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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 addresses assessment of the uncertainties of atmospheric dispersion model predictions of nuclear aerosols and gasses from the Fukushima Daiichi nuclear accident.

The DMI meteorological numerical ensemble forecasting system involving the 21 ensemble members 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 analyzed and forecast numerical weather-prediction ensemble-statistical data will be used by the Danish and Norwegian operational atmospheric dispersion models. Corresponding ensembles of atmospheric dispersion will be computed from which uncertainties of predicted radionuclide concentration and deposition patterns are derived In the present report, first results are presented.

Key words

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

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First Year Report of the NKS-B FAUNA activity

Contract: AFT/B(14)2

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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, 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.

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 will be 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 EEMEP (Bartnicki *et al.*, 2011), respectively, will be run based on data of the meteorological ensemble assuming that a realistic source term is available in near real time. Corresponding ensemble-statistical parameters will be calculated, e.g. percentiles of the concentration and deposition fields. The predictions will be made available to the ARGOS decision-support system for display and dose modelling. Thereby, the project will imitate real-time emergency management taking into account estimates of the uncertainty of the dispersion model results.

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. Source term estimates for the Fukushima Daiichi accident

The source term for the Fukushima Daiichi accident has been described by Terada *et al.* (2012) for the two radionuclides I-131 and Cs-137 covering the period from the start of the release until 1 May 2011. This work is based on previous 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. Even though the source description by Terada *et al.* 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 25 days of the release period.

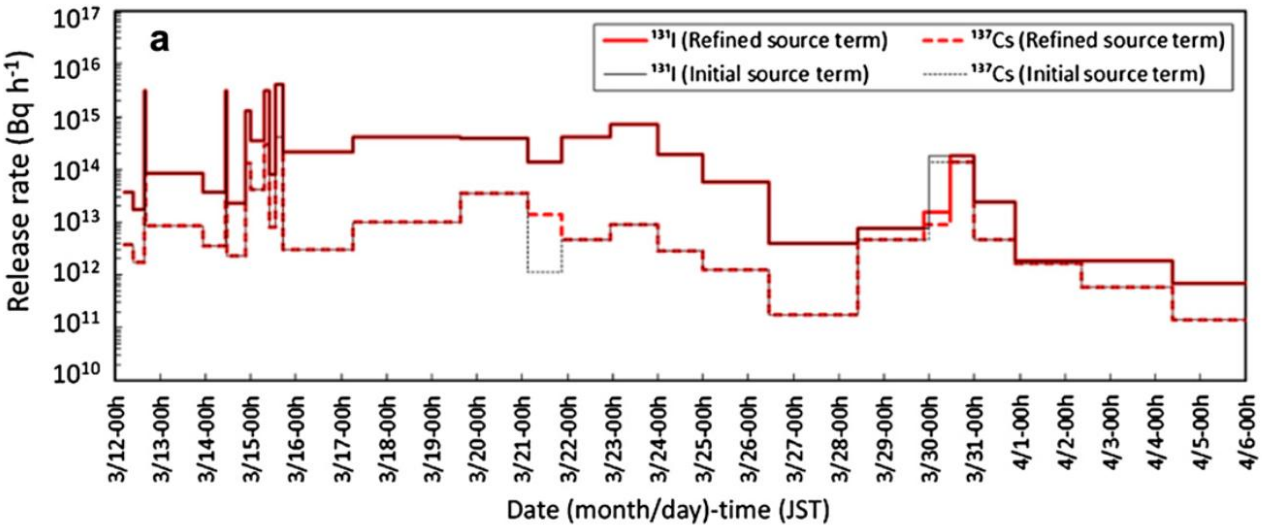

Figure 1. Emission rate of I-131 and Cs-137 for the first 25 day of the release period, figure by Terada *et al.* (2012).

The HIRLAM EPS 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 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.

Very recently, Katata *et al.* (2014) published a new source description which is based on the same observational data as Terada *et al.* (2012) employed, however, supplemented also by sea surface concentration values of the radionuclides in question arising from deposition. An inverse source-term estimation methodology quite similar to that of Terada *et al.* (2012) was employed. 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 one by Terada *et al.* (2012). It should be considered to use this source term for the second phase of FAUNA instead of the one by Terada *et al.* (2012).

3. HIRLAM meteorological forecast model ensembles for Japan and surroundings

Meteorological forecasts are made using the HIRLAM model (HIRLAM; Undén *et al.*, 2002) for an area covering Japan. 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 10 hPa.

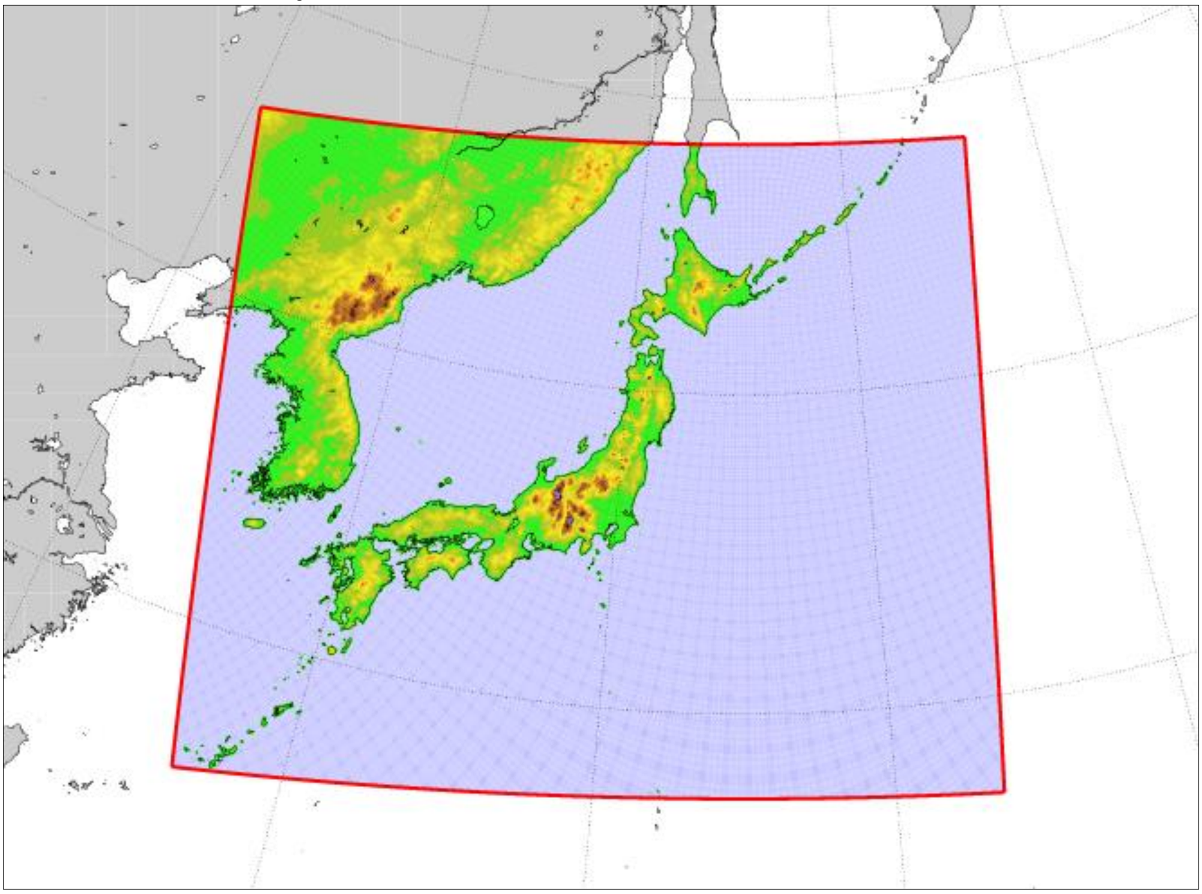

Figure 2 HIRLAM model domain.

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).

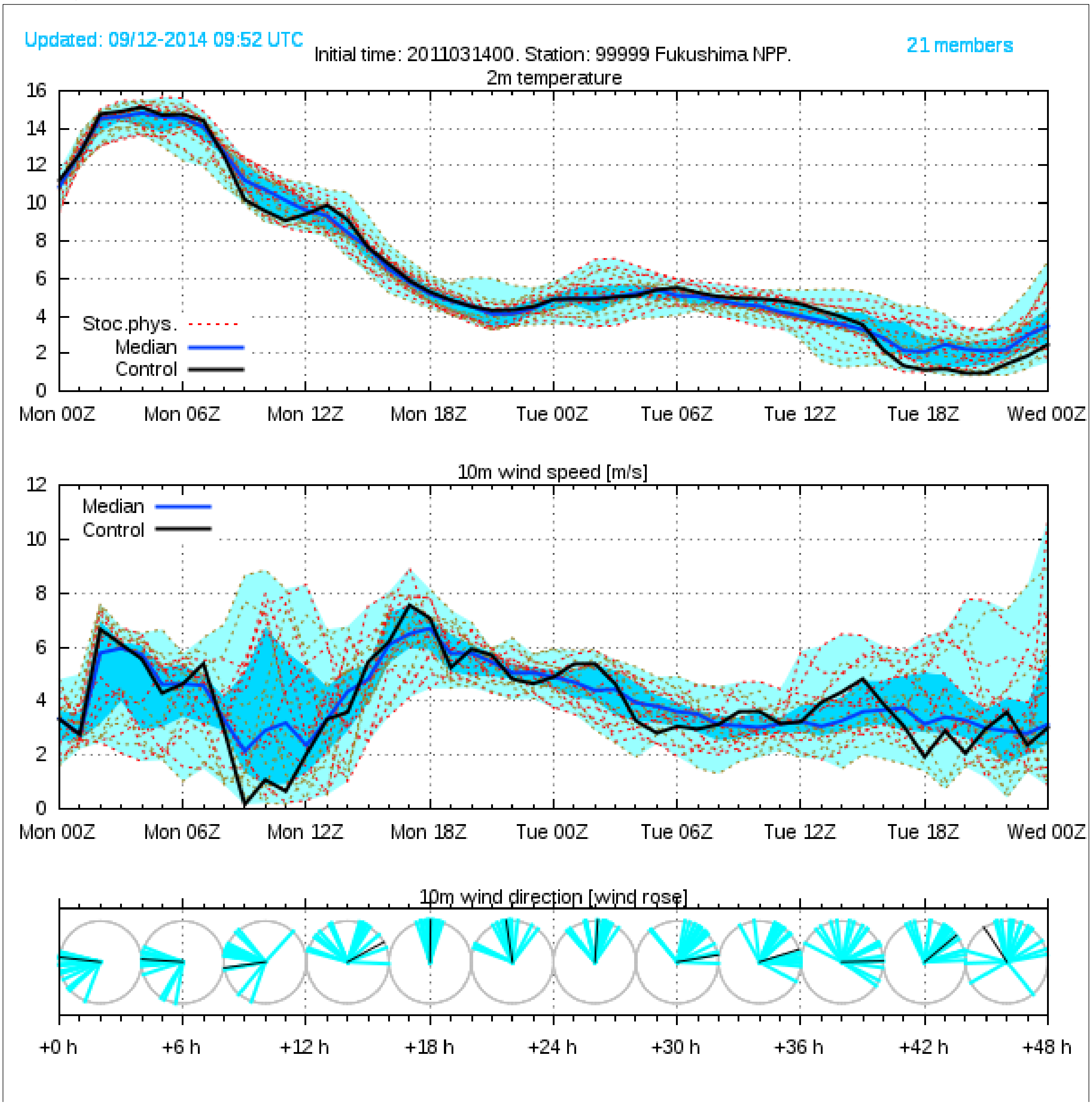

Figure 3 Ensemble meteogram for Fukushima NPP. Top panel shows 2 m temperature, middle panel shows 10 m wind speed; bottom panel shows 10 m wind direction. See text for more details.

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.

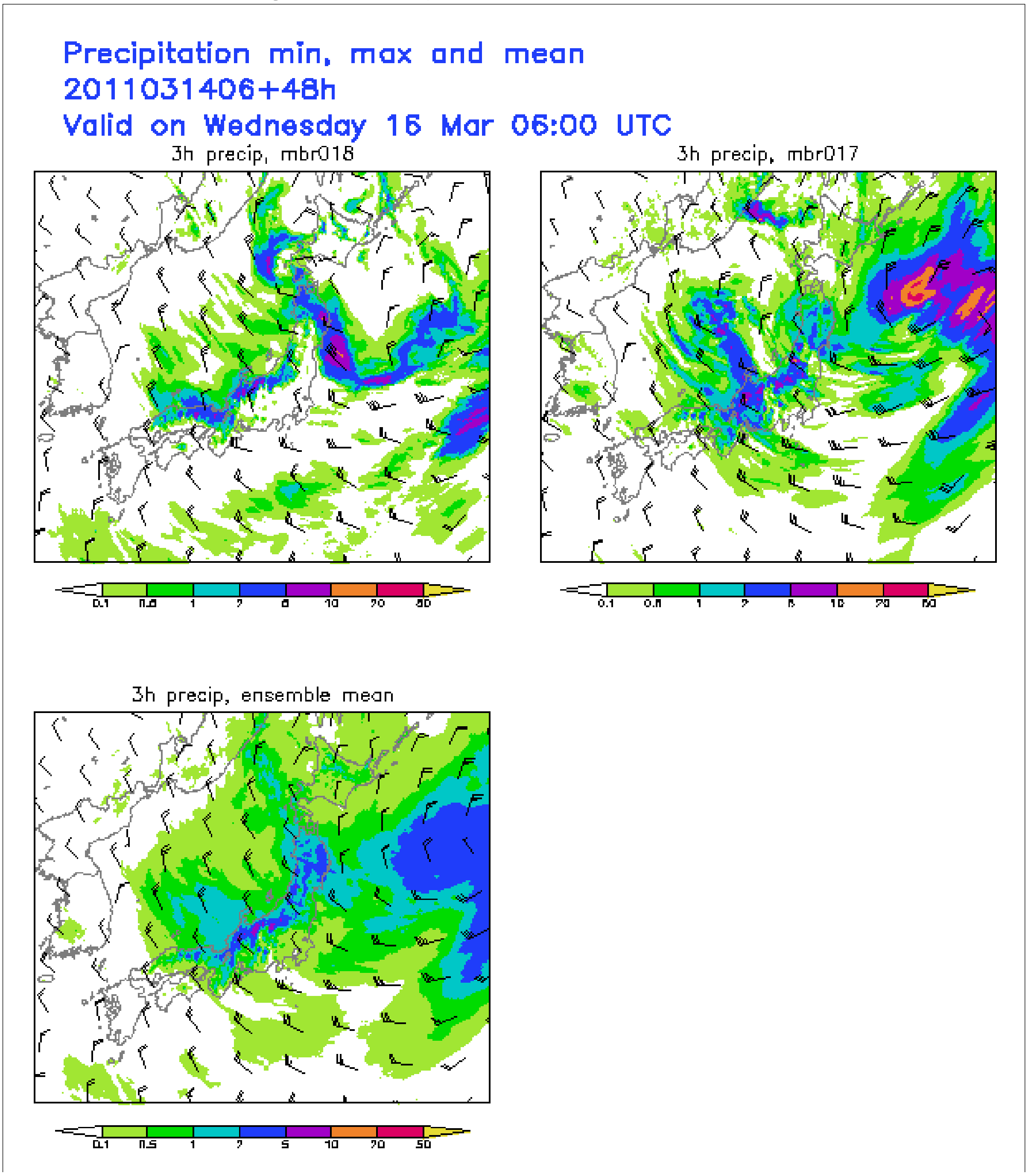

Figure 4 Two members of the same ensemble, illustrating the spread in precipitation. Panels show precipitation accumulated between forecast hours 45 and 48. Top: members 18 and 17; bottom: ensemble mean.

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 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.

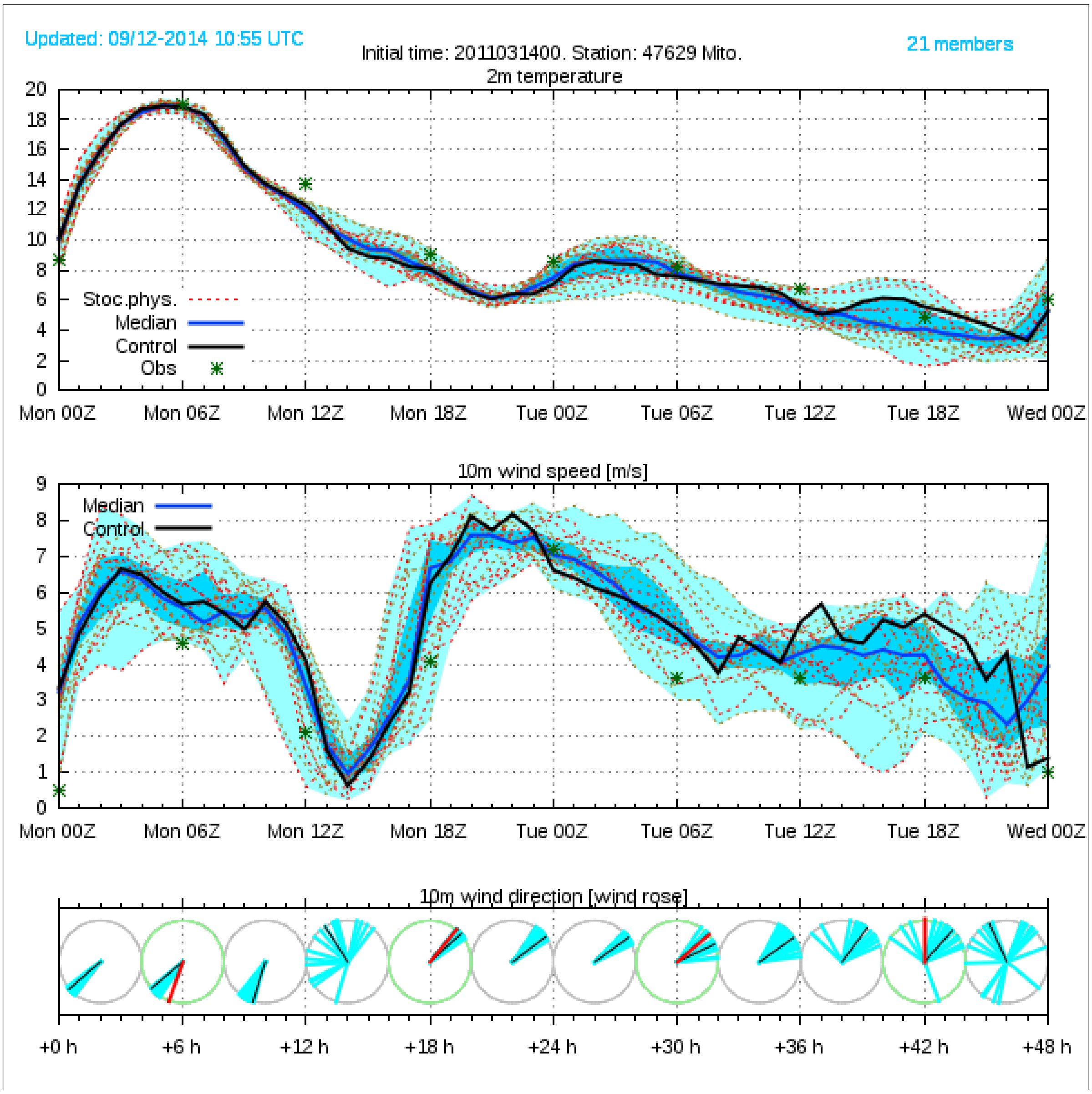

Figure 5 Ensemble meteogram for Mito (approx. 150 km SSW of Fukushima NPP). Verifying observations are shown as asterisks in temperature and wind speed panels and as red needles in wind direction panel.

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.

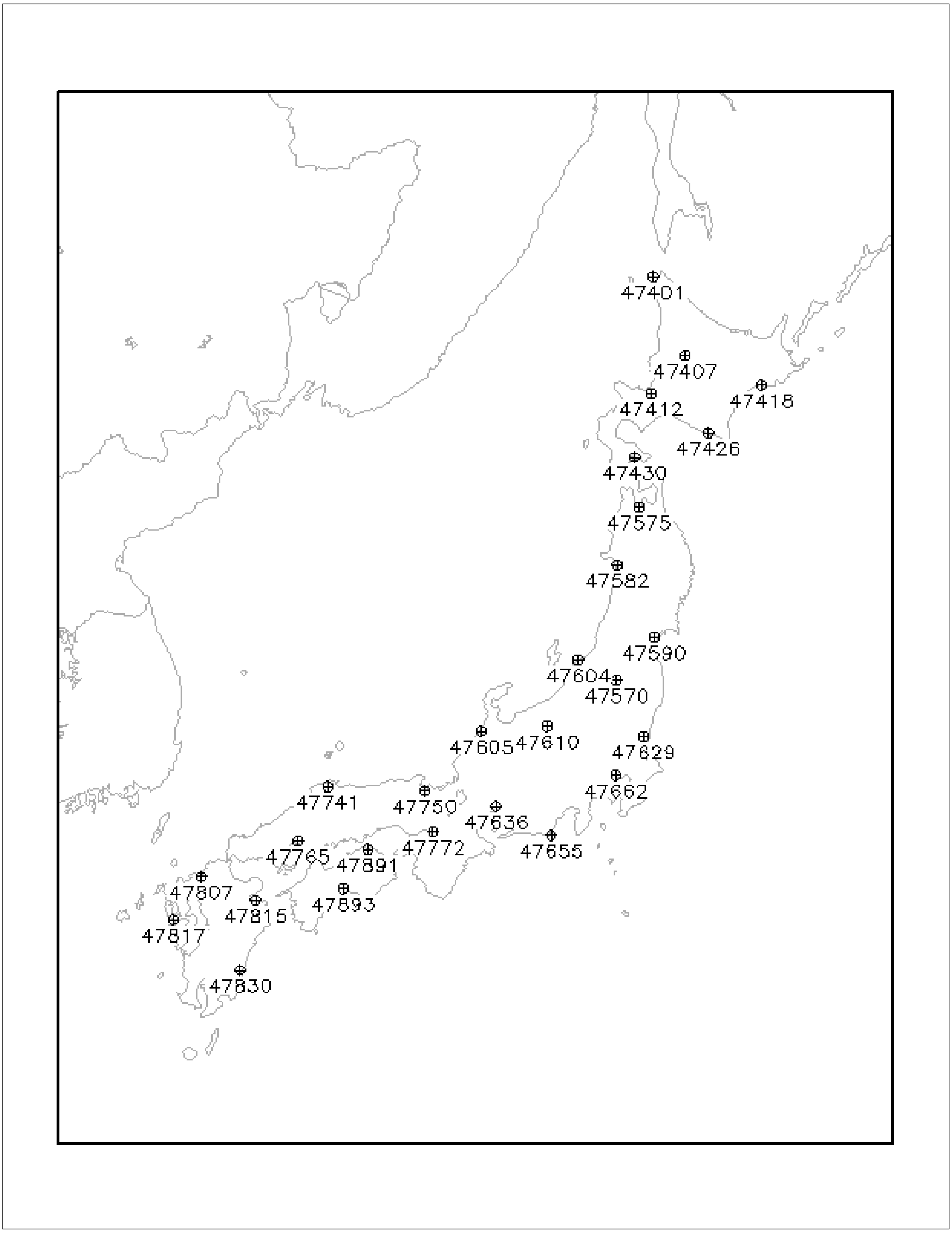

Figure 6 Meteorological synoptic observation stations used for verification. Numbers are identifiers used by the World Meteorological Organization.

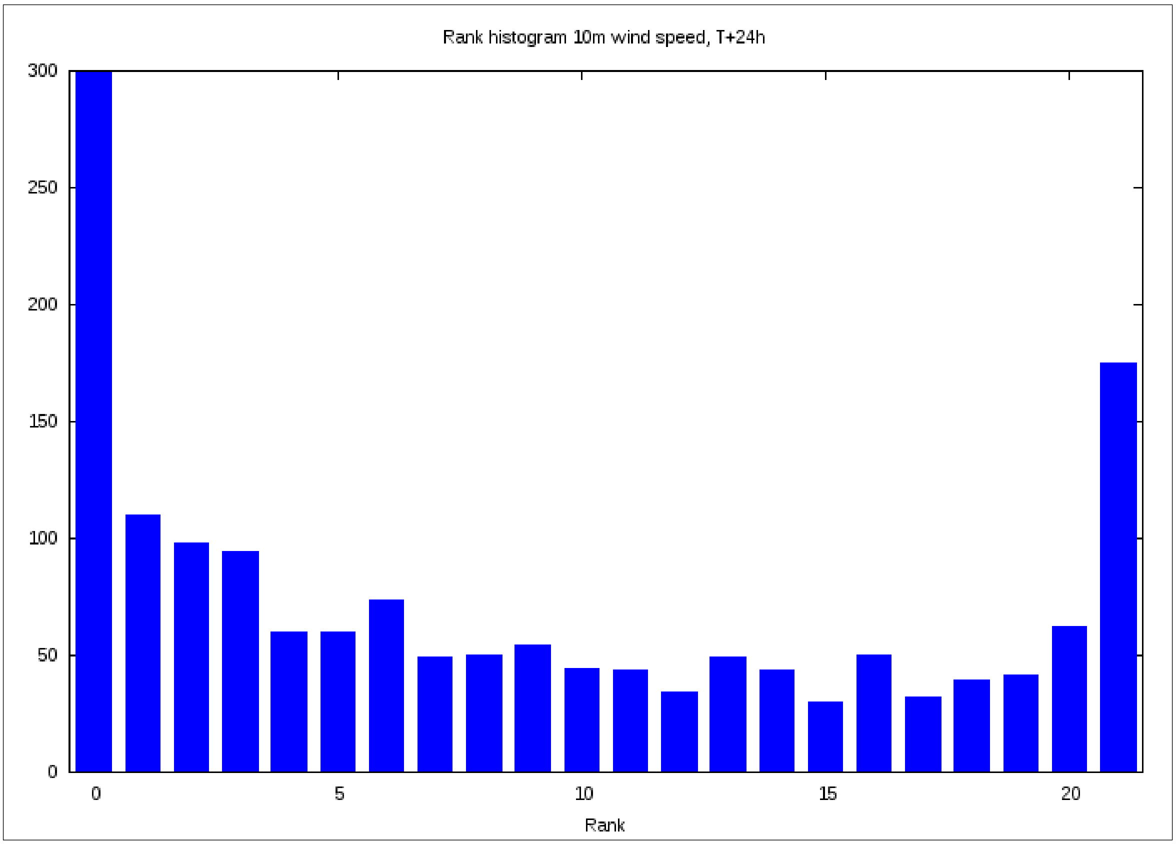

Figure 7 Rank histogram for Japanese observation sites for 24 h forecasts in the period 17-31 March 2011.

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.

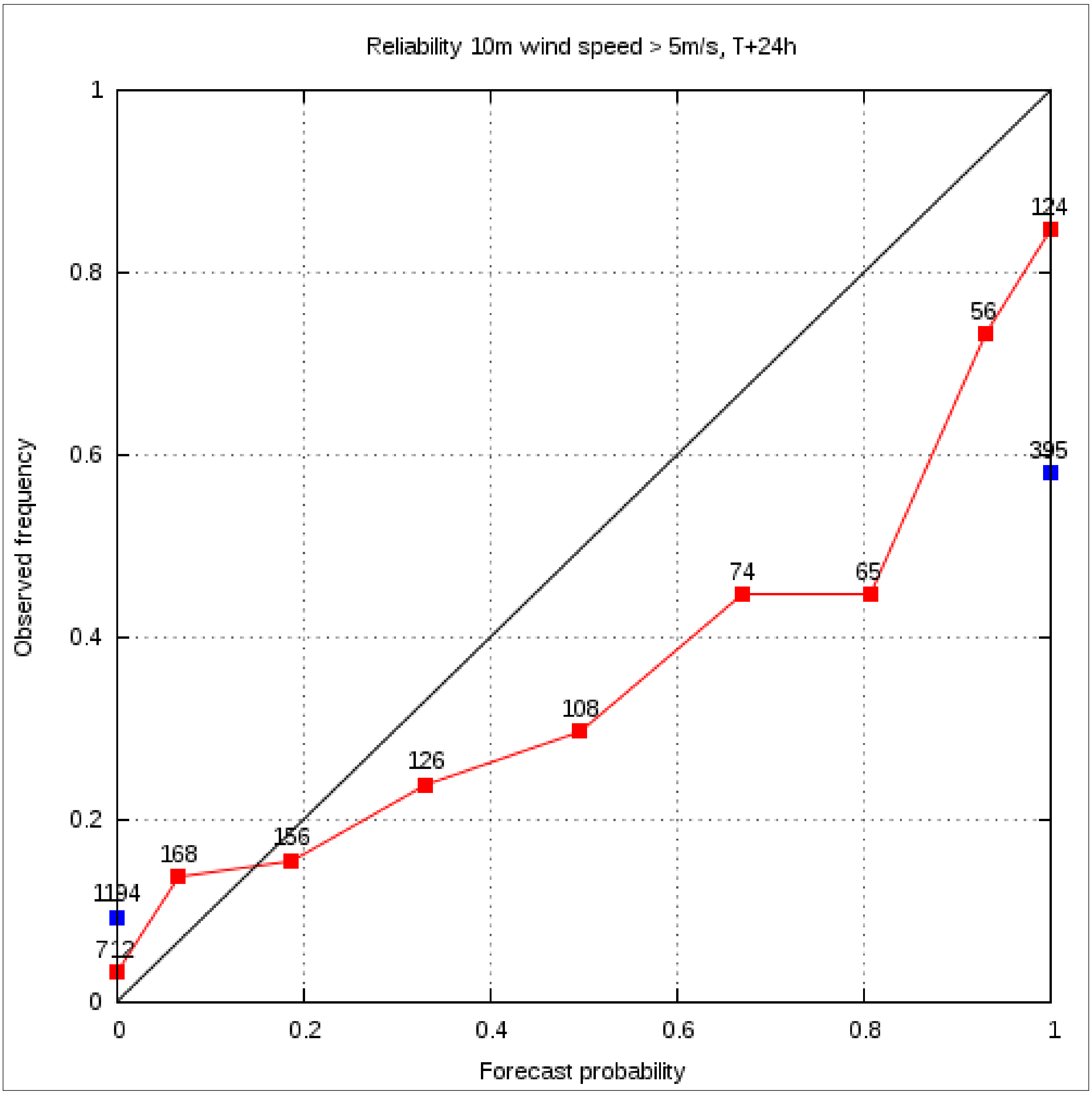

Figure 8 Reliability diagram for Japanese observation sites for 24h forecasts in the period 17–31 March 2011. Numbers show distribution of forecasts. Blue markers show reliability of control forecasts.

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.

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.

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

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 and minimum. 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

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

and similarly for the minimum

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

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 like 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, fulfills 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 increase the amount of data transferred from the NMS to the DSS much and put additional burdens on the DSS computer.

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

So far, only a few atmospheric dispersion scenarios have been calculated and described in the FAUNA project. Here, we present dispersion results as they would have been available in real time provided the ensemble modelling system was available. The scenario is a hypothetical gathering of an expert group at the headquarters of a Nordic national radiation protection authority in the morning of 14 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, 14 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.

We assume that a realistic release description is available, in this case as given by Terada *et al.* (2012). Obviously, this is not realistic, but in FAUNA we have confined ourselves to meteorological uncertainties and refrain from including uncertainties in the source term.

During the forecast period, the plume turns from eastwards over the Pacific Ocean to southwards in the direction of Tokyo, cf. Fig. 9 below which depicts the time series of ensemble average instantaneous concentration of Cs-137.

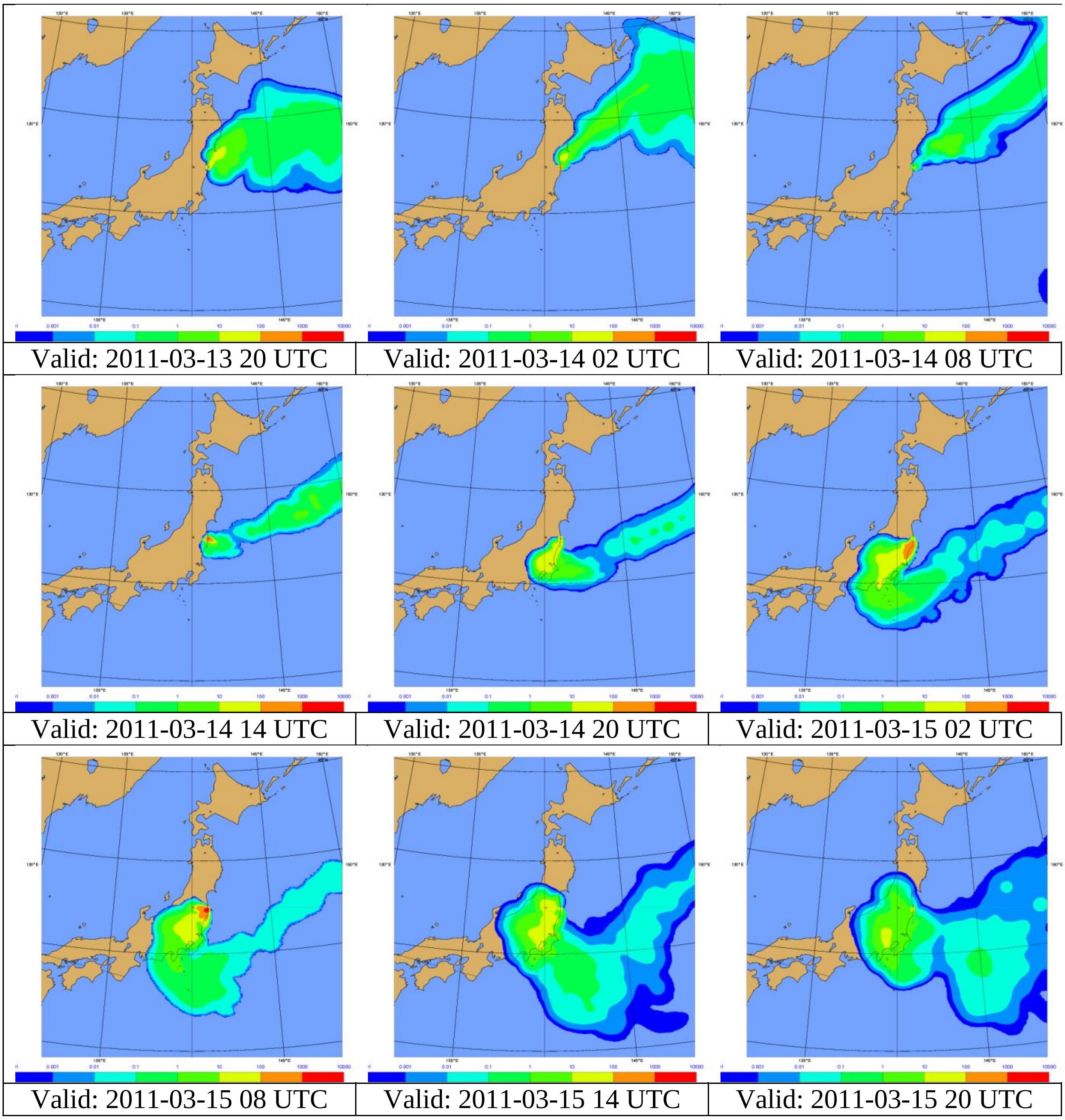

Figure 9 Time series of average values of instantaneous concentration of Cs-137.

In the first row of Fig. 10 is shown the ensemble minimum, mean and maximum values of accumulated deposition of Cs-137. 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. As can be seen, the variability, or uncertainty, is considerable in the selected scenario.

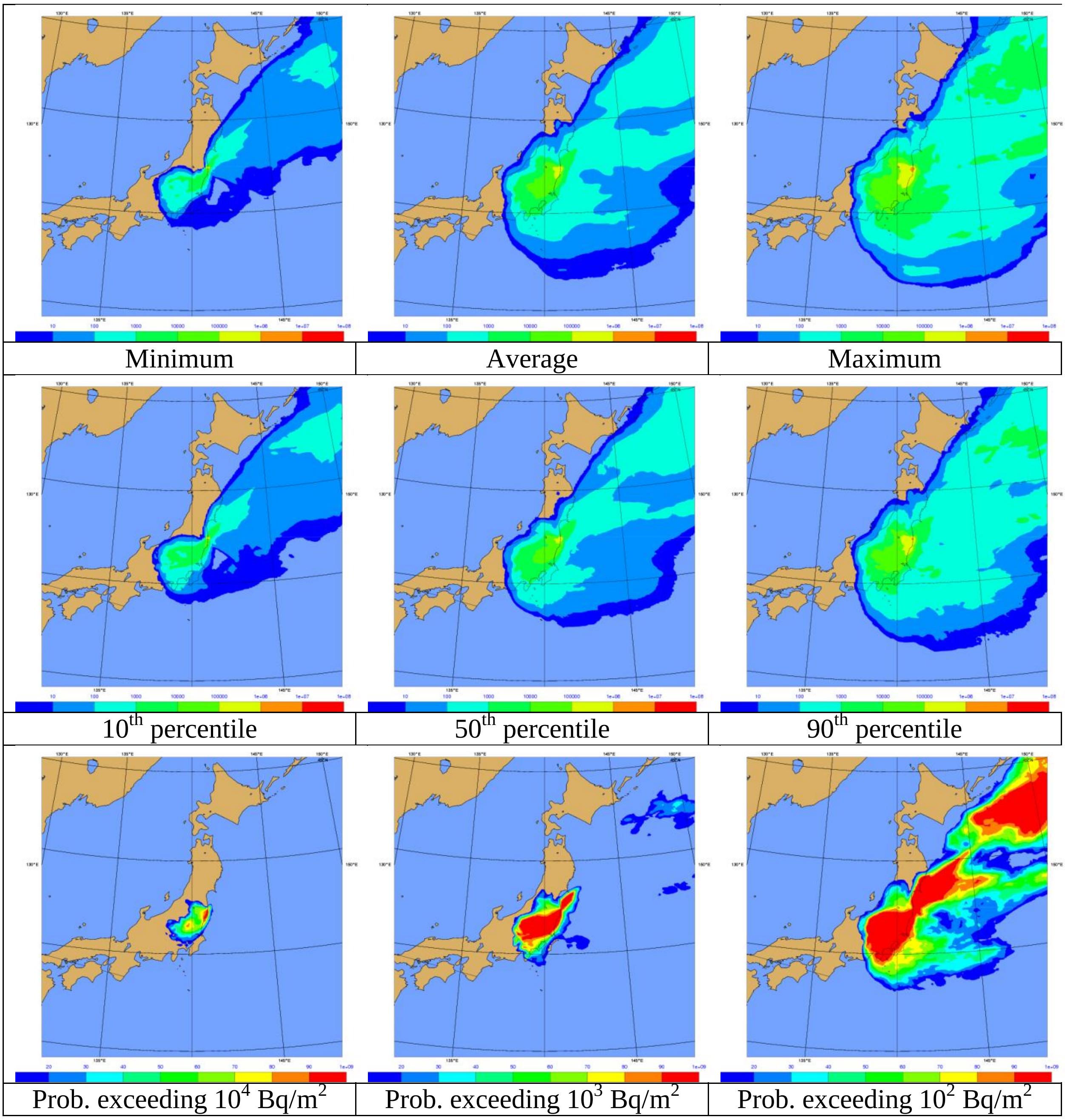

Figure 10 Accumulated deposition of Cs-137 at 0 UTC on 16 March, 2011, using 48 hours forecast meteorological data.

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

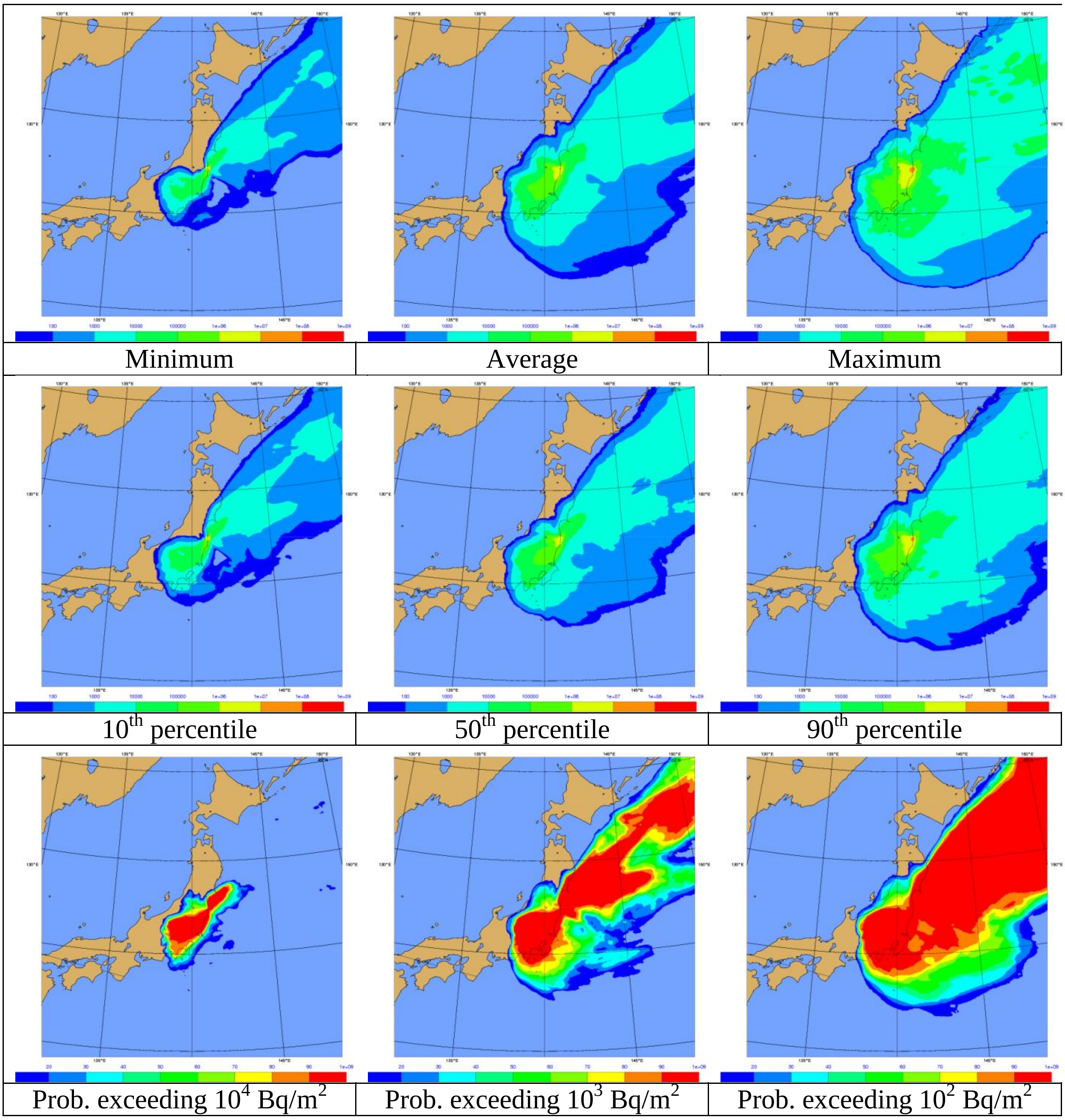

Figure 11 Accumulated deposition of I-131 at 0 UTC on 16 March, 2011, using 48 hours forecast meteorological data.

6. Conclusions and outlook

In the NKS-B project FAUNA, the ensemble-statistical methodology developed in the NKS-B project MUD (Sørensen *et al.* 2014) is applied to the Fukushima Daiichi NPP accident. By quantitatively estimating the uncertainties associated with numerical weather prediction as well as their impact on atmospheric dispersion model results, FAUNA addresses real-time nuclear emergency management. As demonstrated in MUD (Sørensen *et al.*, 2014) these uncertainties can be substantial depending on the meteorological situation. 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 DMI meteorological numerical ensemble forecasting system involving the 21 ensemble members 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 meteorological analysed and forecast ensemble-statistical data will be used by the Danish and Norwegian operational atmospheric dispersion models. In the present report, first results are presented.

A literature study has been carried out on source descriptions for the Fukushima Daiichi accident. A well suited realistic source term has been selected to be used by the dispersion models. The numerical results of FAUNA will be made available in a format which facilitates import in the ARGOS decision-support system, which will thereby host a demonstration of the FAUNA results. Finally, investigation of implications of uncertainty estimates for decision support will be studied and described.

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Disclaimer

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