21st International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
27-30 September 2022, Aveiro, Portugal

EVALUATION OF A MILITARY CBRN-HAZARD PREDICTION PROCEDURE WITH A LAGRANGIAN DISPERSION MODEL

Tristan Carion[1,3], Andy Delcloo[2], Bart Janssens[1], Piet Termonia[2,3]

[1]Royal Military Academy, Brussels, Belgium
[2]Royal Meteorological Institute of Belgium, Ukkel, Belgium
[3]Ghent University, Ghent, Belgium

Abstract: A modelling framework for assessing the impact of CBRN-type incidents is currently being developed by the Royal Military Academy of Belgium and is hosted on the European Weather Cloud system. The framework has been designed to provide dispersion modelling capabilities for any worldwide release, benefiting from real-time access to the latest global forecasts from the Integrated Forecasting System of ECMWF. It implements a simple and fast military CBRN incidents model and a more complex and demanding Lagrangian dispersion model. The present study aims to improve the first basic model by comparing its results with the second more precise model for multiple pre-defined scenarios sampled from a real-scale experiment in Suffield, Canada in 2014. The evaluation criteria are defined, and their dependency on the inputs is discussed. The results show a good agreement with the theory of particle transport and dispersion modelling. This preliminary analysis opens the door to developing a more in-depth metamodel, which will provide a better risk assessment in emergency situations induced by the release of CBRN agents.

Key words: *CBRN, validation, Lagrangian dispersion model.*

INTRODUCTION

The impact assessment after the – intentional or accidental – release of a CBRN (Chemical, Biological, Radiological and Nuclear) agent is a key capability for mitigating the consequences on military personnel and civilians. As CBRN threats imply the release of hazardous airborne species, atmospheric transport and dispersion models (ATDM) can help assess the risk by predicting the plume's spatial extent and temporal evolution. An important input for ATDM is the local meteorological data, which for military operations should be available for any location in the world.

To tackle the challenge of having accessible dispersion modelling capabilities with global high-quality weather forecasts, a web-based application has been developed in collaboration with the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Royal Meteorological Institute of Belgium (RMI). This web-based modelling and visualisation framework is hosted on the European Weather Cloud and benefits from fast access to the latest ECMWF operational forecasts to run ATDM models for predicting the impact of CBRN-type incidents. As modelling outputs are fundamentally uncertain, it is important to acknowledge decision-makers with the limits and weaknesses of the models (Saltelli et al. 2020). In this context, the modelling framework is also designed to provide uncertainty quantification and sensitivity analysis.

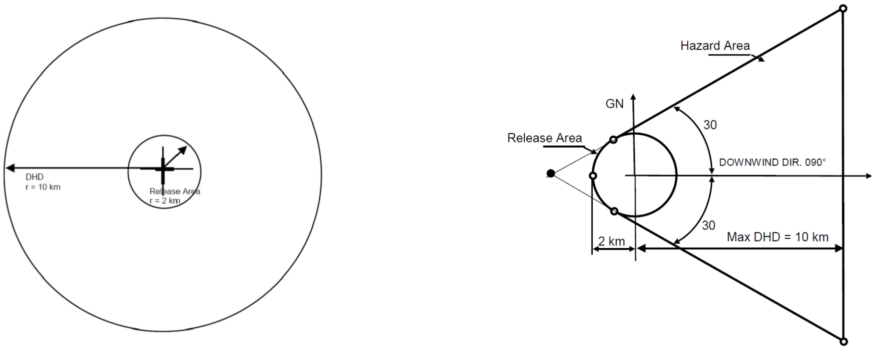
Two models available in the modelling framework are ATP-45 (ATP-45 2014) and FLEXPART (Stohl et al. 2005; Pisso et al. 2019). Both these models are conceptually and practically very different, and both have advantages and drawbacks. The simplified version of ATP-45 (here called ATP-45 for brevity) comes from a NATO hazard prediction procedure in case of CBRN-type incidents. It predicts geospatial areas defining hazard zones according to the wind velocity at the location of the release. Whereas it is very limited in precision, it almost instantly predicts the zone impacted by the release with little knowledge of the release conditions. FLEXPART is a comprehensive Lagrangian ATDM that calculates the transport, convection and deposition of fictitious particles driven by numerical weather prediction data. It can predict the time evolution of the spatial distribution of the particle concentration at multiple vertical levels. Therefore, it gives more accurate predictions but at the cost of computation time, required meteorological data and source inputs.

The time-consuming simulations and retrieval of meteorological data, along with the number of required source inputs, can limit the suitability of complex models like FLEXPART in emergency situations. Therefore, using the results of pre-simulated scenarios for emergencies has been investigated. For example, Wang, Chen, and Zhao (2015) trained a neural network by correlating the simulation results of a gas dispersion model with the concentrations measured by gas detectors at specific locations. This led to a metamodel that can quickly predict the concentration with acceptable accuracy at remote target locations when source information is limited. In this work, we follow a similar approach by comparing the performance of ATP-45 against FLEXPART for multiple pre-defined release scenarios. Several approaches can be considered to evaluate the performance of a dispersion model (Leelőssy et al. 2018). Here we especially focus on the arrival time at a specific location and the peak concentration values of the plume. We then study these evaluation metrics' dependency on the models' inputs by running both models with source conditions sampled from a field experiment and archive weather data from ECMWF. Finally, we discuss the agreement with the theory of this dependency. This work establishes a proof of concept for further developing a proper metamodel with a more representative sample of the possible input conditions.

SIMULATION BACKGROUND

The ATP-45 model

ATP-45 is a simple model that is mainly used by the military for quickly assessing and reporting the impacted area after CBRN-type incidents. It solely depends on the wind speed and direction at the location of the incident. It determines geospatial zones marking out the hazard area, defined as the area where the agent may affect unprotected personnel and materiel. As shown in Figure 1, it defines a circle-like area with a 10 km radius around the release location in case of wind speed less than 10 km/h and a triangle-like area following the wind direction in case of wind speed higher than 10 km/h. The hazard zone is defined to be valid for 2 hours and is supposed to be reevaluated after this time.



(a) Wind speed < 10km/h

(b) Wind speed > 10km/h

Figure 1: Simplified version of ATP-45 (ATP-45 2014)

The FLEXPART model

The FLEXPART Lagrangian particle dispersion model requires a detailed source characterisation (release height, duration, mass, specie properties…) and can use meteorological fields from several numerical weather prediction models (ECMWF, NCEP, WRF…). The time evolution of the concentrations is determined on a regular latitude-longitude-altitude grid.

Release scenarios description

The release scenarios used for the analysis are extracted from an experimental campaign that occurred in Suffield, Canada in 2014. This campaign aimed to understand the phenomenology of hyperspectral imaging when applied to CBRN-type releases by collecting extensive airborne and ground-based hyperspectral and complementary sensor data during multiple controlled releases of gasses near the ground. 146 records have been selected and used as input for the simulations. As shown in Figure 2, most releases were short in time (the median is about 1 minute). The stack height was 1.32m or 7.32m.

The meteorological data were provided by 1-hourly archive operational forecasts from ECMWF on a 0.2x0.2° grid.

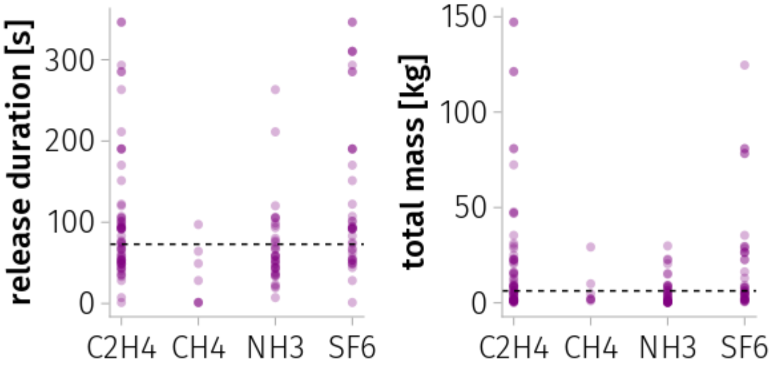


Figure 2: Scatter of the release durations and quantities for each specie. The dashed line is the median value.

METHODOLOGY

Plume footprint

After running ATP-45 and FLEXPART for each scenario, we obtain the hazard zone defined by ATP-45 and the horizontal concentration at several vertical levels calculated by FLEXPART. Next, we define the plume footprint as the geospatial zone where a non-zero concentration is predicted at the height of 2 meters. Figure 3 shows the evolution of these plume footprints for two release scenarios for each of the ATP-45 occurrences (wind speed below and above 10 km/h).

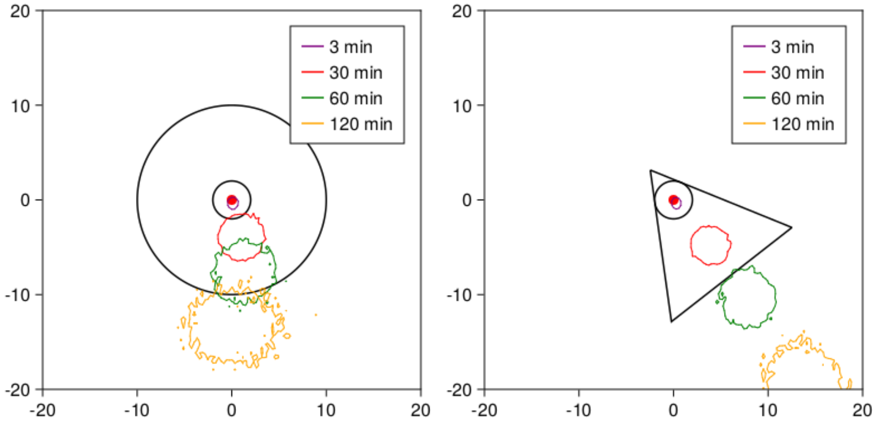


Figure 3: Examples of the time evolution of the plume footprint. Black lines are the ATP-45 hazard zones. Coloured lines are the FLEXPART footprints. The horizontal scale is in kilometres.

Overlap coefficient and Exit time

One way of comparing the ATP-45 results against FLEXPART is by measuring how long the plume footprint is evolving inside the hazard zone. To quantify this, we first define the overlap coefficient OR:

$$OR(t) = \frac{A_{fp}(t) \cap A_{hazard}}{A_{fp}(t)}$$

where A_{fp} is the area of the plume footprint and A_{hazard} is the area of the hazard zone. It represents the - time evolving - portion of the plume footprint lying inside the hazard zone. From the time series of the overlap coefficient, we obtain the exit time T_e, which is the time at which the overlap coefficient is about 0, i.e. when the plume has fully excited the hazard zone (see Figure 4).

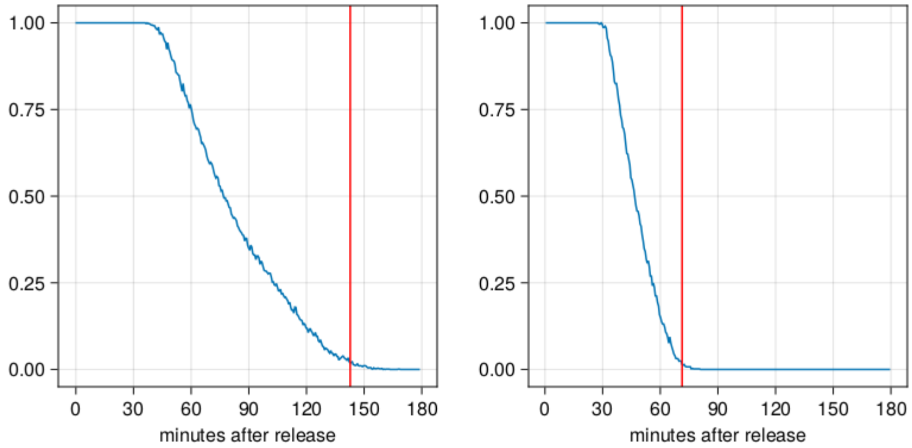


Figure 4: Time evolution of the overlap coefficient for the scenarios in Figure 3. The overlap coefficient decreases over time as the plume leaves the hazard zone. The red line is the exit time.

RESULTS

After calculating the exit time for each scenario, we discuss the dependency of the exit time with simulation inputs (see Figure 5). As expected, the exit time decreases with increasing wind speed. For most scenarios, the plume has exited the hazard zone before the end of validity stated by the ATP-45 procedure. We observe a different correlation for both ATP-45 cases, with higher uncertainty for wind speeds lower than 10 km/h.

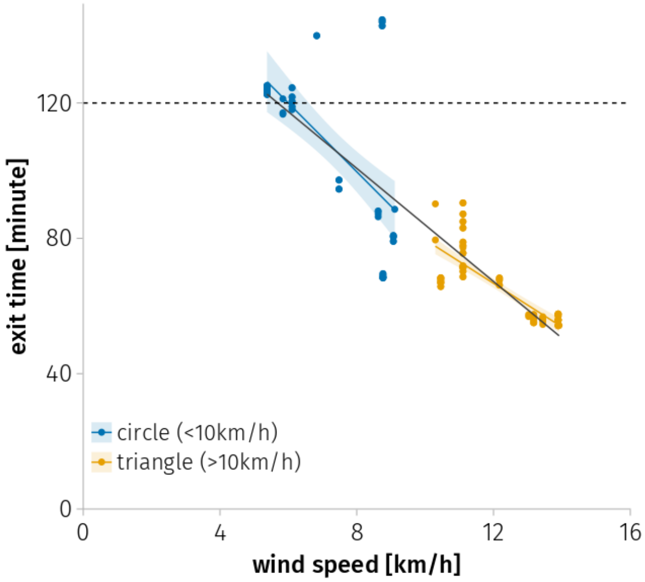


Figure 5: Dependency of the exit time with the wind speed. The black line is the linear regression for all the scenarios, while the colours separate the two ATP-45 cases. The dashed line is the validity limit of ATP-45 (2 hours).

At this point, the quality of the ATP-45 prediction has been increased since, with the same amount of information (i.e., the wind velocity), an estimate of the residence time of the plume within the hazard zone is available. However, nothing is known about the plume concentration when it leaves the hazard zone. The peak concentration of the plume at the time of exit is therefore considered (see Figure 6). We observe that the peak concentration increases linearly with the initial total released mass, which agrees with the theory when considering simple Gaussian plume models (Stockie 2011). However, the correlations are different when the data are separated between stable and unstable atmosphere conditions, giving higher concentration near the ground in a more stable atmosphere. Again, this agrees with the theory.

In cases where the release quantity and the atmosphere stability are known, the ATP-45 model has now been trained to predict the peak concentration when the plume leaves the hazard zone.

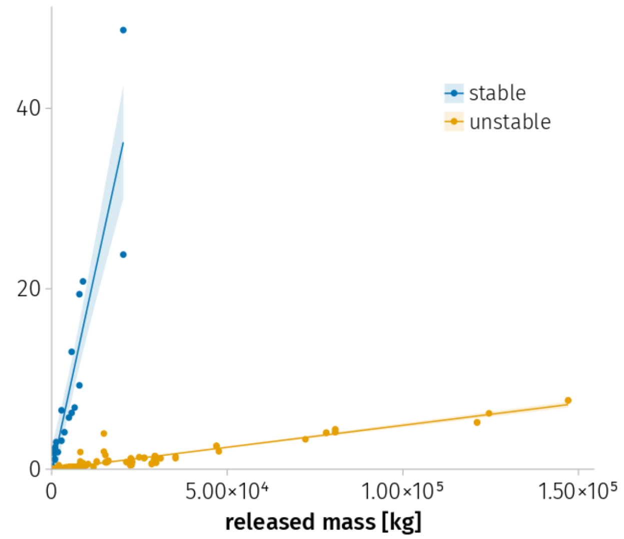


Figure 6: Peak concentration at exit time in mg/m³ w.r.t the total released mass. The colours differentiate the scenarios between unstable conditions (Pasquill classes A, B, C) and stable conditions (Pasquill classes E, F).

CONCLUSION AND FURTHER WORK

This paper has presented a proof of concept for improving a simple military dispersion model using computer experiments (Sacks et al. 1989). It has been seen that with the same inputs, the improved model can provide indications about the time validity of the predicted hazard zone. Moreover, it can estimate the concentration level if more detailed source and atmosphere conditions are known. We also qualitatively analysed the relations between the inputs and outputs variables and saw that they agree with the particle dispersion theory. This preliminary analysis allowed us to evaluate the relevance of the simulation results before injecting them into a machine-learning black box.

This analysis relies on experimental scenarios that do not reflect the spectrum of the potential source and atmosphere conditions. While it is straightforward to control the source inputs for FLEXPART, it is less easy to control the meteorological inputs since the model uses complex weather prediction data. One way to deal with this could be to take a sufficiently large sample of random geographical locations so that it produces a representative sample of the possible meteorological conditions. This meteorological input sample, combined with randomly generated source inputs, can be used to perform the same process as described in this paper. Finally, these generated data can feed a multivariate regression algorithm and create a proper metamodel based on ATP-45 and FLEXPART.

REFERENCES

ATP-45, NATO, 2014: Warning and Reporting and Hazard Prediction of Chemical, Biological, Radiological and Nuclear Incidents (Operators Manual). Edition E version 1.

Leelőssy, Ádám, István Lagzi, Attila Kovács, and Róbert Mészáros, 2018: A Review of Numerical Models to Predict the Atmospheric Dispersion of Radionuclides. *Journal of Environmental Radioactivity,* **182,** 20–33.

Pisso, Ignacio, Espen Sollum, Henrik Grythe, Nina I. Kristiansen, Massimo Cassiani, Sabine Eckhardt, Delia Arnold, et al., 2019: The Lagrangian Particle Dispersion Model FLEXPART Version 10.4. *Geoscientific Model Development,* **12**, 4955–97.

Sacks, Jerome, William J. Welch, Toby J. Mitchell, and Henry P. Wynn, 1989: Design and Analysis of Computer Experiments. *Statistical Science,* **4**, 409–23.

Saltelli, Andrea, Gabriele Bammer, Isabelle Bruno, Erica Charters, Monica Di Fiore, Emmanuel Didier, Wendy Nelson Espeland, et al., 2020: Five Ways to Ensure That Models Serve Society: A Manifesto. *Nature,* **582** (7813), 482–84.

Stockie, John M. 2011: The Mathematics of Atmospheric Dispersion Modeling. *SIAM Review,* **53** (2), 349–72.

Stohl, A., C. Forster, A. Frank, P. Seibert, and G. Wotawa. 2005: Technical Note: The Lagrangian Particle Dispersion Model FLEXPART Version 6.2. *Atmospheric Chemistry and Physics* **5** (9), 2461–74.

Wang, Bing, Bingzhen Chen, and Jinsong Zhao. 2015: The Real-Time Estimation of Hazardous Gas Dispersion by the Integration of Gas Detectors, Neural Network and Gas Dispersion Models. *Journal of Hazardous Materials,* **300**, 433–42.