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NEAR-FIELD (R<200M) ATMOSPHERIC DISPERSION SIMULATION AND SENSITIVITY ANALYSIS FOLLOWING A FULL-SCALE ATMOSPHERIC TRACER EXPERIMENT

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Abstract:

Evaluating the risks associated with chronic or accidental industrial releases requires precise simulation and analysis of near-field atmospheric dispersion and associated uncertainties. The aim of this study was, firstly, to assess the effectiveness of an atmospheric simulation tool, SLAM (Safety Lagrangian Atmospheric Model), through comparison with a comprehensive full-scale atmospheric tracer experiment conducted in the near field, then to characterize the sensitive parameters affecting the near-field simulations. SLAM is a Lagrangian stochastic particles dispersion model, coupled with a wind and turbulence field database computed from the CFD code, ANSYS Fluent. This case study includes 19 trials involving various meteorological conditions. We used both statistical and graphical indicators to perform the model-to-data comparison. Results indicate that SLAM performs better under neutral or slightly unstable meteorological conditions. SLAM demonstrated a better accuracy in simulating the near-field dispersion (within 100 m) compared to Gaussian models. A global Sobol sensitivity analysis was also performed for a challenging low wind speed case under unstable atmospheric conditions. This sensitivity analysis focused on analysing how the meteorological parameters affect the output variance, represented by the statistical score FAC2. The results showed that the wind speed and wind direction are the first two primary factors impacting the near-field atmospheric dispersion. SLAM exceeded the acceptance threshold (FAC2≥0.5) in all trials by slightly adjusting these sensitive input parameters. This study confirms SLAM's effectiveness in accurately predicting near-field atmospheric dispersion and its potential for improving safety assessments in industrial contexts. It highlights the primary importance of meteorological inputs in atmospheric simulations, especially in the very near-field area, and some limits of the models in the immediate vicinity of the buildings.

Key words: *Near-field simulation, atmospheric dispersion, Lagrangian, sensitivity study.*

INTRODUCTION

Estimating the atmospheric dispersion of radionuclides following chronic or accidental releases, and assessing subsequent radiological risks, are paramount for decision-makers. This study focuses on the dispersion of fluorine 18 (^{18}F) following its release during production in a cyclotron. ^{18}F is a radioactive nuclide that decays primarily through β^+ emission, with a half-life of 110 minutes, which is extensively used as a tracer in the medical diagnostical tools. A fraction of gaseous ^{18}F is released in the atmosphere during the production process when the installation is not equipped with a temporary gas retention device. Given that medical cyclotrons are usually located in the urban or peri-urban areas, near hospitals, accurately estimating the near-field impact of ^{18}F release is crucial. Therefore, to enhance our understanding of the near-field dispersion, French institute for radiation protection and nuclear safety (IRSN) has initiated the DIFLU (Dispersion du Fluor 18 en Mileu Urbain) project in 2019 (Laguionie et al. 2022). The project's initial phase involved conducting full-scale atmospheric tracer measurements within 500 meters of a cyclotron facility, assessing tracer concentrations across various atmospheric conditions. This measurement campaign provided a valuable database for validating atmospheric dispersion models. During the second phase of the project, a series of modelling and simulations was conducted to elucidate the intricacies of the near-field dispersion process (Charvolin-Volta et al., 2021). Gaussian models, known for their simplicity and efficiency in predicting the mid-to-far-field pollutant concentrations, have been widely used for operational simulations and have demonstrated good performance to predict air concentration measurements up to a few kilometres from the release. Conversely, more complex computational fluid dynamics (CFD) solvers, grounded in the Navier-Stokes equations, offer improved accuracy by accounting for complex terrains, building or vegetation effects, though their lengthy calculation times limit operational use. To tackle this problem and benefit from the high accuracy of CFD simulations, an approach coupling stochastic Lagrangian particle models with offline precalculated flow fields emerges as an efficient alternative (Armand et al. 2014; Vendel 2011). SLAM (Safety Lagrangian Atmospheric Model), developed by Vendel et al. 2010 and based on a Lagrangian model, is the main simulation tool of this study. The current work is the continuation of previous studies from Laguionie et al., (2022) and Charvolin-Volta et al. (2021). Additionally, a quantitative Sobol sensitivity study was conducted to identify sensitive factors affecting the near-field atmospheric dispersion.

SIMULATION AND MEASUREMENTS DESCRIPTIONS

The simulation tool SLAM is based on a stochastic Lagrangian particle model. This solver is coupled with a pre-calculated CFD flow database that includes18 wind directions and seven different atmospheric stabilities and was generated with the commercial software ANSYS FLUENT. More detailed information about this solver can be found in Vendel et al. (2010) and Vendel, 2011.
IRSN's Gaussian puff model pX includes several Gaussian diffusion laws, both discrete and continuous (based on similarity theory). It is IRSN's operational model, included in its emergency response platform C3X and used in case of accidental releases of radionuclides in the atmosphere. It was validated both on classical atmospheric dispersion experiments and compared to environmental measurements within 80 kilometres of the Fukushima Nuclear Power Plant (Korsakissok et al., 2013; Jacques et al., 2022).

The measurement campaigns were performed within a 500-meter radius of a cyclotron situated near Beuvry hospital, located in a suburban area in Northern France. Stable helium was released at stack location (10m high) and used as dispersion tracer. The campaigns were divided into two phases: the first in October, comprised nine trials ranging from case #1-1 to case #1-9, and the second in December, consisted of ten trials from case #2-1 to case #2-10. The atmospheric stability was neutral (class D) or slightly unstable (class C). Only the cases 2-4, 2-5 and 2-8 are in unstable atmospheric conditions (class B) (Laguionie et al., 2022). Among them, the wind speed for case 2-4 is the lowest. The meteorological parameters used in this study were retrieved from Lidar measurements at an altitude of 40 meters. More details can be found in Laguionie et al. (2022) and Charvolin-Volta et al. (2021).

RESULTS DISCUSSIONS

Model-to-measurements comparisons with pX and SLAM

This section presents the comparison between measurements and simulation results with SLAM and pX models. To provide an evaluation of the simulations versus measurement data, we employ the statistical indicator FAC2, which is the proportion of simulated values that fall within a factor 2 of observed values, with 1 indicating a perfect model and FAC2>0.5 signifying a well-performing model (Chang and Hanna 2004). For each case, this indicator was computed using concentration values from all available receptors. Figure 1 shows the comparisons of FAC2 for each of the 19 trials. The results of the Gaussian model are shown for different standard deviation laws (Briggs-rural, Briggs-urban, Doury and Similarity). The blue shadow region highlights the acceptable model range (FAC2$\geq$ 0.5). The SLAM results indicate that 47% of the cases across both campaigns meet the acceptable model criteria. SLAM predicts better results for the first campaign compared to the second campaign. This discrepancy may be linked to the second campaign's receptor locations being closer to the discharge source. All sampling receptors were positioned within a 500-meter arc from the discharge point, with 88% of campaign #2's receptors within 100 meters—6% more than in campaign #1. The more unstable atmospheric conditions during campaign #2 may also have influenced the model's performance. In contrast, the Gaussian models achieved the acceptable model threshold (FAC2≥ 0.5) in only 16% of cases. Among these, the Briggs-urban model exhibited the best performance in predicting near-field concentrations, particularly for camp #1, while the Doury model yielded the lowest results. Similar to SLAM, Gaussian models yielded better results for camp #1 than camp #2, underscoring the influence of receptor proximity and atmospheric conditions on model efficiency.

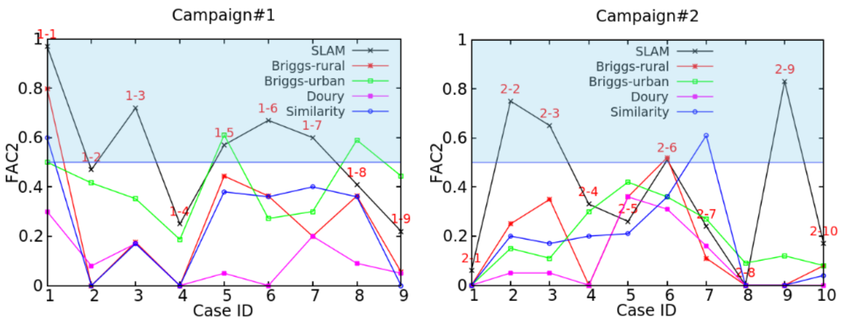

Figure 1. Comparisons of statistical indicator FAC2 among different simulation models.

The distribution of FAC2 along the distance to the discharge source point is presented in Figure 3. Instead of using the actual distances to the discharge point, the maximum distance index was preferred to denote proximity to the source. This approach divides the 500-meter range into 10 equal intervals, as shown in Figure 3, with each interval's maximum value serving as its representative index. For instance, an index of 50 corresponds to receptors located within 50 meters of the source point, indicating these are the closest measurements. The index 150 symbolizes the receptors whose distances to the source point fall into the range of 100 m to 150 m.

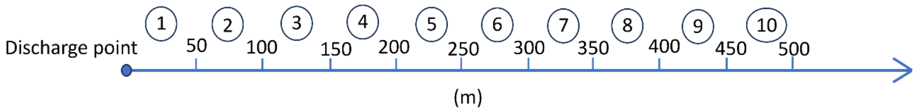

Figure 2. Demonstration of the 10 homogeneous intervals within 500 m.

As shown in Figure 3, the closer receptors are to the source point (x <50 m), the more accurate are SLAM concentration values compared to those predicted by the Gaussian models. This enhanced performance is consistent with SLAM's detailed consideration of near-field obstacles and turbulence. From the distances of 50 m to 200 m, the Briggs-urban model has outperformed all the other models with a FAC2 of 0.62—0.75 in the camp#1 cases. However, this outperformance has not been sustained in the camp#2. It is found that SLAM emerges as the more accurate estimator across most conditions, except for the 200 m—250 m distance interval in camp#2. Beyond 250 meters, the similarity model shows distinct advantages compared to the other models.

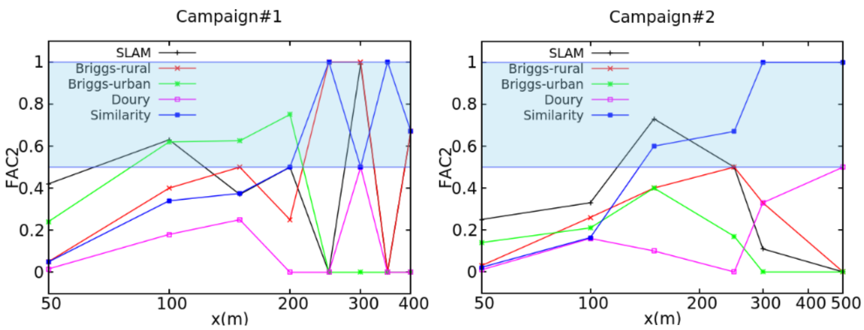

Figure 3. Comparisons of FAC2 for SLAM, Briggs-rural, Briggs-urban, Doury and Similarity Gaussian models as a function of distance x to the discharge point. FAC2 is used to evaluate the simulated concentrations compared to the measurements. The acceptable region is marked with light blue shadow.

Sensitivity study

To understand the factors affecting the near-field dispersion, a quantitative Sobol sensitivity study was performed. This global variance-based method quantifies how different input variables affect the output variance within a model, providing a comprehensive understanding of each factor's importance along with their interactions. We selected case 2-4 for this analysis due to its challenging conditions, characterized by unstable meteorological conditions, low wind speeds, and the proximity of receptors to the discharge point (less than 50m). As a first step, only the meteorological conditions were chosen as the input parameters. Among the six meteorological input parameters (wind speed, wind direction, temperature, nebulosity, precipitation, and boundary layer height) in SLAM, precipitation was not considered as the meteorological conditions were dry. The height of boundary layer is not critical in affecting the concentration at these distances and was also neglected in this study. Based to the uncertainty in the measurements, the variation range of each parameter is listed in following table. The statistical index FAC2 was selected to represent the output variance. The distribution of the sampling space followed Saltelli's scheme (Saltelli et al. 2008), leading to 1280 sampling points, i.e. 1280 calculations with SLAM. The results of the sensitivity analysis including the first-order indices and total order indices are shown in Figure 4.The first-order indices represent the independent effect of each input parameter on the output, while the total-order indices represent the overall effect of input parameters including the parameter interaction. Both indices consistently show that wind direction is the most influential parameter on the output, followed by wind speed, nebulosity, and temperature. Specifically, wind direction's independent effect is significantly greater than that of other parameters. The independent contribution of wind speed and nebulosity is similar. Temperature, although affecting the Monin-Obukhov length, has a negligible impact on tracer concentration. Notably, the analysis revealed conditions leading to higher FAC2 values, particularly within wind directions of 206°-212° and wind speeds of 2.5-4 m/s, as shown in Figure 4(b). The maximum value of FAC2 has improved from 0.33 by using the mean meteorological data (see Figure 1) to 0.5, reaching the acceptable model threshold (FAC2 ≥ 0.5).

Table 1. Input parameters and their uncertainty ranges

Parameter index	**(x_1)Wind speed (m/s)**	**(x_2)Wind direction (°)**	**(x_3)Temperature (℃)**	**(x_4) Nebulosity (Octa)**
Variation range	[1.56, 4]	[206, 221]	[5, 10]	[5, 8]

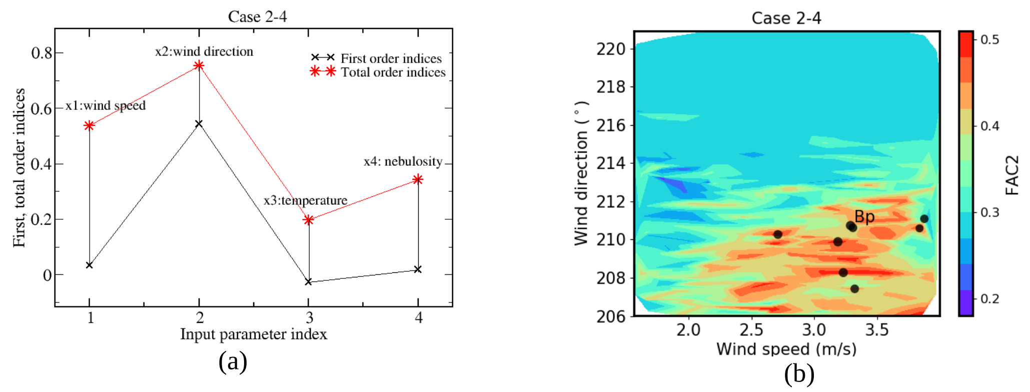

Figure 4. (a) Results of sensitivity study: first order and total order indices for the four analysed input parameters. (b) Contour of wind speed and wind direction coloured with corresponding FAC2 values. The 'Bp' points represents the best FAC2 points.

CONCLUSIONS AND PERSPECTIVES

This work has presented the evaluation of the near-field atmospheric simulation tool SLAM against a full-scale atmospheric tracer measurement, and its comparison to the operational Gaussian puff model pX. The analysis reveals that SLAM meets the criteria for an acceptable model in 47% of the cases across varied atmospheric conditions. SLAM exhibits significant advantages in simulating near-field dispersion (x<100 m), surpassing traditional Gaussian models in accuracy, while the Gaussian model with similarity theory parameters shows acceptable performance at distances further than 200 meters from the source. A global Sobol sensitivity analysis on meteorological conditions confirms wind speed and direction as the principal factors influencing concentration levels compared to other parameters. Future work will extend the uncertainty analysis to incorporate additional input variables, such as source terms, and to all experimental cases, to further refine our understanding of near-field atmospheric dispersion.

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