STATE-OF-THE-SCIENCE ATMOSPHERIC DISPERSION AND SOURCE RECONSTRUCTION MODELLING APPLIED TO THE NUCLEAR SECURITY

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Abstract

This paper aims at providing an overview of the last ten years improvements in atmospheric dispersion modelling and radiological source term estimate and insights on how 3D simulation in these fields can contribute to nuclear security. The progression through the paper is organized as follows. Firstly, we describe the multiscale modelling chain developed by France atomic and alternative energies commission (CEA) to forecast the weather and simulate the dispersion of nuclear or radioactive materials (or other noxious substances) at high resolution in complex built-up environments (industrial site or urban district) and to the inside of 3D meshed buildings (indoor / outdoor transfers). The outcome of the modelling chain is exemplified by the EMERGENCIES project in which weather prediction and fictive radiological (or other toxic) dispersions were calculated at metric resolution over a huge urban domain under the responsibility of Paris fire brigade in a time suitable for emergency preparedness and response. Secondly, we depict the validation of the flow and dispersion 3D modelling suite used by the CEA at the local and regional scale against experimental wind tunnel and field campaigns. Benchmarking our model in the framework of European and international exercises is crucial to make simulation results credible for emergency players and foster the use of 3D modelling and decision-support system in a radiological urgency (or any other contingency). Thirdly, we come to the source term reconstruction using an original method based on together the Bayesian probabilistic approach, dispersion simulations in backward mode, and an adaptive algorithm seeking for the source term parameters. This method is illustrated by a fictive complex urban scenario, in which detections are available from a network of sensors and utilized to identify the location and magnitude of a radioactive release. It is worth noticing that our method could also be used for a source of radiation. Finally, we briefly comment on the concepts of use and benefits of the atmospheric dispersion (and irradiation) modelling in the pre-event, in the course and in the post-event of a nuclear / radiological urgency. We argue that state-of-the-art models combined with high performance computing are qualified to bring a very valuable contribution to nuclear and radiological security in the frame of preparatory, responsive, and remedial strategies.

1. INTRODUCTION

Nuclear or radioactive materials may pose a serious health risk for the population when disseminated into the atmosphere (or as liquid effluents) or present as irradiating sources. The exposure of human beings to these materials can occur in various circumstances ranging from more or less serious accidents to criminal activities. Let it be of uncontrolled or of deliberate origin, events such as the dispersion of radionuclides or the existence of hidden / lost sources may be anticipated to result in adverse human consequences and social disruption.

Thus, these events are a matter of concern for the governmental national and local authorities together with the security services. They are also at the crossroads of the scientific and technical advances, inter alia in the field of dispersion and radiation modelling. Indeed, decision-makers need reliable, and preferably quick, health impact assessments of the events implying nuclear / radioactive materials before taking proper protection measures of the people. Nowadays, such accurate assessments may be drawn on 3D modelling capabilities and computational resources that have been drastically improved in the last decades. The present paper develops three topics illustrating the input of modelling to nuclear or radiological security: 3D dispersion modelling in complex environments, “in-depth” validation of the modelling systems, and nuclear / radioactive source term estimate. After commenting on these topics, the paper gives feedback and guidance about the concepts of use of models integrated in modelling and decision-support systems.

2. DISPERSION MODELLING IN COMPLEX BUILT-UP ENVIRONMENTS

Urban districts and industrial plants concentrate most of the economical activity and a large part of the population and are thus likely targets. They deserve a special attention, all the more that modelling the dispersion in such areas is very complex due to the influence of the topography and the buildings geometry combined to evolving meteorological conditions. To address this critical issue, a toolbox of generic and flexible 3D models has been developed by the CEA to evaluate the dispersion (and irradiation) of radionuclides at the regional scale and the local scale, especially around and inside buildings, and critical infrastructures as the case may be. The models account for the strong effects of the buildings on the flow, dispersion, deposition and irradiation, as well as the indoor / outdoor (and vice versa) transfer of nuclear / radioactive materials. Computations are carried out in 3D with high space and time resolution in all the potentially affected area. The main technical details about the modelling system are given hereafter.

For the last ten years, the CEA has developed a unique and original suite of 3D models whose evolutions have enabled the construction of a comprehensive multi-scale computational chain for atmospheric flow and dispersion. The system is based on WRF weather reconstruction and forecast model and on Parallel-Micro-SWIFT-SPRAY (PMSS) that explicitly accounts for the influence of the buildings on flow and dispersion. This both downscaling and upscaling system is generic as its underlying principles are the same, irrespective of the dispersion situation, and flexible as the computational domains can be moved to any place in the world.

Initially, Micro-SWIFT-SPRAY (MSS) (Tinarelli *et al.*, 2013) [1] was developed to provide a simplified, but rigorous CFD solution of the flow and dispersion in built-up environments in a low amount of time. MSS includes the local scale versions of the 3D terrain-following mass-consistent diagnostic model SWIFT which accounts for the relief and buildings and provides 3D fields of wind, turbulence, and temperature, and of the 3D Lagrangian Particle Dispersion Model SPRAY also accounting for the buildings. The introduction of nesting capability in SWIFT allowed the calculation of the wind flow from the meso-scale to the local scale (Duchenne and Armand, 2010) [2]. Last years, parallel versions of SWIFT and SPRAY have been developed leading to the PMSS system (Oldrini *et al.*, 2017) [3]. Furthermore, a momentum solver has been implemented in PSWIFT in order to simulate more accurate velocity and pressure fields in built-up environments than those obtained with the diagnostic flow model (Oldrini *et al.*, 2016) [4].

In practice, weather predictions at the meso-scale are produced with WRF with different kinds of global input data (NCEP/GFS, ECMWF or, more recently, AROME data of “Météo France”). WRF is operated in two-way nesting mode and provides the wind flow to the finest resolution (1 km) reasonably achievable with a meso-scale weather model. Then, PSWIFT takes over the downscaling modelling. It is run in one-way nesting mode, introducing the topography and the land-use at an increasingly finer resolution. PSWIFT is able to take account of the vegetation via a canopy model similar to the model defined for the urbanized areas (Coceal and Belcher, 2004) [5]. Vegetation is featured by a mean height and density; a drag coefficient is applied to the fluid cells of the calculation domain where vegetation is present. Then, the final step of downscaling consists in introducing all the buildings at the local scale and the finest resolution (1 m). The flow in the built-up area is resolved using either the mass-consistent diagnostic or the momentum version of the PSWIFT model.

Recent improvements in the PSPRAY model allow dealing with atmospheric dispersion not only inside the inner most, often built-up, domain, but also in all the nested domains where PSWIFT computations are carried out with possible upscaling or downscaling. The principle of the nesting in PSPRAY is to consider the transfer of numerical particles from a domain to another with a different level of nest in the same way as their transfer between the sub-domains or “tiles” of a large domain in which PSWIFT computations are performed in parallel. Finally, PSWIFT has been coupled with the Code_SATURNE CFD model in order to achieve 3D turbulent flow computations both outside and inside buildings (among them critical infrastructures are of high interest). Then, PSPRAY uses together PSWIFT and Code_SATURNE flow input to evaluate the distribution and the transfers of harmful materials both indoor and outdoor (Nibart e*t al.*, 2000) [6].

One of the most relevant and emblematic application of the multiscale 3D modelling chain developed by the CEA is the EMERGENCIES project launched in 2014. In this project, the dispersion of fictive atmospheric releases was simulated in a giant domain covering all Paris city, its urbanized vicinity and airports, which are under the responsibility of Paris Fire Brigade. The goal was to demonstrate the feasibility and interest of these computations to support decision-making in an emergency implying noxious or explosive releases into the air (Oldrini *et al.*, 2016) [7].

The 3D simulations were performed at the High Performance Computing (HPC) center of the CEA on an intensive cluster using from ~1,000 to 25,000 computational cores. PMSS domain had more than 6 billion nodes with horizontal dimensions of 40 km x 40 km and a vertical extent of 1,000 m. It was meshed horizontally at 3 m, and divided in ~1,000 sub-domains (the so-called "tiles") distributed to cores computing in parallel the flow with PSWIFT, then the dispersion with PSRAY. Details about the performances of the PMSS parallelization in time, space, and numerical particles can be found in Oldrini *et al.* (2017) [8].

Weather was predicted with WRF over Paris region at 1.6 km resolution and downscaled to the PMSS domain accounting for the fine scale topography and 1.5+ million buildings. The turbulent flow field computed with PSWIFT was used by PSPRAY to transport and disperse potentially noxious gases or aerosols fictitiously released near or inside public buildings in Paris (a museum, a train station, and an administrative building were chosen as examples). Moreover, nested domains were defined to mesh the buildings inside at 1 m resolution and computations done with Code_SATURNE coupled to PMSS to evaluate indoor / outdoor transfers.

As an illustration, Figure 1 shows the hazardous (possibly radioactive) plumes in the districts of the train station and the administrative building and inside the buildings 20 minutes after the releases and Figure 2 shows the print of the plumes at a larger scale 2 hours after the first release. The intricate concentration pattern reflects the complexity of the transport and dispersion of the released threat agents that are influenced by the individual buildings and the dense street network as by the evolving meteorological conditions. This illustrates how much the agent 3D distribution through the city may be counter-intuitive, what can affect the practical operations in the field in case of a hazmat dispersion event. For instance, the simulation shows that the deployment of the advance medical post should be done cautiously and the relevance of its location confirmed (after the first actions have been taken) by considering the local built-up configuration.

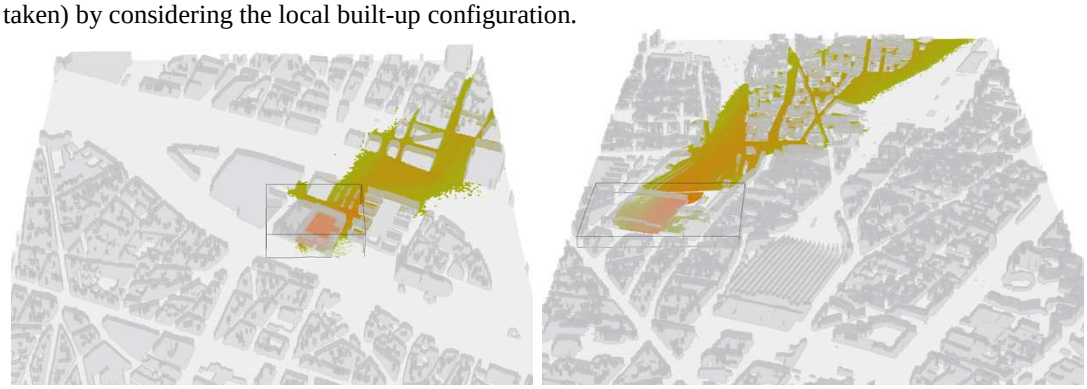

FIG. 1. Close views of the fictitious radioactive plume near the ground in the vicinity of the administrative building (left) and the train station (right).

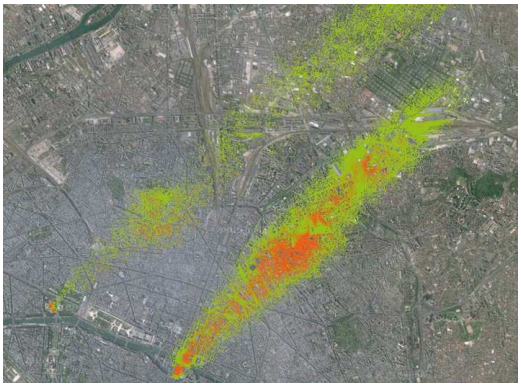

FIG. 2. Web GIS view of the fictitious radioactive plumes 2 hours after the first release.

Eventually, the EMERGENCIES project proved the capability of PMSS modelling system to predict one day of urban meteorology at high resolution in less than 2 hours (thus, forecast could be carried out each day for the next one) and 5 hours of dispersion in about 1 hour (factor of 5 acceleration between the real time and the computational time). These high resolution simulations could be produced and their operational results (like 2D maps of the exposure in case of radiological releases) transmitted from a reach back center to the firefighters and their local and / or national authorities to train the emergency players in the frame of a civilian security exercise as it was the case in the "Toxic 2014" exercise (Armand *et al.*, 2015) [9], or even in a real emergency situation.

3. MODELS "IN-DEPTH" VALIDATION AGAINST EXPERIMENTAL CAMPAIGNS

Still today, it is very challenging to model environments with complex characteristics in 3D, specifically within and around buildings in urban or industrial areas. This fact is underlined by European and international activities dedicated to validate models on diverse experimental test-cases in the recent years. These activities encompassed among others the European "COST Action ES1006" (Trini Castelli *et al.*, 2016; Armand *et al.*, 2016) [10-11]. The test-cases in this Action were elaborated with an increase in the complexity level, from idealized to realistic urban mock-ups, wind tunnel scale to full scale situations, and continuous releases to highly variable puff releases. In parallel with its development, PMSS has been permanently and thoroughly validated against experimental results. In particular, it was enrolled in the COST Action ES1006 in which, in the interest of the benchmarking exercise, the PMSS simulations were done by three independent teams of modelers making different choices regarding the flow input data and the numerical options, thus pointing out the robustness of the modelling system. All PMSS results were compared to measurements and PMSS performances were evaluated through a statistical analysis of the fractional bias (FB), normalized mean square error (NMSE), and fraction of predictions over measurements in a factor of 2 (FAC2). Following Hanna and Chang (2012) [12], the acceptance criteria for the results of dispersion models in built-up landscapes are $|FB| < 0.67$, $NMSE < 6$, and $FAC2 > 0.30$. The whole results of the validation exercise are gathered in Trini Castelli *et al.* (2018) [13]. After a description of the experimental test-cases, this section gives a glimpse of the COST Action ES1006 validation exercise.

Within COST Action ES1006, the wind tunnel facility of Hamburg University was leveraged to make measurements for continuous and puff releases in a neutrally stratified boundary layer flow. The Michelstadt experiment was designed in order to validate dispersion models within a fictive building structure representing an idealized city. Then, the complex urban terrain experiment (CUTE) was developed to test dispersion models in the real densely built-up downtown of a Central-European city including measurements from wind tunnel and field. In order to make the exercise more challenging for the models and modelers, most of the trials were blind tests with minimum information available for the inflow as it would be the case in a real accident.

In the case of Michelstadt test-cases, PMSS was run by the three teams of modelers to investigate the sensitivity of the modelling system to the meteorological input data or the numerical options. The scatter plots in Figure 3 compare the predicted and observed mean concentrations for all the continuous releases. Most of the numerical results are in a factor of two of the experimental results. Different locations were chosen for the source of the release. One can notice the better agreement for a release taking place in an open square (S2) than for a release occurring in a street-canyon (S4 and S5), at a crossroad (S6 and S7), or inside a courtyard (S8). The scatter plots in Figure 4 compare the predicted and observed mean dosages and mean puff durations for all puff releases. Notwithstanding the complexity of the tests, the passage of the puff is timely captured, and a reasonable accuracy is obtained for the largest values of the dosage (while the smallest values of the dosage tend to be underestimated). As for the puff duration, quite all numerical results are in a factor of two of the experimental results.

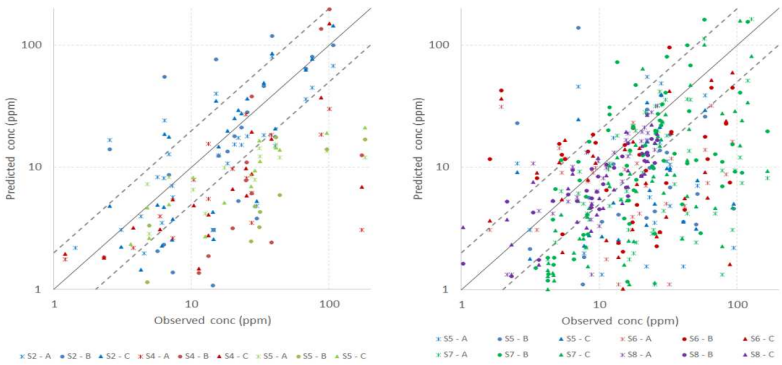

FIG. 3. Scatter plots of Michelstadt continuous releases mean concentrations, for the non-blind (left) and the blind (right) test-cases in three PMSS configurations.

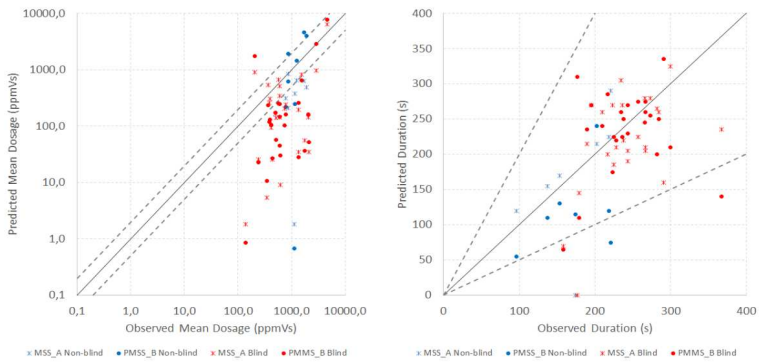

FIG. 4. Scatter plots of Michelstadt puff releases dosages (left) and puff durations (right), for the non-blind (blue) and the blind (red) test-cases in three PMSS configurations.

In the case of CUTE test-cases, PMSS was again run by three teams of modelers to study the sensitivity of the system to the turbulence input data, the wind input profile or the flow model. The scatter plots in Figure 5 compare the predicted and observed mean concentrations for all continuous releases. For the field experiment, the best agreement is obtained with the most relevant wind direction profile (called MSS_W2). For the wind-tunnel experiment, the predictions fairly agree with the measurements in all configurations, especially for highest concentrations. The scatter plots in Figure 6 compare the predicted and observed mean dosages and mean puff durations for the wind tunnel puff releases. While the paired data are few, they provide interesting insights as there is a tendency to underestimate the lowest dosages, whereas the highest values are well reproduced by the predictions. These results are fully in line with the findings in Michelstadt cases (see the previous paragraph).

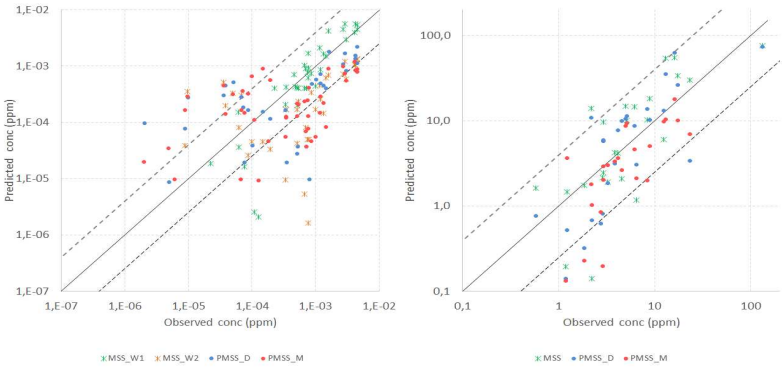

FIG. 5. Scatter plots of CUTE field experiment continuous release (left) and wind tunnel continuous release (right) concentrations in five PMSS configurations.

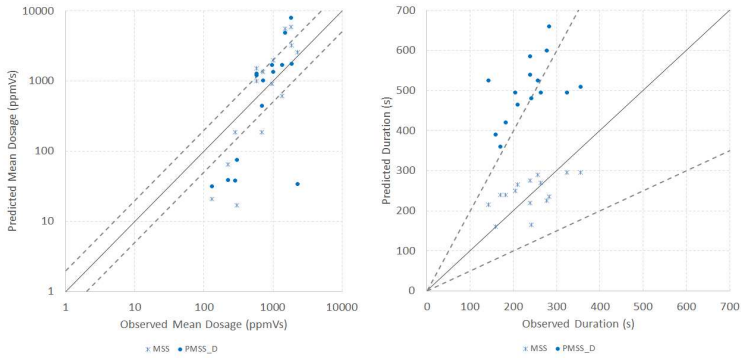

FIG. 6. Scatter plots of CUTE wind tunnel puff releases mean dosage (left) and mean duration (right) in two PMSS configurations.

In the whole, albeit there is some variability among the PMSS configurations, FAC2, FB and NMSE are predominantly satisfying. The quality of the results is not better for the non-blind or blind cases suggesting that PMSS performances are robust. Finally, the concentrations and dosages are more accurate with no systematic underestimation of the lowest values when the momentum version of PSWIFT flow model is used compared to the diagnostic version of PSWIFT.

4. NUCLEAR / RADIOACTIVE SOURCE TERM ESTIMATE

In some cases, the irradiation or release by the source can be surreptitious without immediate obvious trace (like smoke or an explosion). However, the effect of the source may be detected by a network of sensors or people in trouble. Then, the quick and efficient identification of the source location and strength is of crucial importance for the recue teams. Once more, models and mathematical methods developed by the CEA can help in reconstructing the source term parameters, given a set of measurements coming from a network of sensors.

While the problem is very challenging due to its ill-posed nature, different kinds of methods have been developed in the field of source term estimate. Most of the methods rely on an optimization problem where a cost function has to be minimized using least squares or genetic algorithms (Winiarek *et al.*, 2012) [14]. Another possibility is the probabilistic Bayesian approach which has many upsides as it allows the incorporation of both model and observational errors and the use of potential a priori information about the source. The framework provided by Bayesian analysis formulates the point estimation problem as the search of the posterior probability density function of the source parameters. Several related examples exist in the literature, that use the Markov Chain Monte Carlo (MCMC) algorithm (Delle Monache *et al.*, 2008; Keats *et al.*, 2007; Yee *et al.*, 2014) [15-16-17]. Nevertheless, these MCMC techniques are prone to issues regarding the inherent burn-in time necessary before the convergence, or the choice of how to initialize properly the Markov chain. In the recent years, the CEA has focused on another Bayesian method called Adaptive Multiple Importance Sampling (AMIS) adding an advanced adaptive layer to the IS scheme. The method is presented in Rajaona *et al.* (2015) [18].

The computational time of a stochastic simulation-based technique is highly dependent of the dispersion model that is associated to it. Indeed, for each generated sample of the source location, a forward run of the dispersion model must be performed to evaluate the likelihood of the measurements. In a complex environment, an elaborate modelling system like PMSS has to be utilized to have an accurate evaluation of the dispersion. While each run of PMSS has a moderate computational time, it can be time-consuming to run PMSS several times during the procedure. Thus, the original method has been improved in order to strongly reduce the number of dispersion computations by utilizing the duality relationship between the dispersion model and its adjoint, which is equivalent to the dispersion model run in backward mode. Furthermore, the output of the retrograde dispersion model has been efficiently used both in the initialization step and the adaptive proposal distribution to improve respectively the convergence speed and the robustness of the inference approach.

The full problem formulation and the source term estimation in the Bayesian framework using the AMIS algorithm and the PSPRAY Lagrangian Particle Dispersion Model run in backward mode are documented in Septier *et al.* (2019) [19]. While this approach was validated against the FFT 2007 measurements (known to be well adapted to benchmarking source term estimate methods), the CEA applied it further to realistic situations in built-up environments. An example is given by the twin experimented presented in the Figure 7 that shows a real urban district of 1.1 km x 0.9 km x 1.6 km meshed horizontally and vertically at a resolution of 2 meters. The green cross symbolizes the location of the fictitious source of emission and the 20 red plus a virtual network of 20 sensors. In the experiment, a radionuclide was supposed to be released from the source and real evolving meteorological conditions were considered. The 3D flow in the urban district was computed with PSWIFT and PSPRAY was first run in direct mode, from the source to the sensors, to generate synthetic measurements as can be seen in Figure 7.

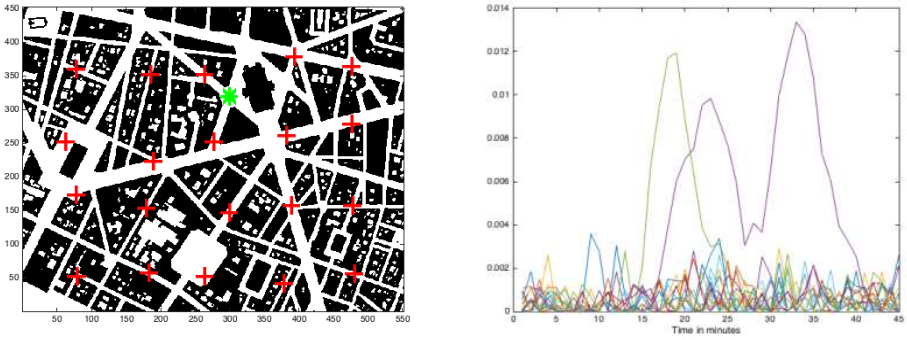

FIG. 7. Presentation of the fictive scenario under study. Location of the source (green cross) and of the 20 sensors (red plus) (left). Synthetic measurements obtained every minute by the 20 sensors in the simulated time period (from 09:00 to 09:45) (right).

The source term estimate was tested by applying the aforementioned described methodology. PSPRAY was run in backward mode, with unit releases emitted each minute from the 20 sensors (over a 45-minute period) to the whole simulation domain representing every potential positions of the source. In this twin experiment, the meteorological conditions varied gradually with the wind blowing successively from the west-northwest to the north-northeast. Finally, the retrograde dispersion results were used within the AMIS algorithm to produce the probability density function (pdf) of the source properties. Figure 8 shows the results of the source term estimate. The horizontal coordinates x_S and y_S and release rate q of the source are presented on, respectively, the left, middle, and right parts of the figure. The pdf of the source location is represented by the red curve whose peak is very close to the true position represented by the dash black line. The mean of the release rate is the black curve with a ±2σ confidence interval in grey and it has to be compared to the ground truth which is the red curve. The results illustrate the very good performances of the AMIS algorithm for both the source location and the release rate, even in this twin experiment combining a complex environment and a complex time series of the release. Moreover, it was demonstrated that using the output of the backward dispersion model in the initialization step and the adaptive proposal distribution of the AMIS allows sampling the region of highest interest directly in the first iterations of the algorithm, thus leading to a rapid convergence to the correct solution.

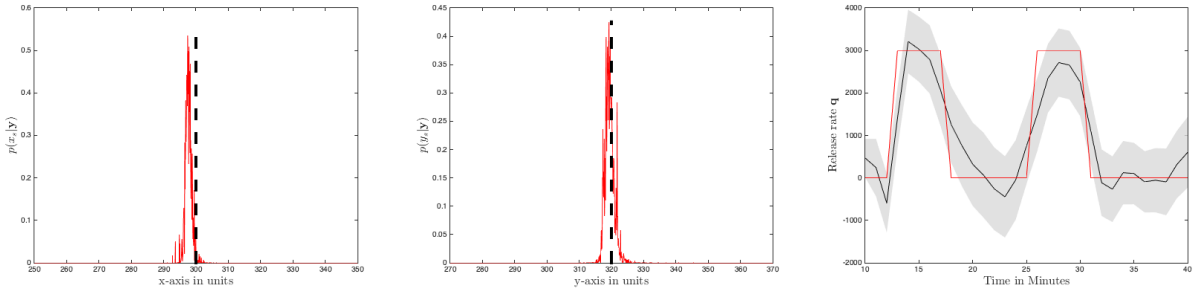

FIG. 8. Results of the AMIS for the source term estimation knowing the observations y. Pdf of the horizontal coordinates $p(x_s|\mathbf{y})$ and $p(y_s|\mathbf{y})$ (red) and the true value (dashed black) (left and middle). Pdf of the release rate $p(q|\mathbf{y},\hat{x}_s)$ (black) and ±2σ confidence interval (grey) compared to the ground truth (red) (right).

5. CONCEPTS OF USE OF UP-TO-DATE 3D DISPERSION AND RADIATION MODELLING

The features of the 3D models as outlined in the previous sections give information on their conceptual usage: on one hand, studies for safety or planning purpose, on the other hand, real-time use with security services and their authorities wishing to know as quickly and accurately as possible where the dangerous areas, and also the safe areas, are located. More precisely, in case of a radiological event, arising questions are when and where shelter-in-place, evacuation and / or iodine prophylaxis are recommended to mitigate the population exposure. The contribution of 3D modelling in the phases of a nuclear / radiological event can be described as follows.

In the pre-event phase, simulations are of help to assess a representative set of accidental or intentional events implying nuclear / radioactive materials targeting specific places as they can bring an informative a priori apprehension of the human, material and organizational impact resulting from this kind of event. Furthermore, scenarios for table top and field exercises may be developed that are more precise on a technical point of view than the practice based on usual simple modelling. This should foster the in-depth work of the involved services. Up-to-date 3D models are also useful for planning purpose of both the plant operators and the rescue teams, e.g. in the development of evacuation procedures and routes or for the optimal design of detection networks.

In the course of an emergency, experts agree that the major challenge for the players is to have the best possible representation of the past events and potential evolution of the situation. The aim of modelling is not to replace the first actions of the rescue teams (especially in the case of events of short or medium duration) but to help in diagnosing and anticipating the situation. Even if the nature of the release into the air is not known, a preliminary 3D flow and dispersion computation is instructive. In this situation, a realistic calculation performed during the early stages of the emergency can provide useful information regarding the features of the dispersion that may occur in built-up environments. This can be appreciable to make decisions regarding the intervention of rescue teams, even if the exact activity concentration levels are not yet known. It is worth noticing that models provide supporting information whatever the releases are prolonged (some hours for “continuous” releases) or short (some seconds or minutes for puff releases) as, in the latter case, the end of the release is definitely not the end of the emergency.

In the post-event phase or for the feedback, models have still an important role to play, all the more that a full range of reliable input data from the field is available and the time constraint is less stringent (but not absent) permitting the most complete and detailed modelling options to be utilized. In most of the cases, the event can be precisely reconstructed in 3D and future possible stages after the urgency be analyzed for a set of remediation actions with models participating in drawing critical lessons from the event.

In essence, there are at least two benefits in integrating up-to-date modelling in emergency preparedness and response: firstly, to enhance a common understanding of the situation which evolves in both space and time (what helps in making better decisions and taking adapted measures for the population protection), secondly, to enhance the communication between the emergency players (what helps in optimally coordinating the local and / or national command centers). In this respect, all the urgency players may take advantage of shared results of the models supporting the operative decisions of the rescue teams at the field level, providing a better understanding of the situation and its evolution at an intermediate decision-making level, and facilitating the communication with the population at the highest decision-making level.

6. CONCLUSIONS AND PERSPECTIVES

This paper sums up the impressive capabilities of nowadays multiscale modelling developed by the CEA in the field of atmospheric dispersion. The main parts of the paper are dedicated successively to the presentation of the downscaling and upscaling chain of 3D models and its application to huge urban domains with a metric resolution, the fundamental effort dedicated to the experimental validation of the local scale modelling system, an innovative and efficient method developed by the CEA to estimate the probabilistic features of source terms using the measurements from detectors, and the principal concepts of use of the dispersion models.

Throughout the paper, examples are given of applications to the nuclear / radiological security of up-to-date 3D dispersion modelling and simulation taking advantage of the High Performance Computing. Accidents or terrorist attacks are poorly known, and generally occur over a rough terrain, in a built-up environment, with changing meteorological conditions. Simulations are thus a promising way to tackle such complex situations, and provide to the rescue teams and their authorities, realistic and reliable impact assessments with the appropriate level of details, from the location of the event up to the largest extent of the affected area, in a limited amount of time consistent with the emergency management (using ad hoc computational resources).

The applications depicted in the paper highlight the worthy properties of timeliness, accuracy, reliability, and relevance of the CEA chain of models. Besides its own interest, the validation of the high resolution local scale modelling suite addresses the positioning of Lagrangian Particle Dispersion Models as a trade-off between speed and precision of the computations and their suitability to deliver a valuable support in the conditions of an emergency.

In the nowadays practice, decision-makers in command centers as first responders in the field are still provided with results (which may be not conservative) of simplistic Gaussian models definitely not appropriate for complex environments. Response procedures based on this kind of models may thus be not effective, not incisive, and sometimes misleading. It is thus time to switch to the modern paradigm drawing on 3D multiscale modelling as already experimentally availed of in the framework of civilian security exercises (Armand *et al.*, 2014; 2015; 2017) [20-21-22].

In the recent years, R&D carried out at CEA in the field of atmospheric dispersion applied to the nuclear / radiological security has not only focused on modelling, but also encompassed the adequacy of the models with the organization and missions of the urgency players. The soundness of this approach is well recognized and it translates into increasing appreciation and trust of the emergency players for state-of-the-art 3D simulations to diagnose and anticipate critical situations.

REFERENCES

[1] TINARELLI, G., L. MORTARINI, S. TRINI CASTELLI, G. CARLINO, J. MOUSSAFIR, C. OLRY, P. ARMAND, D. ANFOSSI, “Review and validation of Micro-Spray, a Lagrangian particle model of turbulent dispersion”. In Lagrangian Modeling of the Atmosphere, Geophys. Monograph, Volume 200, American Geophysical Union (AGU) (2013) 311-327.

[2] DUCHENNE, C., P. ARMAND, “Development of a 3D modelling suite from the global scale to the urban scale using MM5 and Micro-SWIFT-SPRAY. Application to the dispersion of a toxic release in New York City”, Proc. of the 13th Int. Conf. on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Paris, France, 1-4 June 2010.

[3] OLDRINI, O., P. ARMAND, C. DUCHENNE, C. OLRY, G. TINARELLI, “Description and preliminary validation of the PMSS fast response parallel atmospheric flow and dispersion solver in complex built-up areas”. J. of Environmental Fluid Mechanics, 17-3 (2017) 1-18.

[4] OLDRINI, O., M. NIBART, C. DUCHENNE, P. ARMAND, J. MOUSSAFIR, “Development of the parallel version of a CFD – RANS flow model adapted to the fast response in built-up environments”, Proc. of the 17th Int. Conf. on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Budapest, Hungary, 9-12 May 2016.

[5] COCEAL, O., S. E. BELCHER, "A canopy model of mean winds through urban areas. Q. J. R. Meteorol. Soc., 130 (2004) 1349-1372.

[6] NIBART M., P. ARMAND, C. OLRY, C. DUCHENNE, A. ALBERGEL, “The indoor / outdoor pollutant transfer of a hazardous release: application to a Parisian railway station”, Proc. of the 14th Int. Conf. on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Kos, Greece, 2-6 Oct. 2011.

[7] OLDRINI, O., S. PERDRIEL, M. NIBART, P. ARMAND, C. DUCHENNE, J. MOUSSAFIR, “EMERGENCIES – A modelling and decision-support project for the Great Paris in case of an accidental or malicious CBRN-E dispersion”. Proc. of the 17th Int. Conf. on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Budapest, Hungary, 9-12 May 2016.

[8] OLDRINI, O., P. ARMAND, C. DUCHENNE, C. OLRY, G. TINARELLI, “Description and preliminary validation of the PMSS fast response parallel atmospheric flow and dispersion solver in complex built-up areas”, Env. Fluid Mech., 17-3 (2017) 1-18.

[9] ARMAND, P., C. DUCHENNE, L. PATRYL, “Is it now possible to use advanced dispersion modelling for emergency response? The example of a CBRN-E exercise in Paris”. In: Air Pollution Modeling and its Application XXIV, Springer International Publishing, Switzerland (2015) 433-446.

[10] TRINI CASTELLI, S. *et al.*, “Evaluation of local-scale models for accidental releases in built environments. Results of the modelling exercises in COST Action ES1006”. In Air Pollution Modeling and its Application XXIV, Springer International Publishing (2016) 497-502.

[11] ARMAND, P. *et al.*, “Best practice guidelines for the use of atmospheric dispersion models at local scale in case of hazmat releases into the air”, Proc. of the 17th Int. Conf. on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Budapest, Hungary, 9-12 May 2016, 459-465.

[12] HANNA, S.R., J.C. CHANG, “Acceptance criteria for urban dispersion model evaluation”, Met. Atmos. Phys., 116 (2012) 133-146.

[13] TRINI CASTELLI, S., P. ARMAND, G. TINARELLI, C. DUCHENNE, M. NIBART, “Validation of a Lagrangian particle dispersion model with wind tunnel and field experiments in urban environment”, Atmos. Env., 193 (2018) 273-289.

[14] WINIAREK, V., M. BOCQUET, O. SAUNIER, A. MATHIEU, “Estimation of errors in the inverse modeling of accidental release of atmospheric pollutant: Application to the reconstruction of the cesium-137 and iodine-131 source terms from the Fukushima Daiichi power plant”, J. of Geophysical Research, 117(D5):D05122 (2012).

[15] DELLE MONACHE, L. *et al.*, “Bayesian Inference and Markov Chain Monte Carlo Sampling to Reconstruct a Contaminant Source on a Continental Scale”, J. of Applied Meteorol. and Clim., 47-10 (2008) 2600–2613.

[16] KEATS, A., E. YEE, F. S. LIEN, “Bayesian inference for source determination with applications to a complex urban environment”, Atmospheric Environment, 41-3 (2007) 465-479.

[17] YEE, E., I. HOFFMAN, K. UNGAR, “Bayesian Inference for Source Reconstruction: A Real-World Application”, International Scholarly Research Notices, 1 (2014) 1–12.

[18] RAJAONA, H., F. SEPTIER, P. ARMAND, Y. DELIGNON, C. OLRY, A. ALBERGEL, J. MOUSSAFIR, "An adaptive Bayesian inference algorithm to estimate the parameters of a hazardous atmospheric release", Atmospheric Environment, 122 (2015) 748–762.

[19] SEPTIER, F., C. DUCHENNE, P. ARMAND, "Application of the Bayesian approach and inverse dispersion modelling to source term estimates in built-up environments", Proc. of the 19th Int. Conf. on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Bruges, Belgium, 3-6 June 2019.

[20] ARMAND, P., C. DUCHENNE, Y. BENAMRANE, C. LIBEAU, T. LE NOUËNE, F. BRILL, "Meteorological forecast and dispersion of noxious agents in the urban environment – Application of a modelling chain in real-time to a fictitious event in Paris city". Proc. of the 15th Int. Conf. on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Madrid, Spain, 6-9 May 2013, 724-728.

[21] ARMAND, P., C. DUCHENNE, E. BOUQUOT, "Atmospheric dispersion modelling and health impact assessment in the framework of a CBRN-E exercise in a complex urban configuration". Proc. of the 16th Int. Conf. on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Varna, Bulgaria, 8-11 Sept. 2014, 638-643.

[22] ARMAND, P., C. DUCHENNE, O. OLDRINI, S. PERDRIEL, "EMERGENCIES Mediterranean – A prospective high-resolution modelling and decision-support system in case of adverse atmospheric releases applied to the French Mediterranean coast". Proc. of the 18th Int. Conf. on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Bologna, Italy, 9-12 Oct. 2017.