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Fukushima Accident: UNcertainty of Atmospheric dispersion modelling (FAUNA)

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Abstract

By employing the methodology developed in the NKS-B project MUD, the FAUNA project has addressed assessment of the uncertainties of atmospheric dispersion model predictions of nuclear aerosols and gasses from the Fukushima Daiichi nuclear accident.

A meteorological numerical ensemble forecasting system has been set up and applied to Japan and surroundings for the period of the main atmospheric release of radionuclides from the Fukushima Daiichi NPP in 2011. The resulting analysed and forecast numerical weather-prediction ensemble-statistical data have been used by the Danish and Norwegian operational atmospheric dispersion models. Corresponding ensembles of atmospheric dispersion are computed from which uncertainties of predicted radionuclide concentration and deposition patterns are derived.

Implications of using the methodology for nuclear emergency management and decision support are discussed.

Key words

Fukushima Daiichi accident, nuclear emergency preparedness, atmospheric dispersion model, meteorology, uncertainty,
ensemble prediction

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Final Report of the NKS-B FAUNA activity

Contract: AFT/B(15)1

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1. Introduction

The NKS-B project Fukushima Accident: UNcertainty of Atmospheric dispersion modelling (FAUNA) applies the ensemble-statistical methodology developed in the NKS-B project Meteorological Uncertainty of atmospheric Dispersion model results (MUD) (Sørensen *et al*,. 2014) to the Fukushima Daiichi NPP accident. The project addresses real-time forecasting of atmospheric dispersion and deposition of radionuclides released from a nuclear installation taking into account the meteorological uncertainties. Under certain weather conditions, these uncertainties can be large, and, as demonstrated by MUD (Sørensen *et al.*, 2014) consequently also the uncertainties of the dispersion model results.

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, e.g. probability 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 are computed from which air concentration and deposition patterns can be obtained, including estimates of the uncertainty in the model calculations.

The objective of the FAUNA project is to apply the MUD methodology to a realistic setting of the Fukushima accident, and to investigate the implications of the uncertainty estimates for the emergency management. Thus, for the first time a study has been carried out on the influence of meteorological uncertainties on real-time assessments of geographical areas affected by radioactivity from the Fukushima accident.

A meteorological ensemble forecasting system has been set up and run on DMI's super-computer for the period of concern and for a geographical domain covering Japan and surroundings. For the full period, two-day meteorological forecasts have been generated four times a day, as would be the case for an operational system in real time.

For selected dates and times in the release period, the Danish and the Norwegian long-range atmospheric dispersion models, DERMA (Sørensen *et al.*, 2007; Sørensen, 1998) and SNAP (Bartnicki *et al.*, 2011), respectively, have been run based on data of the meteorological ensemble assuming that a realistic source term is available in near real time. Corresponding ensemble-statistical parameters are calculated, e.g. percentiles of the concentration and deposition fields. The predictions have been made available to the ARGOS (Accident Reporting and Guidance Operational System) decision-support system (Hoe *et al.*, 2002; Hoe *et al.*, 1999) for display and dose modelling. Thereby, the project imitates real-time emergency management taking into account estimates of the uncertainty of the dispersion model results.

2. Source term estimates for the Fukushima Daiichi accident

Recently, the source term for the Fukushima Daiichi accident has been described by Katata *et al.* (2014) for the two radionuclides I-131 and Cs-137 covering the period from the start of the release until beginning of April 2011. By taking into account also observed sea-water radionuclide concentrations in the Pacific Ocean, this work is an improvement of a previous study by Terada *et al.* (2012), which again builds on earlier work by Chino *et al.* (2011) in which a reverse estimation method is applied to dust sampling data from measurement stations around the Fukushima Daiichi nuclear power plant. Using this release description, they have analysed the atmospheric dispersion and surface deposition by comparing the simulation results with measurements of daily and monthly surface depositions (fallout) over land in eastern Japan from March 12 to April 30, 2011. In certain periods, especially when the plume was predominantly transported over the sea, the resulting source term is substantially larger and with a more detailed structure than the previous one by Terada *et al.* (2012).

Even though the source description by Katata *et al.* (2014) includes only two of the dose-contributing radionuclides, it is considered that this is enough for demonstration purposes, and therefore this source term may well be used in the FAUNA project. In Fig. 1 is shown the estimated release rates of I-131 and Cs-137 for the first three weeks of the release period.

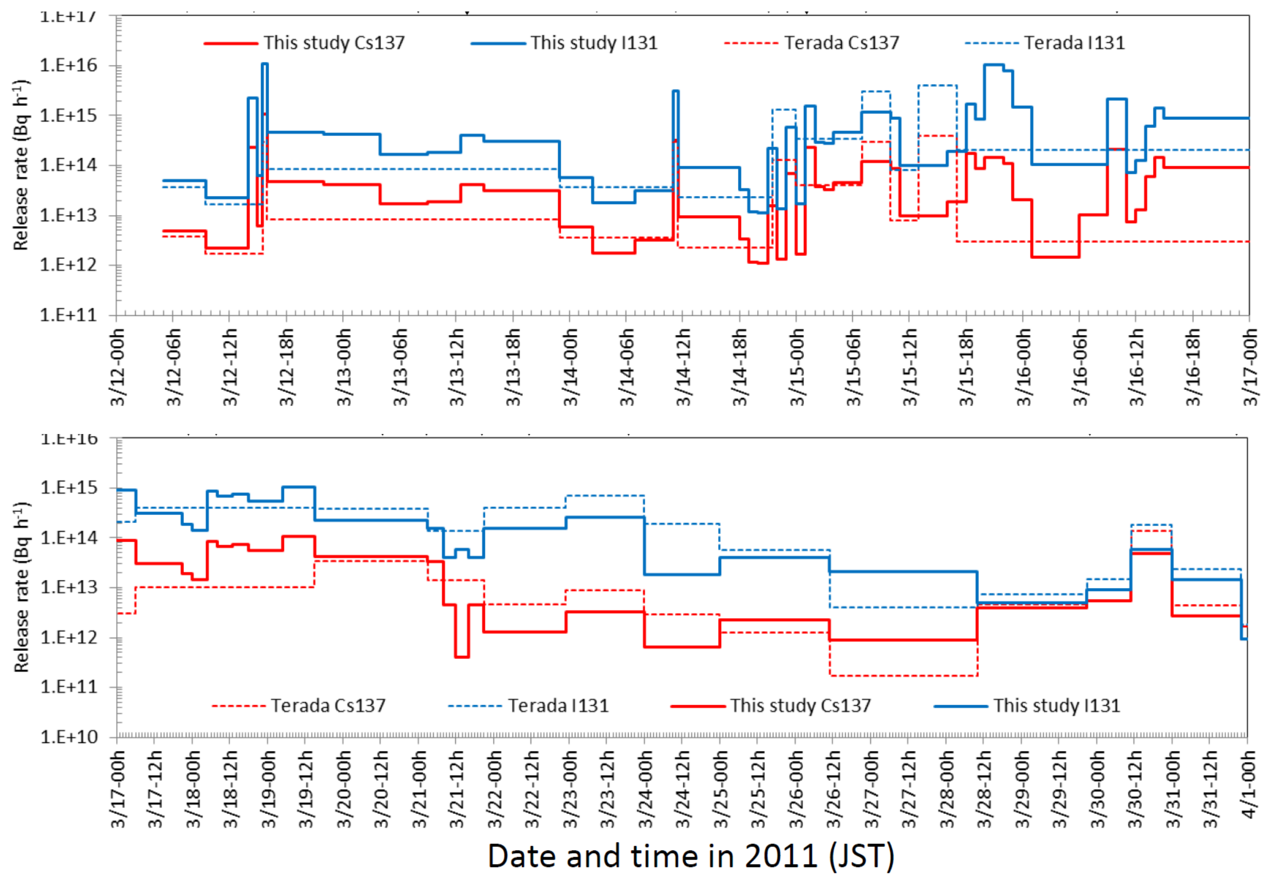


Figure 1. Realese rates of I-131 and Cs-137 for the first three weeks of the release period; figure by Katata *et al.* (2014). The rates by Katata *et al.* (2014) are shown by solid lines, the rates by Terada *et al.* (2012) by dashed lines. Cs-137 values are shown in red, I-131 in blue.

The DMI HIRLAM ensemble prediction model has been run from the start of the release at 11 March 2011 and until 5 April thus covering the main part of the atmospheric release as depicted in Fig. 1.

In another study, Saunier *et al.* (2013) propose to use a method employing dose-rate measurements which are obtained by common dose-rate stations. They arrive at a source description involving eight main radionuclides, Xe-133, Cs-134, Cs-136, Cs-137, Ba-137m, I-131, I-132 and Te-132.

3. HIRLAM meteorological forecast model ensembles for Japan and surroundings

Meteorological forecasts have been made using the HIRLAM model (HIRLAM; Undén *et al.*, 2002) for an area covering Japan and surroundings. The model domain is shown in Figure 2. The model grid has a horizontal resolution of 0.05°×0.05° corresponding to 496×420 grid boxes in a rotated grid. There are 40 vertical layers from the surface to the 10-hPa isobaric surface.

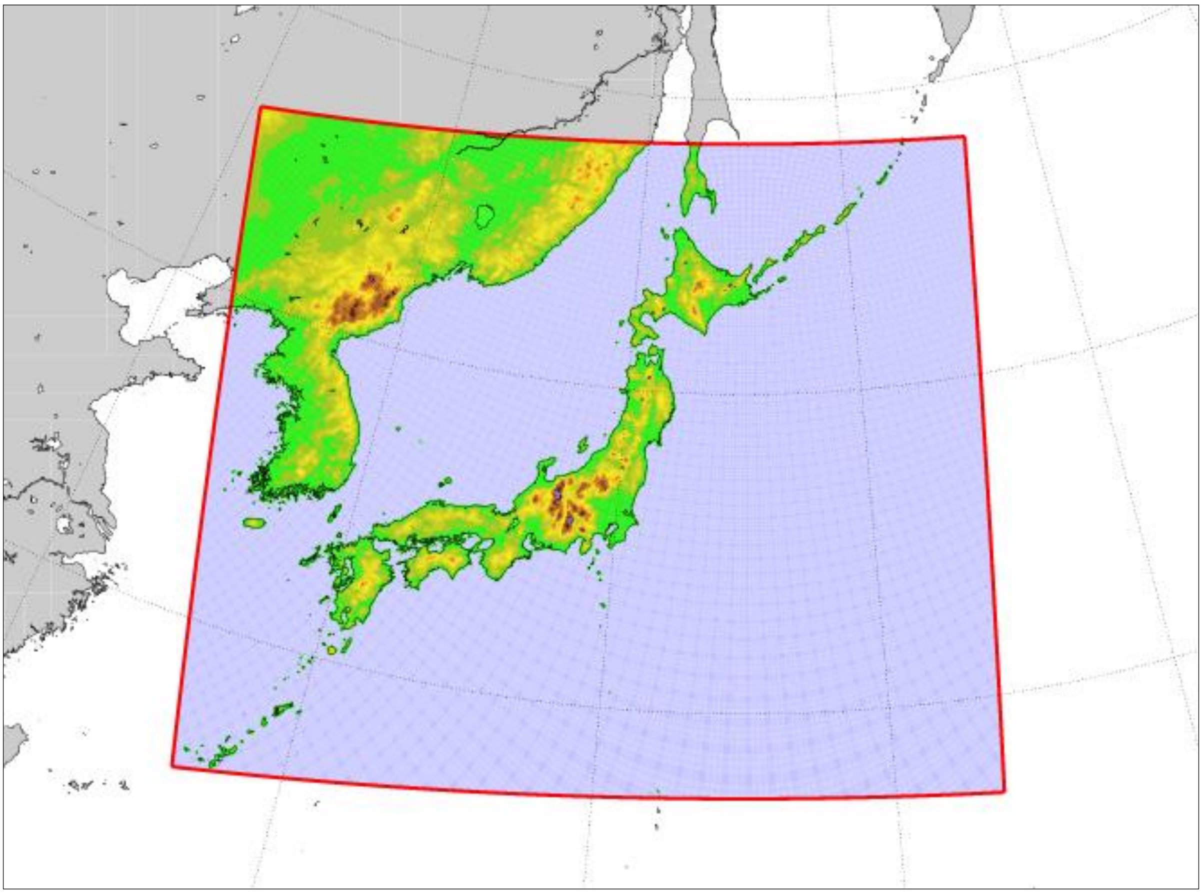


Figure 2 HIRLAM model domain.

Ensemble forecasts out to 48 hours are run every six hours in the period 10 March – 5 April 2011. An ensemble comprises 21 HIRLAM forecasts; the spread of the ensemble members is used to estimate the forecast uncertainty. The ensemble members differ from each other by the choice of initial and lateral boundary conditions and model configuration. One member, the control run, uses interpolated forecasts from the global ECMWF model as initial and lateral boundary conditions; the other 20 members use different small perturbations of the interpolated ECMWF forecasts. The perturbations are based on scaled forecast error estimates, i.e. differences between forecasts that are valid at the same time. Perturbations are always applied in pairs of control ± perturbation. The scaling is simply a factor that ensures that all perturbations have the same magnitude in terms of a kinetic energy norm. Separate surface analyses are run for each ensemble member. Half of the perturbed ensemble members are run with the cloud scheme "STRACO"; the other half with another cloud scheme "Kain/Fritsch-Rasch/Kristjansson" (Undén *et al.,* 2002). For half of the perturbed members the prognostic model variable tendencies are perturbed stochastically ("stochastic physics") during the model run (Buizza *et al.,* 1999). Cloud scheme, stochastic physics and "+" or "-" perturbations are combined as uniformly as possible, so there is no dominating combination in the ensemble.

Figure 3 shows an example of a point forecast for Fukushima (37.42°N, 141.03°E) from 0 UTC on 14 March 2011. The black line shows the control forecast, the blue shading in the temperature and wind speed plots shows the ensemble distribution (the darker blue showing the middle 50% of the members), and the dark blue line shows the median. The individual members are shown with dashed lines, red for members including stochastic physics, olive for the rest. For the wind direction each perturbed member is shown in cyan and the control in black. The plot is made in wind rose style, i.e. it shows where the wind is blowing from, e.g., at Monday 06Z the wind blows from a westerly direction in the control run (black "needle"), while 12 hours later at 18Z it blows from a northerly direction. We note substantial spread in both wind direction and wind speed (10 m above ground). Much of the spread can be explained by differences in the timing of moving weather systems; in the actual case in the beginning of the forecast we have an east-moving low pressure system north of Japan with an associated front that causes a change in wind direction from westerly to northerly (not shown).

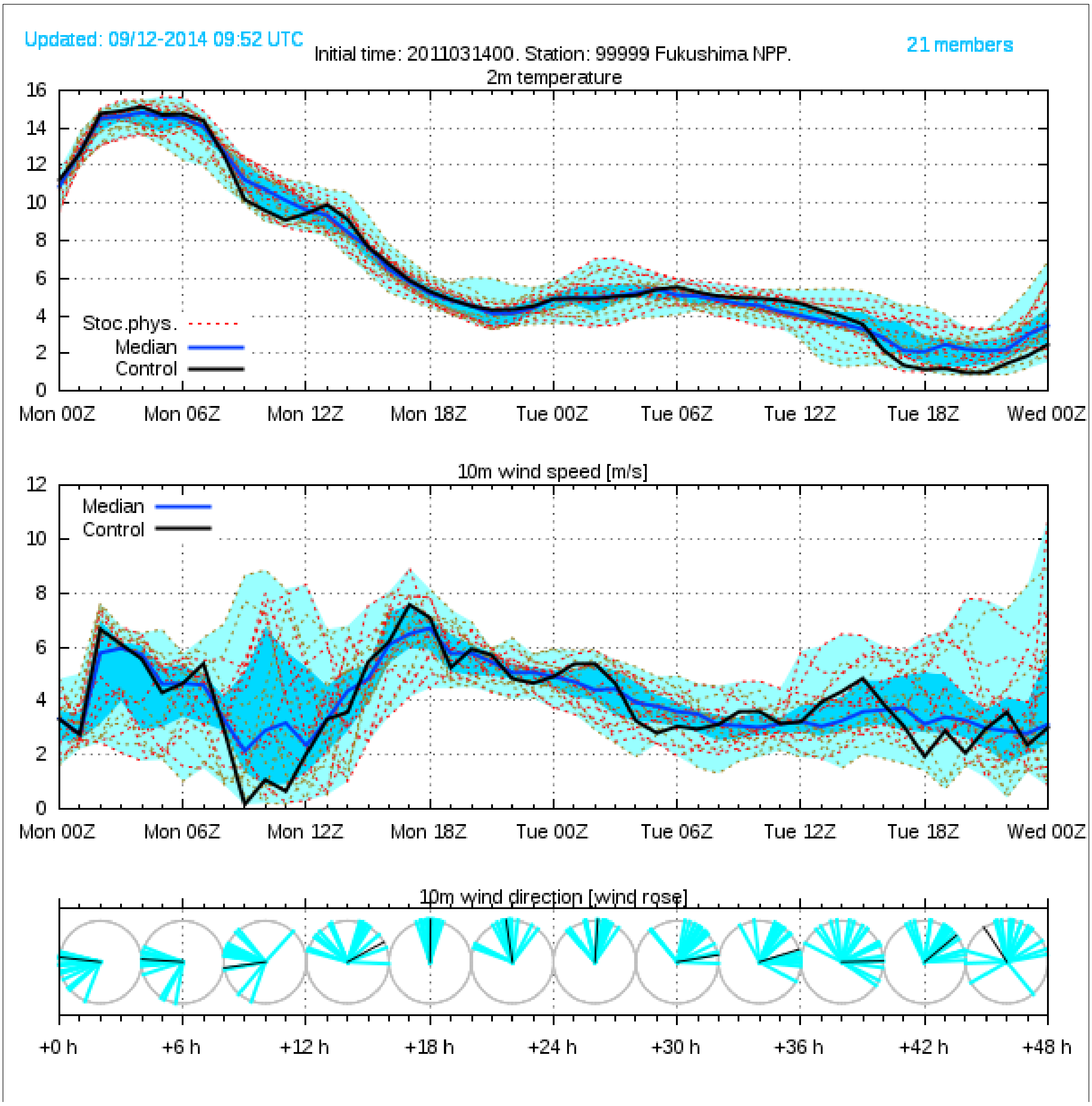


Figure 3 Ensemble meteogram for Fukushima NPP. Top panel shows 2 m temperature, middle panel shows 10 m wind speed; bottom panel shows 10 m wind direction. See text for more details.

One of the most uncertain forecast parameters is precipitation, especially on day two of the forecast. Figure 4 shows an example of the precipitation field for a 48 hour forecast for two members of the ensemble (selected as the one that gives the least precipitation over the domain and the one that gives the most) and the ensemble mean.

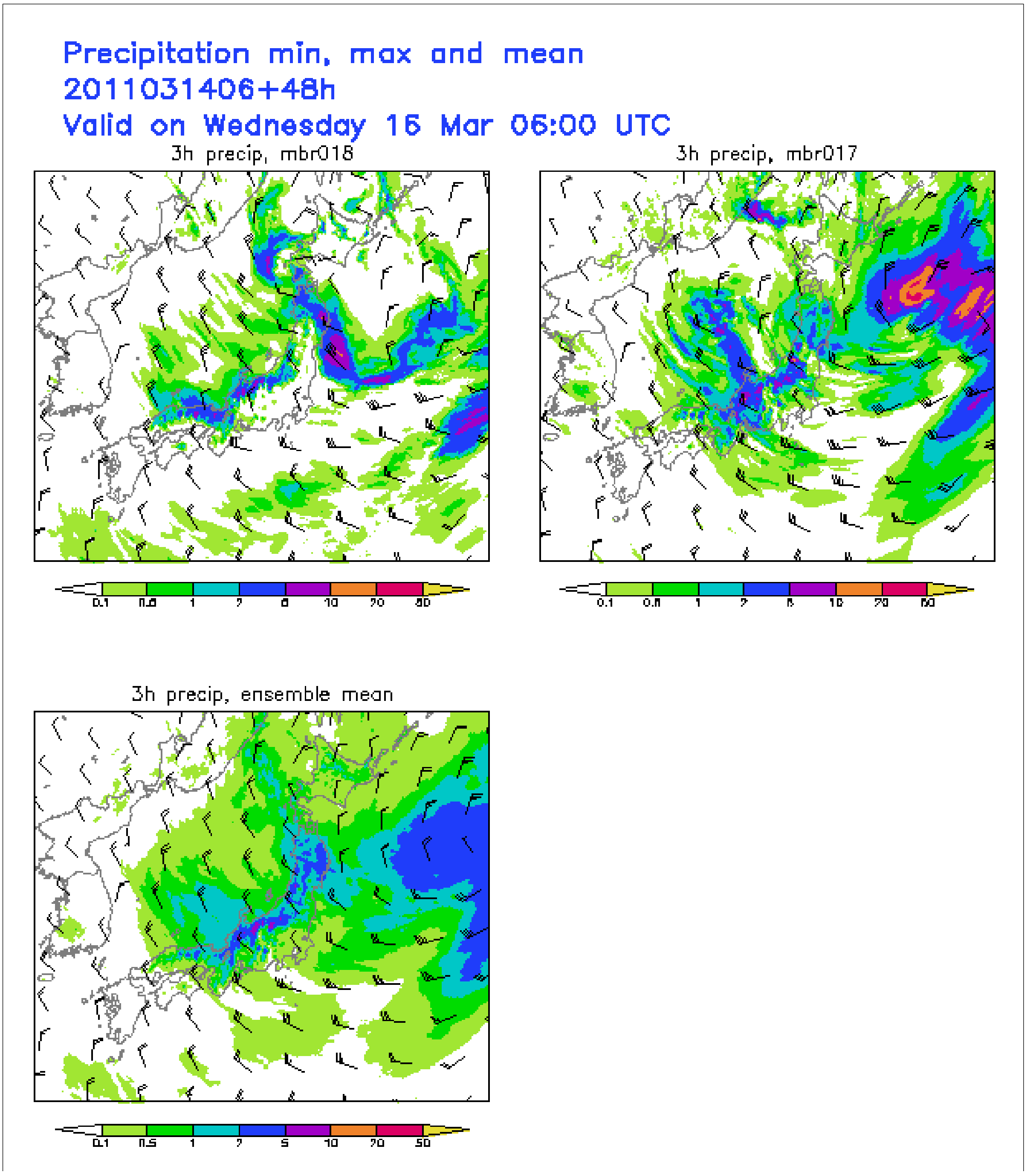


Figure 4 Two members of the same ensemble, illustrating the spread in precipitation. Panels show precipitation accumulated between forecast hours 45 and 48. Top: members 18 and 17; bottom: ensemble mean.

We do not have weather observations available for the site of the Fukushima NPP in March – April 2011, but approximately 150 km SSW in Mito there is an official synoptic weather observation station which we can use for verification of the ensemble forecasts. Figure 5 shows a meteogram for Mito similar to the one for Fukushima in Fig. 3, but with observed values included every six hours (every 12 hours for wind direction). The observations fall mostly inside the ensemble range as desired by a reliable ensemble forecasting system.

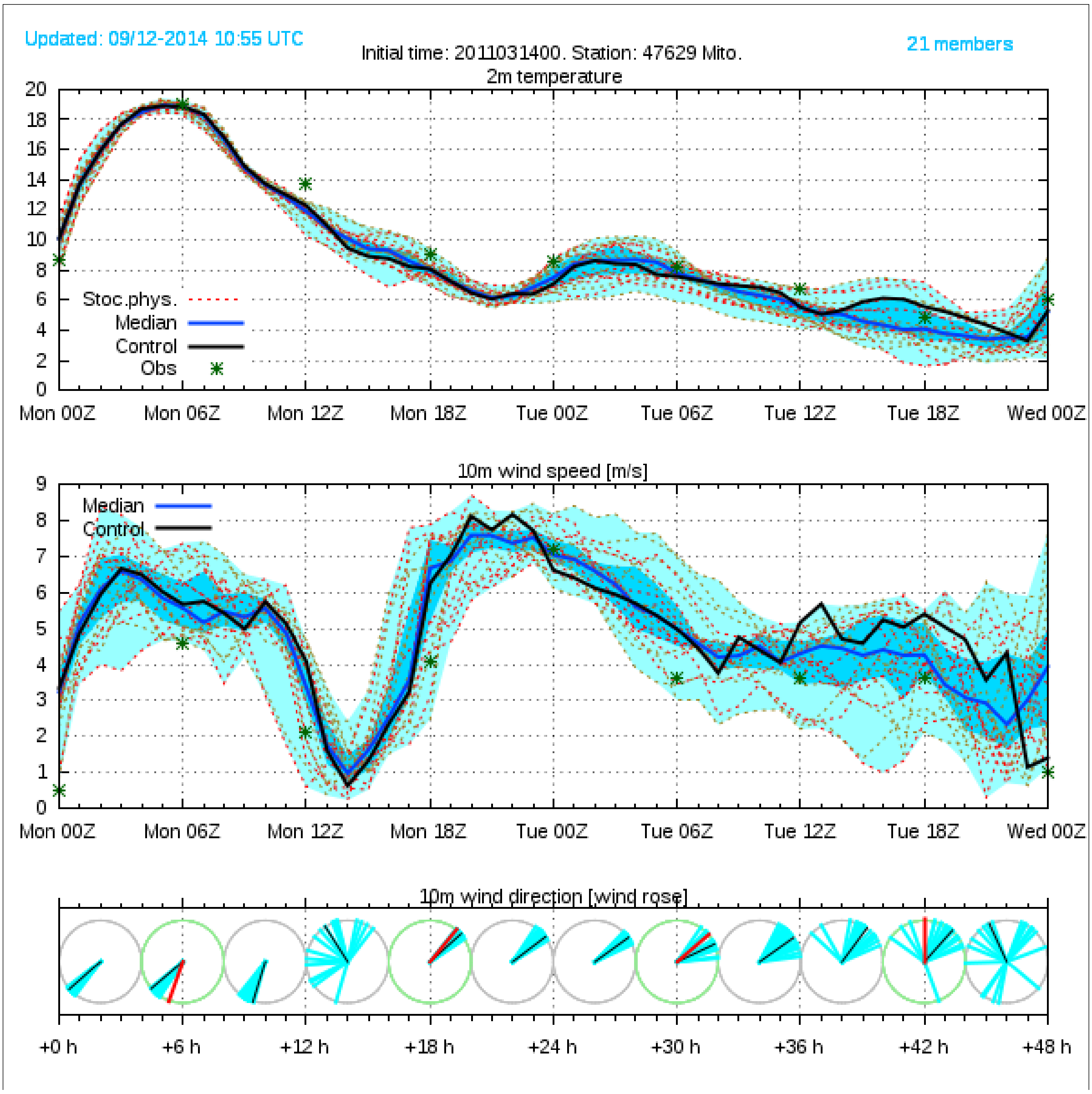


Figure 5 Ensemble meteogram for Mito (approx. 150 km SSW of Fukushima NPP). Verifying observations are shown as asterisks in temperature and wind speed panels and as red needles in wind direction panel.

In order to test the ability of the ensemble system to forecast 10-m wind speed reliably in the sense that the observations fall randomly inside the ensemble range, the ensemble forecasts are verified for 27 meteorological observation sites throughout Japan (see Fig. 6), and a so-called rank histogram is constructed (Jolliffe and Stephenson, 2003). For every forecast for each of the 27 observation sites the observation is ranked relative to the sorted ensemble members: rank 0 means that the observation is less than the smallest ensemble member; rank 1 means between the smallest and second smallest ensemble member, etc. For a perfect ensemble system the rank histogram is flat, but in practice meteorological ensemble prediction systems are almost always under-dispersive, i.e. the ensemble spread is insufficient to capture the verifying observations, resulting in a U-shaped rank histogram. This is also the case for our ensemble prediction system, as shown in Figure 7. Overall, the wind speed is slightly positively biased; if the bias was subtracted from the forecasts, the rank histogram would look better.

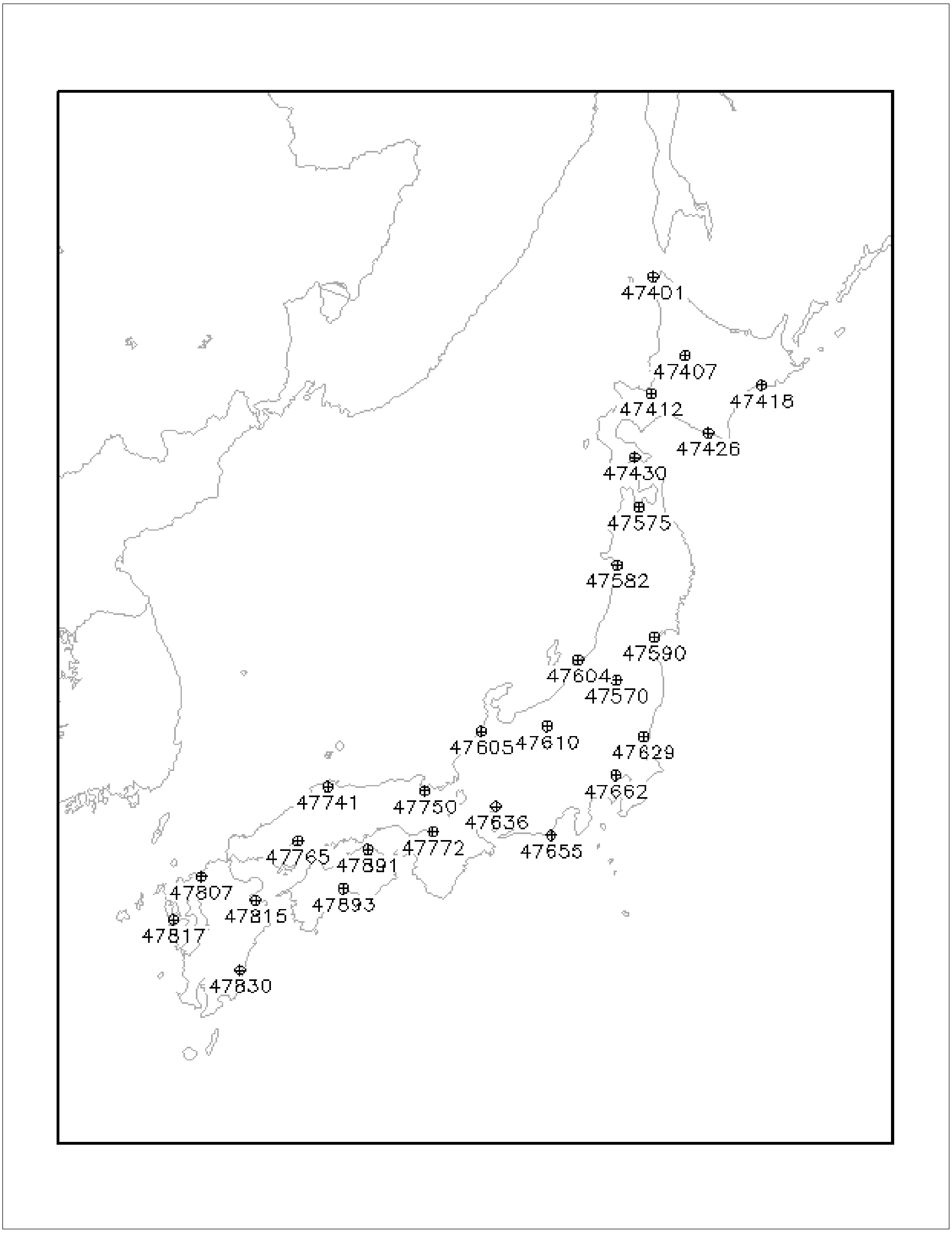


Figure 6 Meteorological synoptic observation stations used for verification. Numbers are identifiers used by the World Meteorological Organization.

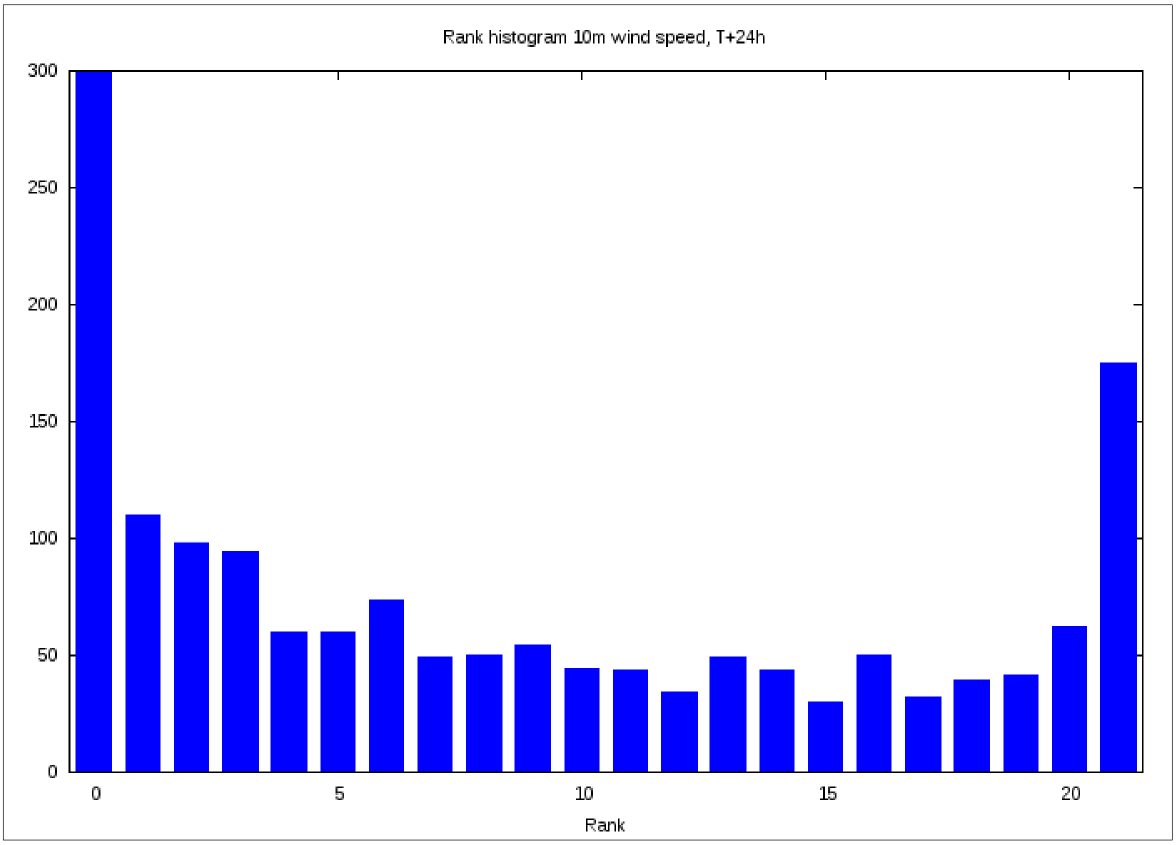


Figure 7 Rank histogram for Japanese observation sites for 24 h forecasts in the period 17-31 March 2011.

Another measure of forecast reliability is the so-called reliability diagram where forecast probabilities for a certain event are plotted against frequencies of verifying observations. Ideally, they should be the same, as we would expect to observe the event, e.g., in 70% of the cases where we forecast a probability of (approximately) 0.7. Figure 8 shows a reliability diagram for 24 h forecasts of the event "10 m wind speed > 5 m/s." We note that the forecasts are slightly over-confident, i.e. forecast probabilities are in general not accompanied by equally high observation frequencies. For comparison the reliability of a single, deterministic forecast (the ensemble control run) is also included and shown with blue markers. It is evident that the ensemble adds value to the single forecast.

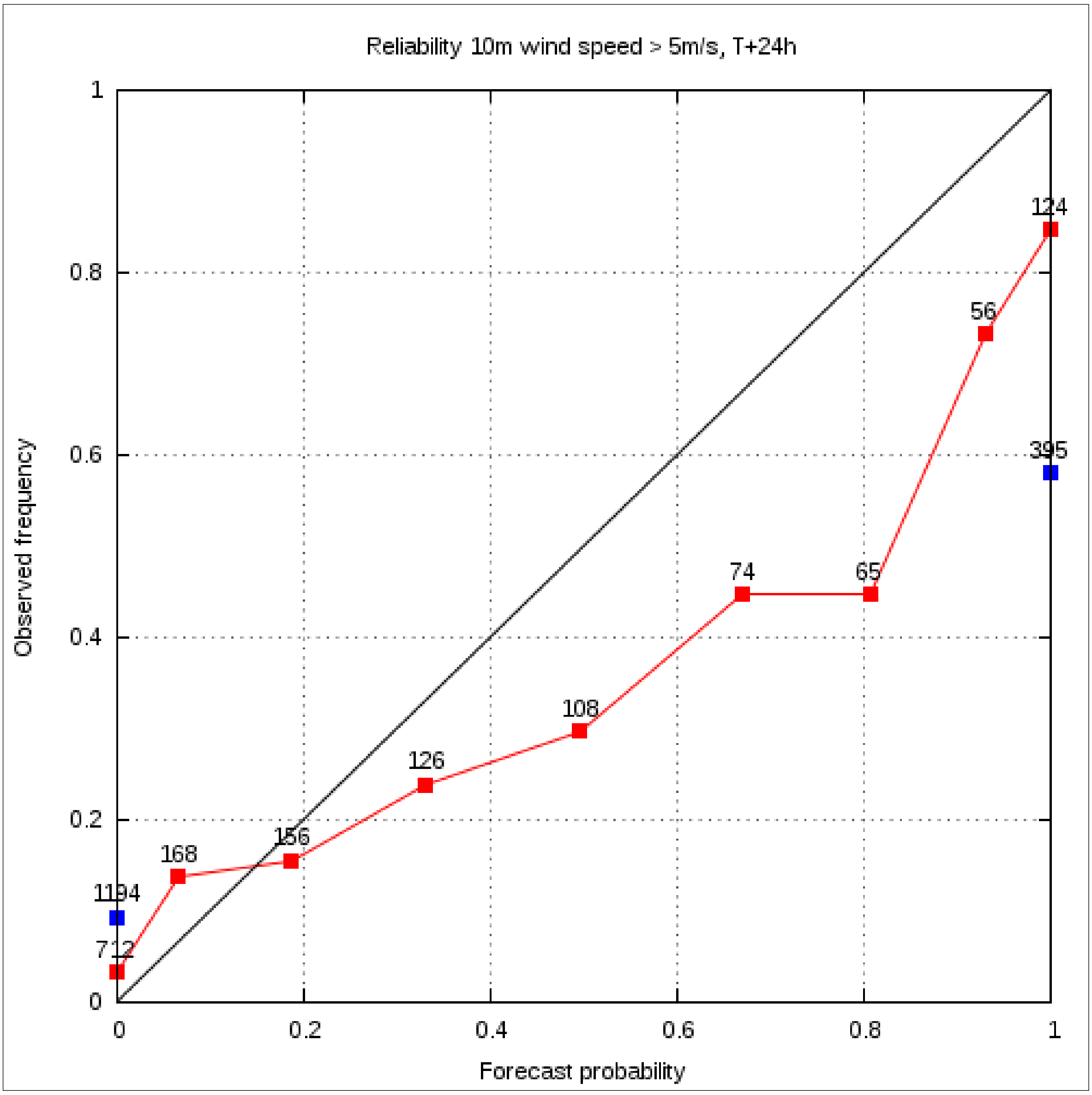


Figure 8 Reliability diagram for Japanese observation sites for 24h forecasts in the period 17–31 March 2011. Numbers show distribution of forecasts. Blue markers show reliability of control forecasts.

In particular, the ensemble simulations with the meteorological model HIRLAM have been carried out for the relevant period. The output is to be used for dispersion simulations by DMI and MET Norway.

4. On the use of quantiles for dose calculation

Human radiation doses can be expressed as linear combinations of radionuclide integral concentration and deposition values,

$$D = \sum_n a_n c_n$$

where n denotes nuclides, c_n integral concentration or deposition, and $a_n$certain positive constants.

In the following, we consider a single fixed location, e.g. a grid point.

For an ensemble of dispersion calculations, a procedure proposed for use in DSSs is to calculate quantiles of doses by calculating doses of quantiles for the individual radionuclides, i.e.

$$\underset{m}{\text{quantile}}\left(\sum_n a_n c_{n,m}\,, p\right) \stackrel{?}{=} \sum_n a_n \underset{m}{\text{quantile}}\left(c_{n,m}, p\right)$$

Here, m denotes ensemble members, and p the quantile fraction e.g. a percentage. The question is whether this claimed equality holds.

For simplicity, first consider the extreme percentiles, the ensemble maximum ($p = 100\%$) and minimum ($p = 0\%$). In this case, the equality holds only if the maximum (minimum) value is attained at the same ensemble member for all the radionuclides. Thus, in general

$$\max_m(D_m) = \max_m\left(\sum_n a_n c_{n,m}\right) \leq \sum_n a_n \max_m(c_{n,m})$$

and similarly for the minimum

$$\min_m(D_m) = \min_m\left(\sum_n a_n c_{n,m}\right) \geq \sum_n a_n \min_m(c_{n,m})$$

However, at a given location the maximum most often occurs at the same ensemble member for all its radionuclides, and thereby the above are often equalities rather than inequalities. The reason is that for a given ensemble member the advection is quite similar for all nuclides. However, to some extent the deposition is different for the various nuclides, which may occasionally imply that this no longer holds; for instance, if a rain shower appears in some ensemble member and not in others, this will likely change the ordering of ensemble members at such location.

For quantiles in general, the equality holds provided that the ordering of concentration values across ensemble members is the same for all the dose-contributing radionuclei. Again, to some extent this may hold because the advection is quite similar for all nuclei. However, the deposition may obstruct this allegation in some cases.

For release scenarios involving only one radionuclide, the proposed concept *is* fulfilled. And for any release, the arithmetic mean, which is not a quantile, fulfils the equality exactly.

Thus, from a scientific point of view, the suggested procedure for calculation of quantiles of human radiation doses by applying the dose-calculation procedures to the quantiles of concentration and deposition is not valid. Therefore, it was agreed that for FAUNA we shall adhere to atmospheric parameters such as time-integrated concentration and deposition rather than human radiation doses. In fact, it is considered sufficient for the experts providing guidance to the decision makers to know about the uncertainties of concentration and deposition fields in order to communicate the levels of uncertainties to the decision makers in general terms.

In order to calculate quantiles of human radiation doses, two solutions exist:

1. Implement and run the dose models at the national meteorological service (NMS) for each ensemble member. Thereby, the NMS will calculate the ensemble statics of the doses and make the results available to the DSS.
2. Transfer the full set of dispersion calculations for each ensemble member to the DSS. Then, let the DSS calculate doses for each ensemble member, followed by calculation of the ensemble statistics. This will substantially increase the amount of data transferred from the NMS to the DSS, and it will put additional burdens on the DSS computer.

5. DMI results of atmospheric dispersion modelling using the meteorological ensemble

Atmospheric dispersion calculations have been carried out for every day in the period considered based on the 0 UTC NWP model forecasts and using the source term by Katata *et al.* (2014). Thus, this resembles the model-derived quantitative information on the plume development that a Nordic expert group on radioactive emergency management will have available in real time for its early morning meetings. Each of the calculations starts at the time of the start of the release. The calculations for a given scenario are accompanied by generation of a time series of plots covering calculations for the previous day (based on meteorological analysed data and short-time forecasts) as well as the next two days using forecast data.

Obviously, the assumption that a realistic release description is available in real time is not quite realistic. But in FAUNA we have confined ourselves to meteorological uncertainties and refrain from including uncertainties in the source term.

A vast amount of atmospheric dispersion model data and corresponding plots have been generated. Here, we present dispersion results for a few selected dates only. However, for all the dispersion calculations ARGOS formatted data are available thereby enabling import into the ARGOS DSS. Thus, ARGOS can act as a host for demonstration of the FAUNA results.

The first scenario is a hypothetical gathering of an expert group at the headquarters of a Nordic national radiation protection authority in the morning of 13 March 2011. The group has available the latest DERMA simulations from the 0 UTC run of the ensemble system. Thus, the dispersion calculations are based on the latest full forecast series ranging 48 hours ahead from the meteorological analysis of 0 UTC on 13 March as well as analysed meteorological data and 1, 2, ..., 5 hours forecast data in between the analyses describing the period from 11 March until the latest analysis. In Fig. 9 below, time series of ensemble average instantaneous concentration of Cs-137 are depicted. During the forecast period, the plume is predominantly over the Pacific Ocean but meanders between north, east and finally south in the direction of Tokyo.

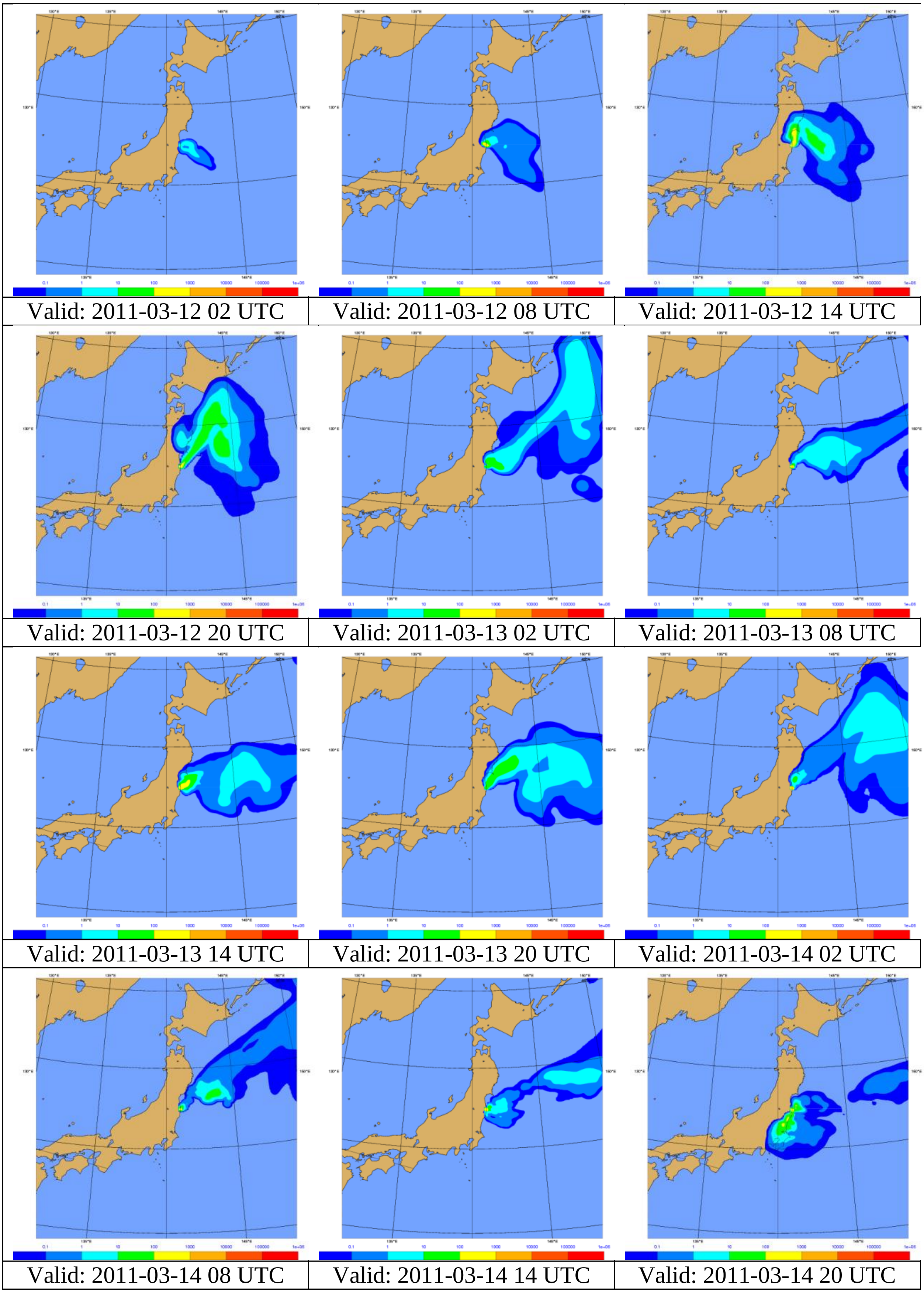


Figure 9 Plume prediction based on NWP forecast of 2011-03-13, 00 UTC. Time series of average values of instantaneous concentration (Bq/m^3) at 2 m above ground of Cs-137.

In the first row of Fig. 10 is shown the ensemble minimum, mean and maximum values of accumulated deposition of Cs-137 valid at the end of the forecast period, i.e. at 23 UTC on 14 March 2011. In the second row is shown the 10^{th}, 50^{th} and 90^{th} percentiles, and in the third row probabilities of exceeding threshold values of 10^4, 10^3 and 10^2 Bq/m^2, respectively.

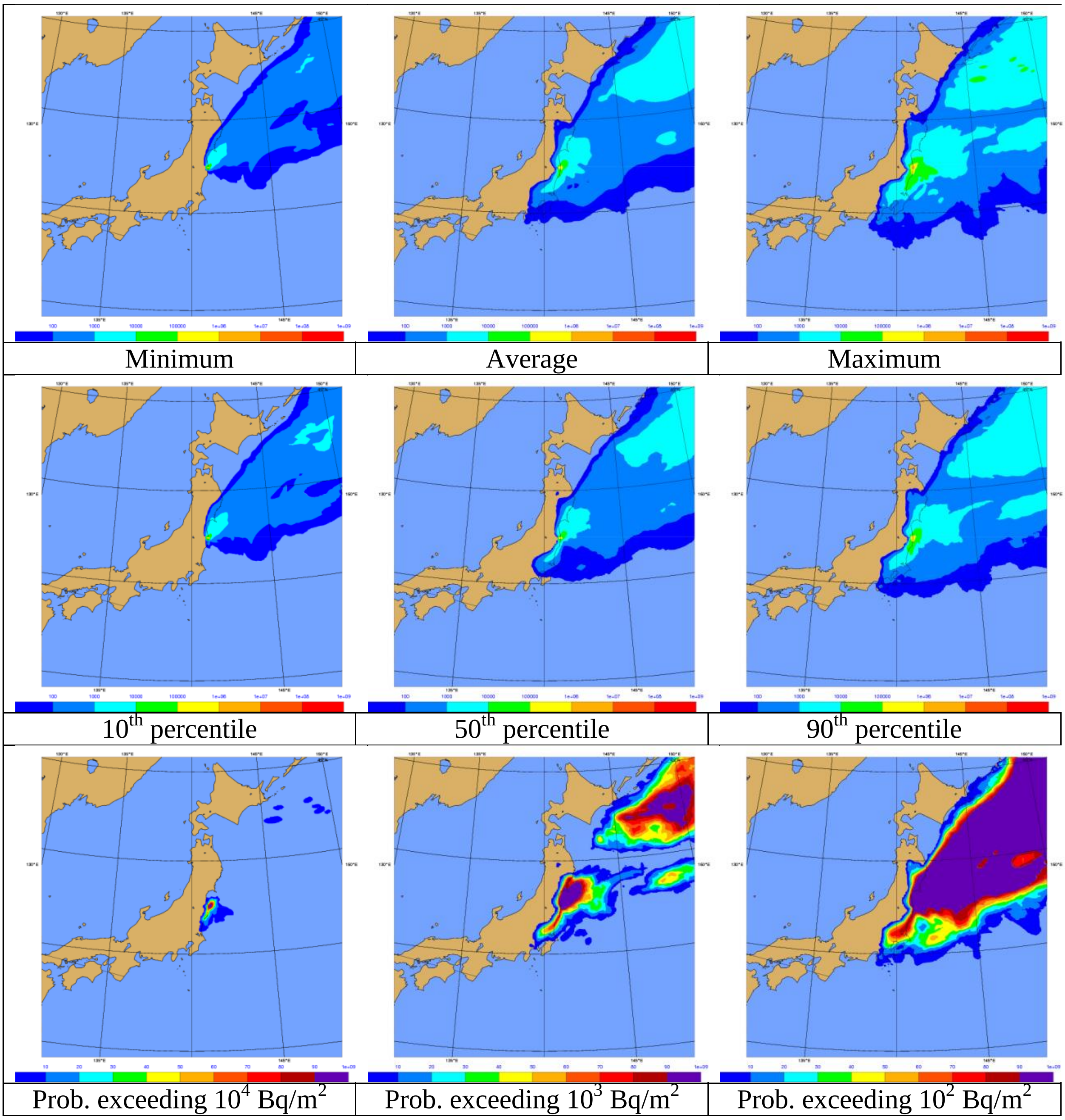


Figure 10 Plume prediction based on NWP forecast of 2011-03-13, 00 UTC. Accumulated deposition of Cs-137 at 23 UTC on 14 March, 2011.

In Fig. 11 are shown the corresponding plots for I-131.

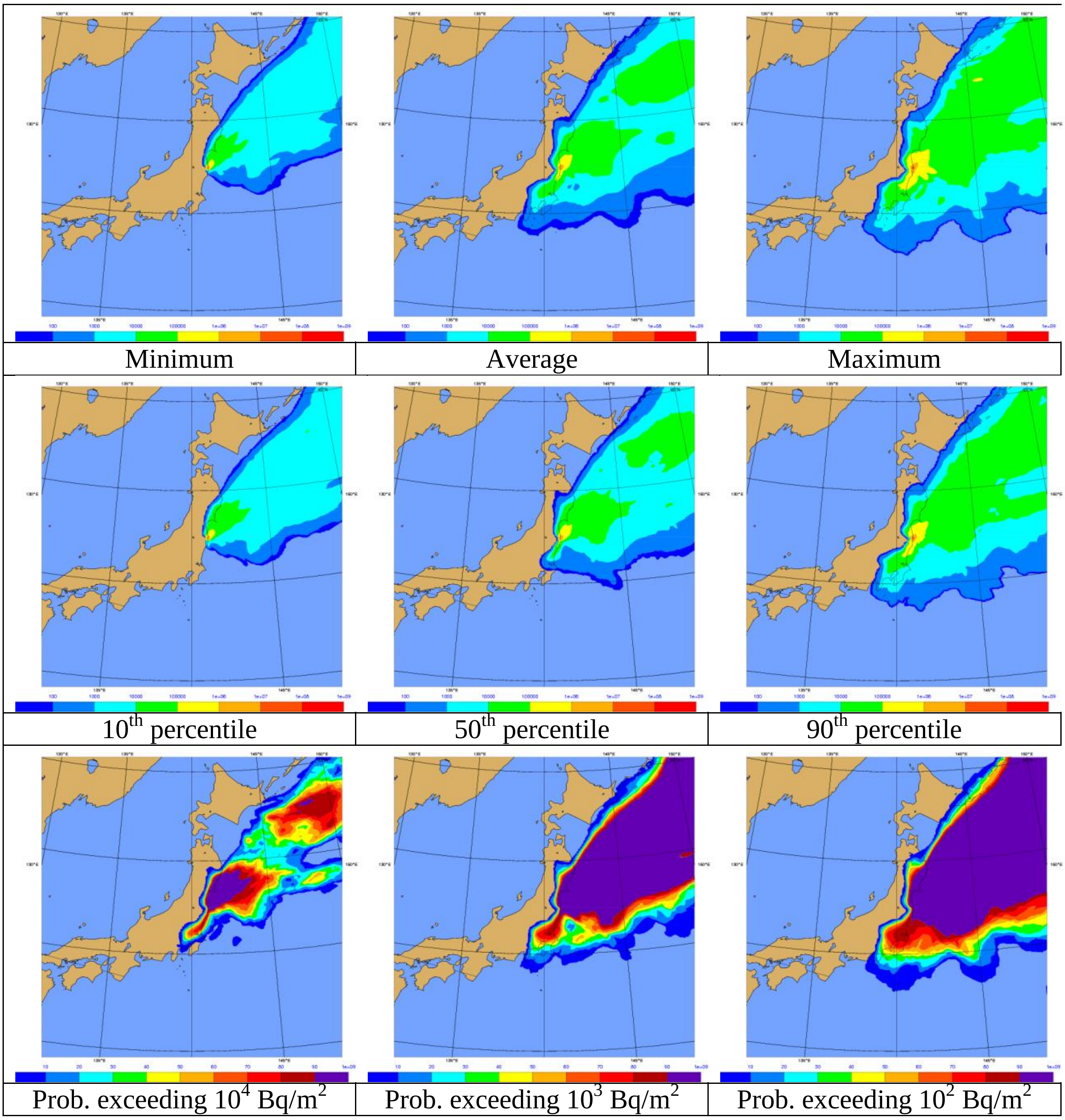


Figure 11 Plume prediction based on NWP forecast of 2011-03-13, 00 UTC. Accumulated deposition of I-131 at 23 UTC on 14 March, 2011.

The second scenario selected consists of the latest DERMA simulations based on the 0 UTC run of the ensemble system on 16 March 2011. In the first row of Fig. 12 is shown the ensemble minimum, mean and maximum values of accumulated deposition of Cs-137 valid at the end of the forecast period, i.e. at 23 UTC on 17 March 2011. In the second row is shown the 10th, 50th and 90th percentiles, and in the third row probabilities of exceeding threshold values of 10^4, 10^3 and 10^2 Bq/m^2, respectively.

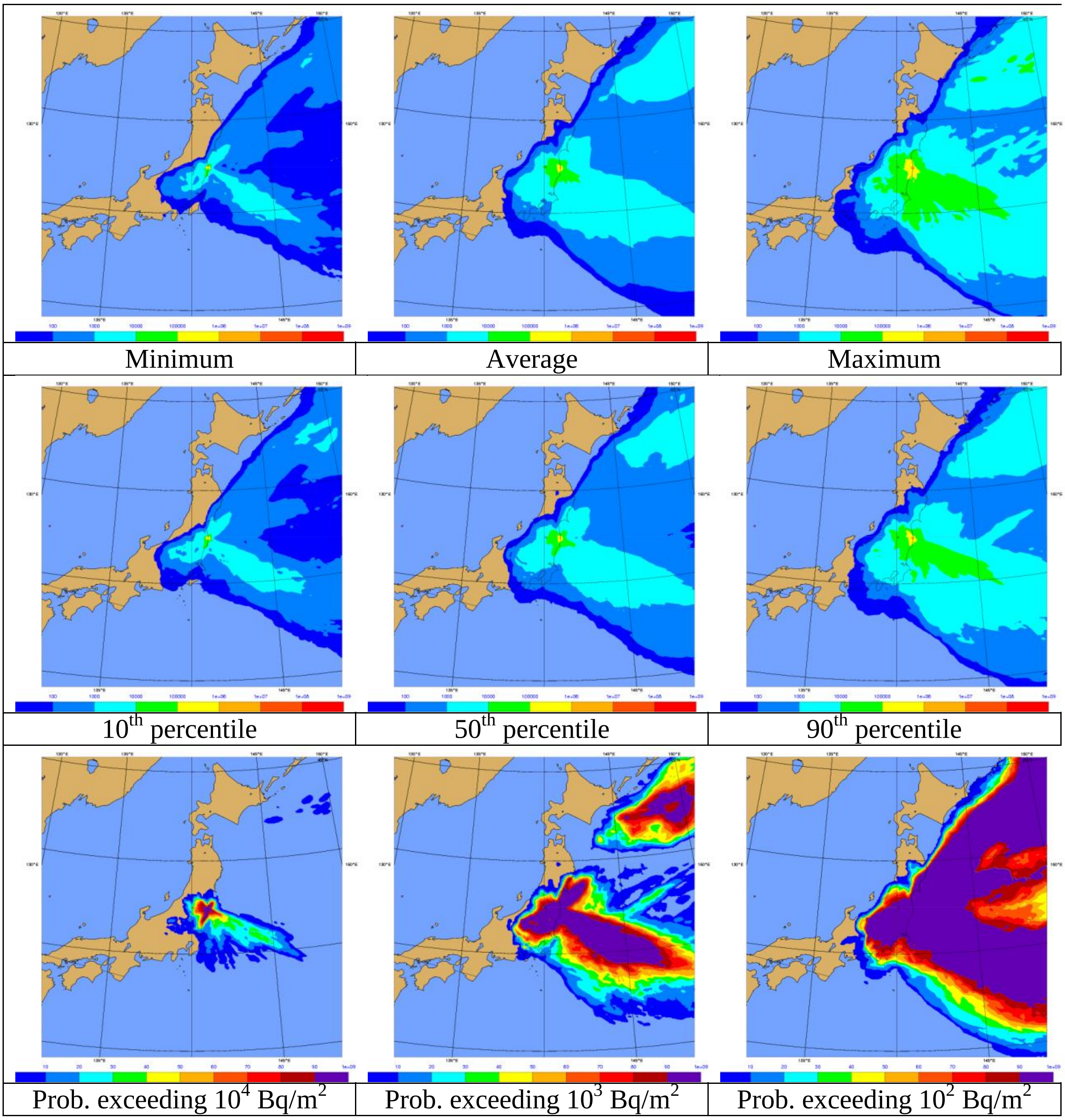


Figure 12 Plume prediction based on NWP forecast of 2011-03-16, 00 UTC. Accumulated deposition of Cs-137 at 23 UTC on 17 March, 2011.

In Fig. 13 are shown the corresponding plots for I-131.

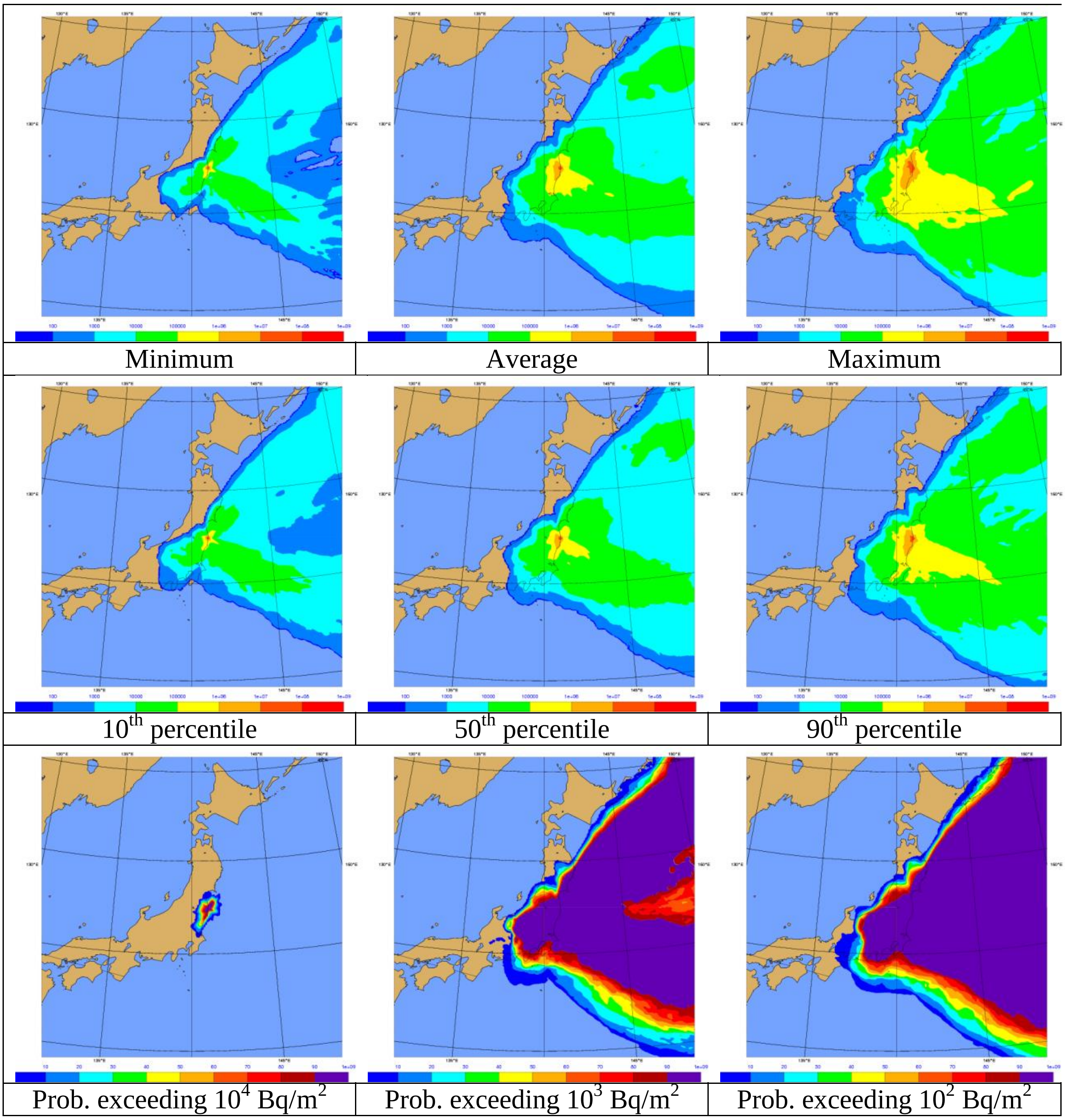


Figure 13 Plume prediction based on NWP forecast of 2011-03-16, 00 UTC. Accumulated deposition of I-131 at 23 UTC on 17 March, 2011.

The final scenario shown here concerns dispersion modelling based on analysed NWP ensemble model data, which are available at the synoptic hours 00, 06, 12 and 18 UTC, as well as few hour forecasts in between (+01, +02, +03, +04 and +05). Thus, this scenario concerns the best dispersion model results that can possibly be obtained from the NWP ensemble model. As can be seen below, there is still a substantial amount of uncertainty left. In the first row of Fig. 14 is shown the ensemble minimum, mean and maximum values of accumulated deposition of Cs-137 valid at the end of the period considered, i.e. at 5 UTC on 5 April 2011. In the second row is shown the 10th, 50th and 90th percentiles, and in the third row probabilities of exceeding threshold values of 10^4, 10^3 and 10^2 Bq/m^2, respectively.

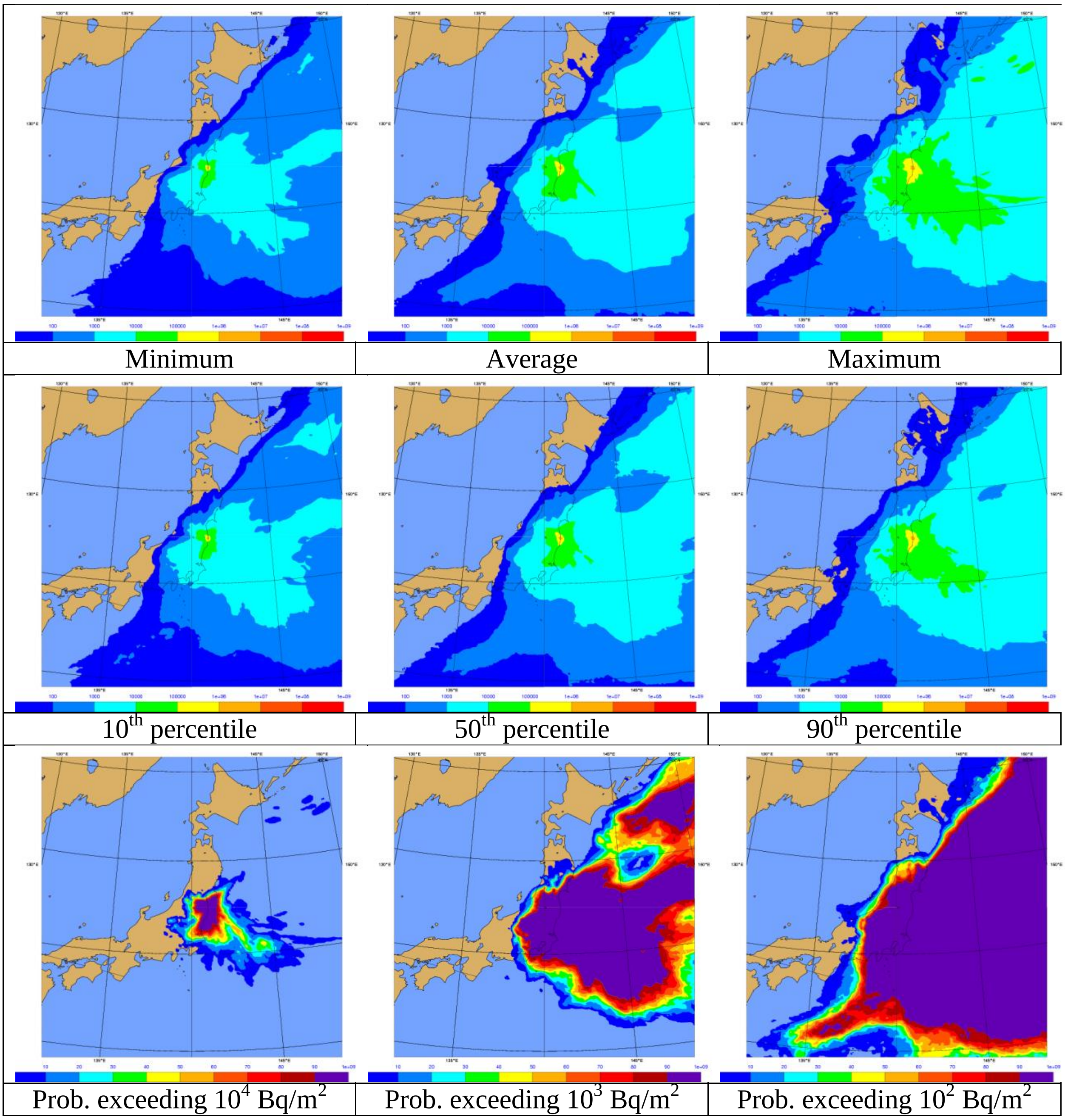
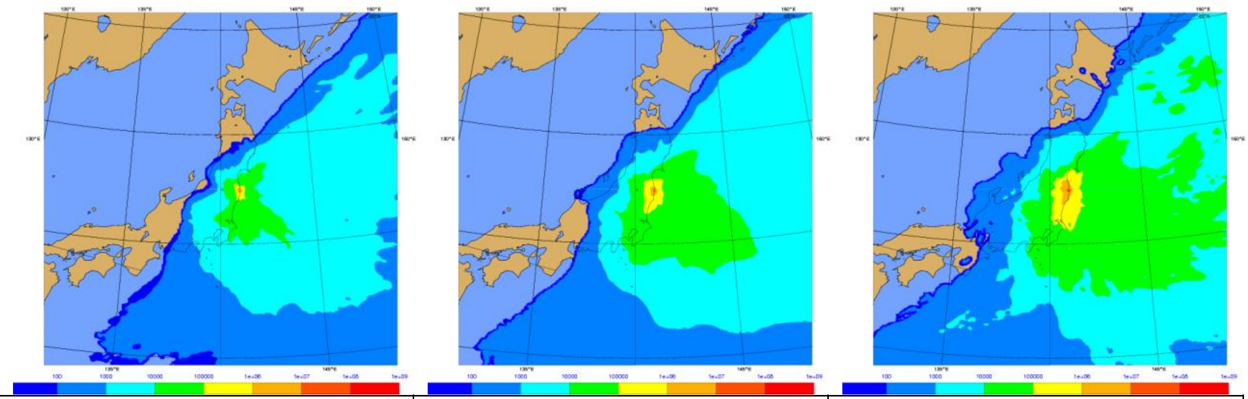
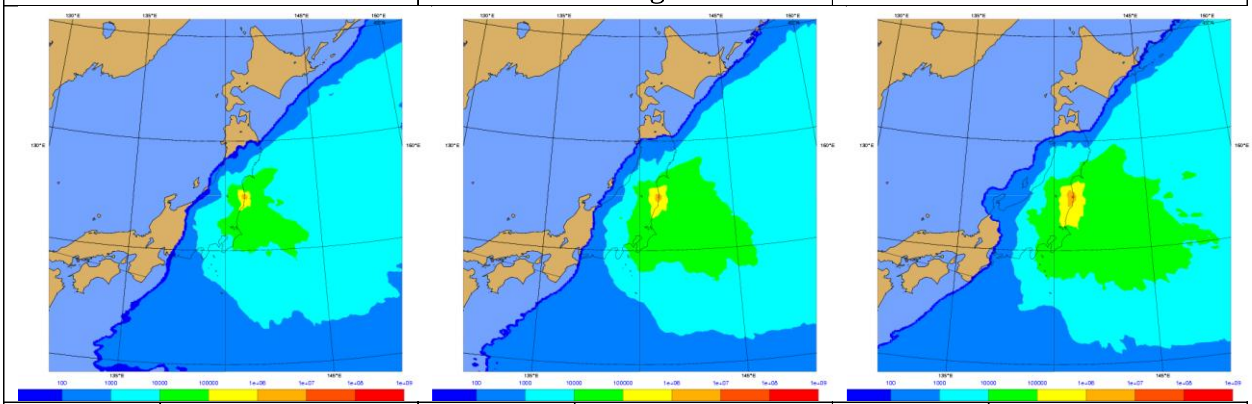


Figure 14 Plume prediction based on analysed NWP ensemble model data. Accumulated deposition of Cs-137 at 5 UTC on 5 April, 2011.

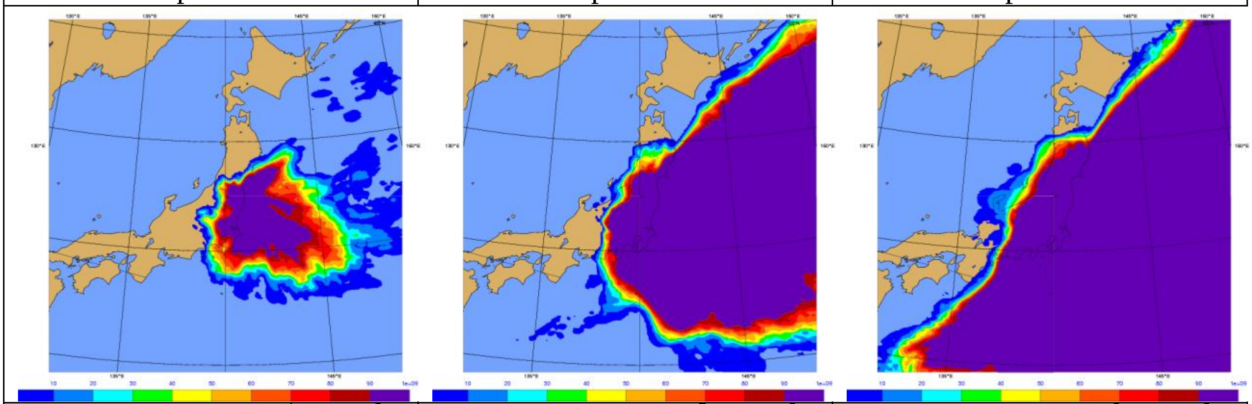
In Fig. 15 are shown the corresponding plots for I-131.



Minimum	Average	Maximum



10^{th} percentile	50^{th} percentile	90^{th} percentile



Prob. exceeding 10^4 Bq/m^2	Prob. exceeding 10^3 Bq/m^2	Prob. exceeding 10^2 Bq/m^2

Figure 15 Plume prediction based on analysed NWP ensemble model data. Accumulated deposition of I-131 at 5 UTC on 5 April, 2011.

6. MET Norway results of atmospheric dispersion modelling using the meteorological ensemble

The same setup for the DMI Atmospheric dispersion calculations has been used for the MET Norway results with the SNAP model. The source term by Katata *et al.* (2014) was used, and every day forecasts based on the 00, 06, 12 and 18 UTC NWP model forecasts from DMI where used as input. Each of the calculations starts at the time of the start of the first release. The calculations for each scenario created hourly output, starting from the first release to the current analysis time plus 48 hours forecast. Statistics over the 21 ensemble members were derived for each of these 104 starting-times, and time-series of plots have been created covering the 24 h before the analysis time to 48 h forecast after that time. Only meteorological uncertainties have been taken into account using the meteorological ensemble data provided by DMI. Other uncertainties were out of scope of this project.

As a result of the MUD project, the most useful statistical results for atmospheric dispersion calculations based on meteorological ensemble data are: average values, percentile plots, and probability plots using different thresholds. These plots have been created for I-131 and Cs-137, resulting in a total of more than half a million plots. In this report, we will only present selected cases, while other plots can be delivered on demand. The output of the SNAP model is the compact netcdf4 format, which unfortunately is not readable directly by the ARGOS DSS. MET Norway has software to convert the data into ARGOS-readable grib format and can do so on demand.

The first scenario chosen from the SNAP model is a hypothetical gathering of an expert group at the headquarters of a Nordic national radiation protection authority in the morning of 15 March 2011, two days after the first DMI results. The group has available the latest SNAP simulations from the 0 UTC run of the ensemble system. Thus, the dispersion calculations are based on the latest full forecast series ranging 48 hours ahead from the meteorological analysis of 0 UTC on 15 March as well as analysed meteorological data and 1, 2, ..., 5 hours forecast data in between the analyses describing the period from 11 March until the 15 March 2011. In Fig. 16 below, time series of ensemble average instantaneous concentration of Cs-137 are depicted.

From the 14^{th} to the 15^{th} the wind direction is changing and the plume moves along the eastern coast of Japan. At the end of the forecast, the predicted diffusion of the SNAP model is lower than the spread of the ensemble, resulting in visible trajectories of the different forecast members.

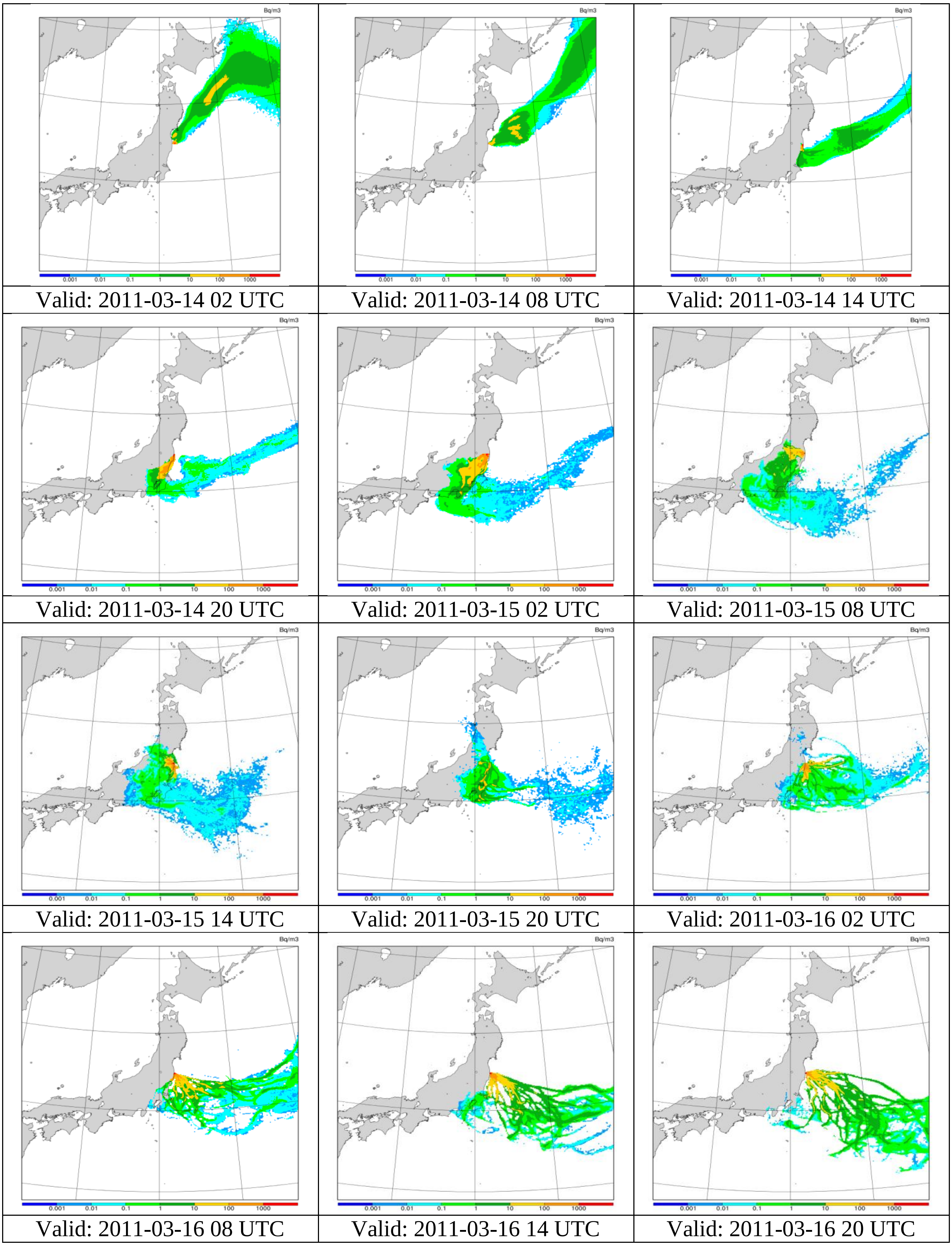


Figure 16 Plume prediction based on NWP forecast of 2011-03-15, 00 UTC and SNAP model runs. Time series of average values of instantaneous concentration (Bq/m^3) of Cs-137 in the lowest model layer.

In the first row of Fig. 17 is shown the ensemble minimum, mean and maximum values of accumulated deposition of Cs-137 valid at the end of the forecast period, i.e. at 23 UTC on 15 March 2011. In the second row is shown the 10^{th}, 50^{th} and 90^{th} percentiles, and in the third row probabilities of exceeding threshold values of 10^4, 10^3 and 10^2 Bq/m^2 in fractions, respectively.

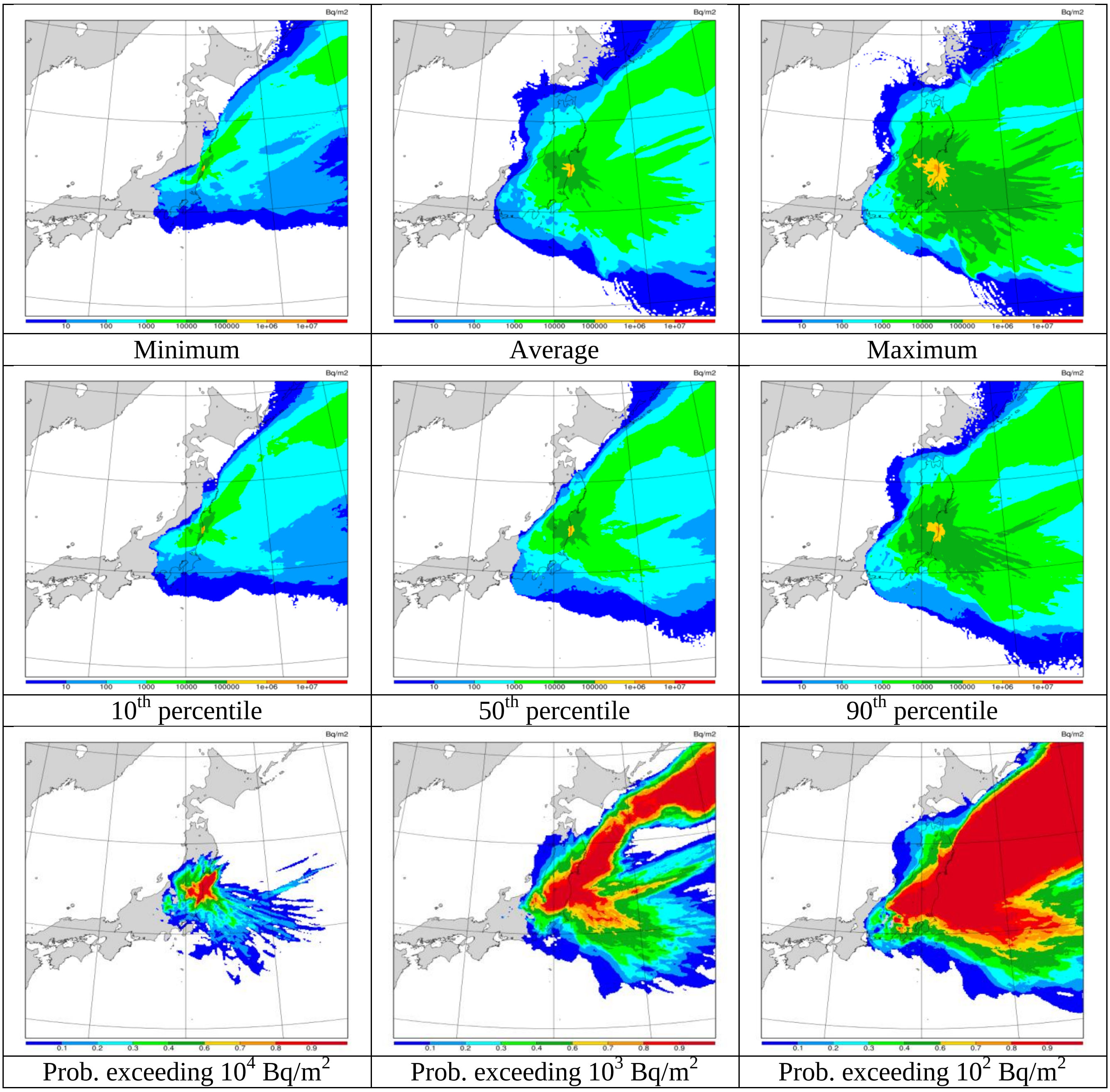


Figure 17 Plume prediction based on NWP forecast of 2011-03-15, 00 UTC and SNAP model runs. Accumulated deposition of Cs-137 at 23 UTC on 16 March, 2011.

In Fig. 18 are shown the corresponding plots for I-131.

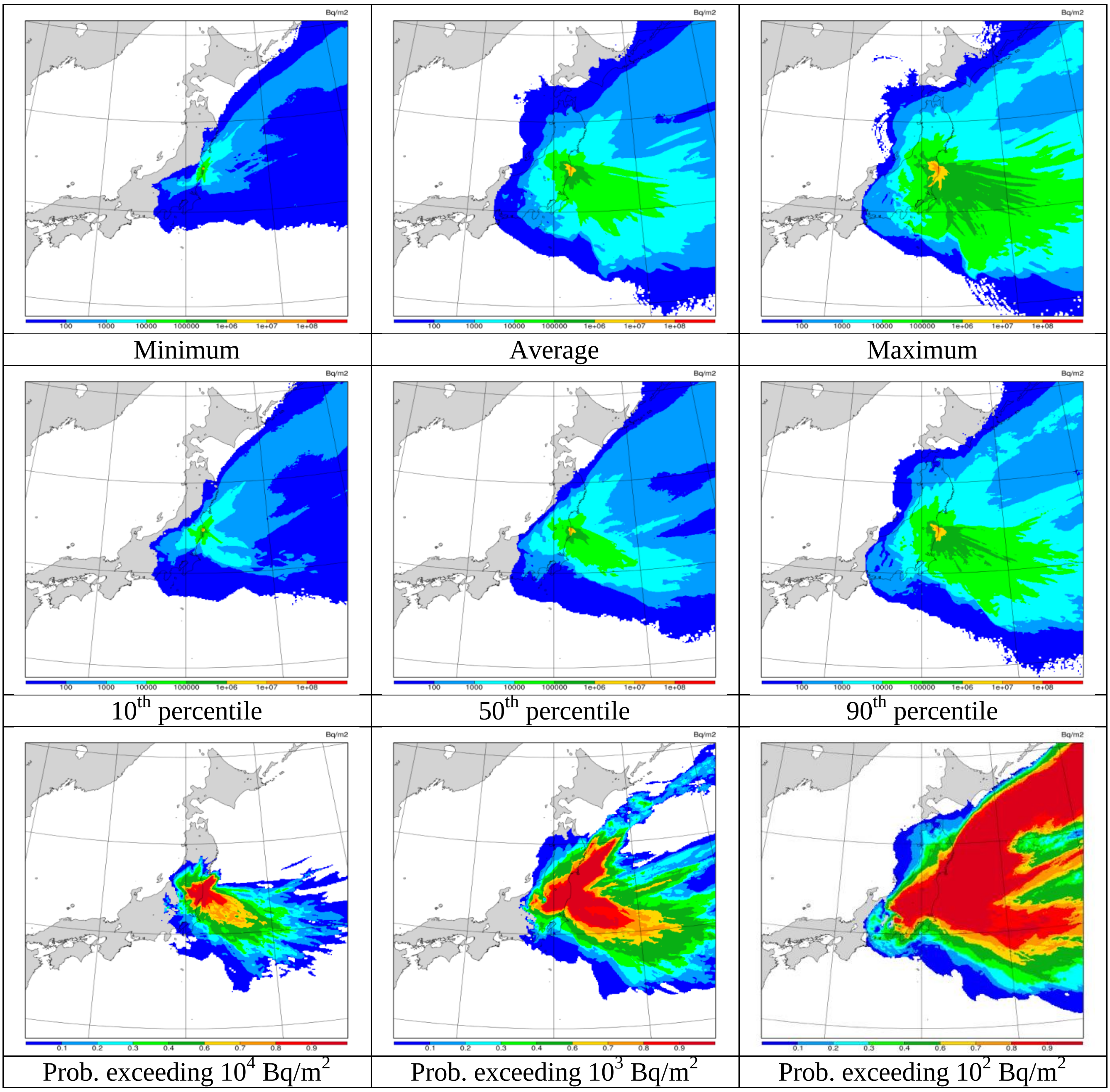


Figure 18 Plume prediction based on NWP forecast of 2011-03-15, 00 UTC and SNAP model runs. Accumulated deposition of I-131 at 23 UTC on 16 March, 2011.

The second scenario selected consists of the latest SNAP simulations based on the 0 UTC run of the ensemble system on 18 March 2011. In the first row of Fig. 12 is shown the ensemble minimum, mean and maximum values of accumulated deposition of Cs-137 valid at the end of the forecast period, i.e. at 23 UTC on 19 March 2011. In the second row is shown the 10th, 50th and 90th percentiles, and in the third row probabilities in fractions of exceeding threshold values of 10^4, 10^3 and 10^2 Bq/m^2, respectively.

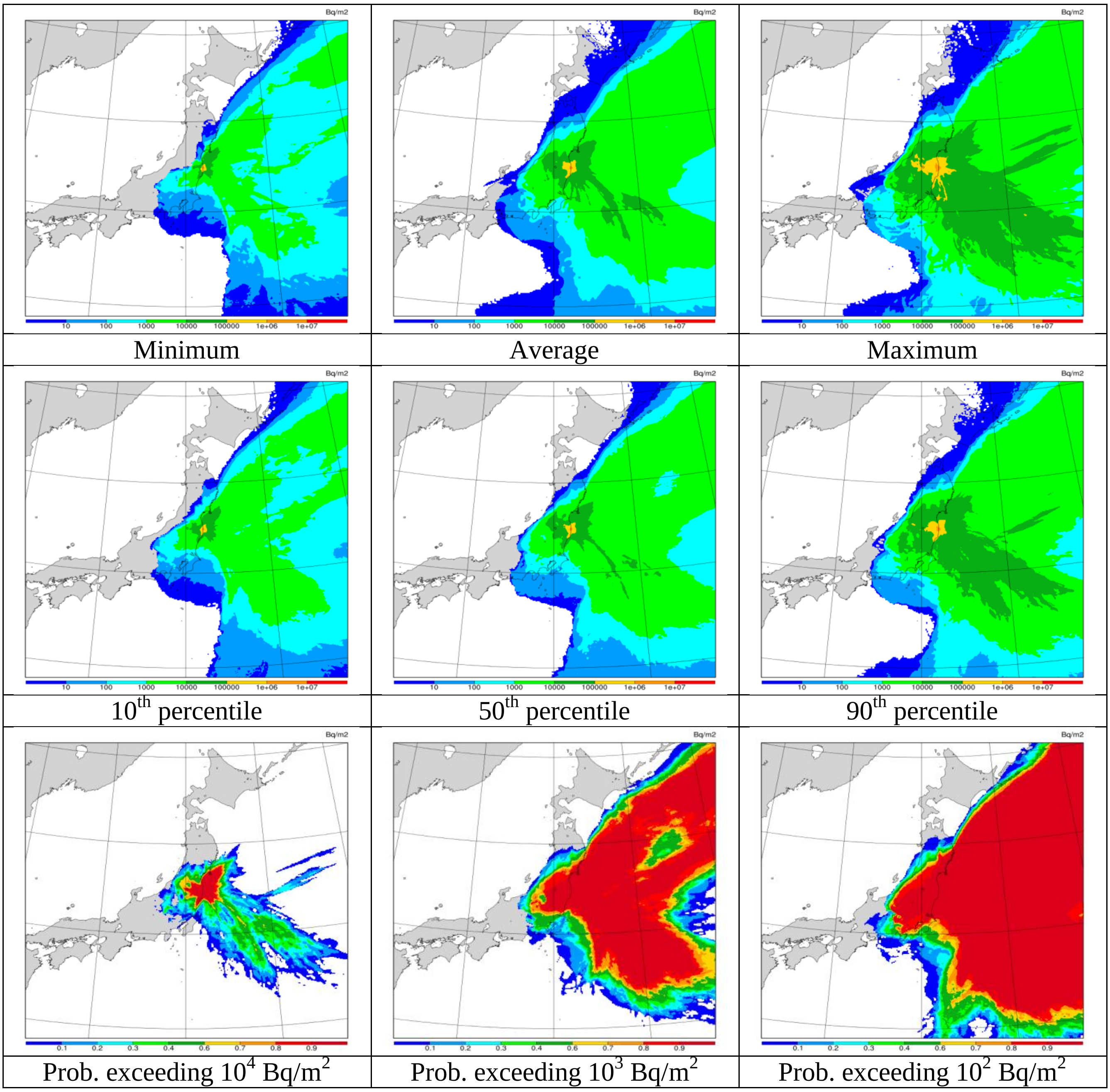


Figure 19 Plume prediction based on NWP forecast of 2011-03-18, 00 UTC and SNAP model runs. Accumulated deposition of Cs-137 at 23 UTC on 19 March, 2011.

In Fig. 20 are shown the corresponding plots for I-131.

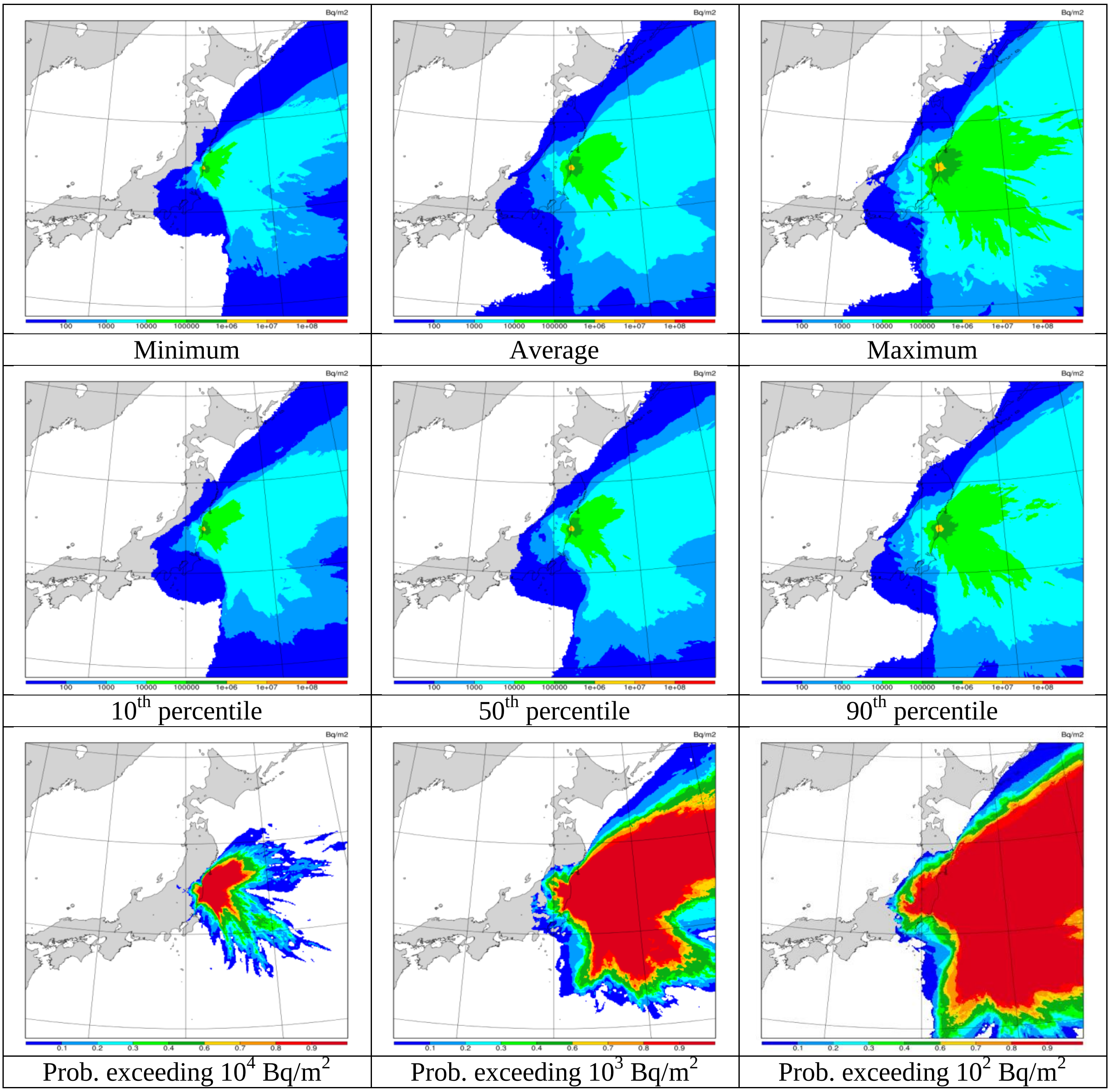


Figure 20 Plume prediction based on NWP forecast of 2011-03-18, 00 UTC and SNAP model runs. Accumulated deposition of I-131 at 23 UTC on 19 March, 2011.

The final scenario selected consists of the latest SNAP simulations based on the 0 UTC run of the ensemble system on 22 March 2011. In the first row of Fig. 21 is shown the ensemble minimum, mean and maximum values of accumulated deposition of Cs-137 valid at the end of the forecast period, i.e. at 23 UTC on 23 March 2011. In the second row is shown the 10^{th}, 50^{th} and 90^{th} percentiles, and in the third row probabilities in fractions of exceeding threshold values of 10^4, 10^3 and 10^2 Bq/m^2, respectively.

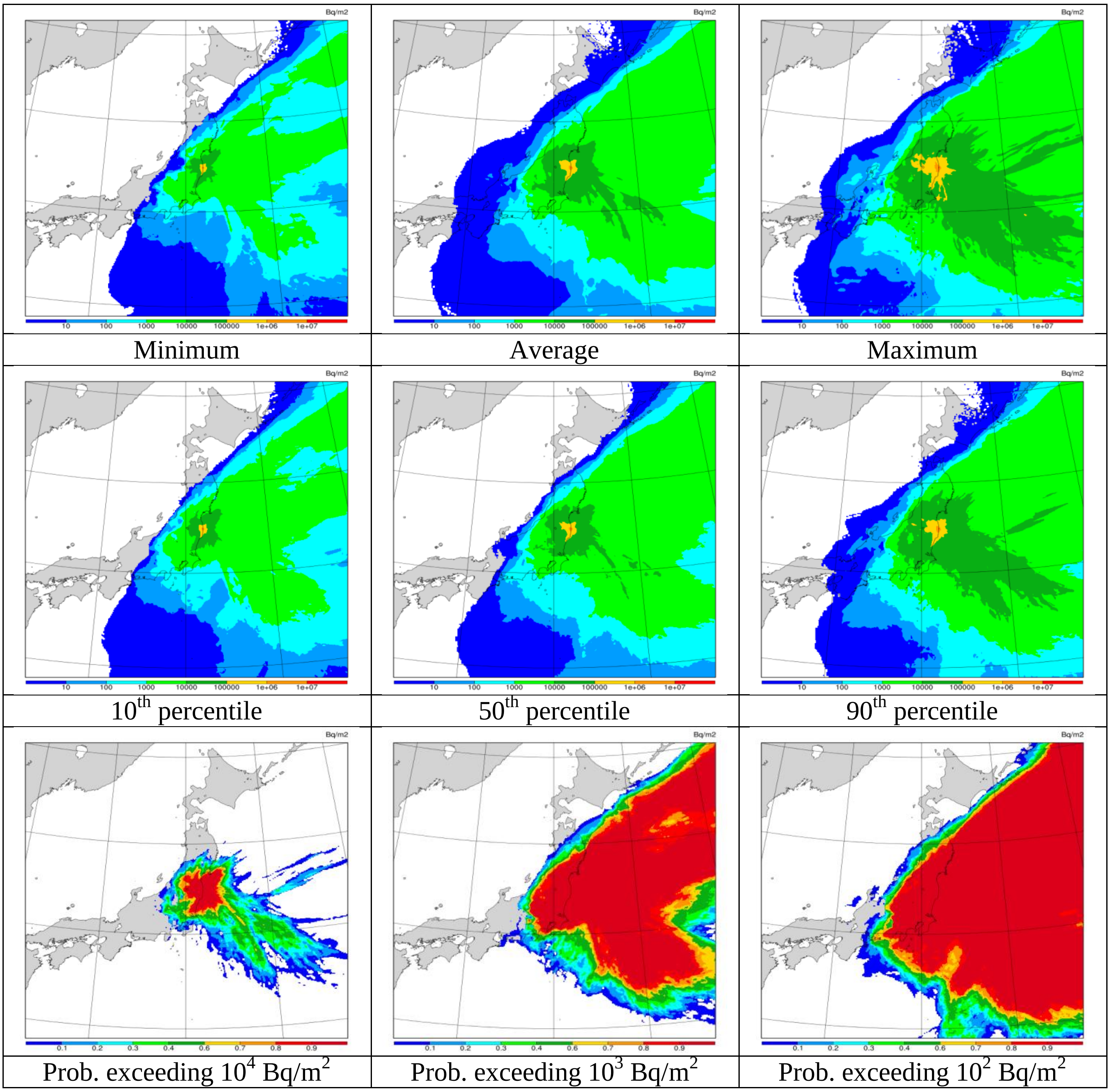


Figure 21 Plume prediction based on analysed NWP ensemble model data and SNAP model runs. Accumulated deposition of Cs-137 at 23 UTC on 23 March, 2011.

In Fig. 22 are shown the corresponding plots for I-131.

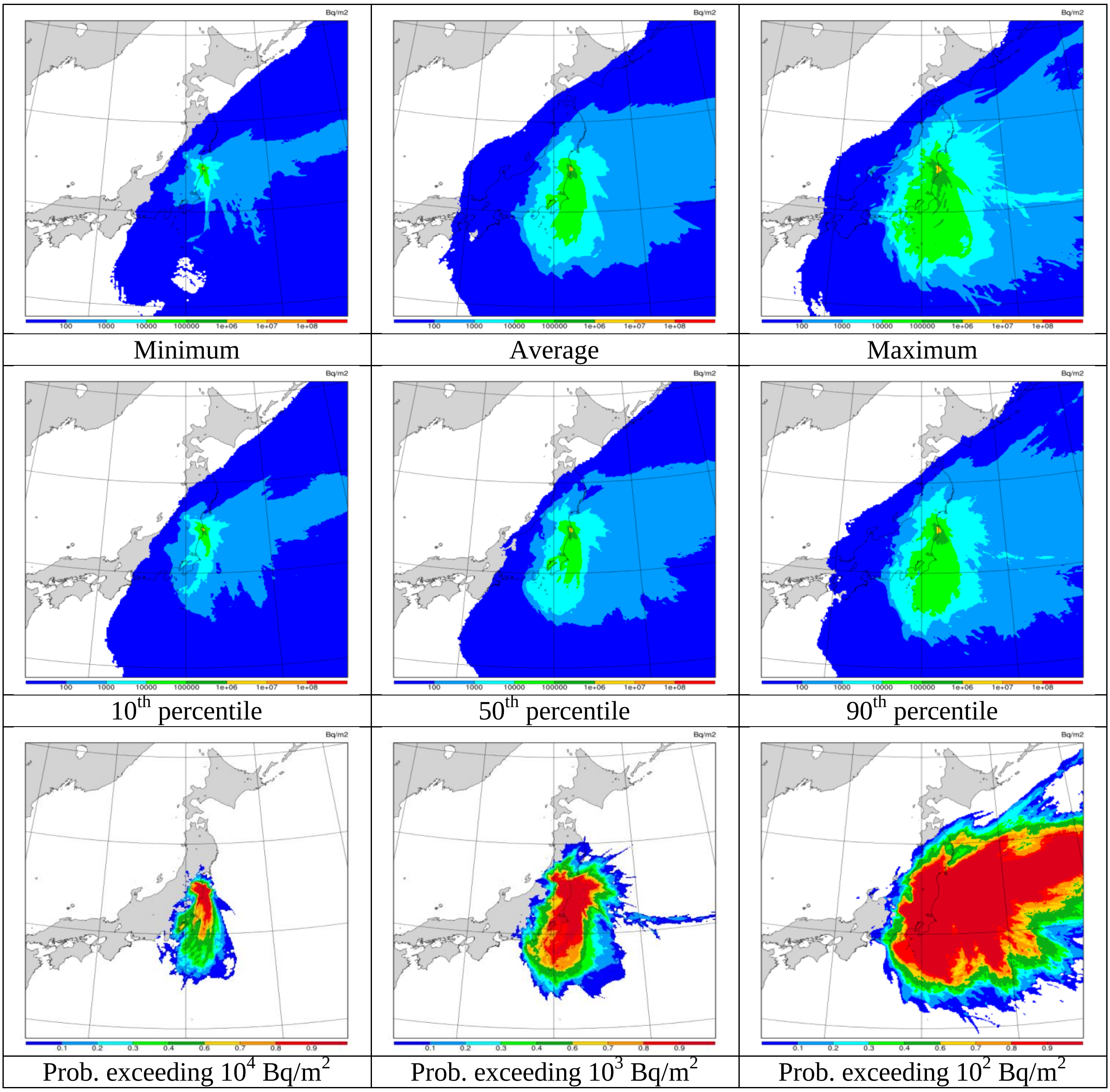


Figure 22 Plume prediction based on analysed NWP ensemble model data and SNAP model runs. Accumulated deposition of I-131 at 23 UTC on 23 March, 2011. The accumulated depositions start being lower due to the half-life of I-131 of about 8 days.

7. NKS FAUNA workshop on Meteorological Uncertainty Estimates for Decision Making during a Nuclear Emergency

One of the FAUNA tasks was to organize an NKS workshop for experts, model developers and decision makers on the use of uncertainty estimates for decision making during a nuclear emergency. The workshop, which took place on 10 September 2015, attracted 28 participants from Australia, Brazil, Canada, Denmark, Ireland, Lithuania, Norway, Poland, Sweden and United Kingdom.

Below is listed the invitation to the selected participants, the participant list, the agenda, the introduction of group discussions and a summary of the findings from the discussions.

7.1 Invitation

Workshop on the use of meteorological uncertainty estimates for decision making during a nuclear emergency

10 September 2015, 10 am – 4 pm

Danish Meteorological Institute (DMI), Lyngbyvej 100, DK-2100 Copenhagen

The workshop addresses real-time forecasting of atmospheric dispersion and deposition of radionuclides released from a nuclear installation. Meteorological uncertainties can be large and lead to uncertain atmospheric dispersion model predictions, even in the case where the radionuclide source term is known. Within the NKS-B MUD and FAUNA projects, methods for deriving and presenting these uncertainties have been developed and investigated, and the implications for decision support have been addressed.

The workshop, which is aimed at experts, model developers and decision makers, will open discussions on operational uses of uncertainty estimates. We hope that the workshop will shed light on the new possibilities for presenting real-time uncertainties for decision support and will provide valuable feedback from decision makers to the further model development and implementation in current decision support systems.

For registration and more information, please contact Jens Havskov Sørensen at DMI (jhs@dmi.dk) or Bent Lauritzen at DTU Nutech (blau@dtu.dk) before August 17, 2015.

7.2 Participant List

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2. Simon French, University of Warwick, UK, simon.french@warwick.ac.uk
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5. Oscar Björnham, FOI, Sweden, oscar.bjornham@foi.se
6. Jan Pehrsson, PDC-ARGOS, Denmark, jp@pdc-argos.com
7. Dominique Nsengiyumva, Health Canada, dominique.nsengiyumva@hc-sc.gc.ca
8. Pedro P. de Lima-e-Silva, Nuclear Energy National Commission, Brazil, pp.argos@gmail.com
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10. Wojciech Krysiński, National Atomic Energy Agency, Poland, krysinski@paa.gov.pl
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18. Jerzy Bartnicki, MET Norway, jerzyb@met.no
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26. Ulrik Smith Korsholm, DMI, Denmark, usn@dmi.dk
27. Knud-Jacob Simonsen, DMI, Denmark, kjs@dmi.dk
28. Jens Havskov Sørensen, DMI, Denmark, jhs@dmi.dk

7.3 Agenda

Welcome (Jens Havskov Sørensen, DMI)

Workshop objectives (Bent Lauritzen, DTU Nutech)

Uncertainty of numerical weather prediction and atmospheric dispersion results of NKS-B projects MUD and FAUNA (Jens Havskov Sørensen, DMI)

FOI project on uncertainties for decision support (Oscar Björnham, FOI)

Norwegian perspective on uncertainties (Heiko Klein, MET Norway)

Possibilities for implementation in ARGOS (Steen Hoe, DEMA)

DMI operational use of meteorological uncertainties (Knud-Jacob Simonsen, DMI)

Group discussions – introduction (Bent Lauritzen, DTU Nutech)

Plenum: Summary and conclusion

7.4 Presentations

Pdf versions of the presentations given at the workshop have been uploaded to the NKS workshop web-site, http://www.nks.org/en/seminars/previous_seminars/nks-b-fauna.htm, together with the agenda and the list of participants.

7.5 Group Discussions

Background:

A nuclear emergency is developing at the Brokdorf Nuclear Power Plant, and a large release of radionuclides is imminent. In Denmark, the highest national emergency level is declared and the National Operative Staff (NOST) has been informed about the situation. NOST has requested advice on protective actions.

You are a member of the expert advisory group, assembled to assess the radiological situation and to issue recommendations to NOST.

The meteorological office has estimated the anticipated thyroid doses to the population based on a release of radioiodine compatible with a core-meltdown accident scenario described in the emergency planning guidelines for the NPP.

The met office has provided you with the plots below showing not only the expected atmospheric dispersion and deposition of radioiodine (in the form of isocurves for the thyroid doses), but also the uncertainty associated with the atmospheric dispersion and deposition predictions.

The national guidelines for iodine prophylaxis countermeasure following a nuclear accident is that iodine tablets are administered, if thyroid doses exceed 50 mGy to adults or 10 mGy to children. Iodine tablets are available at local emergency centers.

Your tasks:

Your group will discuss the information provided by the met office and address the questions below.

Assess and describe the situation:

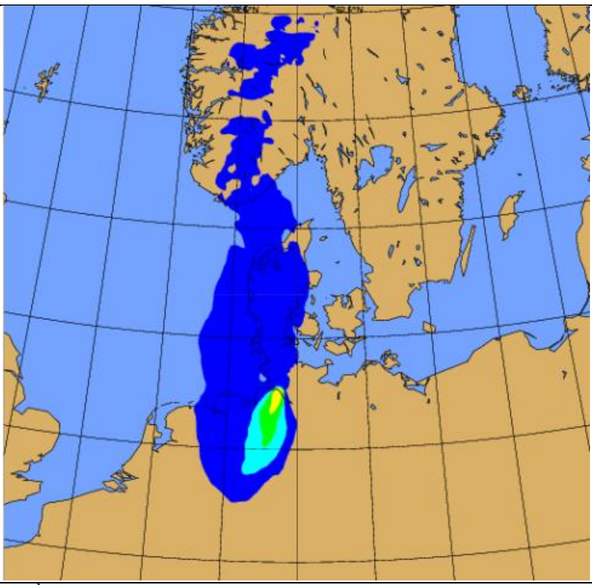
- Are the plots understandable?
- Are the percentile plots useful?
- Are the probability plots useful?
- How would you describe the uncertainty to the decision makers?

Issue recommendations:

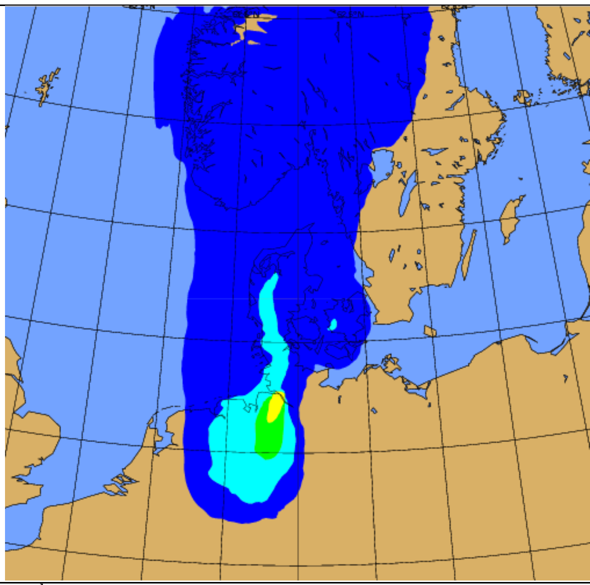
- Would you advise intake of iodine tablets, and in what geographical area?
- What advice would you give regarding monitoring strategies, based on the plots?
- What advice would you give on other actions?
- How would you describe the uncertainty to the decision makers?

Plenary session:

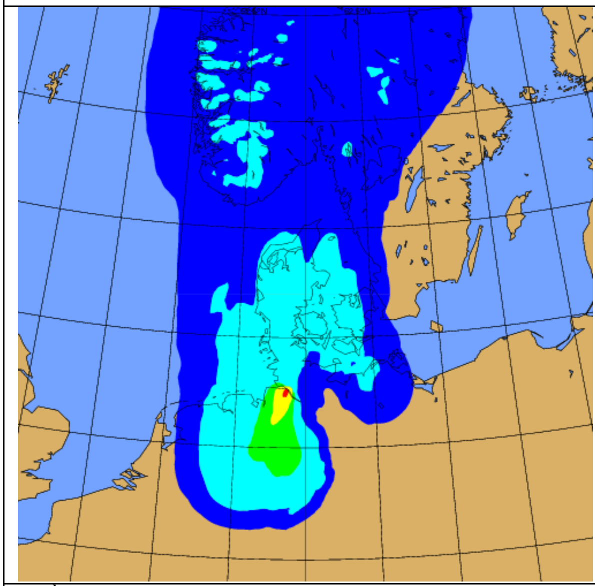
Your group selects a spokesperson who presents your results and conclusions in plenum.



10th percentile of projected thyroid dose 54 hours after start of release.



50th percentile of projected thyroid dose 54 hours after start of release.



90th percentile of projected thyroid dose 54 hours after start of release.

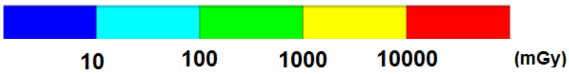
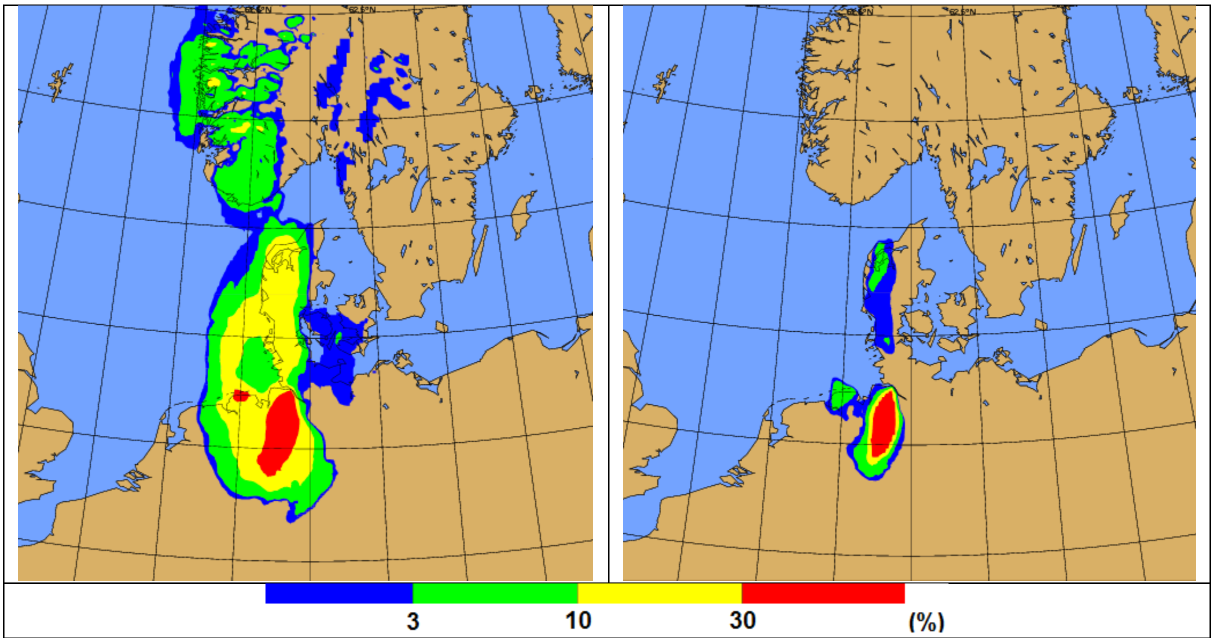


Figure 23 Percentiles of thyroid dose from a hypothetical release.



Probability of projected thyroid dose exceeding 10 mGy 54 hours after start of release.	Probability of projected thyroid dose exceeding 50 mGy 54 hours after start of release.

Figure 24 Probabilities of thyroid dose exceeding given threshold values from a hypothetical release.

7.6 Summary of findings from the group discussions

- It is indeed possible for experts to understand the plots that show release of radioiodine from the Brokdorf NPP with indications of uncertainties. There is a tendency among the groups to conclude that the plots that show *probabilities* are easier to understand than the plots that show *percentiles*.
- It was suggested to avoid the term *percentile* as this could easy be confused with *percentage*, e.g. in the meaning of percentage of the population. Instead the word *quartile* or *quantile* could be used when showing (isocurves of) dose levels, for which a given fraction of calculations have results less than the dose levels indicated.
- The plots with the high percentiles, 90th and to some extend 50th, are the most useful and these could form a basis for decision making, e.g. on monitoring strategies
- Colour schemes should be used with care. Too many and too strong colours could give a faulty impression of the danger involved with the predicted radiation doses. When showing probability plots, the shading style should be different from the style used for other purposes, in order not to confuse these plots with ordinary maps of e.g. doses or radionuclide concentrations.
- The plots can be used for decision making in the early phases of a nuclear accident. However, all groups hesitate towards presenting maps with percentile and probability plots to decision makers. Use of uncertainties requires education/training of emergency response staff, and careful communication with decision makers.
- The plots can be used as a basis for decisions on implementation of protective actions, such as distribution of stable iodine for iodine prophylaxis, including prioritization of protective actions. For instance, if iodine is only available in a limited amount, priority should be given to the part of the population under the age of 18 that is located in areas where there are the highest risks for receiving doses that exceed the dose criteria for iodine prophylaxis.
- The plots can be used to communicate uncertainties to the decision makers and eventually to members of the public. Risks, however, should be communicated as “high”, “low” etc., i.e. terms which are more understandable than *percentile* and *probability*. A system for communication of risks in connection with nuclear accidents should be inspired by the system that DMI uses to communicate risks of large amount of rain and other severe weather phenomena.

8. Conclusions and outlook

In the NKS-B project FAUNA, the ensemble-statistical methodology developed in the earlier NKS-B project MUD (Sørensen *et al.* 2014) has been applied to the Fukushima Daiichi accident in 2011. By estimating the uncertainties associated with numerical weather prediction, as well as their impact on atmospheric dispersion model prediction, FAUNA provides a realistic example of application of the new methodology, or tool, for real-time nuclear emergency management.

The DMI ensemble model system for numerical weather prediction was set up for Japan and surroundings for the first month of the accident, the period of the main atmospheric release of radionuclides. Four times a day, 48 hour meteorological forecasts are produced.

A literature study has been carried out on source description for the Fukushima Daiichi accident, and a well suited realistic source term was selected.

Using the meteorological ensemble prediction data, atmospheric dispersion calculations have been calculated for every day in the period considered based on the 0 UTC NWP model forecasts. This resembles the quantitative information on the plume development that a Nordic expert group on radioactive emergency management would have available in real time for its morning meetings.

As demonstrated by MUD, the uncertainties can be substantial depending on the meteorological situation, and the FAUNA project has revealed that this was indeed also the case during the Fukushima Daiichi accident. Obviously, there are other sources of uncertainty than the meteorological, e.g. associated with the source term, but they are outside the scope of FAUNA.

The added value of MUD and FAUNA is that now one may have not only a single deterministic dispersion model prediction available for decision support but also a quantitative assessment of the associated uncertainty. Rhetorically speaking, what is the value of a prediction if you don’t know how much confidence you may have in it?

It may be claimed that by introducing uncertainties one is not making life easier for the decision makers. However, by taking into account the meteorological uncertainties, the risk of making decisions based on an incorrect prediction of the dispersion is much reduced. In other words, by assessing the uncertainties a more comprehensive basis for the decision making is provided.

An NKS workshop was organized for experts, model developers and decision makers on the use of uncertainty estimates for decision making during a nuclear emergency. Selected conclusions include:

1. Application of the methodology can be a basis for decisions on implementation of protective actions, such as distribution of stable iodine for iodine prophylaxis, including prioritization of protective actions.

2. In order to facilitate the communication with decision makers, and possibly also to the public, the calculated risks should be communicated as “high”, “low” etc. rather than in terms of quantitative measures of uncertainty.

3. Use of uncertainties for decision making requires education and training of emergency response staff, as well as careful communication with the decision makers.

4. By introducing quantitative assessment of the inherent meteorological uncertainty of atmospheric dispersion prediction, one is probably not making life easier for the experts advising the decision makers. However, a more comprehensive basis is provided for expert guidance and decision making.

The MUD and FAUNA projects addressed meteorological uncertainties at regional scale, and as shown, they can be large. However, an open question still remains: "To what extent does this apply to the short-range dispersion models employed for nuclear emergency preparedness?"

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Disclaimer

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Abstract max. 2000 characters	By employing the methodology developed in the NKS-B project MUD, the FAUNA project has addressed assessment of the uncertainties of atmospheric dispersion model predictions of nuclear aerosols and gasses from the Fukushima Daiichi nuclear accident. A meteorological numerical ensemble forecasting system has been set up and applied to Japan and surroundings for the period of the main atmospheric release of radionuclides from the Fukushima Daiichi NPP in 2011. The resulting analysed and forecast numerical weather-prediction ensemble-statistical data have been used by the Danish and Norwegian operational atmospheric dispersion models. Corresponding ensembles of atmospheric dispersion are computed from which uncertainties of predicted radionuclide concentration and deposition patterns are derived. Implications of using the methodology for nuclear emergency management and decision support are discussed.

Key words	Fukushima Daiichi accident, nuclear emergency preparedness, atmospheric dispersion model, meteorology, uncertainty, ensemble prediction