Towards a probabilistic framework for thunderstorm wind actions on low-rise buildings

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SUMMARY
This study investigates the aerodynamic response of low-rise buildings subjected to thunderstorm winds, contributing to the development of probabilistic models for non-synoptic wind actions. Large-scale experiments were conducted at the WindEEE Dome under isolated downbursts and Atmospheric Boundary Layer (ABL) wind conditions. Pressure measurements were collected on a 1:200 scale building model for multiple radial positions and orientations, with repeated runs enabling statistical characterization. A methodology is proposed to define mean and peak pressure coefficients under transient conditions, based on the identification of a quasi-steady plateau phase and the use of a 1-second moving average. A Local Gust Effect Factor is introduced to quantify transient amplification. Results show that, while global aerodynamic loading patterns resemble ABL conditions, downbursts produce significant differences in pressure magnitude, spatial distribution, and peak localization, particularly on roof surfaces, highlighting the need for dedicated probabilistic approaches.

Keywords: Downburst winds, Pressure coefficients, Probabilistic modelling

1. INTRODUCTION

Wind loading on structures has traditionally been assessed assuming synoptic wind conditions, where the flow can be described as stationary, Gaussian, and horizontally homogeneous. These assumptions underpin most wind tunnel testing methodologies and current design codes, enabling simplified yet robust representations of wind-structure interaction (Davenport, 1963; Ricciardelli, 2023). However, increasing evidence of structural damage associated with thunderstorms has highlighted the limitations of such approaches when applied to non-synoptic wind events.

Downburst outflows are inherently transient, non-stationary, and characterized by strong spatial gradients, short-duration peaks, and non-Gaussian statistical properties, which significantly affect wind-structure interaction (Solari et al., 2020; Canepa et al., 2022). This limitation is particularly relevant in the context of wind engineering, where accurate representation of extreme and transient loading conditions is essential for reliable risk assessment.

Although recent experimental studies, including large-scale testing in facilities such as the WindEEE Dome, have improved the physical reproduction of downburst-like flows (Canepa et al., 2022), the statistical features of the aerodynamic response of buildings under these conditions have not yet been investigated. In particular, limited attention has been devoted to the characterization of pressure coefficient distributions and transient amplification mechanisms under realistic downburst conditions (Chay and Letchford, 2022; Jesson et al., 2015; Asano et al., 2019).

A key challenge in this context lies in the intrinsic variability of thunderstorm events. Unlike synoptic winds, which can be treated as stationary stochastic processes, downbursts are event-based phenomena, where each realization may differ in intensity, duration, and spatial structure. This variability complicates the definition of representative aerodynamic quantities and calls for modelling approaches capable of explicitly accounting for uncertainty and inter-event variability. Within this context, this study aims to provide preliminary insight into the aerodynamic response of a low-rise building subjected to downburst loading, with comparison to conventional ABL conditions. The ultimate objective is to support the development of probabilistic models for thunderstorm wind actions, capable of capturing both the transient nature of the flow and the variability associated with repeated events.

2. METHODOLOGY

The experimental campaign was conducted within the ERIES-ProMoTWA project at the WindEEE Dome, a facility capable of simulating both synoptic and non-synoptic wind fields. Three flow configurations were considered: isolated downburst (DB), Atmospheric Boundary Layer (ABL), and combined DB+ABL flows, with the present study focusing on DB conditions.

A 1:200 scale low-rise building model with gable roof was instrumented with 501 pressure taps, enabling high-resolution measurement of surface pressures. The model was tested at different radial distances from the downburst center (r/D = 0.8, 1.0, 1.2) and for wind directions ranging from 0° to 90°. Each configuration was repeated eight times to capture event-to-event variability.

Given the transient nature of downbursts, a specific procedure was adopted to define aerodynamic coefficients, starting from the standard formulations adopted in wind engineering practice (Picozzi et al., 2022). Mean pressure coefficients were evaluated over a quasi-steady plateau phase identified from the velocity time history (see Fig. 1), where wind speed remains approximately constant. Peak coefficients were instead computed using a 1-second moving average (full scale), consistent with design practice.

To quantify transient amplification, a Local Gust Effect Factor (LGEF) was introduced as the ratio between peak and mean pressure coefficients. The repetition of experiments enabled a statistical characterization of both peak values and associated uncertainty, expressed through the coefficient of variation.

The repetition of each experimental configuration represents a key aspect of the methodology, allowing the transition from deterministic to probabilistic interpretation of aerodynamic coefficients. Unlike conventional ABL testing, where variability is associated with turbulence within a stationary process, the present approach captures the intrinsic variability of transient events, enabling a more realistic representation of thunderstorm-induced loading.

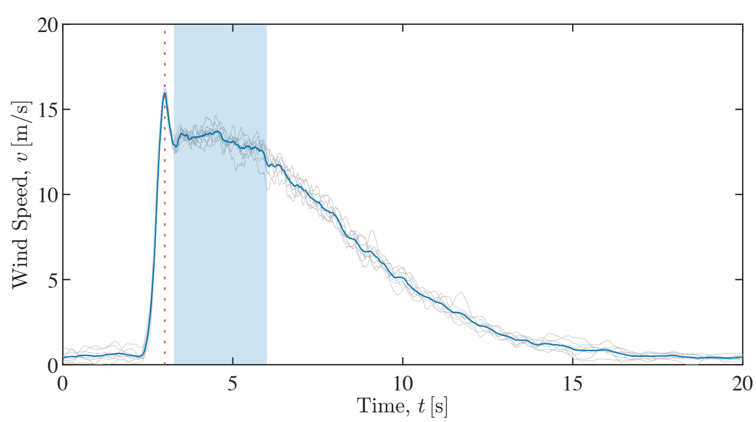

Figure 1. Time histories of 30-second moving average wind speed at ridge height for r/D = 1.0 and θ = 0° under downburst conditions. Grey curves represent the eight individual runs, and the blue curve their ensemble average; the red dashed line highlights the peak region, while the blue shaded area identifies the plateau zone.

3. EXPECTED RESULTS

The preliminary results highlight both similarities and key differences between downburst and ABL loading conditions.

At a global level, the aerodynamic loading pattern of the building is preserved, with positive pressures on windward wall and suctions on the side and lateral walls and over the roof. However, significant quantitative differences emerge. Downburst loading produces higher windward

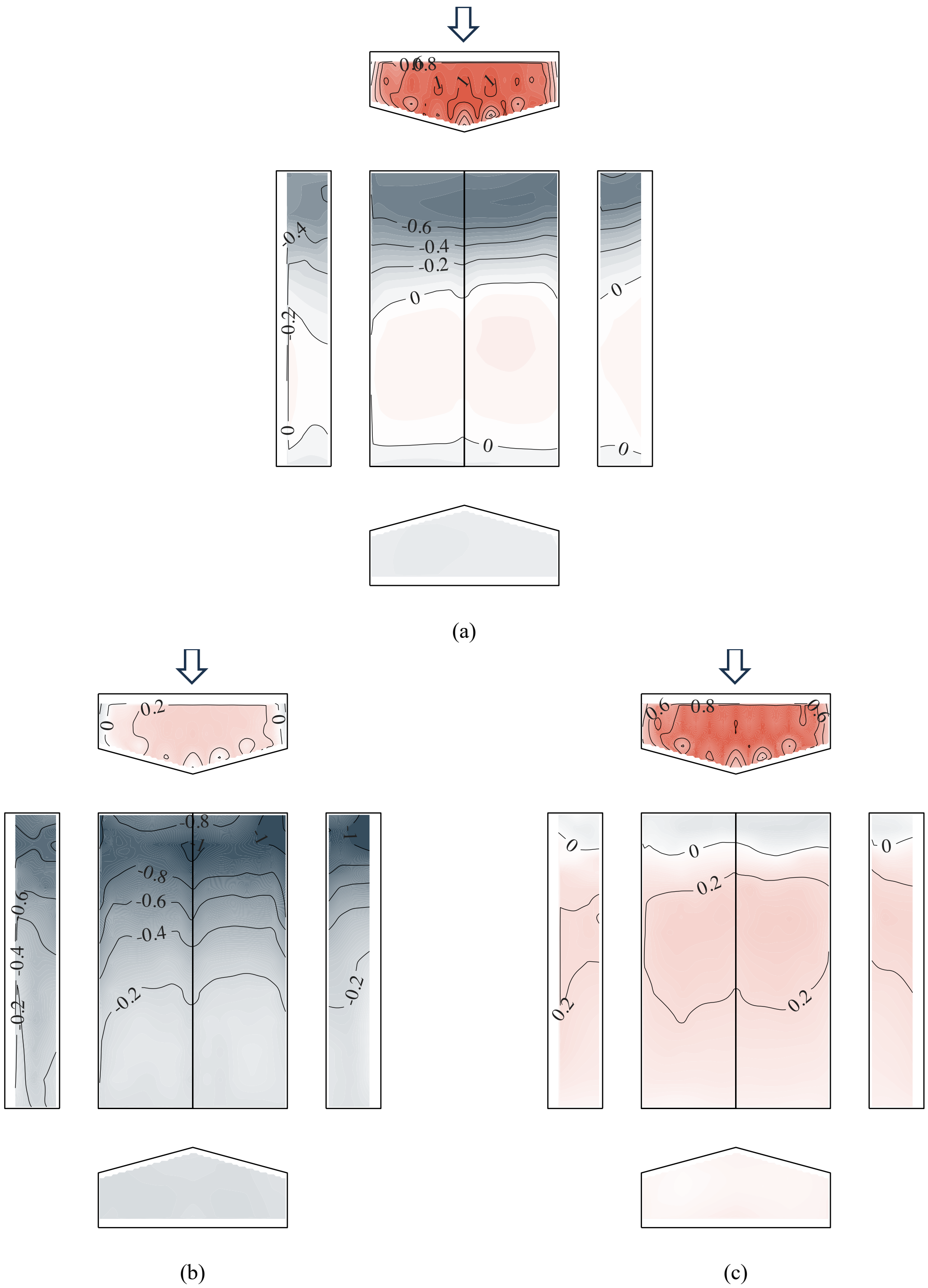

Figure 2. Spatial distribution of pressure coefficients for $r/D = 1.0$ and $\theta = 0°$ under downburst conditions: (a) mean values, (b) minimum peak values, (c) maximum peak values.

pressures and a marked redistribution of roof suctions, with reduced intensity near leading edges and enhanced pressure recovery downstream (as illustrated in Fig. 2). Peak pressure analysis confirms these trends, showing a shift in the location of extreme suctions and a broader distribution of positive pressures over the roof (Fig. 3). These effects are primarily attributed to the vertical velocity component associated with the impinging jet structure of the downburst.

The analysis of repeated runs indicates moderate variability (CoV ≈ 0.1–0.2), supporting the use of ensemble statistics. Furthermore, the LGEF reveals that pressure amplification cannot be explained solely by incoming flow turbulence. In several regions, particularly on the roof and lateral walls, amplification significantly exceeds that associated with dynamic pressure gust factors.

Overall, the study is expected to demonstrate that downburst loading represents a distinct aerodynamic regime, requiring dedicated probabilistic modelling approaches rather than extensions of conventional ABL-based methods.

These findings provide important physical insight into the role of the vertical velocity component associated with downburst impinging jets, which alters separation and reattachment mechanisms compared to ABL flows. In particular, the reduction of corner vortices and the redistribution of roof pressures suggest that traditional design assumptions based on stationary flows may lead to non-conservative or overly conservative estimates depending on the structural component considered. From a modelling perspective, the observed spatial variability and event-to-event fluctuations highlight the importance of dealing with pressure coefficients as stochastic variables. This supports the adoption of probabilistic frameworks capable of capturing both the inherent non-stationarity of thunderstorm outflows and the variability associated with repeated events.

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REFERENCES

Davenport, A. G. (1963). The relationship of wind structure to wind loading. Proceedings of the Symposium No. 16 – Wind Effects on Buildings and Structures, Her Majesty's Stationery Office, London, 53–111.

Ricciardelli, F. (2023). prEN 1991-1-4:2021: the draft Second Generation Eurocode on wind actions on structures – A personal view. Wind and Structures 37(2), 79–94.

Solari, G., M. Burlando, and M. P. Repetto (2020). Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures. Journal of Wind Engineering and Industrial Aerodynamics 200, 104142.

Canepa, F., M. Burlando, D. Romanic, G. Solari, and H. Hangan (2022). Downburst-like experimental impinging jet measurements at the WindEEE Dome. Scientific Data 9(1), 243.

Chay, M., and C. Letchford (2002). Pressure distributions on a cube in a simulated thunderstorm downburst. Journal of Wind Engineering and Industrial Aerodynamics 90(7), 711–732.

Jesson, M., M. Sterling, C. Letchford, and C. Baker (2015). Aerodynamic forces on the roofs of buildings subject to transient winds. Journal of Wind Engineering and Industrial Aerodynamics 143, 42–49.

Asano, K., Y. Iida, and Y. Uematsu (2019). Wind loads on a low-rise building in a downburst using a pulsed jet simulator. Journal of Wind Engineering and Industrial Aerodynamics 184, 313–320.

Picozzi, V., A. Malasomma, A. M. Avossa, and F. Ricciardelli (2022). The relationship between wind pressure and pressure coefficients for the definition of wind loads on buildings. Buildings 12(2), 225.