Large eddy simulations of buoyancy-driven downburst winds

Josip Žužul [1], Andi Xhelaj [1], Massimiliano Burlando [1], Alessio Ricci [2], Federico Canepa [1]

[1]*University of Genoa, Genoa, Italy, josip.zuzul@edu.unige.it – andi.xhelaj@edu.unige.it – massimiliano.burlando@unige.it – federico.canepa@edu.unige.it*
[2]*University School for Advanced Studies IUSS, Pavia, Italy, alessio.ricci@iusspavia.it*

SUMMARY
Isothermal impinging jet models have long served as the standard tool in Wind Engineering for reproducing thunderstorm downburst outflows, yet this practice may underestimate the role played by buoyancy-driven effects. This study aims to investigate downburst winds considering also buoyancy effects, based on the novel configuration based on the ERIES-CLIMATHUNDERR project which couples an impinging jet with a gravity current (GC+IJ) through an imposed temperature difference. High-fidelity Large-Eddy Simulations (LES) are used to numerically reconstruct the experimental tests performed in the CSTB Jules Verne Climatic Wind Tunnel (Nantes, France). Preliminary findings demonstrate that thermal stratification fundamentally reshapes the flow field by amplifying the wind velocities in the downdraft core and intensifying near-velocities surface winds in the radial outflow. By integrating density-driven effects, this study establishes a more physically grounded framework for predicting the severe near-surface wind speeds that dictate the structural integrity of structures.

Keywords: thunderstorm downburst, gravity current, large-eddy simulation

1. INTRODUCTION

Thunderstorm downbursts are violent, short-lived wind events characterized by a descending column of cold air that after hitting the ground spreads radially from the stagnation point. As such, these events have a strong potential to threaten the civil infrastructure (Fujita, 1981). Historically, the wind engineering community has relied predominantly on the isothermal impinging jet approach as a convenient simplified alternative for studying these events both experimentally and numerically, as it can indeed produce realistic downburst outflow features (e.g. Žužul et al., 2024). While this model is certainly efficient, it ignores the most important mechanical trigger of a real-world downburst: buoyancy. The large temperature difference between the air cooled by evaporating precipitation in the cloud and the warm ambient air creates a density-driven, downward-directed flow that a simple mechanically-enforced jet cannot fully replicate. Despite the known importance of thermal effects, experimental data that successfully isolate and control buoyancy are scarce. This study moves past the limitations of the isothermal assumption by focusing on a novel framework combining effects of both an impinging jet and a gravity current. The baseline of this study resides in the reference experimental campaign performed within the ERIES-CLIMATHUNDERR project (Canepa et al., 2025; 2026), which is hereby further extended to provide the full-field flow details using the high-fidelity Large-Eddy Simulations (LES). By numerically replicating the CSTB climatic wind tunnel, these simulations provide a comprehensive, full-field counterpart to the experimental data, offering insights into flow details that are difficult to capture through physical testing alone.

2. EXPERIMENTAL TESTS

To replicate the complex development of a downburst outflow, this study utilizes data from the ERIES-CLIMATHUNDERR project, conducted at the CSTB Jules Verne Climatic Wind Tunnel. Because the natural transition from a cloud-scale downdraft to a ground-level outflow is difficult to capture in a controlled environment, the experimental setup utilizes a dual-initiation strategy by combining the influences of an impinging jet and a gravity current (GC+IJ). That was achieved by synchronizing a translational motion of a mechanical piston, translating at w_p = 0.15 m/s, with an imposed significant thermal gradient. A 2 ×2 ×2 m^3 insulated impinging jet plenum (IJP), positioned 3 m above the floor, discharged cold air (T_{IJP} = 7.9 °C) through a 1 m diameter circular nozzle (D) into an ambient environment of the test section (T_{IJP} = 31.6 °C). This nominal difference of ΔT = 23.7 °C allows for a targeted investigation into buoyancy – a fundamental driver of near-ground wind development Canepa et al. 2025; 2026).

3. LES SIMULATIONS

The computational domain was created to replicate the experimental configuration of the CSTB Climatic Wind Tunnel campaign. As shown in Fig. 1, the domain dimension was set to 20D *x* 10D *x* 5D. In such configuration, domain accurately reflected the physical constraints of the test section with the IJP box in the center. The outlet was placed relatively far from the region of interest to minimize its possible impact on flow development, while the IJP box relative to the surrounding walls was precisely replicated. The domain utilized a fully structured mesh composed of 4.4 million hexahedral elements. The computational grid is detailed in Fig. 2, where Fig. 2a highlights the refined mesh and lateral stretching surrounding the IJP box. Internal grid characteristics are further illustrated using a central vertical slice (Fig. 2b), with close-up views emphasizing the discretization near the downward-moving piston (Fig. 2c) and the vertical plane within the IJP box (Fig. 2d). The transient piston motion was driven by a velocity of at w_p = 0.15 m/s, using a Laplacian-based dynamic mesh motion solver to handle internal grid displacement.

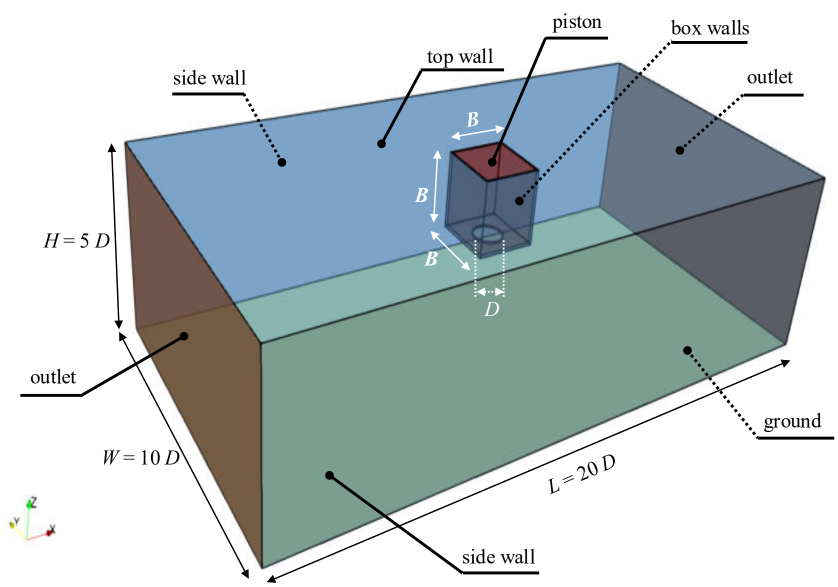

Figure 1. Computational domain with the indication of boundaries replicating the climatic wind tunnel of CSTB.

This study focused on a combined impinging jet–gravity current technique using a nominal temperature difference of ΔT = 23.7 °C. In the experimental setup, the wind tunnel ambient temperature (T_{WT}) was set to 31.6 °C with the IJP box at T_{IJP} = 7.9 °C. Buoyancy effects in this study were modeled using the Boussinesq approximation with one-way thermal-momentum coupling. Simulations were performed using LES simulations which adopted the dynamic model for sub-grid scale turbulence (Meneveau et al., 1996). Near-wall flow was captured using wall functions for smooth surfaces maintaining the non-dimensional distance near the wall of $y^+ \approx 30$, Pressure–velocity coupling was handled using the PISO algorithm in `OpenFOAM`, with a fixed time step of 0.001 s, which resulted in a maximum Courant number of about 0.35 over a 12 s of physical time considered in a simulation. Spatial and temporal discretization schemes adopted in the simulation were of the second order.

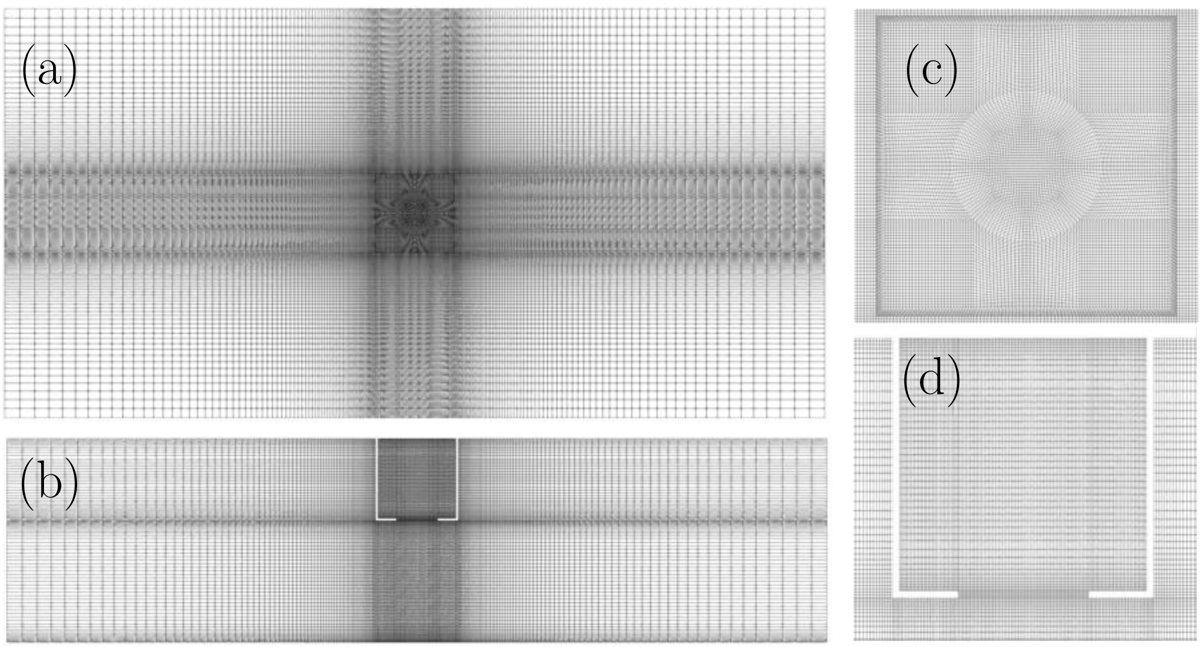

Figure 2. Computational grid: (a) top view; (b) vertical slice through the domain center; (c) grid detail near the piston (top view); (d) vertical slice through the domain with the grid detail within the IJP box.

4. RESULTS

Preliminary LES results are presented in Fig. 3 for the time instance t = 4.5 s, associated with the maximum observed radial outflow velocity when the primary vortex is positioned at a radial distance of R/D = 1.0 from touchdown. Fig. 3a displays the wind speed contours. Preliminary observations indicate that buoyancy considerations have profound influence on downburst flow evolution. Wind velocity contours showcase the flow acceleration within the downdraft itself after exiting the IJP plenum nozzle, showcasing velocity amplifications in the downdraft core throughout its descending phase. Wind speed intensification is found in the radial outflow, while the primary vortex is showcasing features of a squashed structure near the surface. Fig. 3b shows the temperature distribution for the same time instance associated with the maximum outflow velocities. The temperature field highlights the sharp thermal interface between the descending downburst core and the surrounding ambient air, providing clear evidence of strong turbulent mixing within the shear layer. A comprehensive validation against the experimental data will be presented in the full paper.

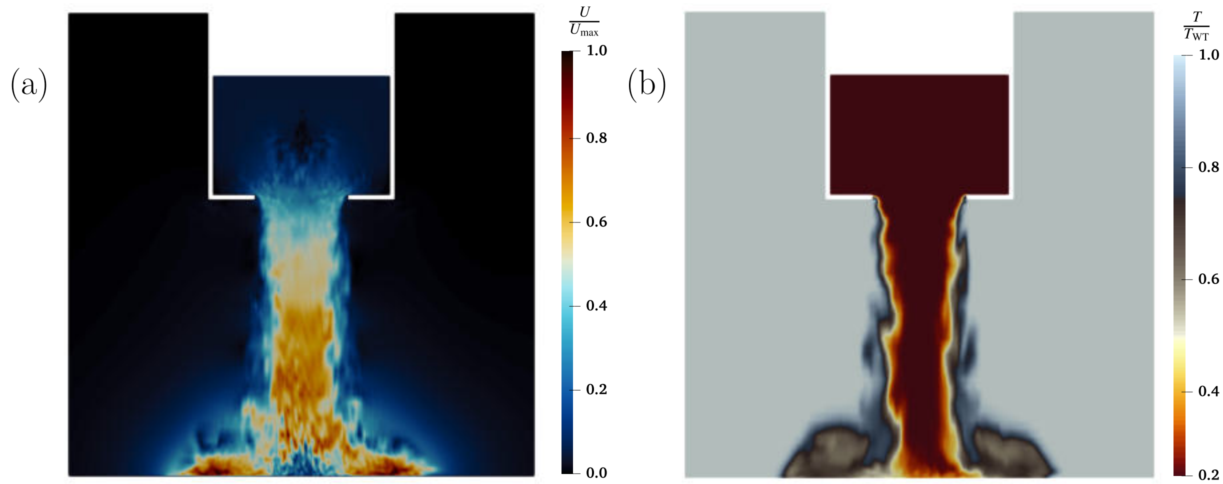

Figure 3. LES results at the time instance of maximum outflow velocity: contours of (a) wind speed, and (b) temperature.

5. CONCLUSIONS

This study utilized high-fidelity LES simulations to numerically reconstruct the downburst outflows generated during the ERIES-CLIMATHUNDERR campaign. By adopting a combined impinging jet and gravity current approach, the simulations captured the intricate evolution of the wind field. Preliminary findings underscored profound influence of the buoyancy in flow development; specifically, the thermal forcing is shown to amplify velocities within the downdraft core and enhance radial outflow compared to traditional isothermal models. A comprehensive analysis of these flow structures, comparison with purely IJ results and further validation will be presented in the full paper.

ACKNOWLEDGEMENTS

This work is part of the transnational access project "ERIES – ERIES-CLIMATHUNDERR", supported by the Engineering Research Infrastructures for European Synergies (ERIES) project (www.eries.eu), which has received funding from the European Union's Horizon Europe Framework Programme under Grant Agreement No. 101058684. This is ERIES publication number C175. The authors acknowledge the support of the Italian supercomputing center CINECA for providing access to their High-Performance Computing (HPC) facilities needed to carry out this research.

REFERENCES

Canepa, F., Guibert, A., Xhelaj, A., Žužul, J., Romanic, D., Ricci, A., Hangan, H., Bouchet, J.-P., Delpech, P., Flamand, O., Burlando, M., 2025. CLIMATHUNDERR: A database of LS-PIV velocity and temperature data from experimental downbursts. A combination of the impinging jet and gravity current techniques [Data set]. Zenodo. https://doi.org/10.5281/zenodo.14609849.

Canepa, F., Guibert, A., Xhelaj, A., Žužul, J., Romanic, D., Ricci, A., Hangan, H., Bouchet, J.-P., Delpech, P., Flamand, O., Burlando, M., 2026. CLIMATHUNDERR: experimental database of buoyancy-driven downbursts, Earth System Science Data, 18, 2133–2152. https://doi.org/10.5194/essd-18-2133-2026.

Fujita, T.T., 1981. Tornadoes and Downbursts in the Context of Generalized Planetary Scales. Journal of Atmospheric Sciences, 38(8), 1511-1534. https://doi.org/10.1175/1520-0469(1981)038<1511:TADITC>2.0.CO;2

Meneveau, C., Lund, T.S., Cabot, W.H., 1996. A Lagrangian dynamic subgrid-scale model of turbulence. Journal of Fluid Mechanics, 319, 353-385. https://doi.org/10.1017/S0022112096007379

Žužul, J., Ricci, A., Burlando, M., Blocken, B., Solari, G., 2024. Vortex dynamics and radial outflow velocity evolution in downburst-like winds. Computers and Fluids, 283, 106393, https://doi.org/10.1016/j.compfluid.2024.106393