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A large-scale experimental study of the thermodynamics contribution to downburst winds

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SUMMARY
In wind engineering, thunderstorm downbursts are typically simulated experimentally using the impinging jet method, which relies on the mechanical generation of the flow, generally through aerial fans. This approach enables a realistic reconstruction of the near-ground flow field. However, natural downbursts are inherently thermodynamic phenomena. To date, limited research has investigated the thermal contribution to overall downburst dynamics and geometry. For the first time, the ERIES-CLIMATHUNDERR project aims to reproduce such thermally driven conditions at large geometric scale at the Jules Verne Climatic Wind Tunnel (CSTB, Nantes, France) by controlling the temperature difference between a cold impinging jet and the warmer chamber. Results indicate that larger temperature gradients enhance buoyancy effects, leading to faster flows and higher wind speeds, while compressing and stretching the vortex structures.
The experimental dataset is openly available (Canepa et al., 2025) and is documented in a dedicated data paper (Canepa et al., 2026).

Keywords: Thunderstorm downbursts, Buoyancy, Climatic wind tunnel

1. INTRODUCTION

Thunderstorm clouds develop when warm, moist air rises to the condensation level. As precipitation forms, the air begins to descend, dragged downward by hydrometeors, thereby initiating a downdraft. During descent, water droplets evaporate cooling the downdraft air. The thermodynamic instabilities between the descending jet and the surrounding ambient air generate complex vortical structures, the first and most intense of which is the primary vortex (PV). The associated cooling increases negative buoyancy, further accelerating the flow toward the ground. Surface weather stations have recorded temperature drops exceeding 10 °C during storm passage (Calotescu et al., 2025). Upon impingement, the downdraft spreads radially, generating intense outflows particularly during the passage of the PV (Fujita, 1985).

Downbursts are highly localized phenomena in both space and time, making full-scale observations rare and difficult to obtain. Consequently, experimental investigations in dedicated laboratories are often required. In wind engineering, the three-dimensional structure of downbursts has traditionally been reproduced using the impinging-jet (IJ) technique (Canepa et al., 2022), in which the flow is mechanically generated by aerial fans. Although this method accurately reconstructs the near-ground wind field—of primary interest for civil engineering applications—it does not capture the fundamental thermodynamic mechanisms driving the phenomenon. In fluid mechanics, downbursts have also been simulated using the gravity current (GC) approach (Yao and Lundgren, 1996), where a denser fluid is released into a lighter ambient fluid to reproduce buoyancy-driven flow development. While this method better represents the thermodynamic component observed in nature, the resulting geometric and velocity scales are generally too small to be directly applicable to civil engineering problems.

The role of thermal effects in shaping downburst intensity and vortex structures therefore remains insufficiently understood. The CLIMATHUNDERR project (CLIMAtic Investigation of THUNDERstorm Winds), funded under the European Research Infrastructures for European Synergies (ERIES) program, addresses this gap through an experimental campaign conducted at the Jules Verne Climatic Wind Tunnel (JVCWT) – Thermal Unit SC2 at the Centre Scientifique et Technique du Bâtiment (CSTB), Nantes, France. By varying the thermal contrast between the impinging jet and the ambient air, the project investigates buoyancy effects on downburst velocity, dynamics, and vortex morphology at large geometric scales. The dataset is openly available (Canepa et al., 2025), and a comprehensive description is provided by Canepa et al. (2026).

2. EXPERIMENTAL METHOD AND SETUP

The test section of the JVCWT Thermal Unit measures 10 m in width (W), 7 m in height (H), and 25 m in length (L). As the facility is a straight-line wind tunnel, the primary experimental challenge was the development of a system capable of generating a vertically descending jet representative of a downburst. To this end, an insulated plywood upper plenum—hereafter referred to as the Impinging-Jet Plenum (IJP)—with dimensions 2 × 2 × 2 m^3 was constructed and mounted on a rigid wooden frame, with its bottom surface positioned 3 m above the test-section floor (Figure 1). A Coolmobile air-conditioning unit was installed externally on one side wall of the IJP (Figure 1b) and connected via three ducts to cool the internal air volume. An opening on a lateral wall allowed the injection of PIV seeding particles (Helium-Filled Soap Bubbles, HFSB). A circular nozzle of diameter D = 1 m was installed at the bottom surface of the IJP, connecting it to the test chamber. The nozzle was equipped with a honeycomb structure to reduce turbulence intensity and improve flow uniformity. A rapid-opening mechanism was designed to reproduce the transient nature of real downbursts and to synchronize data acquisition at the onset of each test. In addition, a piston with the same plan dimensions as the IJP was suspended at the top of the plenum by a winch system. Upon nozzle opening, the piston was released and descended over the 2 m height of the IJP, mechanically forcing the jet toward the outlet. The resulting flow therefore combines a classical impinging-jet component, generated by piston-induced forcing, and a buoyancy-driven component arising from the temperature difference (ΔT) between the cooled IJP air and the warmer ambient environment. Two piston descent velocities were tested, w_{p} = 0.15 m s^{-1} and 0.25 m s^{-1}, corresponding—by mass conservation—to theoretical exit velocities at the nozzle of approximately w_{IJ} = 0.8 m s^{-1} and 1.3 m s^{-1}, respectively. The ambient temperature in the test chamber was maintained at approximately 25 °C using heat exchangers, while the IJP air was cooled to 6–10 °C, producing ΔT values ranging from 0 °C to 25 °C. The complexity of the experimental setup required idle periods between consecutive runs, primarily to ensure uniform thermal conditions within both the chamber and the IJP. In total, 39 experimental cases were conducted by varying w_p and ΔT. To reproduce atmospheric conditions representative of real downbursts, the experiments were designed to approximate full-scale Richardson numbers (Ri). The selected geometric scale resulted in relatively low downdraft velocities to maintain similarity in Ri, which ranged from 0.01 to 0.31 across the test matrix. Given the low velocities involved, Large-Scale Particle Image Velocimetry (LS-PIV) was employed to characterize the flow field

(Figure 1d). The camera field of view (FOV) covered a vertical plane measuring either 2.5 × 2.5 m² or 3.2 × 2.5 m² (horizontal × vertical), depending on the camera used, with origin at the geometric touchdown point of the downburst (Figure 1c). Image acquisition frequencies were 7 Hz or 12 Hz, respectively. Thermocouples were installed both inside and outside the IJP to monitor ΔT, as well as along vertical profiles in the radial direction to capture temperature variations with the passage of the PV and the subsequent outflow (Figure 1c).

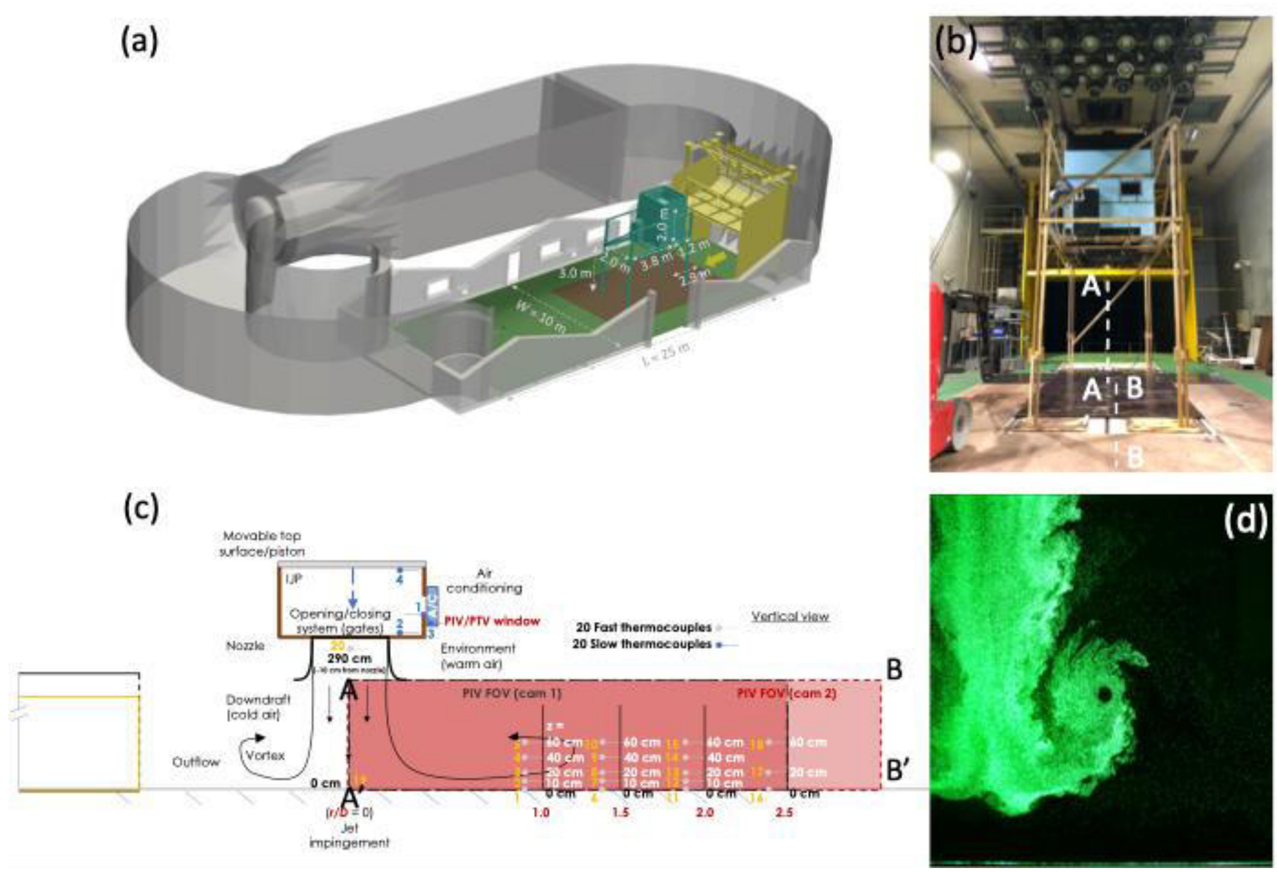

Figure 1. (a) Schematic of the JVCWT thermal circuit with relevant dimensions of the IJP setup; (b) Photograph of the JVCWT thermal circuit with IJP mounted; (c) Schematic (vertical view) of the experimental setup; (d) raw image from LS-PIV acquisition.

3. RESULTS

Figure 2 illustrates the dual influence of buoyancy on the reproduced downburst fields: it enhances the advection of both the downburst flow and its associated vortical structures, while simultaneously compressing the vortex toward the ground and stretching it radially, thereby increasing its rotational speed and the resulting flow velocities. These combined effects lead to an earlier occurrence of the maximum wind speed, $V_{\max}$, while its radial position remains similar between the two cases. At the same time, the flow resembles a near-surface cold gust front rather than a structure dominated by coherent vortices, and is characterized by significantly higher wind speeds. Vertical wind speed profiles exhibit a double-peaked (“double-nose”) structure, in contrast to the single peak observed at higher elevations in the pure IJ case. Temperature profiles show a marked decrease relative to the initial environmental temperature, T_{env}. Moreover, the elongated cold outflow affects measurement locations that have not yet been directly impacted by the vortex.

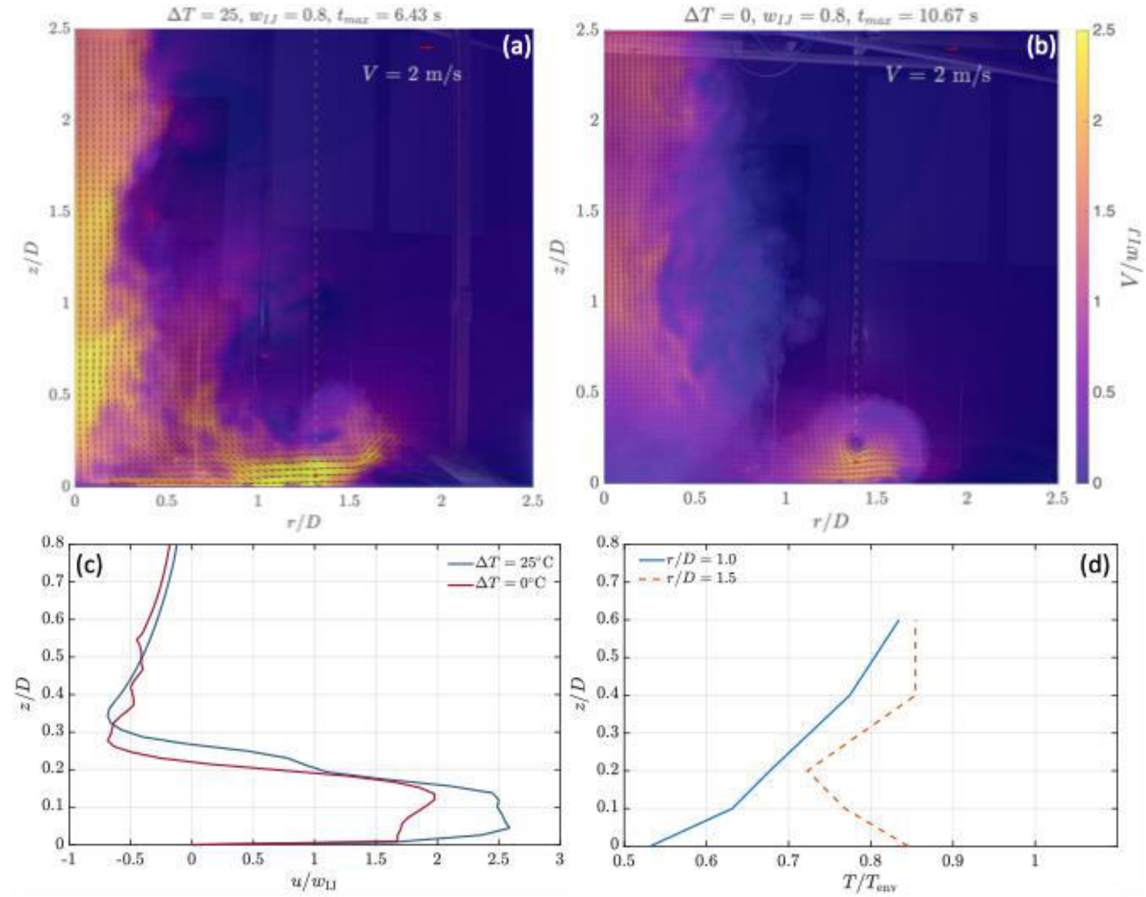

Figure 2. LS-PIV velocity field with superimposed corresponding flow visualization at the time of maximum wind speed, t_{max}: (a) w_{IJ} = 0.8 m s^{-1}, ΔT = 25°; (b) w_{IJ} = 0.8 m s^{-1}, ΔT = 0°. Vertical profiles at t_{max} of: (c) wind speed and (d) temperature (the latter reported for r/D = 1.0 and 1.5 in the case w_{IJ} = 0.8 m s^{-1}, ΔT = 25°).

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