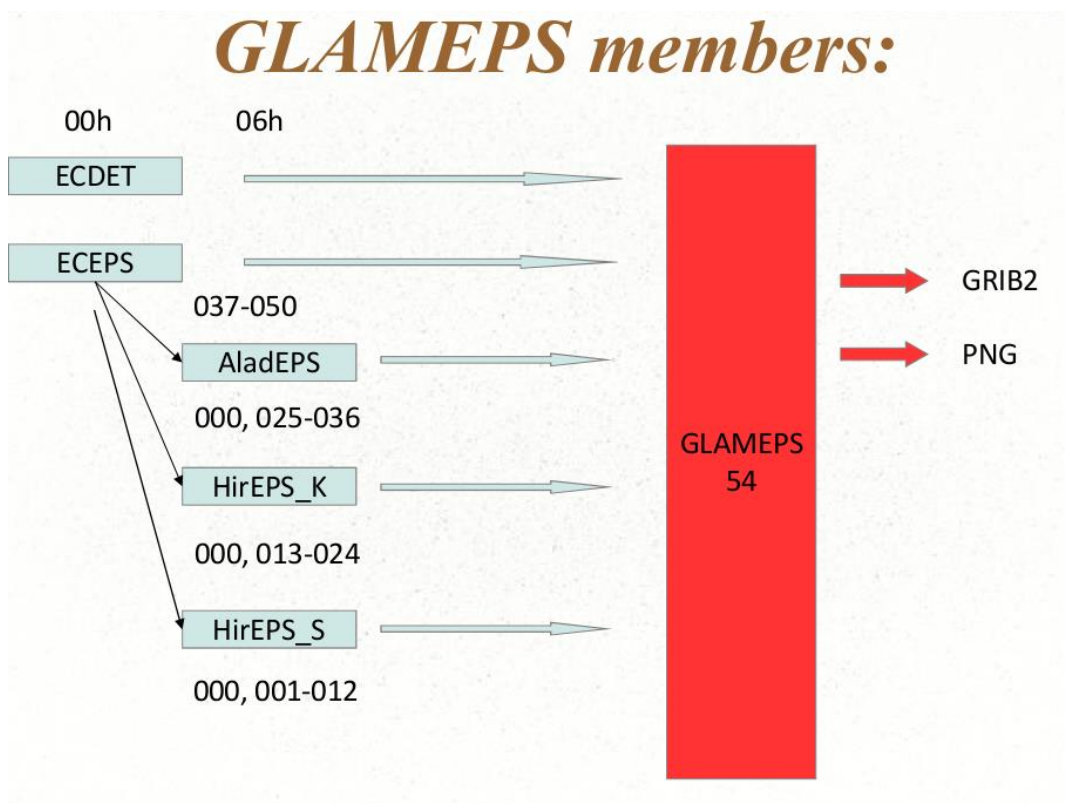


Figure 15. Schematic illustration of GLAMEPS, consisting of the four sub-ensembles HirEPS_S, HirEPS_K, AladEPS and ECEPS, as described in the text.

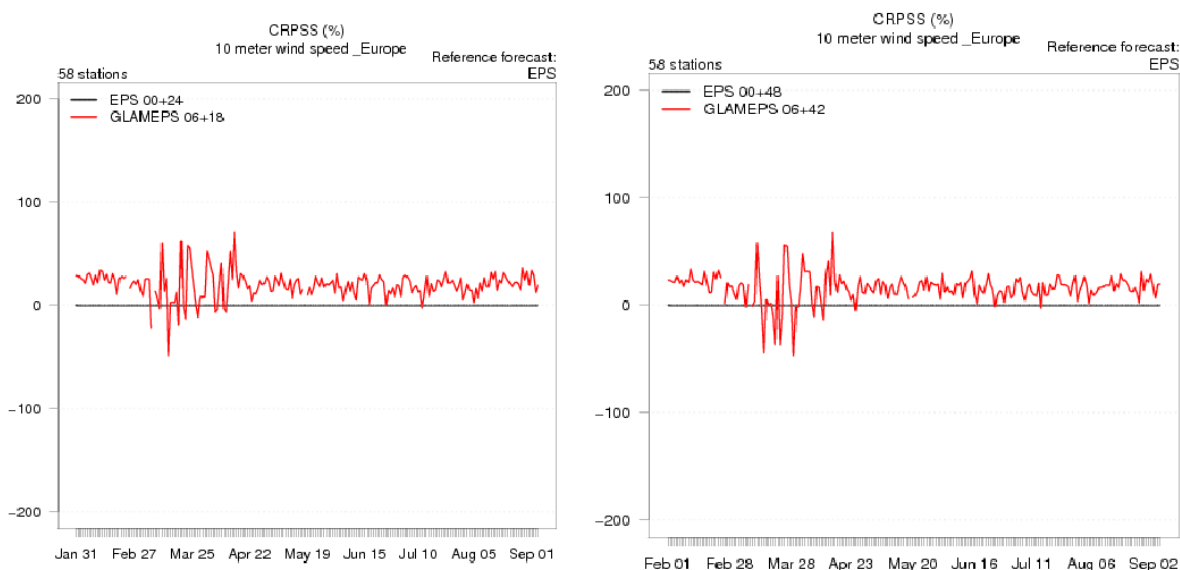


Figure 16. CRPSS for GLAMEPS (red) and EPS from ECMWF (black) for 10 m wind speed over Europe, from February to September 2012. EPS from ECMWF is used as reference, hence it lies on the zero line. Left +18h, right +42h.

9. Description of the DMI atmospheric dispersion model 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.

DERMA has been evaluated against available measurement data from accidental releases and against the European Tracer Experiment (ETEX) involving controlled releases of a tracer gas detected by nearly 200 measurement stations in Europe. ETEX was accompanied by model validations (Graziani *et al.*, 1998) in which DERMA performed well among 28 models from European countries, USA, Canada and Japan. DERMA has also been verified against the Algeciras incidence involving incineration of a medical radioactive source followed by atmospheric dispersion over the Mediterranean. Currently, DERMA takes part in the EU ensemble modelling activities for nuclear emergency preparedness (Galmarini *et al.*, 2004a, 2004b).

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 greater than about 20 km and 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).

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). DMI-HIRLAM utilises nesting technique implying a horizontal resolution ranging from 15 km over the Arctic and Europe down to 3 km over northern Europe.

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 A/S (PDC). ARGOS is currently used in 13 countries. For local-scale modelling of atmospheric dispersion ARGOS makes use of the RIMPUFF system (Mikkelsen *et al.*, 1997), which is developed at the Risø National Laboratory. In Denmark, RIMPUFF utilises high-resolution data (currently 3 km) from DMI-HIRLAM.

The integration of DERMA in the ARGOS system is effectuated through automated online digital communication and exchange of data between the ARGOS system and the DMI server. To this purpose DMI's operational ftp-server (with a backup server) is used as the point of contact. The ARGOS system prepares and uploads a description of the release. This automatically triggers DERMA to run on an operational server (involving a backup) using this information as well as data from each of the various operational meteorological models thereby providing a mini-ensemble of dispersion forecasts. While running, the DERMA system issues status messages to ARGOS, and finally, results are made available. In fact, it is "invisible" to the ARGOS user that the long-range dispersion calculation is performed on a remote on-line connected computer.

9.1 DERMA runs for MUD

The DMI atmospheric dispersion model, the Danish Emergency Response Model of the Atmosphere (DERMA), has been run for the selected release scenario for the four NPPs and the four meteorological scenarios selected, each involving the 25 ensemble members of the DMI meteorological EPS. This amounts to 400 model runs in total. A single result of these calculations is shown in the figure below. More figures are available from Sørensen *et al.* (2013), cf. Appendix A. As expected, in some cases the dispersion model results vary substantially across the ensemble, in others only little variation is observed between the dispersion model ensemble members.

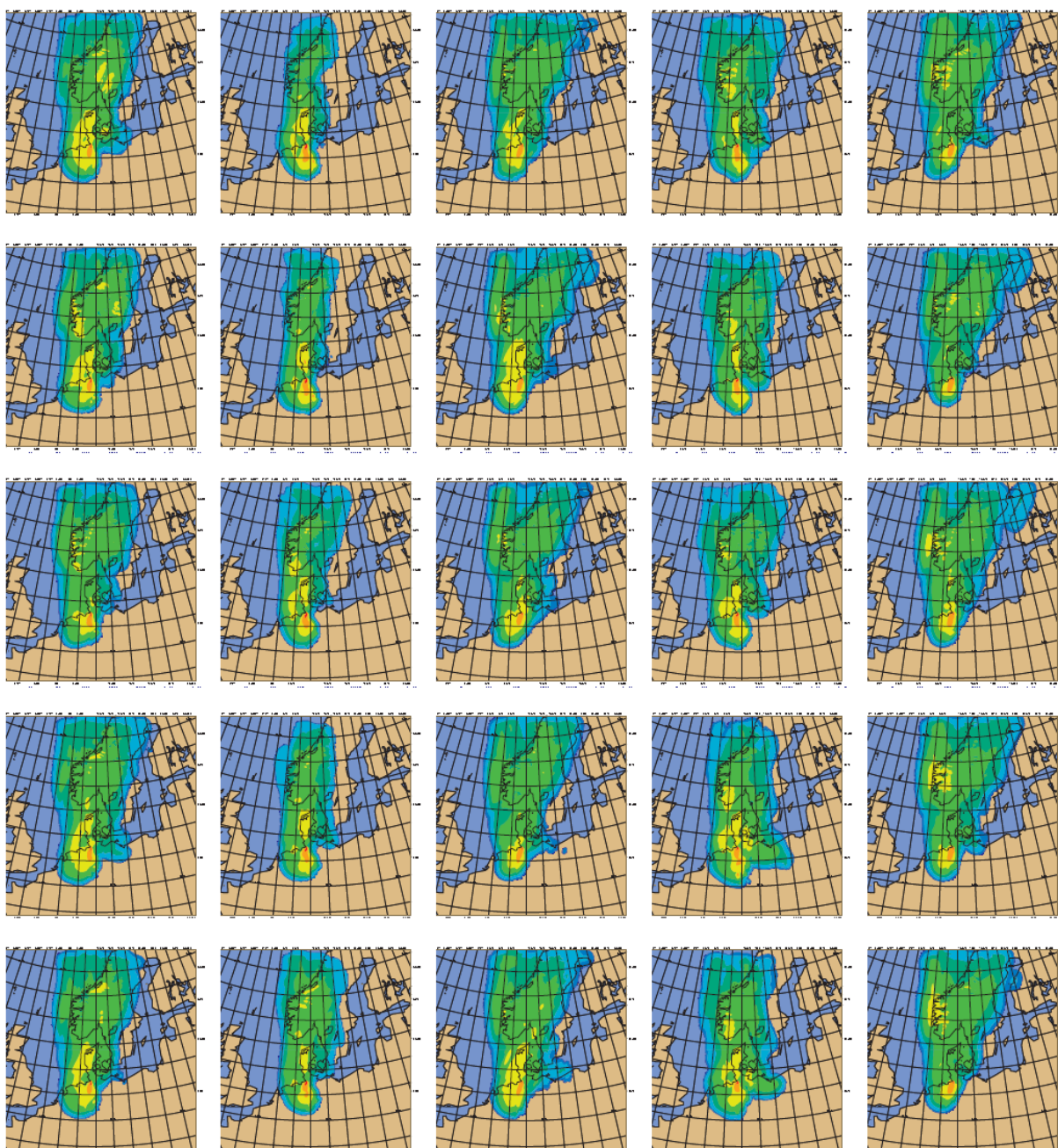


Figure 17. Ensemble of atmospheric dispersion model calculations. Total accumulated deposition of Cs-134 corresponding to a release from Brokdorf on 2011-05-23, 00 UTC.

10. Description of the MET Norway atmospheric dispersion model EEMEP

The Emergency EMEP (EEMEP) model has been developed at Met Norway in 2012 to replace the previous SNAP model (Bartnicki *et al.*, 2011) in operational applications. It is a part of the EMEP MSC-W model (Simpson *et al.*, 2012) which has been routinely run for many years at Met Norway for the needs of Geneva Convention on the Long Range Transport of Air Pollutants. The acronym EMEP stands for European Monitoring and Assessment Program under Geneva Convention and MSC-W stands for Meteorological Synthesizing Centre West of EMEP. The MSC-W has been hosted by the Norwegian Meteorological Institute since the beginning of the EMEP programme in 1979. The main task of the centre is to model transboundary fluxes of acidifying and eutrophying air pollution, photochemical oxidants and particulate matter. The EMEP model has been developed in the Eulerian framework which has many advantages for the models with complicated chemistry. The

EEMEP model is using the same routines for advection, diffusion and partly deposition processes as the EMEP model, but it takes into account radioactive debris emitted in case of nuclear accident or explosion. The EEMEP model is also used for simulating atmospheric transport and deposition of volcanic ash, but here only nuclear applications are relevant. The Eulerian framework has some advantages for simulating transport of pollutants in the large and especially global scale and in case of long term release. The EEMEP model grid system is flexible in spatial and vertical resolution and can be used not only in the global/regional scale, but in much smaller scales as well. Therefore, it was possible to perform EEMEP simulations with the ensemble meteorological data received from the Danish Meteorological Office. Atmospheric dispersion of gases, noble gases and particles of different size and density can be simulated with EEMEP model. The standard computational domain covers the entire earth with input meteorological data from ECMWF. Operational means that two runs are performed every day with the EEMEP model for selected eight nuclear power plants as the potential sources plus two locations of the potential nuclear explosion. Default source terms are used for routine everyday runs having in mind that the direction and time of the transport are the most important factors in the initial phase of potential accident or explosion. In case of emergency, the EEMEP model can be run at any time with much more detailed and extended source term, the latest available.

The EEMEP model is relatively new at MET Norway and its results have not been systematically compared with measurements. Such a comparison based on Fukushima accident simulations will be performed in 2014. However, the results of EEMEP model have been compared in 2012 with the SNAP model results showing similar patterns of deposition and concentration.

10.1 EEMEP runs for MUD

Unfortunately, three-dimensional historical meteorological data from the GLAMEPS ensemble system necessary for selected MUD scenarios were not available at Met Norway in the year 2013. Therefore, the same meteorological fields from DMI EPS are used as described in the previous chapters. These meteorological ensemble data consist of 25 members, and EEMEP dispersion model was run for each individual member of the ensemble. The EEMEP runs were performed for all four nuclear power plants (Table 3), and the same release scenario was used for the selected NPPs.

An example of EEMEP simulations for Sellafield as the source and meteorological scenario from 20110523 00 UTC is shown in Fig. 18. In this example, the total deposition of Cs-134 is shown. For all members of the ensemble, the Cs-134 released in Sellafield travels in a North-East direction reaching the Norwegian territory. The deposition maps in Fig. 18 differ from each other, but it is interesting to notice that some similarities can be observed for the maps in the same column, whereas differences are relatively larger for the maps belonging to the same row. The reason is probably the relatively similar perturbed initial conditions for ensemble members in the same columns. In general, deposition maps for Cs-134 obtained for EEMEP model simulations are similar to those calculated by the DERMA model simulations. More results from the EEMEP model simulations are presented by Sørensen *et al.* (2013), cf. Appendix B. These results are only presented for the meteorological scenario from 2011.

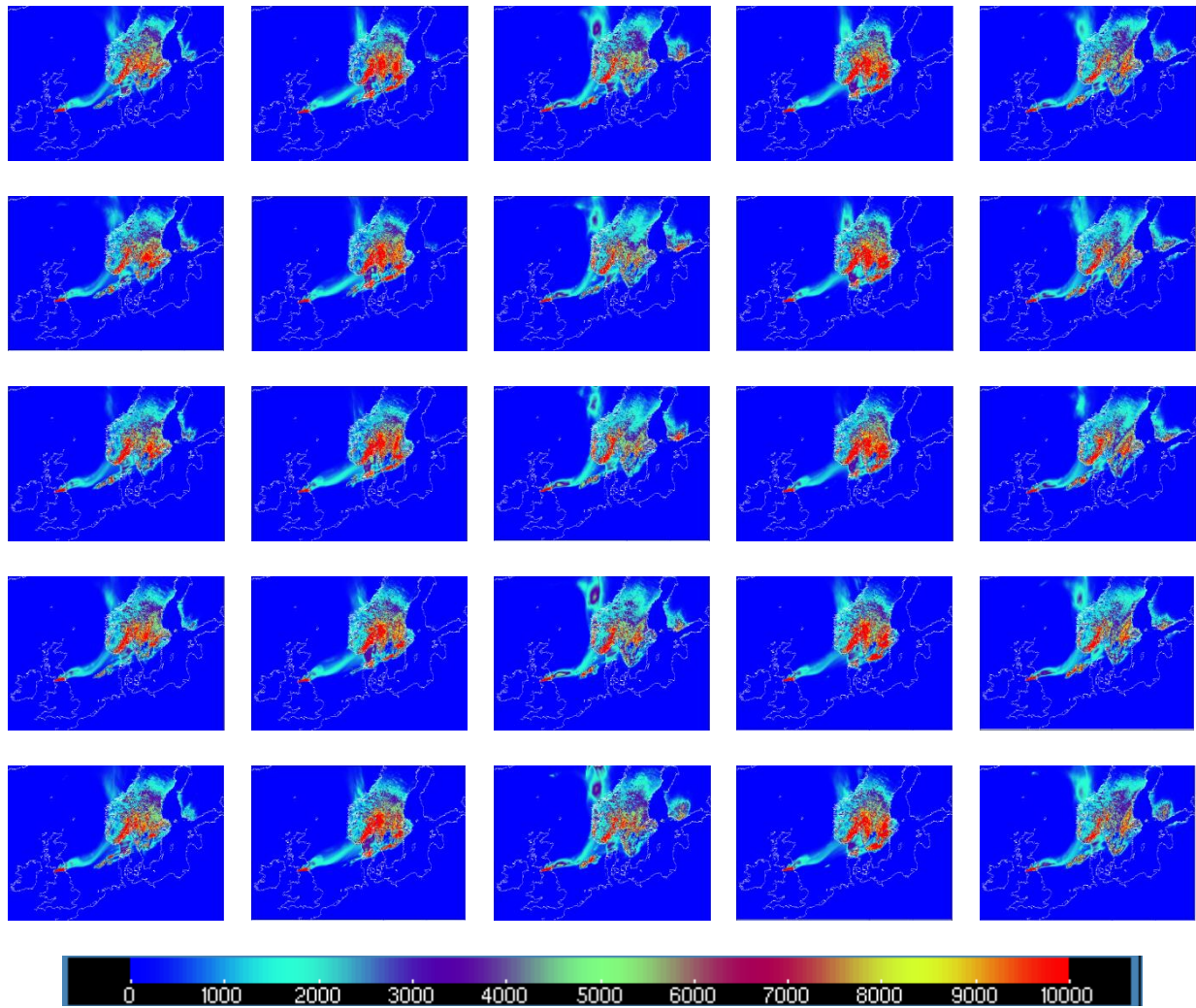


Figure 18. The results of EEMEP model simulations for NPP Sellafield as the source and meteorological scenario from 20110523 00 UTC. Total (dry + wet) deposition of Cs-134 (Bq m^{-2}) is shown for each of 25 meteorological ensemble members.

11 Results on dispersion model uncertainties

In Fig. 19 results are shown for DERMA applied to the scenario with a release from the Ringhals NPP beginning on 2011-05-20 at 18 UTC. The results shown concern time-integrated concentration of I-131 at 54 hours after the start of the release. In the upper row, the ensemble minimum, average and maximum are displayed, which can readily be compared with the low percentile, the median and a large percentile as displayed in the middle row. Finally, probabilities for exceeding values of 10^4 , 10^3 and 10^2 Bq h/m^3 , respectively, are presented in the lower row. As can be seen, the variability is considerable.

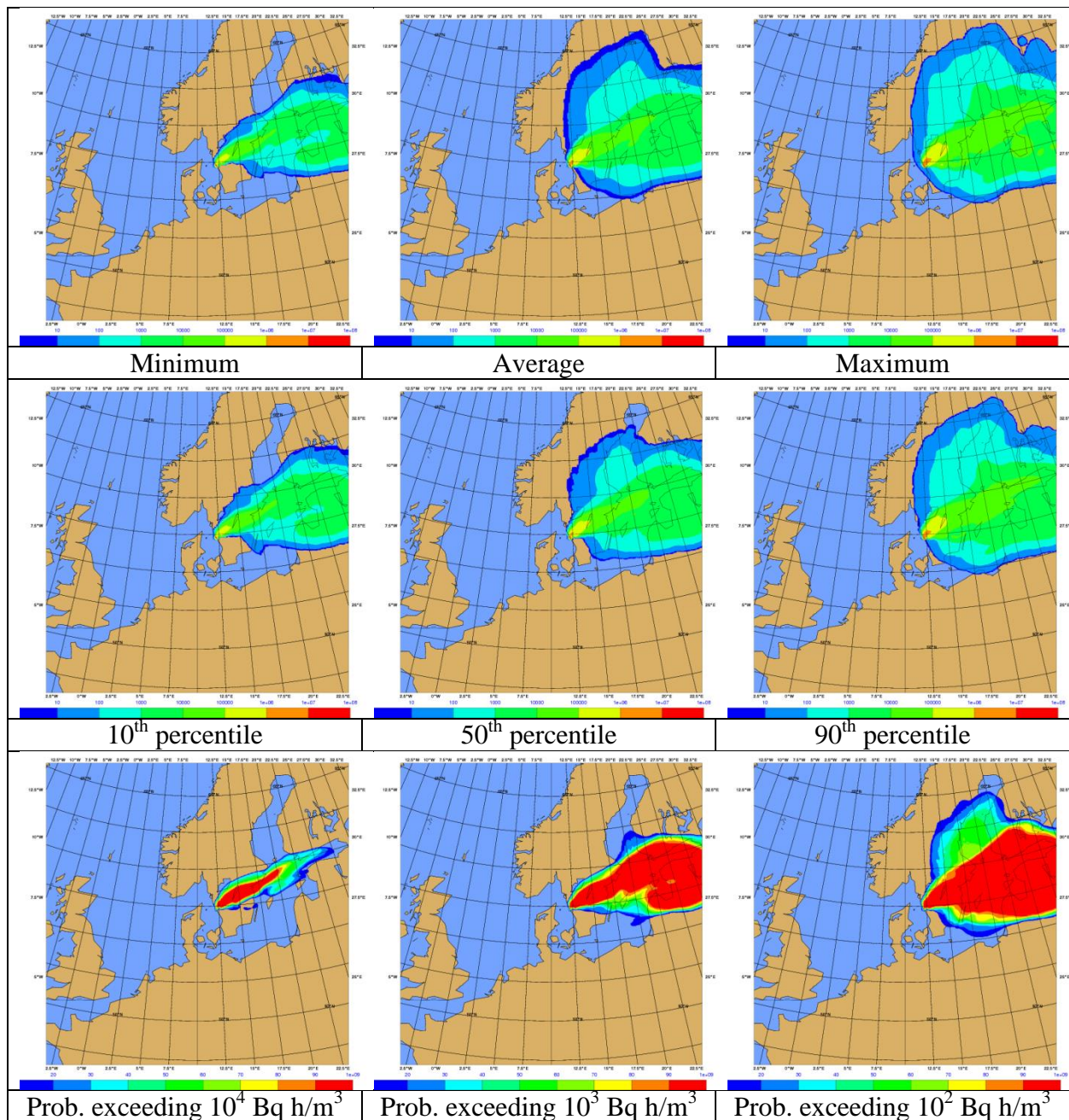


Figure 19 Scenario: 2011-05-23. NPP: Ringhals. Field: Time-integrated concentration 54 hours after start of release. Nuclide: I-131.

In Fig. 20, percentiles are shown for accumulated total (wet plus dry) deposition of Cs-134 at 54 hours after start of the release for the four NPPs. In comparison, the corresponding plots are shown for wet deposition in Fig. 21. Large variations are observed, especially for wet deposition, as a result of the large meteorological uncertainty regarding precipitation.

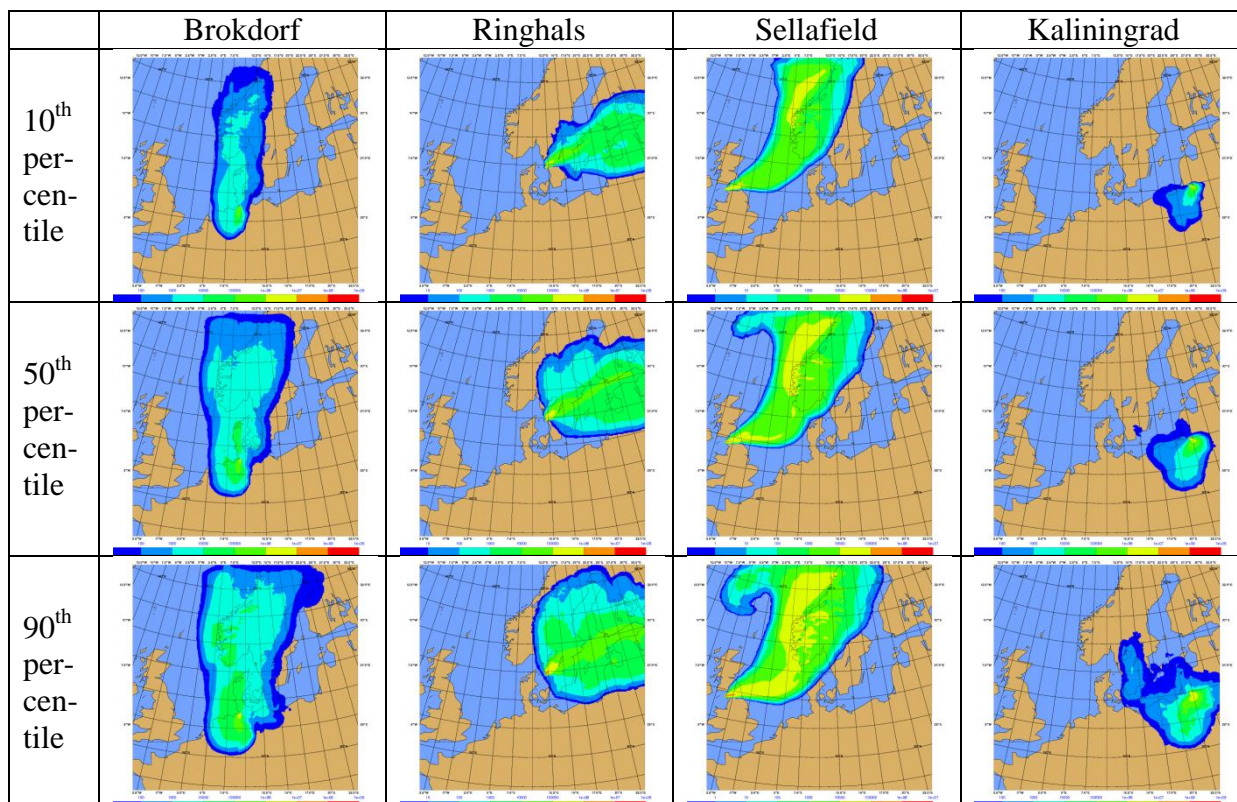


Figure 20 Scenario: 2011-05-23 Field: Accumulated deposition 54 hours after start of release. Nuclide: Cs-134.

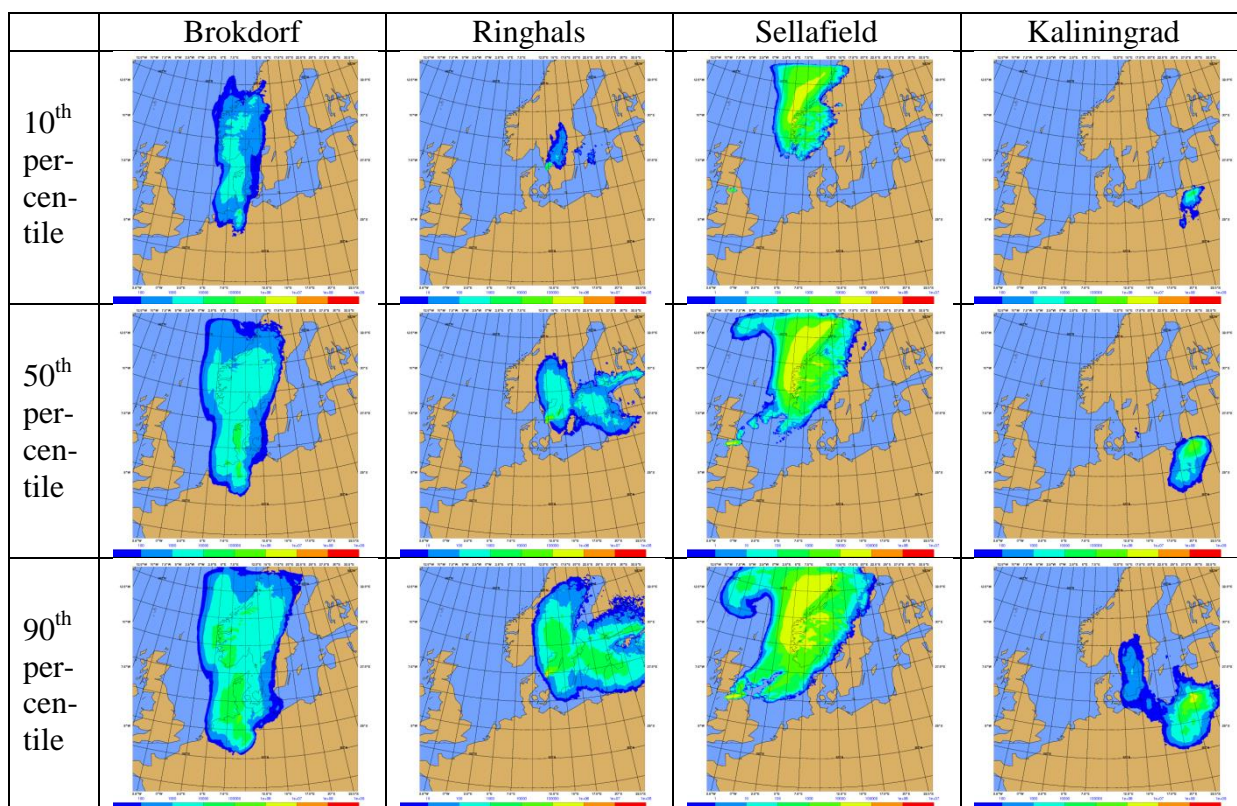


Figure 21 Scenario: 2011-05-23 Field: Accumulated wet deposition 54 hours after start of release Nuclide: Cs-134.

In Figs. 22, 23 and 24, the percentiles are shown for the remaining scenarios, 2011-08-16, 2012-01-10 and 2012-03-09, respectively, for the accumulated deposition of Cs-134 54 hours after start of the release for the four NPPs.

In all cases, significant differences are observed, especially in convective situations. Low wind situations with no or little precipitation, which are challenging for dispersion models, also display meteorological uncertainty.

For nuclear emergency preparedness, a typical time scale for compiling information for decision makers is 20 minutes, and here the parameters and figures show seem sufficient, since they give a quick overview of the meteorological uncertainty. The resulting data have been made available to the ARGOS decision-support system for presentation and dose modelling.

The ensemble dispersion results of Met Norway are also based on the DMI meteorological ensemble, however, using a different dispersion model. The simulations show the same pattern of variability as the DMI dispersion ensemble indicating meteorological uncertainty in most cases, but most pronounced in convective situations.

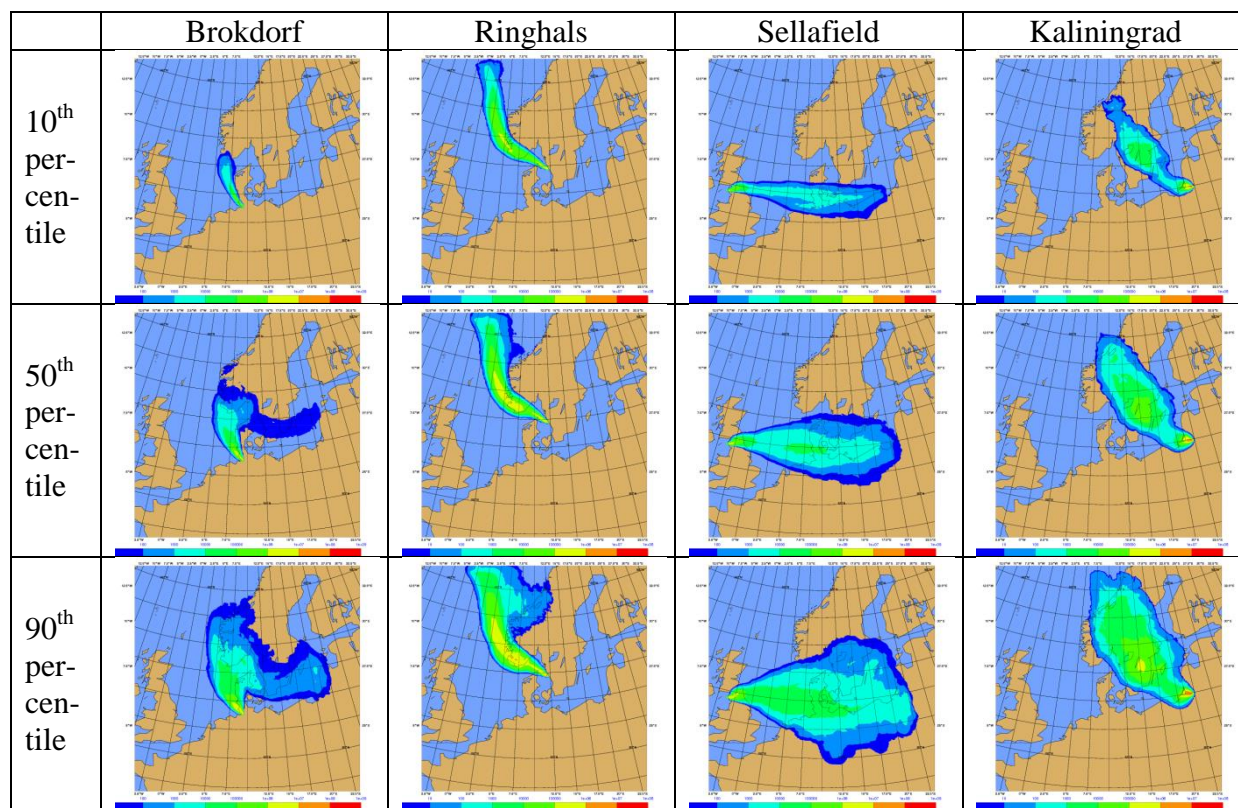


Figure 22 Scenario: 2011-08-16 Field: Accumulated deposition 54 hours after start of release. Nuclide: Cs-134.

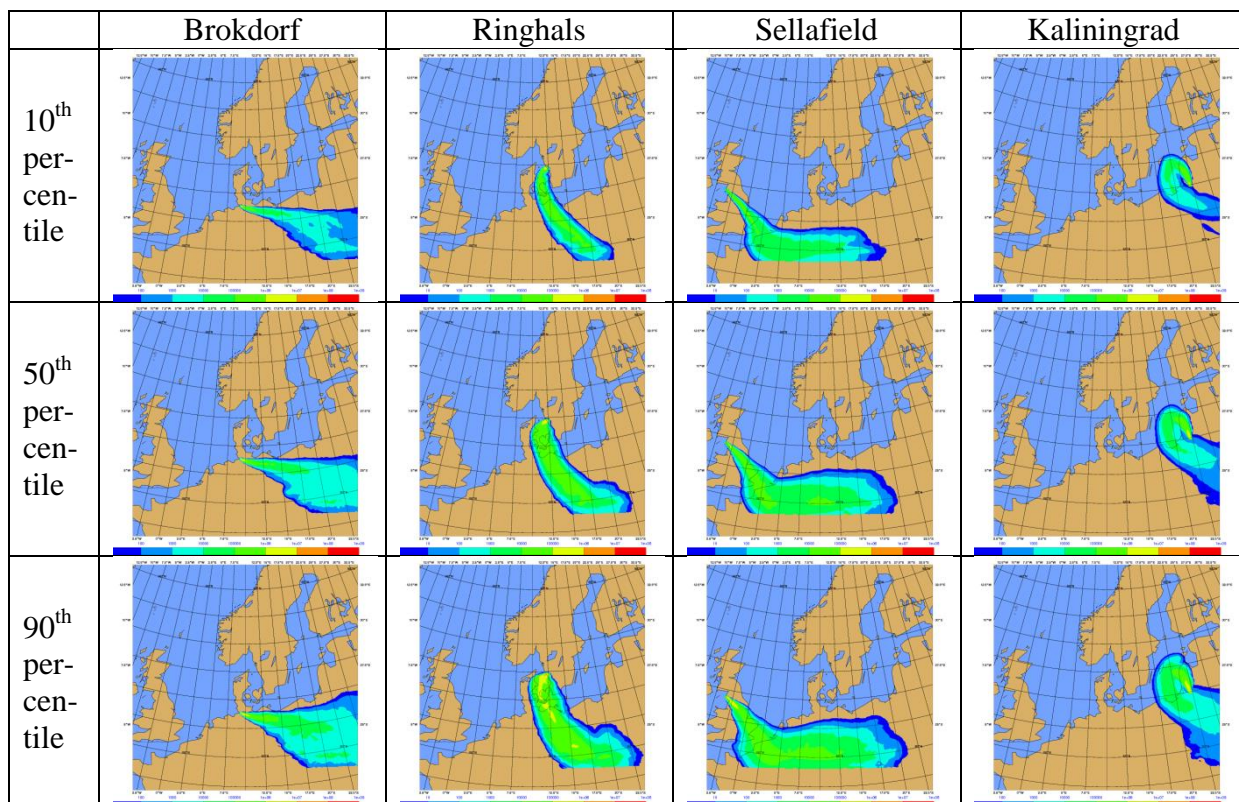


Figure 23 Scenario: 2012-01-10 Field: Accumulated deposition 54 hours after start of release. Nuclide: Cs-134.

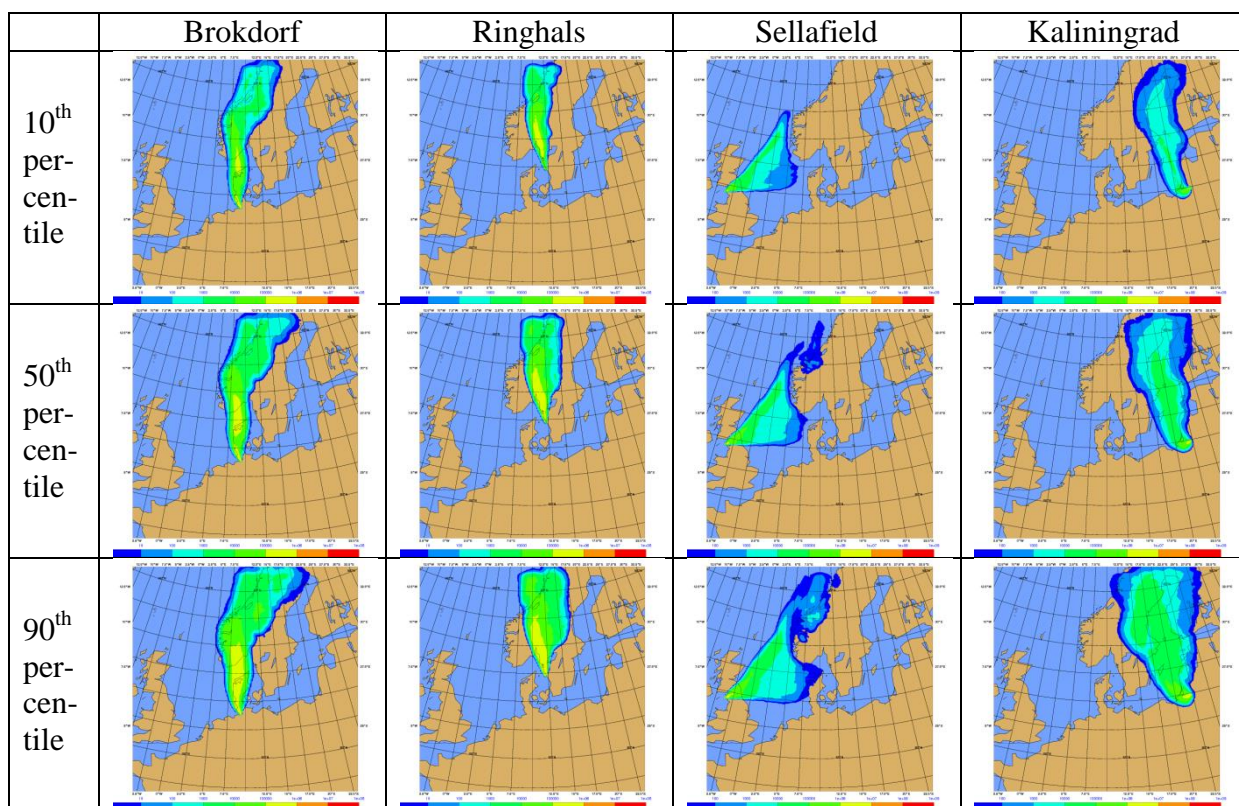


Figure 24 Scenario: 2012-03-09 Field: Accumulated deposition 54 hours after start of release. Nuclide: Cs-134.

The results of the EEMEP model for the meteorological scenario starting from 2011-05-20 at 18 UTC and release from the Ringhals NPP are shown in Fig. 25. The total deposition of Cs-134 is shown, 54 hours after the start of release. The same structure is used as for presenting DERMA results in Fig. 19. In the upper row, the ensemble minimum, average and maximum are presented, which can be easily compared with the low percentile, the median and a large percentile placed in the middle row. The probabilities for exceeding deposition values of 10^4 , 10^3 and 10^2 Bq m^{-2} , respectively, are presented in the bottom row. As in case of DERMA results, the maps with ensemble minimum, average and maximum are very similar to the maps with low, median and large percentile, respectively.

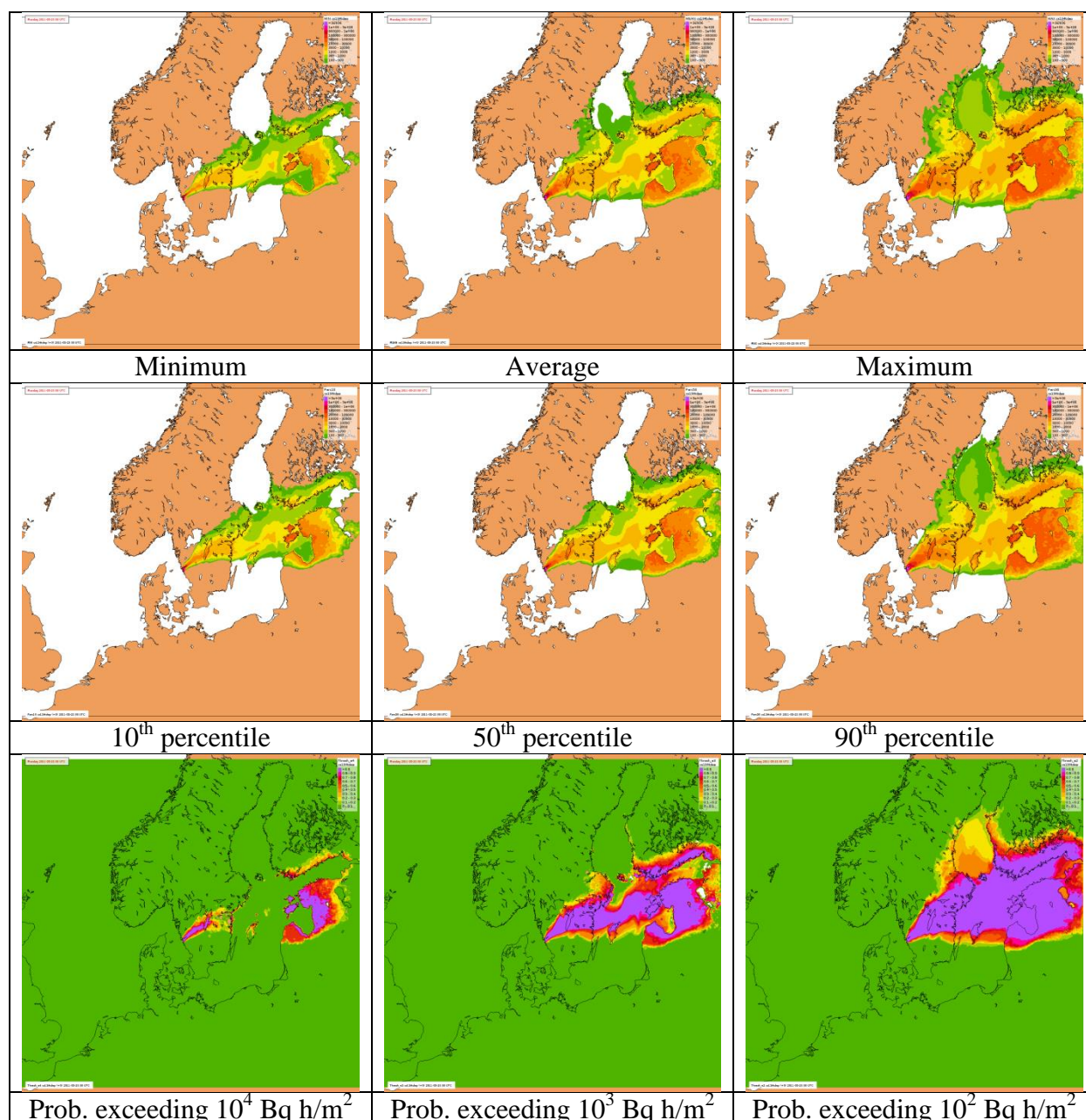


Figure 25 Scenario: 2011-05-23. NPP: Ringhals. Field: Total (dry+wet) deposition 54 hours after start of release. Nuclide: Cs-134. Simulations with EEMEP model.

As another example of EEMEP model results, the 10th, 30th, 50th, 70th and 90th percentiles are shown for total (dry+wet) deposition of Cs-134 in Fig. 26. The results are shown 54 hours after the release start for all four NPPs as a release start. For all NPPs, there is a range difference between the deposition maps with 10th and 90th percentiles.

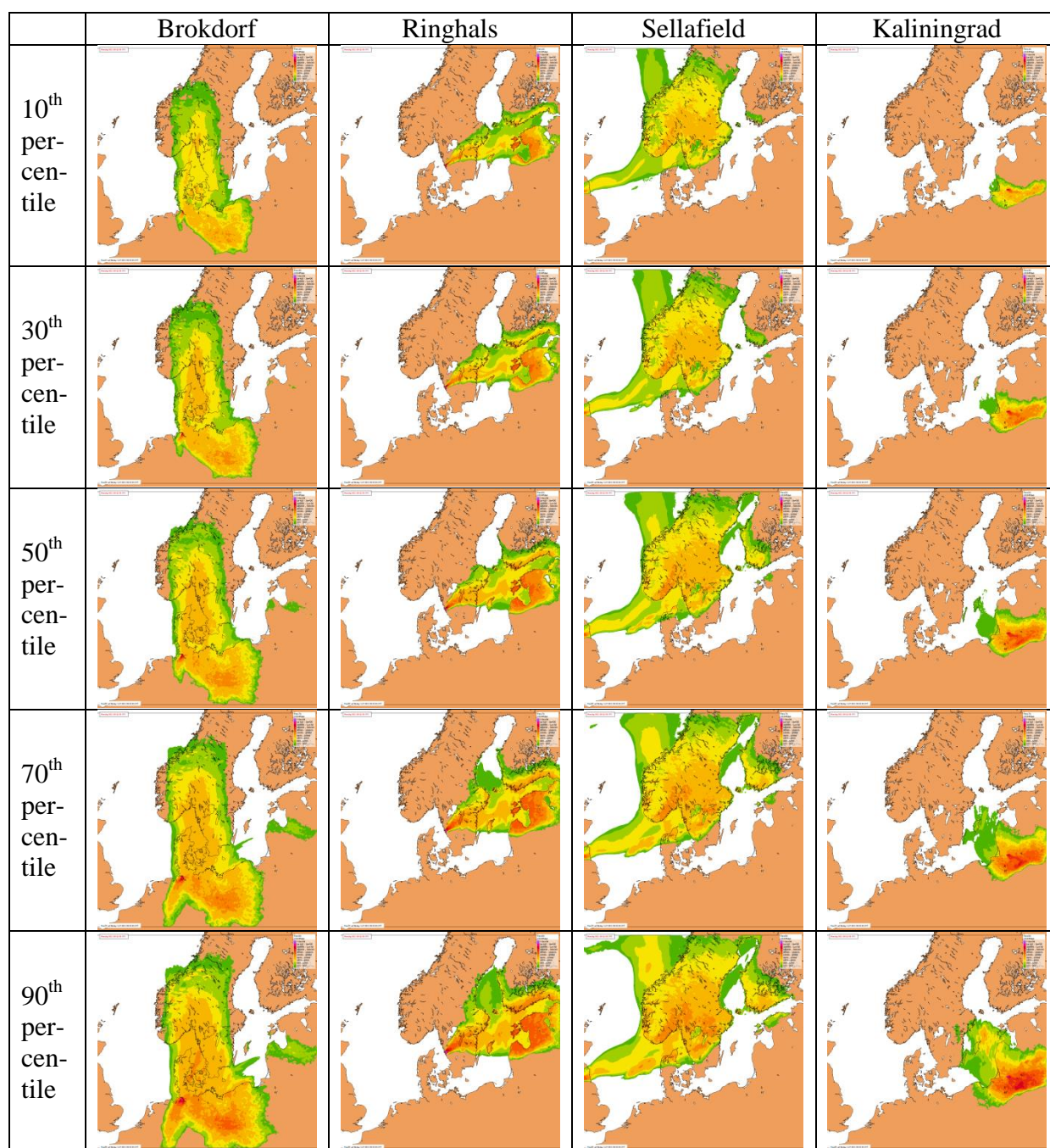


Figure 26 Scenario: 2011-05-23 Field: Total (dry+wet) deposition 54 hours after start of release. Nuclide: Cs-134. Simulations with EEMEP model.

12. EPS for DSS

The atmospheric dispersion model DERMA is interfaced operationally with the ARGOS decision-support system through automated online digital communication and exchange of data between the ARGOS system and the DMI high-performance computing (HPC) facility. In brief, the ARGOS system prepares a description of the release, and DERMA runs are automatically initiated for each of the various meteorological models available, currently four versions of the DMI-HIRLAM numerical weather prediction model (Sass *et al.*, 2002) and the global model run at the European Centre for Medium-Range Weather Forecasts (ECMWF), thereby providing a mini-ensemble of dispersion forecasts. While running, the DERMA system issues status messages to ARGOS, and finally, results are made available. In fact, it is “invisible” to the ARGOS user that the long-range dispersion calculation is performed on a remote on-line connected computer.

As a future extension to this operational set-up, DERMA will also be run for the HIRLAM ensemble in parallel with the runs for the deterministic meteorological models. The DERMA system might make the ensemble of dispersion model data available to ARGOS. However, for simplicity and to ensure fast and robust procedures, it has been decided to carry out the ensemble statistics at the HPC facility, and therefore limit the results files to be transferred to be selected ensemble statistical parameters for each of the radionuclides in question.

12.1 Interactive automatic communication between NMS and DSS

DMI’s operational ftp-servers are used for the exchange of data. The ARGOS system puts the information describing the release of radioactivity in an upload directory on the ftp-server. A computer program (a daemon) checks for such new files uploaded from ARGOS, and moves to the high-performance computer (HPC) where the run is subsequently started.

The DERMA system allows the ARGOS user to follow the progression of the runs through status files. These files are regularly produced by the DERMA system and put on the ftp-server. Finally, for each radionuclide result files (instantaneous concentration at the ground level, time-integrated concentration and the wet and total deposition are made available to ARGOS in a format suitable for import in the decision-support system.

12.2 MUD – an End User Perspective

A conceptual understanding of the results provided to the DSS from the EPS can be obtained by considering the following example:

Consider the scalar parameter c being e.g. the total ground deposition of Cs-134. Thus, $c(\mathbf{r}, t)$ represents the deposition at the geographic location \mathbf{r} at time t resulting from an atmospheric modelling run with a given source term. In any grid cell, the value $c_n(\mathbf{r}, t)$ represents the calculated value of c for ensemble member n in a collection of N individual ensemble runs.

$c_{\text{mean}}(\mathbf{r}, t)$ represents the average of all ensemble members. 10% of the ensemble members predict values less than $c_{10\%}(\mathbf{r}, t)$. Thus 90% of the ensemble members predict values greater than $c_{10\%}(\mathbf{r}, t)$. Likewise, 90% of the ensemble members predict values less than $c_{90\%}(\mathbf{r}, t)$. Thus 10% of the ensemble members predict values greater than $c_{90\%}(\mathbf{r}, t)$.

The functions c_{mean} , $c_{10\%}$ and $c_{90\%}$ can be visualized in the DSS in the same manner as the result from an individual dispersion run, since they all represent the same physical unit (e.g.

Bq/m²). This as opposed to the unit-less probability functions discussed in Sections 4 and 11, which for a given entity express probabilities of exceeding a given (predefined) threshold value. It should, however, be noted that none of the functions c_{mean} , $c_{10\%}$ and $c_{90\%}$ represent individual fallout calculations, as opposed to the individual ensemble members c_n . The functions $c_{10\%}$ and $c_{90\%}$ are not mass (activity) conserving, and none of the functions c_{mean} , $c_{10\%}$ and $c_{90\%}$ can be expected to be consistent with a true meteorological scenario. The function $c_{10\%}$ will underestimate the deposited activity, whereas $c_{90\%}$ in the general case will show a total deposition of activity in excess of what is being released. c_{mean} , $c_{10\%}$ and $c_{90\%}$ will all yield deposition patterns which cannot be expected to be resulting from a physically realizable meteorological situation.

Despite the limitations outlined above, the additional information resulting from the EPS in the form of c_{mean} , $c_{10\%}$ and $c_{90\%}$ may be of value to the decision process.

In the figures below, ground deposition of Cs-134 resulting from an individual ensemble run c_n is shown together with the corresponding functions c_{mean} , $c_{10\%}$ and $c_{90\%}$. It should once again be pointed out that only the functions c_n have the potential of being physically consistent with a given meteorological scenario and source term.

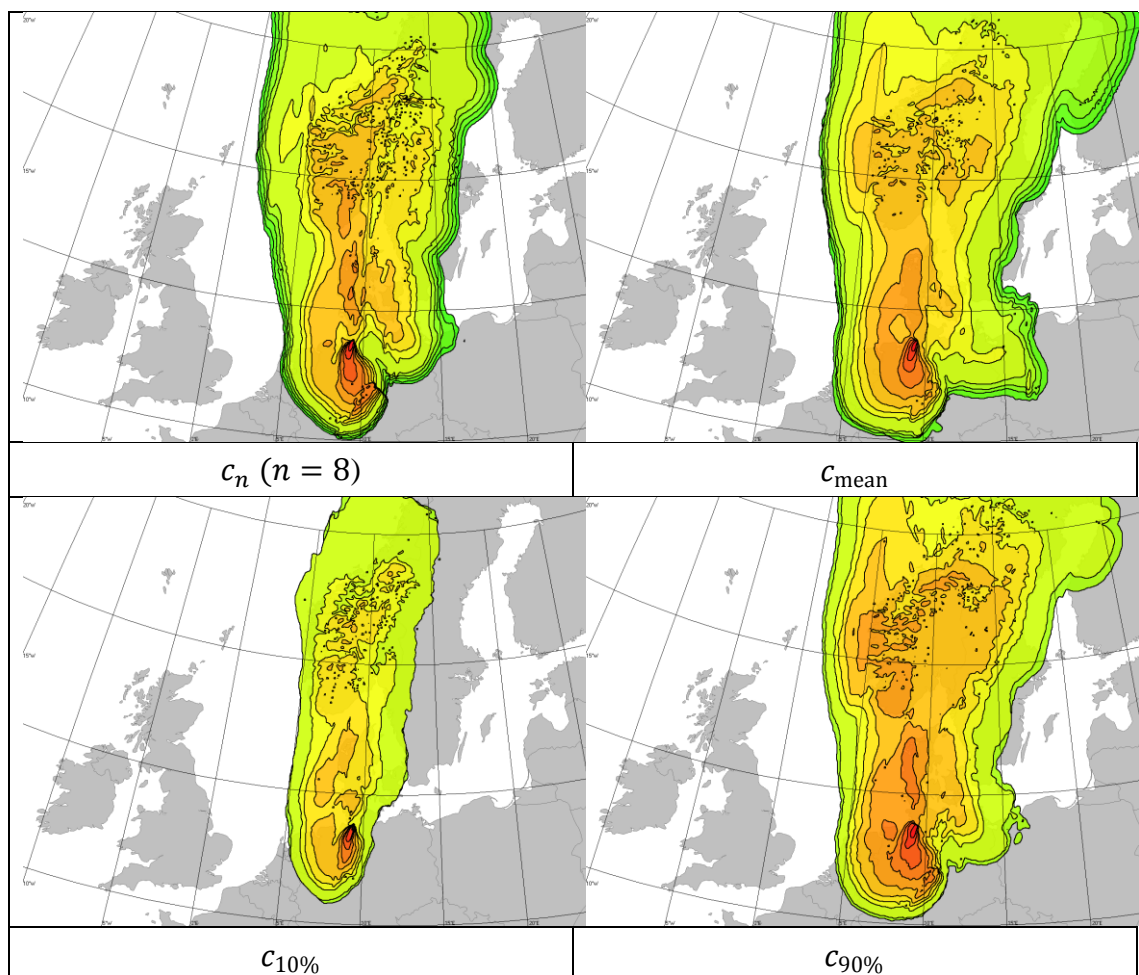


Figure 27 Scenario: 2011-05-23 Field: Accumulated deposition 54 hours after start of release. Nuclide: Cs-134.

In the following figures, the (time-dependent) values of the radioisotopes of iodine present in the plumes of the dispersion modelling have been used to calculate resulting thyroid doses. Two threshold values, corresponding to an organ dose over two days of 1 and 100 mGy,

respectively, are indicated as isocurves in the maps. They represent hypothetical values for which countermeasures could be considered in the decision process.

Based on the results below, and from the perspective of a decision maker, the following (simplified) conclusions can be drawn:

- It is (meteorologically) likely that the given threshold values will be exceeded for the areas indicated in $T_{10\%}$.
- The T_{mean} distribution indicates the most (meteorologically) plausible influence area.
- The exceedance of the given threshold values for the areas indicated in $T_{90\%}$ cannot be (meteorologically) ruled out.
- It is (meteorologically) unlikely that the given threshold values will be exceeded for areas outside of what is indicated in $T_{90\%}$.

This information may be used by decision makers in prioritizing efforts.

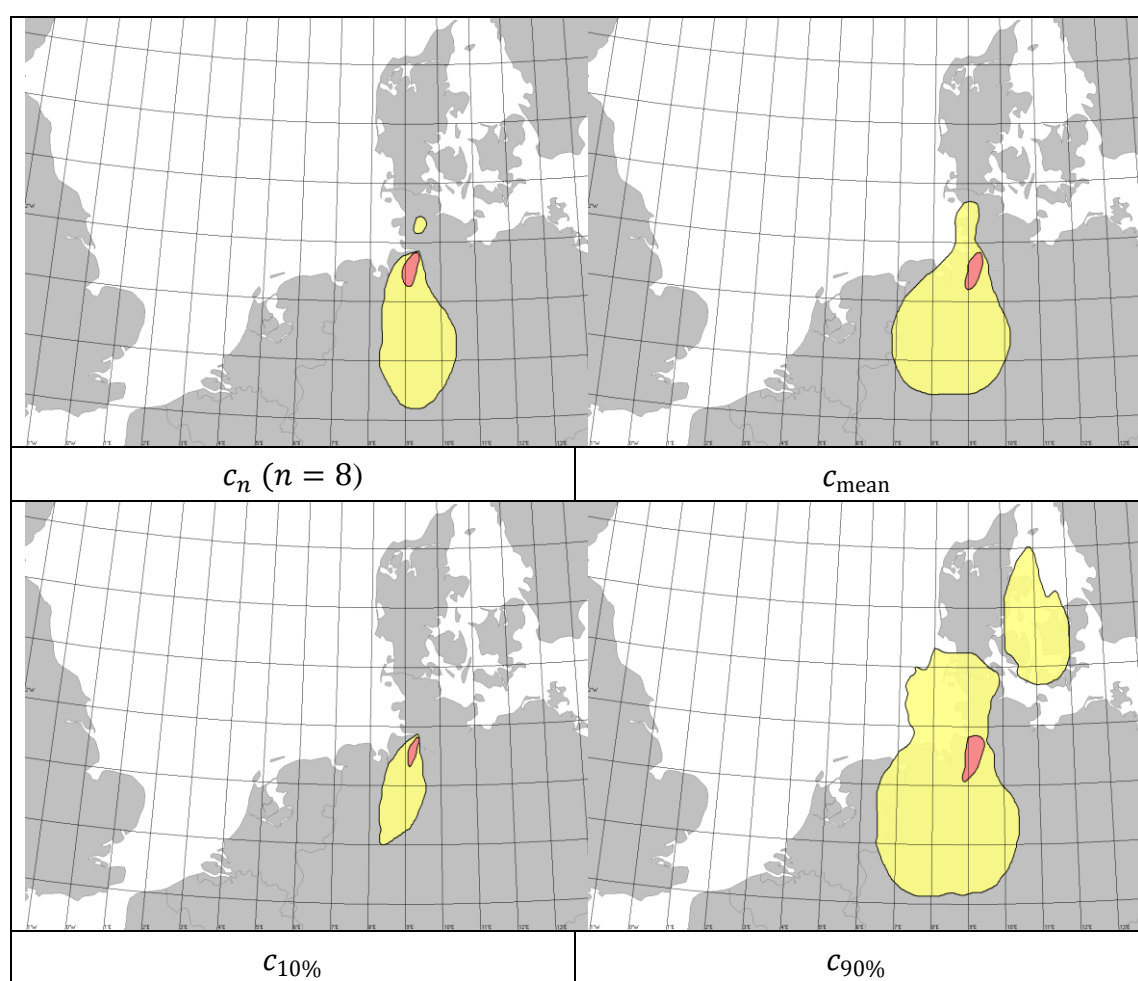


Figure 28 Scenario: 2011-05-23 Field: Thyroid dose 54 hours after start of release. Isocurves at 1 and 100 mGy.

It should once again be emphasized that the dose calculations above are performed not on individual dispersion modelling results as such, but on the statistical results from the ensemble modelling. These results do not as such represent plumes that are physically consistent, but can be mathematically treated as such in the dose calculation process. An advantage of the adopted process is that threshold values do not need to be defined beforehand, but may be dynamically applied to the ensemble modelling results.

13. Conclusions

The MUD project addressed assessment of uncertainties of atmospheric dispersion model predictions caused by meteorological uncertainties, as well as possibilities for presentation to decision makers.

A selection of four NPPs was made as hypothetical release points for atmospheric dispersion model calculations. The NPPs are located in, or in vicinity of, the Nordic countries. The release scenario is the same for all cases. It is defined by low heat release, 40 m release height, and 6-hour emission of the radionuclides Cs-134, I-131, Xe-135 and Pu-239. Four meteorological scenarios involving full forecast series of 54 hours and fulfilling the needs for variability have been selected. The scenarios involve windy cyclonic and low-wind anti-cyclonic conditions, as well as convective summer precipitation influencing the wet deposition, and thereby potentially producing large uncertainties in the resulting deposition patterns. The DMI atmospheric dispersion model DERMA, and the Met Norway dispersion model EEMEP have been run for the selected release scenario for the four NPPs and the four meteorological scenarios selected, each involving the 25 ensemble members of the DMI meteorological EPS. As expected, in some cases (convective and low wind conditions) the dispersion model results vary substantially across the ensemble, in others less variation is observed between the dispersion model ensemble members.

Possibilities for the use and presentation of uncertainties in a nuclear decision support system have been investigated, some of which are based on the meteorological use of EPS for weather forecasting. Of course, there are potentially also large uncertainties associated with the source term estimation. The presentation of such uncertainties in nuclear DSSs could utilize the same approaches developed in MUD. However, though relevant for emergency preparedness, these subjects are considered outside the scope of MUD, which focuses on meteorological uncertainties and their effects on atmospheric dispersion. As part of the project, it has been discussed with the radiation protection authorities taking part in the project how best to present the uncertainties, i.e. the distribution of model results, for decision makers.

There is a risk of information overflow when considering presentation to decision makers, and it must be considered carefully. Current output is in the form of time series of instantaneous concentration, time-integrated concentration, total deposition, wet deposition, 10, 50 and 90% percentiles and minimum, mean and maximum plots. Furthermore, probabilities of exceeding given threshold values (e.g. 10^2 , 10^3 and 10^4 Bq/m² for deposition) were considered.

Methods have been developed for computation of the meteorological uncertainties pertaining to simulations of atmospheric dispersion of radioactivity from accidental releases. Possibilities for optimum presentation to decision makers have been investigated and described, and the methods developed have been applied to the case studies.

Interactive communication between a national meteorological service and a nuclear decision-support system, using ARGOS as an example, was examined as well as use of automatic procedures. Accordingly, the numerical results of MUD have been made available in a format which can be imported in ARGOS, which thereby hosts the demonstration of MUD results.

In brief, the findings are the following:

- Depending on the meteorological situation, the uncertainties can be large, up to a factor of ten, especially when convective precipitation is involved.
- There is a risk of information overflow when considering presentation to decision makers. Therefore, statistical parameters must be selected carefully.
 - The use of percentiles is encouraged, involving a large percentage (depending on the ensemble size), the median and a low percentage. The large percentile indicates the maximum possible influence area, a quantity which is relevant to the emergency management.
 - Probabilities for exceeding given threshold values are also relevant. However, they rely on radionuclide dependent threshold values, which are not available in all cases.
- The methodology developed in course of MUD will be implemented operationally at DMI to be used in ARGOS by DEMA.

Acknowledgements

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

Disclaimer

The views expressed in this document remain the responsibility of the author(s) and do not necessarily reflect those of NKS. In particular, neither NKS nor any other organisation or body supporting NKS activities can be held responsible for the material presented in this report.

14. References

- Baklanov, A. and J. H. Sørensen. Parameterisation of radionuclide deposition in atmospheric dispersion models. *Phys. Chem. Earth* **26** (2001) 787–799
- Baklanov, A., A. Mahura and J. H. Sørensen. Methodology for Prediction and Estimation of Consequences of Possible Atmospheric Releases of Hazardous Matter: ‘Kursk’ Submarine Study. *Atmos. Phys. Chem.* Vol. **3** (2003) 747–762
- Bartnicki, J., H. Haakenstad and Ø. Hov. Operational SNAP model for remote applications from NRPA. Norwegian Meteorological Institute. Report 12/2011 (2011)
- Bianconi, R., S. Galmarini and R. Bellasio. Web-based system for decision support in case of emergency: ensemble modelling of long-range atmospheric dispersion of radionuclides. *Environmental modelling and software* **19** (2004) 401–411
- Buizza, R. and Miller, M.J. and Palmer, T.N. Stochastic representation of model uncertainties in the ECMWF ensemble prediction system. *Q.J.R. Meteorol. Soc.* **125** (1999) 2887–2908
- Burman, J., N. Brännström, O. Björnham, P. Lindgren, L. Persson, P. V. Schoenberg and L. Thanning. Osäkerheter I observationer och beräkningar. *Totalförsvarets forskningsinstitut (FOI), CBRN-skydd och säkerhet, rapport no. FOI-R—3764—SE* (2013)
- Calvo, J. 2007. Kain-Fritsch convection in HIRLAM. Present status and prospects. HIRLAM Newslett. 52, 57–64. Available at http://hirlam.org/index.php?option=com_docman&task=doc_download&Itemid=70&gid=34
- Draxler, R. R. Evaluation of an Ensemble Dispersion Calculation. *Journal of Applied Meteorology* **42** (2) (2002) 308–317
- Feddensen, H. A short-range limited area ensemble prediction system at DMI. *DMI Tech. Rep.*, 09–14 (2009) <http://www.dmi.dk/dmi/tr09-14.pdf>
- Galmarini S., R. Bianconi, R. Bellasio and G. Graziani. Forecasting the consequences of accidental releases of radionuclides in the atmosphere from ensemble dispersion modelling. *Journal of Environmental Radioactivity* **57** (3) (2001) 203–219
- Galmarini, S., F. Bonnardot, A. Jones, S. Potemski, L. Robertsen and M. Martet. Multi-model vs. EPS-based ensemble atmospheric dispersion simulations: A quantitative assessment on the ETEX-1 tracer experiment case. *Atmospheric Environment* **44** (29) (2010) 3558–3567
- Galmarini, S., R. Bianconi, W. Klug, T. Mikkelsen, R. Addis, S. Andronopoulos, P. Astrup, A. Baklanov, J. Bartnicki, J. C. Bartzis, R. Bellasio, F. Bompay, R. Buckley, M. Bouzom, H. Champion, R. D’Amours, E. Davakis, H. Eleveld, G. T. Geertsema, H. Glaab, M. Kollax, M. Ilvonen, A. Manning, U. Pechinger, C. Persson, E. Polreich, S. Potemski, M. Prodanova, J. Saltbones, H. Slaper, M. A. Sofiev, D. Syrakov, J. H. Sørensen, L. Van der Auwera, I. Valkama, R. Zelazny. Ensemble Dispersion Forecasting, Part I: Concept, Approach and Indicators. *Atmos. Environ.* **38** (2004a) 4607–4617

Galmarini, S., R. Bianconi, W. Klug, T. Mikkelsen, R. Addis, S. Andronopoulos, P. Astrup, A. Baklanov, J. Bartnicki, J. C. Bartzis, R. Bellasio, F. Bompay, R. Buckley, M. Bouzom, H. Champion, R. D'Amours, E. Davakis, H. Eleveld, G. T. Geertsema, H. Glaab, M. Kollax, M. Ilvonen, A. Manning, U. Pechinger, C. Persson, E. Polreich, S. Potemski, M. Prodanova, J. Saltbones, H. Slaper, M. A. Sofiev, D. Syrakov, J. H. Sørensen, L. Van der Auwera, I. Valkama, R. Zelazny. Can the Confidence in Long Range Atmospheric Transport Models Be Increased? The Pan-European Experience of ENSEMBLE. *Radiat. Prot. Dosim.* **109** (2004b) 19–24

García-Moya, J., Callado, A., Escribà, P., Santos, C., Santos-Muñoz, D. and Simarro, J. Predictability of short-range forecasting: a multimodel approach. *Tellus A* **63** (2011) 550–563

Gloster, J., A. Jones, A. Redington, L. Burgin, J. H. Sørensen, R. Turner. International approach to atmospheric disease dispersion modelling. *Veterinary Record* 03 (2010a) **166** (12):369. DOI:10.1136/vr.166.12.369a

Gloster, J., A. Jones, A. Redington, L. Burgin, J. H. Sørensen, R. Turner, P. Hullinger, M. Dillon, P. Astrup, G. Garner, R. D'Amours, R. Sellers and D. Paton. Airborne spread of foot-and-mouth disease – model intercomparison. *Veterinary Journal* **183** (2010b) 278–286

Gollvik, S. and P. Samuelsson. A tiled land-surface scheme for HIRLAM. *HIRLAM Rep.* (2010)
http://hirlam.org/index.php?option=com_docman&task=doc_download&Itemid=70&gid=1206

Graziani, G., W. Klug and S. Mosca (editors). Real-time long-range dispersion model evaluation of the ETEX first release. Joint Research Centre, EU, Luxemburg (1998)

Hoe, S., J. H. Sørensen and S. Thykier-Nielsen. The Nuclear Decision Support System ARGOS NT and Early Warning Systems in Some Countries around the Baltic Sea. In: Proceedings of the 7th Topical Meeting on Emergency Preparedness and Response, September 14–17, 1999, Santa Fe, New Mexico, USA

Hoe, S., H. Müller, F. Gering, S. Thykier-Nielsen and J. H. Sørensen. ARGOS 2001 a Decision Support System for Nuclear Emergencies. In: Proceedings of the Radiation Protection and Shielding Division Topical Meeting, April 14–17, 2002, Santa Fe, New Mexico, USA

Hou, D., E. Kalnay and K. K. Drogemeier. Objective verification of the SAMEX '98 ensemble forecasts. *Mon. Wea. Rev.* **129** (2001) 73–91

IAEA Safety Standards Series No. GSR Part 3 (Interim). International Atomic Energy Agency, Vienna (2011).
http://www-pub.iaea.org/MTCD/publications/PDF/p1531interim_web.pdf

Ivarsson, K. I. The Rasch Kristjansson large scale condensation. Present status and prospects. *HIRLAM Newsletter* **52** (2007) 50–56
http://hirlam.org/index.php?option=com_docman&task=doc_download&Itemid=70&gid=33

Kain, J. S. The Kain-Fritsch Convective Parameterization. An update. *J. Appl. Meteorol.* **43** (2004) 170–181.

- Kain, J. S. and Fritsch, J. M. A one-dimensional entraining/detraining plume model and its application in convective parameterization. *J. Atmos. Sci.* **47** (1990) 2784–2802.
- Kolczynski, W. C., D. R. Stauffer, S. E. Haupt and A. Deng. Ensemble Variance Calibration for Representing Meteorological Uncertainty for Atmospheric Transport and Dispersion Modeling. *Journal of applied Meteorology and Climatology* **48** (2009) 2001–2021
- Lauritzen, B., A. Baklanov, A. Mahura, T. Mikkelsen and J. H. Sørensen. K-model description of probabilistic long-range atmospheric transport in the Northern Hemisphere. *Atmos. Environ.* **40** (2006) 4352–4369
- Lauritzen, B., A. Baklanov, A. Mahura, T. Mikkelsen and J. H. Sørensen. Probabilistic risk assessment for long-range atmospheric transport of radionuclides. *J. Envir. Radioactivity* **96** (2007) 110–115
- Lee, J. A., L. Peltier, S. E. Haupt, J. C. Wyngaard, D. R. Stauffer and A. Deng. Improving SCIPUFF Dispersion Forecasts with NWP Ensembles. *Jorunal of Applied Meteorology and Climatology* **48** (11) (2009) 230–2319
- Mahura, A., A. Baklanov and J. H. Sørensen. Methodology for evaluation of possible consequences of accidental atmospheric releases of hazardous matter. *Radiat. Prot. Dos.* **103** (2003) 131–139
- Mahura, A. G., A. A. Baklanov, J. H. Sørensen, F. L. Parker, V. Novikov, K. Brown, K. L. Compton 2004: Assessment of Atmospheric Transport and Deposition Patterns Related to Russian Pacific Fleet Operations. *Environmental Monitoring and Assessment* **101** (2005) 261–287
- Mikkelsen, T., S. Thykier-Nielsen, P. Astrup, J. M. Santabárbara, J. H. Sørensen, A. Rasmussen, L. Robertson, A. Ullerstig, S. Deme, R. Martens, J. G. Bartzis and J. Päsler-Sauer. MET-RODOS: A Comprehensive Atmospheric Dispersion Module. *Radiat. Prot. Dosim.* **73** (1997) 45–56
- Mikkelsen, T., S. Alexandersen, H. Champion, P. Astrup, A. I. Donaldson, F. N. Dunkerley, J. Gloster, J. H. Sørensen and S. Thykier-Nielsen. Investigation of Airborne Foot-and-Mouth Disease Virus Transmission during Low-Wind Conditions in the Early Phase of the UK 2001 Epidemic. *Atmos. Chem. Phys. Disc.* **3** (2003) 677–703
- Molteni, F., Buizza, R., Palmer, T. N. and Petroliagis, T. The ECMWF Ensemble Prediction System: Methodology and validation. *Q.J. R. Meteorol. Soc.* **122** (1996) 73–119
- Potempski, S., S. Galmarini, A. Riccio and G. Giunta. Bayesian model averaging for emergency response atmospheric dispersion multimodel ensembles: Is it really better? How many data are needed? Are the weights portable? *Journal of Geophysical Research* **115** (2010) D21309
- Rao, S. K. Uncertainty Analysis in Atmospheric Dispersion Modeling. *Pure appl. Geophys.* **162** (2005) 1893–1917

- Rasch, P. J. and Kristjansson, J. E. A comparison of the CCM3 model climate using diagnosed and predicted condensate parameterizations. *J. Clim.* **11** (1998) 1587–1614
- Rodríguez, E., B. Navascués, J.J. Ayuso and S. Järvenoja. Analysis of surface variables and parameterization of surface processes in HIRLAM. Part I: Approach and verification by parallel runs. *HIRLAM Tech. Rep.* 58 (2003)
http://hirlam.org/index.php?option=com_docman&task=doc_download&Itemid=70&gid=248
- Sass, B. H. A research version of the STRACO cloud scheme. *DMI Tech. Rep.*, 02–10 (2002)
<http://www.dmi.dk/dmi/tr02-10.pdf>
- Sass, B. H., N. W. Nielsen, J. U. Jørgensen, B. Amstrup, M. Kmit and K. S. Mogensen. The operational DMI-HIRLAM system – 2002 version, *DMI Tech. Rep.*, 02–05 (2002)
<http://www.dmi.dk/dmi/tr02-05.pdf>
- Simpson, D., A. Benedictow, H. Berge, R. Bergström, L. D. Emberson, H. Fagerli, C. R. Flechard, G. D. Hayman, M. Gauss, J. E. Jonson, M. E. Jenkin, A. Nyíri, C. Richter, V. S. Semeena, S. Tsyro, J.-P. Tuovinen, Á. Valdebenito, and P. Wind. The EMEP MSC-W chemical transport model – technical description. *Atmos. Chem. Phys.* **12** (16) (2012) 7825–7865
- Straume, A. G. A more extensive investigation of the use of ensemble forecasts for dispersion model evaluation. *Journal of Applied Meteorology* **40** (3) (2001) 425–445
- Sørensen, J. H., B. Amstrup, H. Feddersen, U. S. Korsholm, J. Bartnicki, I.-L. Frogner, H. Klein, A. Valdebenito, P. Wind, V. Ødegaard, B. Lauritzen, S. Cordt Hoe, and J. Lindgren. Meteorological Uncertainty of atmospheric Dispersion model results (MUD). NKS-291 (2013)
http://www.nks.org/en/nks_reports/view_document.htm?id=111010111766372
- Sørensen, J. H., A. Baklanov and S. Hoe. The Danish Emergency Response Model of the Atmosphere. *J. Envir. Radioactivity* **96** (2007) 122–129
- Sørensen, J. H. Sensitivity of the DERMA Long-Range Dispersion Model to Meteorological Input and Diffusion Parameters. *Atmos. Environ.* **32** (1998) 4195–4206
- Sørensen, J. H., A. Rasmussen, T. Ellermann and E. Lyck. Mesoscale Influence on Long-range Transport; Evidence from ETEX Modelling and Observations. *Atmos. Environ.* **32** (1998) 4207–4217
- Sørensen, J. H., D. K. J. Mackay, C. Ø. Jensen and A. I. Donaldson. An integrated model to predict the atmospheric spread of foot-and-mouth disease virus. *Epidemiol. Infect.* (2000) 124, 577–590
- Sørensen, J. H., C. Ø. Jensen, T. Mikkelsen, D. Mackay and A. I. Donaldson. Modelling the atmospheric spread of foot-and-mouth disease virus for emergency preparedness. *Phys. Chem. Earth* **26** (2001) 93–97

Undén, P., Rontu, L., Jarvinen, H., Lynch, P., Calvo, J. and co-authors. HIRLAM-5 Scientific Documentation HIRLAM-5 Project. (2002) Available from SMHI, S-601767 Norrköping, Sweden

Warner, T. T., R. S. Sheu and J. F. Bowers. Ensemble Simulations with coupled atmospheric dynamic and dispersion models: Illustrating uncertainties in dosage simulations. *Journal of Applied Meteorology* **41** (5) (2002) 488–504

Title	Meteorological Uncertainty of atmospheric Dispersion model results (MUD)
Author(s)	Jens Havskov Sørensen ¹ , Bjarne Amstrup ¹ , Henrik Feddersen ¹ , Ulrik Smith Korsholm ¹ , Jerzy Bartnicki ² , Heiko Klein ² , Peter Wind ² , Bent Lauritzen ³ , Steen Cordt Hoe ⁴ , Carsten Israelson ⁴ , Jonas Lindgren ⁵
Affiliation(s)	¹ Danish Meteorological Institute ² Norwegian Meteorological Institute ³ Technical University of Denmark ⁴ Danish Emergency Management Agency ⁵ Swedish Radiation Safety Authority
ISBN	978-87-7893-385-0
Date	May 2014
Project	NKS-B / MUD
No. of pages	39
No. of tables	3
No. of illustrations	28
No. of references	50
Abstract max. 2000 characters	<p>The MUD project addresses assessment of uncertainties of atmospheric dispersion model predictions, as well as optimum presentation to decision makers. Previously, it has not been possible to estimate such uncertainties quantitatively, but merely to calculate the 'most likely' dispersion scenario. However, recent developments in numerical weather prediction (NWP) include probabilistic forecasting techniques, which can be utilised also for atmospheric dispersion models.</p> <p>The ensemble statistical methods developed and applied to NWP models aim at describing the inherent uncertainties of the meteorological model results. These uncertainties stem from e.g. limits in meteorological observations used to initialise meteorological forecast series. By perturbing the initial state of an NWP model run in agreement with the available observational data, an ensemble of meteorological forecasts is produced. In MUD, corresponding ensembles of atmospheric dispersion are computed from which uncertainties of predicted radionuclide concentration and deposition patterns are derived.</p>
Key words	nuclear emergency preparedness, atmospheric dispersion model, meteorology, uncertainty, ensemble prediction

Available on request from the NKS Secretariat, P.O.Box 49, DK-4000 Roskilde, Denmark.
Phone (+45) 4677 4041, e-mail nks@nks.org, www.nks.org