CWE-8
June 7-11, 2026
London, ON, Canada

Exploring downburst propagation in idealized urban environments using large-eddy simulations

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SUMMARY

Downbursts are intense downdrafts of negatively buoyant air generated within thunderstorms. Their intense winds near the ground pose significant risks to urban safety. Previous studies have mainly focused on isolated downburst-like winds or the propagation of atmospheric boundary layer (ABL) winds in cities. Consequently, the interaction between downbursts, ABL winds, and urban geometries remains relatively underexplored. This study employs large eddy simulations (LES) to fill this gap. The simulations are validated against experimental studies through two scenarios: one involving ABL winds in urban environments and the other focusing on isolated downburst-like winds. The results indicate that the channelling effect causes wind speeds at pedestrian level to exceed the downburst centerline velocity. Although the spatially averaged velocity in urban areas is generally lower than in open terrain, the high-intensity winds persist over a greater vertical distance. This exacerbates the impact of downburst outflows on the built environment.

Keywords: *Downburst, Urban environment, LES, CFD, Experiments.*

1. INTRODUCTION

Downbursts are negatively buoyant air currents generated within thunderstorms that impinge on the ground and spread radially (Hjelmfelt, 1988). Their high-intensity, transient, and localized winds set them apart from typical atmospheric boundary layer (ABL) flows, with gusts often exceeding 60 m s^{-1} at 50–120 m above ground level (Solari, 2020). These hazards can be amplified in urban areas, where interactions with buildings further intensify local wind speeds (Hadavi and Romanic, 2025).

Obtaining full-scale downburst data in cities is difficult due to their short duration, non-stationarity, and the complexity of urban terrain, leading to limited high-resolution observations. Wind-tunnel experiments face financial and physical constraints when exploring many configurations (Hangan et al., 2017). Computational Fluid Dynamics (CFD) therefore plays a crucial complementary role, offering full-field flow information and enabling the interpretation of complex dynamics. With growing computational resources, Large-Eddy Simulation (LES) has become increasingly common, resolving a substantial portion of the turbulent spectrum needed to capture downburst behaviour (Aboshosha et al., 2015).

A widely used approach for simulating downburst-like (DB) winds is the impinging-jet (IJ) method, in which a turbulent, axisymmetric jet impacts the ground and spreads radially. This technique effectively reproduces key downburst features, including primary and secondary vortices (McConville et al., 2009). While many studies have examined ABL flows in urban environments (Ricci and Blocken, 2020; Hadavi and Pasdarshahri, 2021) and isolated downbursts in empty domains (Romanic and Hangan, 2020; Žužul et al., 2024), the combined interaction between DB winds, ABL winds, and urban settings remains relatively underexplored. This gap is increasingly relevant given projected rises in thunderstorm activity (Rädler et al., 2019) and continued urbanization (Uttara et al., 2012). This study therefore investigates the propagation of a downburst-like outflow through a representative urban environment under the influence of a background ABL wind.

2. METHODOLOGY

2.1. Case scenarios

This study considered two validation cases. First, the behavior of ABL winds in an urban-like environment was validated using wind tunnel measurements. A case from the Architectural Institute of Japan (AIJ) database (Tominaga et al., 2008) was selected to represent a typical idealized urban neighborhood. Second, an isolated IJ without ABL wind or buildings was numerically simulated; the results were compared against various experimental and numerical studies. Due to space limitations, the validation results are reserved for the final full paper and are therefore not included in this 4-page extended abstract.

2.2. LES setup

The unsteady, isothermal LES simulations were performed with the Smagorinsky model using the *pimpleFoam* solver in *OpenFOAM* v2306. The Courant–Friedrichs–Lewy number was kept below 0.5, and the ratio of resolved to total turbulent kinetic energy ($k_{\text{res}}/k_{\text{tot}}$) exceeded 80% (Pope, 2001). Simulations were run over 15 s in three phases. Phase 1 (0–10 s) develops the ABL wind without jet forcing. Phase 2 (10–14 s) applies a 10 m s^{-1} jet inflow. Phase 3 (14–15 s) turns the jet off to capture the decay stage. A *uniformFixedValue* condition with 0.5-s transition intervals ensured smooth ramp-up and ramp-down of the jet velocity.

The idealized urban area consists of nine cubic buildings (H_{Urban} = 0.2 m). A uniform cell size of $H_{Urban}/10$ = 0.02 m was applied in the target region (Figure 1), with a stretching ratio below 1.05 across the domain, yielding ~9.3 million cells. No-slip conditions were imposed on the ground, top, side walls, and building surfaces. Zero static gauge pressure was set at the outlet, and the inlet ABL wind profile was prescribed from wind-tunnel data. Turbulent inflow conditions were generated using the divergence-free Synthetic Eddy Method. Near-wall flow was modeled using Spalding's universal law of the wall. The downburst-like wind was represented by a jet 2 m in height and diameter. The urban array was placed one jet diameter from the jet centerline, corresponding to the location of maximum radial velocity.

3. RESULTS

Figure 2 illustrates the wind flow variations along horizontal lines at heights z/H_{urban}=0.1, 0.5, 1, 2 for the scenario of DB outflow embedded in background ABL wind (DBABL) in both open terrain (i.e., no-buildings) and the urban-like environment. The profiles correspond to the time step when maximum radial velocity occurred in the open terrain scenario. As expected, recirculation zones behind buildings show the lowest wind speeds. In contrast, the channelling effect in unshielded areas between urban blocks accelerates wind speeds. These speeds exceed those in the no-urban case and even w_{jet}, worsening the impact of the downburst outflow on the built environment. Farther downstream from the jet impingement, even uncovered locations experience a decrease in wind speeds (Figure 2f, h), due to turbulent eddies generated by the DB propagation.

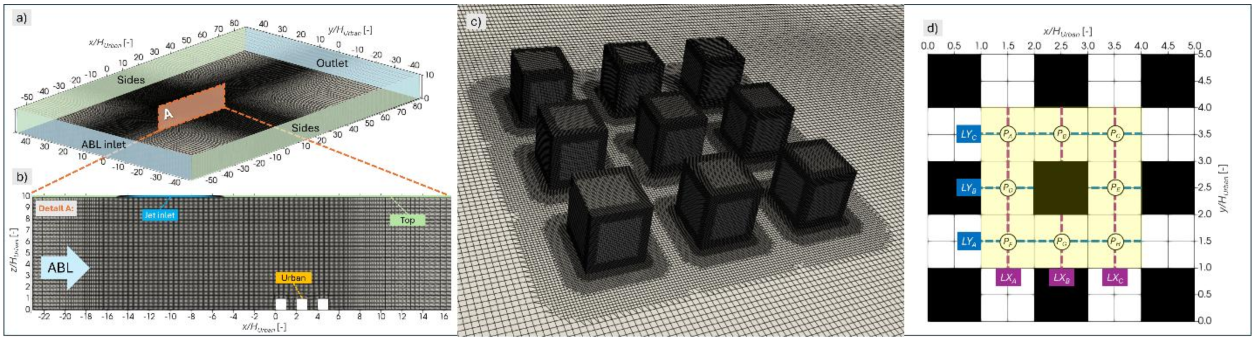

Figure 1: (a–b) Computational domain showing mesh refinement in the target region and boundary conditions; (c) 3D view of the computational mesh around the buildings; (d) geometry of the urban neighbourhood.

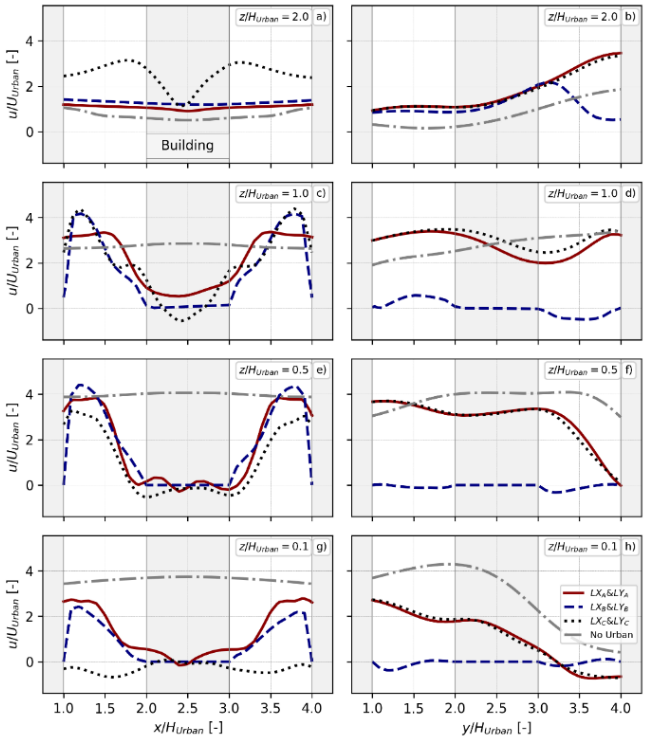

Figure 2: Horizontal wind speed variations along several lines between the urban blocks at four heights: z/H_{Urban}= (a-b) 2; (c-d) 1; (e-f) 0.5; (g-h) 0.1. The profiles correspond to the time step when the maximum radial velocity was recorded in the open terrain scenario.

The maximum wind speed rises with height (Figure 2c, e, g) as the impact of surface friction decreases and the ABL wind intensifies. In the open terrain scenario, wind speed peaks at z/H_{urban}=0.5 (Figure 2e) before declining at higher elevations, indicating the gust front thickness. Above the urban area (Figure 2a), wind speeds along LX$_\mathrm{A}$, LX$_\mathrm{B}$, and the no-urban case are similar, showing the diminished urban impact. However, behind the second row of buildings (LX$_\mathrm{C}$), an intense peak occurs before a sharp velocity drop. This observation indicates that flow characteristics differ between the first and second roads. On the other hand, LY$_\mathrm{A}$ and LY$_\mathrm{C}$ show consistent patterns at all heights, pointing to nearly symmetrical wind flow behavior parallel to ABL and DB winds. Finally, the increase (Figure 2b) and decrease (Figure 2h) in wind speeds along LY$_\mathrm{A}$ and LY$_\mathrm{C}$ after y/H_{urban} ≈2.5 result from vortical structures generated downstream of the jet. This pattern is also seen in the no-urban case.

4. CONCLUSIONS

This study investigates the combined effects of downburst winds, background ABL winds, and an idealized urban layout. Large-eddy simulations were performed and validated against experiments for both urban ABL flow and an isolated downburst-like jet. Results show that channeling between buildings accelerates local winds beyond those in the no-urban case and even above the downburst centerline velocity. The flow exhibits near-symmetry along the dominant wind directions. Although not shown here due to space limitations, spatially averaged velocities decrease in urban areas due to wakes, but strong winds persist over a greater vertical extent, leading to increased aerodynamic loads at higher elevations and greater vulnerability of urban infrastructure to downburst events.

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