

**23rd International Conference on  
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**EXTENDED ABSTRACT**

*Numerical Study of Atmospheric Dispersion Under Tornado Conditions*

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## **1. Introduction**

The consequences of an EF2-EF3 type tornado are a safety issue for sensitive facilities. Tornadoes combine extreme winds, strong shear and intense, localized turbulence, generating dispersion patterns that differ from standard atmospheric transport. Existing models from the 1970s–1990s (Pepper, 1975; Pepper & Crawford, 1981; Weber & Hunter, 1996) were designed for large-scale scenarios and fail to represent near-field dynamics within 10 km. To address this gap, we developed a new model delivering physically consistent estimates at the local scale and within operational computational timescales.

Previous models relied on Gaussian formulations assuming homogeneous and stationary dispersion under a mean wind, which is not suitable for tornado conditions dominated by strong 3D gradients and shear. They also assumed that most material rises into the storm cell, a scenario more suitable for very large vortices (radius > 500 m). For EF2–EF3 tornadoes (radius < 200 m), most material is expected to remain within the vortex and near the ground surface. Furthermore, the coarse grid resolutions used historically (~2 km) prevent an explicit representation of tornadoes at the local scale (within a few hundred meters or kilometers of facilities), limiting these models to far-field analysis and neglecting critical local effects.

To address these limitations, we developed a new dispersion model specifically designed for the local scale. The main objective was to create an operational tool grounded in physically consistent principles, able to reproduce key tornado dynamics and estimate dispersion patterns with sufficient resolution to capture local impacts. This approach aims to strike a balance between overly simplistic Gaussian models and computationally expensive CFD simulations, which remain impractical for operational applications.

## **2. Methodology**

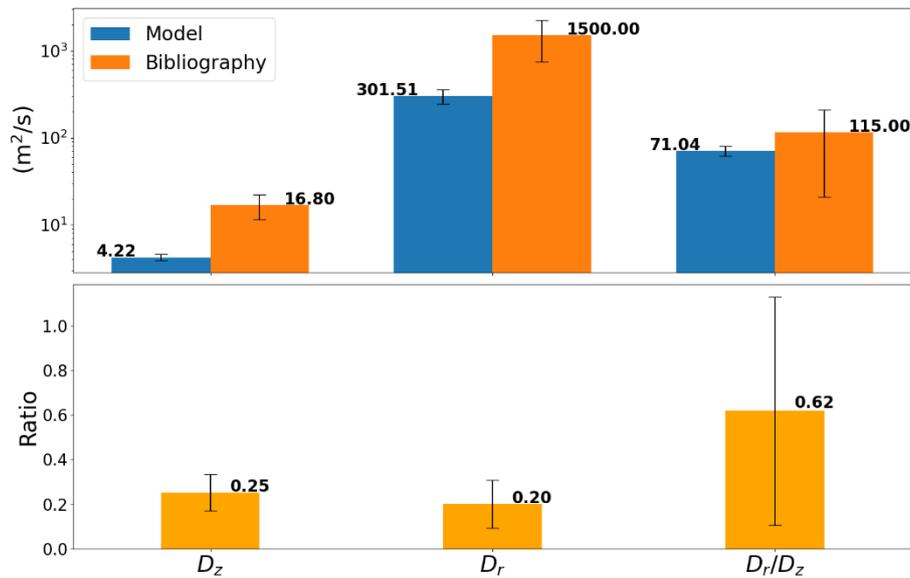
The model relies on three main components : an analytical tornado wind field, a stochastic Lagrangian dispersion scheme and simplified deposition processes. The wind field is based on an analytical solution of the incompressible steady-state Navier–Stokes equations (Yadav et al., 2024), reproducing key features of tornado such as a strongly rotating core, near-surface inflow, an ascending jet core and peripheral downdrafts. For greater realism, this basic flow was extended with horizontal translation and temporal decay to represent the vortex life cycle while preserving mass conservation.

Turbulence is modeled in a simplified manner to avoid any uncertainty regarding the calibration of the turbulent diffusivity coefficient. Large ensembles (up to millions of particles) ensure statistical convergence through the law of large numbers. Deposition is modeled using empirical laws for dry and wet removal, without microphysical or chemical complexity, to meet the operational constraints of rapid scenario assessment.

## **3. Main results**

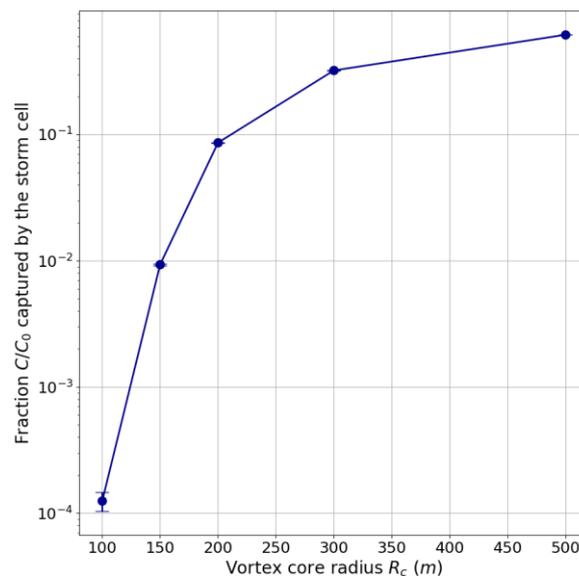
Model outputs were analyzed to assess both physical consistency and sensitivity to key parameters. An analysis of effective eddy diffusivity values was performed by comparing sets of simulated trajectories with and without turbulent fluctuations. These estimates were compared with empirical values reported for hurricanes by Tang et al. (2018) and Zhang and Montgomery (2012). Similarity in flow geometry justified. Although tornado diffusivities were unsurprisingly of lower magnitude, the anisotropy pattern between the radial and axial directions was preserved, confirming the physical plausibility of the proposed turbulence representation. Figure 1 illustrates these comparisons, highlighting the high variability inherent to hurricane observations, which supports the adoption of a first-order modeling approach for tornado-induced turbulence.

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*Figure 1 – Comparison of global turbulent diffusion coefficients computed from post-processing of the developed dispersion model simulation with values reported in the literature for hurricanes (Tang et al. (2018) for the vertical component and Zhang and Montgomery (2012) for the horizontal component).*

Another major result concerns the fraction of material entrained into the storm cell. Our simulations show that this fraction rarely exceeds ten percent for tornadoes with radius of less than 200 meters, typical of EF2–EF3 categories. This result challenges the fundamental assumption of historical models, which considered the complete entrainment of material into the storm cell. Figure 2 presents the variation of injected fraction as a function of vortex radius, highlighting the high sensitivity of this parameter.



*Figure 2 – Log-linear evolution of the relative Cs-137 content captured by the thunderstorm cloud as a function of the tornado vortex radius.*

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Despite improvements over previous approaches, the model retains simplifications : turbulence is treated as quasi-stationary without explicit production–dissipation balance, deposition uses empirical laws and considers a limited range of grain sizes, and thermodynamic effects are neglected. These choices have resulted in a functional and efficient tool, which allows obtaining orders of magnitude in first approach, in order to select relevant safety scenarios. Validation remains complicated due to the lack of experimental, but consistency with analytical vortex models and diffusivity trends derived from hurricanes confirms the trend of observed behaviors, confirming the potential of the model for safety assessments.

## **4. Conclusion and Perspectives**

This study introduces a new model for near-field atmospheric dispersion induced by tornadoes, combining an analytical three-dimensional wind field, a stochastic Lagrangian approach and simplified deposition schemes. The methodology provides a physically consistent framework while maintaining computational efficiency, thus offering an operational alternative to current unsuitable models. Future work will focus on improving the turbulence parameterization, incorporating more realistic deposition processes over a wider range of particle sizes, and integrating radioactive daughters. These efforts aim to bridge the remaining gap between operational modeling needs and the physical complexity of tornado-induced transport.

## **References**

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