

# Local- and Small-Scale Atmospheric Dispersion Modeling Towards Complex Terrain and Building Layout Scenario Using Micro-Swift-Spray

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Abstract. Atmospheric dispersion models (ADMs) have been widely used in simulating the contamination from released pollutants, which supports the emergency response and assist the inverse modeling for unknown source, due to its balance between accuracy and speed of calculation. The Micro-SWIFT-SPRAY modeling system (MSS) is one of the candidates that are able to accurately reproduce the wind and concentration fields with inputs of meteorology, topography, and source information. The obstacle treatments benefit its performance over dense buildings. Applying the optimal parameters to MSS, both the local and small-scale simulations were carried out in the vicinity of the same nuclear power plant (NPP) site with dense buildings and surrounded by mountains and sea. In these scenarios, the airflows came from the NE direction and cross over the sea and buildings to mountains. Both the wind and concentration results were evaluated against the measurements of two wind tunnel experiments. The results demonstrate that MSS can reproduce the variations of wind and concentration towards the changes in terrain elevation or building layout. The local-scale simulation well matches the measurements in the mountain area, whereas the small-scale one better reconstructs those around the buildings. The clusters of wind direction and speed are found that result from the topography of monitoring networks. The high concentration area around the release position is successfully reproduced, which indicates the turbulence is sufficient facing complex obstacles. Besides, MSS outperforms the concentration simulations in the local-scale scenario with a FAC5 of 0.710 and a FB of -0.010. However, the VG of the local-scale scenario reaches 15.510 meaning many extremes are introduced. The small-scale scenario obtains a lower VG of 2.303. Considering different performance dominances of two scales, nesting grids may bring improvement in the case both the simulations in the mountain and building areas are meant for the emergency response.

Keywords: Atmospheric dispersion  $\cdot$  Wind field reproduction  $\cdot$  Concentration simulation  $\cdot$  Wind tunnel data validation

# **1** Introduction

Atmospheric dispersion models are designed to simulate the behaviors of ambient pollutants when released into the atmosphere, involving the wind-driven advection, turbulent diffusion, deposition, material transformation, and decay if considering radionuclides [1–5]. They can provide the spatiotemporal distribution of the contamination, with the input of source information, meteorological data, terrain, and land use data. In the early phase of emergency response, the impact of unplanned release into the atmosphere can be predicted with ADMs, which support the decision-making of appropriate countermeasures for public protection and monitoring arrangements. Besides, the ADMS is also an indispensable tool for inverse modeling in the case of unknown sources [6].

To ensure the required speed of response, many Gaussian plume models are developed which assumes point-wise source released in the homogenous and stationary wind and turbulence intensity, e.g., ADMS [7] and AERMOD [8]. In local-scale modeling, physical turbulence parameterizations replaced the empirical stability classes to improve model accuracy [9]. Gaussian puff dispersion models have been also developed which hybrid the Gaussian plume modeling with Lagrangian modeling, e.g., RIMPUFF [10]. The appropriate scale of cases using such Gaussian-based is the local scale of 1–10 km and may oversimplify some dispersion patterns, even the urbanized ADMS-Urban model [9, 11]. In contrast, the computational fluid dynamics method (CFD) provides solutions for reproducing complicated dispersion patterns, especially the scenarios with a builtup area like buildings [12]. But CFD method requires quite more computational time compared to Gaussian-based models, due to handling with the Navier-Stokes equations. Considering the limited resources in operational platforms, a compromise between the accuracy and the response time is unavoidable.

The Micro-SWIFT-SPRAY (MSS) is a promising system for fast airflow and dispersion modeling that ensembles a trade-off approach for the obstacle parameterizations using Röckle's method [13]. Both modules of MSS, i.e., SWIFT and SPRAY, are able to consider the presence of obstacles. Among them, SWIFT provides the derived diagnostic turbulence around an obstacle area, and SPRAY, therefore, treats bouncing against obstacles and computes deposition on walls or roofs [11]. The applicate scenarios of MSS refer to both the local and the small scale in the vicinity of heterogeneous terrain and complex obstacles. Many efforts have been made to evaluate the performance of MSS (or one of its modules) in different scenarios, including the field experiments with complex terrain e.g. WSMR [14], DP26 [15], and OLAD [16], or with buildings e.g. MUST [17] and Jack Rabbit II [18], or referring to real cities as Oklahoma [19], Rome [20], and Paris [21]. Besides, there are also many evaluations of MSS based on wind tunnel experiments, e.g., RUSHIL [22], a case with a replicated urban area [23], and cases with a replicated nuclear power plant (NPP) site [24–27].

In practice, the NPP sites are commonly located with complex layouts and are surrounded by mountains and rivers. The sensitivity analysis of MSS applied to such scenarios in the local scale [25] and small scale [27] guides the parameter optimization as the number of particles, the horizontal and vertical resolutions, and the lower bound of turbulence intensity. The comparison of MSS performance in the same NPP site but with different scales remains to carry out for demonstrating the differences in dispersion behaviors and serving as a reference for scale selections in the operational application. Herein, two atmospheric dispersion scenarios of local and small scales have been applied in an NPP site featured with the aforementioned topography with the corresponding optimal parameters. These scenarios are all with NE direction airflow incoming, across over buildings to mountains. The simulation involves wind and concentration fields, which are further compared to measurements from wind tunnel experiments qualitatively and quantitatively.

### 2 Materials and Methods

#### 2.1 MSS Modeling

MSS is a 3D flow and dispersion modeling system that works well in both local and small-scale simulations. It is constituted by two individual modules, i.e., the SWIFT and the SPRAY [5]. This system has a parallelization version called PMSS [3].

SWIFT is a diagnostic wind field generator featured with mass-consistent and terrainfollowing over complex terrain, which was derived from the MINERVE wind model [16]. This module can ultimately provide the wind, turbulence, pressure, temperature, humidity, and other variables with the input of topography data over the entire calculation domain and meteorological data from sparse monitoring sites. The main steps of SWIFT operation involve the determination of an initial field by interpolation of raw data, the modification of previous fields considering the presence of obstacles, and the adjustment of the final non-divergent field that satisfies the boundary conditions, atmospheric stability, and consistency equation. This mass-consistency is achieved via Eq. (1)which minimizes the difference between the modified and initial wind vectors U and U<sub>0</sub> over the calculation volume V under the mass conservation constraint [11].

$$\min_{\mathbf{U}} \int \left(\mathbf{U} - \mathbf{U}_0\right)^2 d\mathbf{V} \text{ with } \operatorname{div}\left(\mathbf{U}\right) = 0 \tag{1}$$

SPRAY is a Lagrangian particle dispersion calculator, which can reproduce the physical and chemical behaviors of airborne pollutants released in various atmospheric conditions, with the input of emission information, meteorological fields, and obstacle descriptions if required.

In this module, pollutants are treated as a certain number of fictitious particles. These particles can be considered as the indivisible unit of pollutants, and their 3D distribution represents the spatial pattern of the pollutant. The velocity of one particle is the time-integrated of a transport component that defines by the averaged wind, and a stochastic component that stands for the influence of turbulence. The concentration field is therefore determined by calculating the density of particles on each grid. The motion of one particle P at the location  $X_p$  and time t is formulated as Eq. (2), which is the aggregate of the average wind and a stochastic component.

$$d\mathbf{X}_{p}(t)/dt = \mathbf{U}_{p}(t)$$
(2)

$$d\mathbf{U}_{p}(t) = a(\mathbf{X}, \mathbf{U})dt + \sqrt{B(\mathbf{X}, t)dt}d\mu$$
(3)

where a and B are generally functions of position and time, while  $d\mu$  is a stochastic standardized Gaussian term.

#### 2.2 Wind Tunnel Experiment

Two wind tunnel experiments under a neutral stratification situation were conducted by China Institute for Radiation Protection (CIRP), with incoming airflows of 3.8 m/s (in a real-world scale) from the NE direction. Both the surface topographic models of experiments replicated the heterogeneous topography and dense buildings at a nuclear power plant site in China, but with different scales of 1:2000 and 1:600 that represent local and small scenarios (Fig. 1). Among them, the release location of tracers is in the domain center (the star in Fig. 1), in the vicinity of many buildings placed. Besides, there is mainly flat terrain of sea area in the upwind direction of the release position and continuous mountains in the downwind direction. In the experiments, the airflow or concentration is sampled and measured when the mass reaches a steady state. The numerical conversion of measurements is based on the similarity theory.



Fig. 1. Topography of wind tunnel experiments.

The measurement networks of wind fields are presented in Fig. 2, where the left and right panels represent local and small scales respectively. These sites are located around the release position and are distributed along with the NE direction. The local scale scenario places more sites in the mountain area, while the small scale one owns dense sites around the building area. The total number of measurement sites is 50 in two scenarios.

As for the measurement networks of concentration fields, the amount of sites is varying in different scenarios. The local scale scenario owns 244 sites whereas the small scale scenario takes 179 sites, due to the consideration of network density and measure accuracy. These sites are placed from near the release position to the downwind area,



Fig. 2. Networks of wind measurements.

and the density of the sites is generally sparser with the distance further away. Similar to the placements of the sites for wind measurement, the arrangement of sites in the local scale scenario deep extends to the mountain area, whereas the small scale scenario covers more areas around the buildings (Fig. 3).



Fig. 3. Networks of concentration measurements.

#### 2.3 Model Parameter Settings

The parameter settings of MSS used to simulate in different scales are according to previous sensitivity analysis [25, 27]. Essential inputs were collected to drive the simulations, e.g., the annual meteorological observations from monitoring stations, terrain elevation, and building information, which obey the relevant relationship of the wind tunnel experiments. The calculation domain of the local scale scenario is  $15 \text{ km} \times 15 \text{ km}$ , whereas that of the small scale is  $3 \text{ km} \times 3 \text{ km}$ . For both scenarios, the emission time step was set to 10 s, and the averaging period was 600 s. Besides, the dispersion duration was all set to 4 h to ensure that the airflow and concentration reach a steady state. The turbulence calculation follows the Louis model [28]. Other key parameters are listed in Table 1, including the grid size, the number of particles released per time step, and the lower bound of turbulence intensity.

Parameters	Local scale	Small scale
Horizontal grid size	100 m	5 m
vertical grid size	10 m	5 m
Particle number (per time step)	10,000	10,000
Low bound of turbulence intensity (m/s) SUMIN, SVMIN, SWMIN	0.9, 0.9, 0.3	0.3, 0.3, 0.3

Table 1. Key parameters of MSS simulations.

### 2.4 Statistical Evaluation Methodology

Quantitative evaluation of MSS modeling in the aspect of model-to-measurement discrepancies of concentration fields. The used statistical metrics include the fraction of predictions within a factor of 2 (FAC2) and 5 (FAC5), fractional bias (FB), and geometric variance (VG). FAC2/5 can provide robust access over outliers. And FB measures the mean bias of pairs of data, whereas VG works well for indicating differences across orders of magnitude. These two metrics are defined as follows:

FAC2 = fraction of data for which 
$$0.5 \le \frac{C_p}{C_o} \le 2.0$$
 (4)

FAC5 = fraction of data for which 
$$0.2 \le \frac{C_p}{C_o} \le 5.0$$
 (5)

$$FB = 2\left(\frac{\overline{C}_p - \overline{C}_o}{C_p + C_o}\right) \tag{6}$$

$$VG = \exp\left(\frac{1}{N}\sum_{i}\ln\left(\frac{C_p}{c_o}\right)^2\right)$$
(7)

where  $C_p$  and  $C_o$  are the predicted and observed values of concentration respectively.  $\overline{C}$  denotes the average values of simulations or measurements.

## 3 Results and Discussion

#### 3.1 Wind Field

Figure 4 exhibits the simulated wind field of two scenarios compared with the measurements obtained from sites in Fig. 2. For the local-scale simulation, the calculation domain is featured with many mountains (Fig. 1), most of which are located in downwind places. The airflows show a consistent tendency with terrain changes when passing over mountains, which is manifested by their increased speed and deflected direction (red arrows in Fig. 4a). The spatial distribution of measurements confirms the accuracy of the trend (blue arrows in Fig. 4a). Due to the length of buildings varies from 5.2 m to 225 m, a horizontal grid size of 100 m may smooth out some details of the airflows in the building area. For the small-scale simulation with a grid size of 5 m, it allows a comparison of wind changes in the building area that occupies most of the domain center. As shown in Fig. 4b, the speed of airflows in the gaps between buildings is noticeably low, whereas those across the sides of buildings show overestimated speed. Although biased speed, the wind direction there was adjusted according to the building layout and reaches a high consistency.

The scatterplots in Fig. 5 compare the direction and speed of airflows that are simulated and measured at the monitoring sites. For the local-scale scenario, the clusters of simulated direction and speed are around 42 and 3 m/s respectively. This phenomenon represents the evolution change of airflows along with the mountains where the lower altitude exists. The accuracy in simulating the wind direction is high than the speed, as shown in Fig. 5a and 5b that the variation range of direction is much narrower. However, there are extremes out of 2 fold lines in both the direction and speed simulations. As for the small-scale scenario, the clusters of around 62 and 2.3 m/s of simulation demonstrate the behaviors of airflows around the buildings. The simulated direction is normally overestimated when compared with the measurements (Fig. 5c). And there appears an extreme of about 115, of which the site locates in the narrow gap between two buildings. Some of the simulated wind speed is below 2 m/s but exist many overestimations (Fig. 5d) which are consistent with the visual airflows in Fig. 4b.

#### 3.2 Concentration Field

The simulated concentration fields are compared with the measurements in Fig. 6. Both two scenarios show an overall satisfactory consistency between the simulations and the measurements (Fig. 6a and 6c). For the local-scale scenario, some points in the middle of the plume are overestimated (the arrow in Fig. 6a), but the MSS succeeded in reproducing the high concentration area ( $>10^{-11}$  s/m<sup>3</sup>) in the center of the plume and the upwind of release position (the arrow in Fig. 6b). This phenomenon is absent in the previous study using RIMPUFF mode [24], which demonstrates the importance of turbulence for dispersion modeling in complex terrain and building layout.

Figure 6b also shows that the simulations are consistent with the measurements in front of central mountains, but significantly overestimate the downwind direction of the mountains. For the small-scale scenario, Fig. 6c shows that the model-to-measurement discrepancies at the edge of the plume are within an acceptable range for those far away from the release position (0 m < x < 1000 m), while the simulation at the central axis of the plume is underestimated by one order of magnitude. Besides, the simulations around the release position match the measurements well (Fig. 6d). However, the simulations show underestimation at the rear of a building compared with the measurements (the circle in Fig. 6d), for that the plume is affected by the building effects.

Table 2 summarizes the quantitative metrics of MSS modeling in two scenarios with different spatial scales. For the local-scale scenario, the FB of -0.010 indicates a significant low model-to-measurement discrepancy but the large VG of 15.510 reminds us of the presence of many extremes. In contrast, MSS achieves a large FB while accompanied by a small VG. It demonstrates that the concentration varies by several orders of magnitude, but the discrepancies between pairs of simulation and measurement are not noticeable in logarithm. Comparing the FAC2/5, MSS outperforms in the local-scale



Fig. 4. Comparison of simulated horizontal wind fields with measurements in the local (a) and small (b) scales.

scenario, of which the simulations in the mountain area improve the overall scores. The biased airflows on the sides of the buildings result in underestimated concentration, which accounts for the worse FAC2/5.



**Fig. 5.** Comparison of simulated and measured direction and speed in the local (a, b) and small (c, d) scales. The red dots and blue crosses represent the sites near the buildings and mountains respectively.



**Fig. 6.** Comparison of simulated concentration fields with measurements (colored squares) in the local (a, b) and small (c, d) scales. (b) and (d) are the zoom-in plots for (a) and (c) respectively.

Scenario	FAC2	FAC5	FB	VG
Local scale	0.370	0.710	-0.010	15.510
Small scale	0.239	0.543	-1.530	2.303

Table 2. Performance metrics of concentration fields in sites of different scenarios.

## 4 Conclusions

Fast and accurate support for public protection and arrangement of sampling is essential in case of a nuclear emergency. ADMs are widely welcomed in such a situation rather than the CFD method, thanks to a trade-off between accuracy and execution speed. They can provide forward simulations of the movements of airborne pollutants released into the atmosphere, which serve as a part of emergency response systems and assist the source inversion. Among them, the MSS has been extensively evaluated and feedback with benefit performances, which includes a modified mass consistent wind interpolator and a Lagrangian particle dispersion model. The presence of an independent component for obstacle treatments inside MSS enables it to fine model the atmospheric dispersion around dense buildings.

In practice, the nuclear power plant (NPP) sites usually are surrounded by various topography, e.g., the mountains and sea or rivers, and lies dense building layout. Both local-scale and small-scale evaluations of MSS in the vicinity of such an NPP site have been published, which provide suites of optimal parameters in these two scenarios including the number of particles per time step, the horizontal and vertical grid sizes, and the lower bound of turbulence intensity. But the comprehensive comparison of MSS's performance in the same topography but in different scales has not been demonstrated using the recommended settings. Thus, two such scenarios were selected for MSS evaluation with incoming airflows from the NE direction airflow incoming, across over buildings to mountains. The simulations of MSS involve the wind and concentration fields, which are further compared to measurements from wind tunnel experiments qualitatively and quantitatively.

The results demonstrate the MSS reproduces acceptably accurate ground wind and concentration. Due to separate processes for buildings, airflows display sharp changes in building area, while those over mountain reserve details as well. The simulated wind results show clusters of wind and speed in the monitoring sites, in which 42 and 3 m/s for the local-scale scenario and 62 and 2.3 m/s for the small-scale one. These differences are related to the measurement networks of the wind and represent the influences of nearby topography. Many local-scale sites are located in the mountain area, whereas the small-scale sites are placed more in the building area.

For the concentration fields, the high concentration area around the release position and its upwind area is well reproduced, due to the optimal lower bound of turbulence intensity. MSS outperforms the concentration simulations in the local-scale scenario, in which the FAC5 metric reaches 0.710 when comparing the simulations in monitoring sites with measurements, whereas the small-scale scores 0.543 of FAC5. The negative FBs in two scenarios indicate the frequent underestimations, which are -0.010 and -1.530 for local and small scales respectively. The VG of 15.510 in the local-scale simulation shows many extremes are introduced. And the model-to-measurement discrepancies in an algorithm are acceptable in the small-scale simulation, due to a VG of 2.303 although a large FB exists. The local-scale simulation of MSS benefits the performance in the mountain area while that of the small-scale one is in the building area. A nesting calculation domain may be required if both the mountain and building areas are weighted equally to the emergency response.

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