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TOWARDS THE USE OF METEOROLOGICAL ENSEMBLES FOR SHORT DISTANCE DISPERSION OF RADIONUCLIDES IN CASE OF AN ACCIDENTAL RELEASE IN THE ATMOSPHERE

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Abstract: Numerical models of atmospheric dispersion are used for predicting the health and environmental consequences of nuclear accidents, in order to anticipate the countermeasures necessary to protect the populations. However, the simulations of these models suffer from significant uncertainties, arising in particular from input data: weather conditions and source term. To characterize weather uncertainties, it is essential to combine a well-known source term data and meteorological ensembles to generate ensemble dispersion simulations which has the potential to produce different possible scenarios of radionuclides dispersion during emergency situations. In this study, the fine-scale operational weather ensemble AROME-EPS from Météo-France is coupled to the Gaussian puff model pX developed by the French Institute for Radiation Protection and Nuclear Safety (IRSN). The source term data is provided by Orano La Hague reprocessing plant (RP) that regularly discharges ^{85}Kr during the spent nuclear fuel reprocessing process. Then, to evaluate the dispersion results, a continuous measurement campaign of ^{85}Kr air concentration was recently conducted by the Laboratory of Radioecology in Cherbourg (LRC) of IRSN, around RP in the North-Cotentin peninsula. This work investigates the meteorological uncertainties in dispersion simulations at local and medium distances (2-20km). The probabilistic performance of the dispersion ensemble simulations was evaluated using two probabilistic scores: Relative Operating Characteristic (ROC) curves and Peirce Skill Score (PSS). The results highlight the added value of ensemble forecasts compared to a single deterministic one, and their potential interest in the decision process during crisis situations.

Key words: *Ensembles, meteorological uncertainties, atmospheric dispersion model, ^{85}Kr, pX, AROME-EPS.*

INTRODUCTION

The dispersion of radionuclides released into the atmosphere depends on the physico-chemical properties of the released substances, the emission parameters (e.g. source elevation, timing and duration of the release) and meteorological conditions at the accident site (e.g. wind speed and direction). In order to forecast the dispersion of radionuclides in the early phase of nuclear accidents and to support decisions and warnings, atmospheric dispersion models (ADM) are commonly used to predict the transport of radioactive pollutants through the atmosphere as well as the quantities of radioactive material deposited on the ground. This information is essential for decision makers in order to anticipate the countermeasures necessary to protect the population against contamination.

The outputs from ADM simulations suffer from significant uncertainties that hinder their use in an operational context. Meteorological forecasts, which are an essential input data, are one of the main sources of these uncertainties. Weather information used for dispersion prediction is, frequently, provided by Numerical Weather Predictions (NWP) as 3-D or 4-D physical fields. For weather prediction, meteorological uncertainties are usually accounted for by building an ensemble of NWP instead of using a single, deterministic forecast. The objective of this work is to investigate the impact of the meteorological uncertainties on local-scale dispersion by using the operational high-resolution meteorological ensemble AROME-EPS (Bouttier et al., 2012) of Météo-France. It is a 16-members ensemble with a resolution of

2.5 x 2.5 km and hourly forecasts. Given the objective of the study, only first 25 vertical levels [10-3000 m] are used to cover the entire Atmospheric Boundary Layer (ABL). Then, AROME-EPS ensembles are used as input of IRSN’s short-range Gaussian puff model pX (Korsakissok et al., 2013) around La Hague Reprocessing Plant (RP) at local and medium scales (2-20 km) (Figure 1).

CASE STUDY

The present study focuses on the dispersion of ^{85}Kr at short and medium distances (less than 20 km), in the North-Cotentin peninsula located in the North-West of France territory (Figure 1). The potential interest of the La Hague area is that the release rate of ^{85}Kr emitted by the RP into the atmosphere is known with a good accuracy. In addition, there is a sufficient density of meteorological measurements combined with ^{85}Kr radiological air concentration measurements (Figure 1). Meteorological measurements are carried out by Météo-France on a regular basis. IRSN's LRC laboratory regularly performs meteorological and radiological measurements in the framework of measurement campaigns (Connan et al., 2014). In this work, continuous radiological measurements (every 1 minute) were conducted by LRC as part of the DISKRYNOC project (DISpersion of KRYpton in the NOrth-Cotentin). Additional meteorological and air concentration measurements, as well as release data (every 10 minutes), are carried out by Orano for the environmental monitoring of the RP. For these reasons, the La Hague experimental site is an ideal environment for the study and validation of atmospheric dispersion simulations.

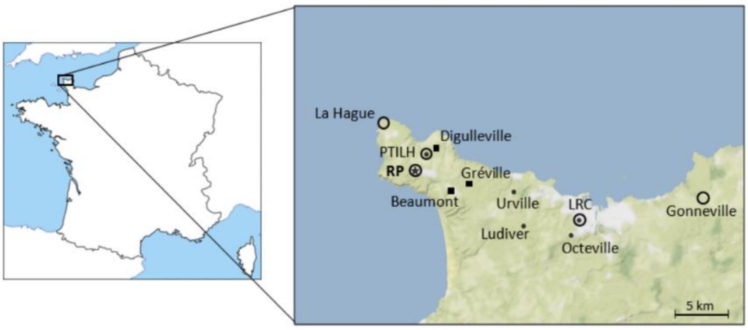

Figure 1. Location of North-Cotentin peninsula (left panel) and map of the monitoring sites (right panel). The dots and squares indicate the locations of the ^{85}Kr measurement stations carried out by IRSN and RP, respectively, as part of the DISKRYNOC campaign. The RP facility location is marked with a star. The circles indicate the locations of the 3D-wind measurement sites (from IRSN or Météo-France).

COUPLING AROME-EPS ENSEMBLES TO DISPERSION MODEL pX

Before coupling the numerical weather predictions from AROME-EPS to the pX model, it is necessary to evaluate them in order to have an exhaustive overview of their quality and to take it into account in the interpretation of atmospheric dispersion simulations. Wind speed and direction are the most influential variables on the transport of a plume through the atmosphere. The meteorological ensembles were thus evaluated by calculating comparative evaluation scores (e.g bias, spred-skill ratio, rank diagram) based on the observations of 3D-wind over a two-months period (Dec. 2020-Jan. 2021). The results of this evaluation showed that the high horizontal, vertical and temporal resolution of the AROME-EPS forecasts allow them to correctly represent the uncertainties within ABL, despite slight errors in the wind speed forecast.

Simulations set-up

Once meteorological forecasts from AROME-EPS have been qualified, they are coupled to the Gaussian dispersion model pX by running in parallel several simulations with the pX model, each using a different member of the AROME-EPS ensemble as input (Figure 2), along with the source term data provided by RP La Hague. This allows to generate an ensemble of dispersion simulations composed of 16 members. Furthermore, in order to quantify the benefit of using ensembles instead of deterministic simulations, an additional pX simulation was performed using the deterministic weather forecast from AROME as input of the model. Then, in order to ensure that the source emission does not occur above the ABL, a minimum value of 200 m is imposed to the ABL height before being applied to the pX simulations. In addition, the effects of the complex topography (coastline, rocky terrain) and buildings on the plume dispersion may lead to downwash effects that are not explicitly taken into account by the Gaussian puff model. To compensate for this limitation, 8 effective heights have been tested: 20, 50, 100, 150 and 200 m. The most optimum simulations were obtained by using the physical stack height of 100 m.

Even though the NWP forecasts are given with an hourly frequency, the pX simulations were performed in this study with a time step of 10 minutes in order to better capture the temporal variations of the plume. Two stability diagnoses were used to perform pX simulations: Pasquill and Doury (El-Ouartassy et al., 2022).

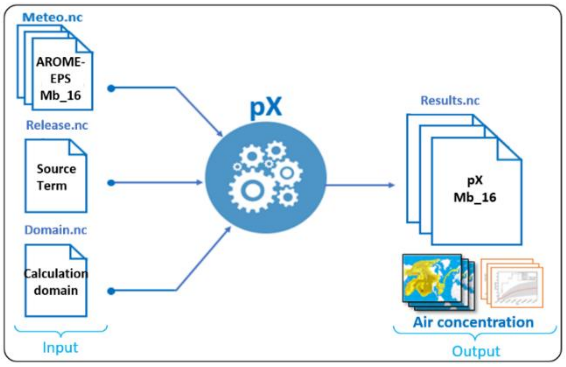

Figure 2. Coupling of AROME-EPS meteorological ensembles to the Gaussian dispersion model pX.

Statistical indicators for dispersion ensemble evaluation

It is often a desirable feature for a dispersion model to be able to correctly predict a threshold exceedance. It is particularly useful for decision-making purposes, when protective actions for the population are based on the prediction of zones where a given dose threshold could be exceeded. Evaluating the model performance for this kind of purpose is often based on contingency tables allowing to compare the series of observations and simulations by counting four features: (i) true positive (TP) when a peak is observed and well simulated, (ii) false negative (FN) when a peak is observed but not simulated, (iii) false positive (FP) when there is no observed but simulated peak and (iv) true negative (TN) when there is no observed and no simulated peak. Then, the performance of the ensemble is measured using hit rate (H) and false alarm rate (F) metrics. The hit rate is the fraction of the observed events that are successfully reproduced (Equation (1)). The false alarm rate is the fraction of the simulated peaks that are not observed (Equation (2)).

$$H = \frac{TP}{TP + FN} \tag{1}$$

$$F = \frac{FP}{FP + TN} \tag{2}$$

In the case of the AROME-EPS-pX ensemble, there are 16 possible decision thresholds (x=1,2,...,16). In order to identify the most optimal ones, the ROC (Relative Operating Characteristic) curves are commonly used as a graphical summary of the decision-making skill of an ensemble, by connecting all points [F(x), H(x)] for each decision threshold x. In addition, to better capture the internal variation of the performance of the model according to the decision thresholds, the Peirce skill score (PSS) was calculated for each x, as follows:

$$PSS(x) = H(x) - F(x) = \frac{TP \times TN - FP \times FN}{(TP + FN) \times (FP + TN)} \tag{3}$$

Note that the threshold that presents a better compromise between the probability of detection and the probability of false detection of events corresponds to the one that maximizes the PSS.

RESULTS

Simulations and observations at all stations were aggregated in order to investigate the probabilistic performance of the ensembles, using ROC curves and PSS. As shown in Figure 3, The pX-Pasquill ensembles perform better than pX-Doury, with a PSS_{MAX}=0.72 corresponding to an optimal decision thresholds of 3 and 4 members (against a PSS_{MAX}=0.63 and optimal decision thresholds of 3 members for pX-Doury ensembles). This difference in performance seems normal given that the variation in atmospheric stability conditions is better captured with the Pasquill's stability classes (six classes for Pasquill against two classes for Doury). In both cases, the ensemble performs better than the deterministic simulation in a range of seven decision thresholds, which represents almost 50% of the possible values of the decision thresholds. These results highlight the robustness of the probabilistic simulations compared to the deterministic simulation in the process of the prediction of threshold exceedances.

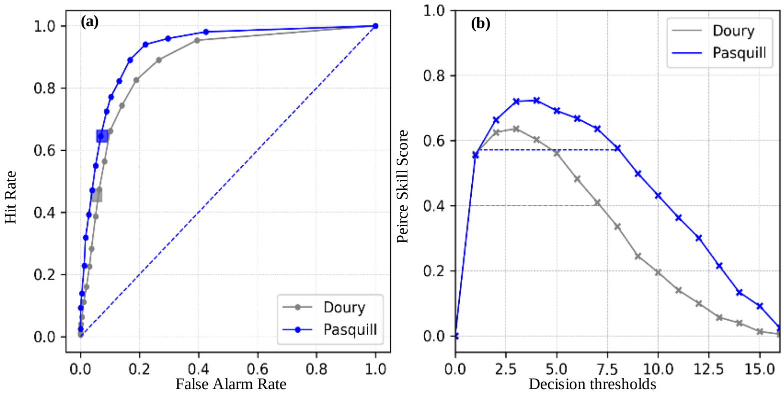

Figure 3. ROC curves (a) and the PSS as a function of decision thresholds (b) of the pX ensemble simulations performed with Pasquill stability classes and Doury classes, by aggregating simulations and observations at all stations. The values of the scores for the deterministic pX simulation are indicated by squares in the ROC curves and by horizontal dashed lines in the PSS curves. The diagonal dashed lines are the no-skill lines (H=F).

To go further into the analysis of the probabilistic performance of the ensembles, the effect of the distance from the source is investigated in Figure 4. In this case, the dispersion simulations were generated, with the two diffusion configurations of Pasquill and Doury, by aggregating data for two groups of stations. The first is the *-10km* group which contains stations at distances less than 10km from the source: PTILH (2km), Digulleville (2.6km), Beaumont (4.2km) and Gréville (5.2km). The second is the *+10km* group which contains stations beyond 10km: Urville (10.4km), Ludiver (12.7km), Octeville (17.7km) and LRC (18km). For both groups of stations, pX-Pasquill simulations give better scores than pX-Doury, both for deterministic and ensemble pX outputs.

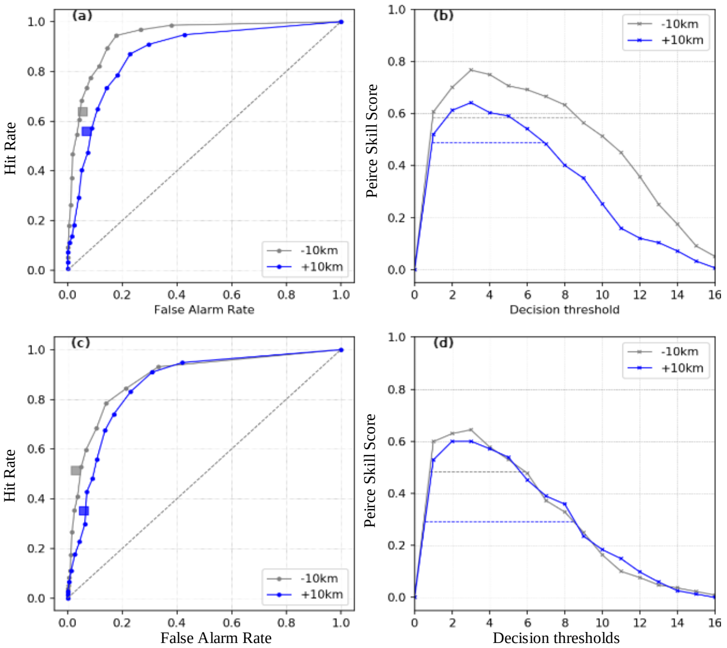

Figure 4. ROC curves (a, c) and the PSS as a function of decision thresholds (b) of the pX ensemble simulations performed with Pasquill stability classes (a, b) and Doury classes (c, d), by aggregating data in the two groups of stations: -10km (gray) and +10km (blue).

Taking into account both meteorological and model uncertainties would imply generating an ensemble by also perturbing model parameters (Pasquill/Doury, source elevation, stability). In this perspective, a 32-member super-ensemble was generated by combining pX-Pasquill and pX-Doury ensembles. The result (not shown here) is very similar to the pX-Pasquill ensemble.

CONCLUSIONS AND PERSPECTIVES

In this study we explored the potential value of using fine-scale spatial and temporal meteorological ensembles to represent the effect of meteorological uncertainties on ADM outputs. The high-resolution operational forecasts AROME-EPS of Météo-France have been coupled to IRSN's Gaussian puff short-range dispersion model pX to generate a 16-member dispersion ensemble which accounts for meteorological uncertainties. This study presents a strategie to evaluate the ability of a dispersion ensemble to forecast threshold exceedances, using probabilistic scores. For this purpose, we used an original data set of continuous ^{85}Kr air concentration measurements (DISKRYNOC campaign recently conducted by IRSN), along with a well-known source term (every 10 minutes, provided by Orano La Hague RP) and meteorological data (NWP from Météo-France and continuous observations from Météo-France/IRSN).

As a first step, the assessment of the quality of the AROME-EPS forecasts, in terms of wind speed and direction, in the North-Cotentin peninsula was carried out, using meteorological observations, over the two-month period of interest (Dec. 2020-Jan. 2021). The results showed that AROME-EPS performs well in the North-Cotentin area. Then, an ensemble dispersion modeling chain was implemented using the AROME-EPS forecasts as inputs to the pX model. Then, two configurations of dispersion simulations were run, with Pasquill and Doury Gaussian standard deviations. The probabilistic consistency of the two resulting dispersion ensembles was then compared by calculating two probabilistic scores: ROC curves and PSS. This evaluation process was performed in two parts. First, by comparing the overall performance of the two configurations by aggregating the data from all the measurement stations. In this case the best results were obtained with Pasquill standard deviations. Secondly, by comparing the performance of the two configurations in the near fields (stations located less than 10km from the source) and far fields (stations beyond 10km from the source). The results showed that the Pasquill simulations were still the most consistent with observations. In all cases studied, the best decision threshold is 3 members, and the ensembles performed better than the deterministic simulations. For operational purposes during emergency situations, this result would imply that in this configuration, when 3 or more members of the ensemble forecast a threshold exceedance, protective actions should be recommended.

To complement this study, it would be interesting to develop complementary indicators that evaluate the consistency of dispersion ensembles in terms of intensity between the simulated and observed peaks. Another perspective of this study is to work on the clustering of the meteorological ensembles in a perspective of reducing the number of members while keeping the consistency of the dispersion ensembles. This can significantly reduce the computational time of ADM runs, which is a crucial issue in the case of a real nuclear accident.

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