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Physical simulations of the effects of ABL-like winds and storm translation on downburst-like outflows

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ABSTRACT: Downbursts develop from thunderstorm clouds as downdraft of cold air that spreads out radially upon impingement on the ground. A thorough experimental campaign on downburst winds was recently carried out at the WindEEE Dome, at Western University in Canada. The study aims to quantitively investigate the interplay between the individual flow components that form the final downburst outflow (e.g., background winds and isolated downburst). The WindEEE Dome has the unique capability of reproducing the three main components of the downburst system – (i) isolated downburst in the form of an impinging jet, (ii) background Atmospheric Boundary Layer (ABL) flow, (iii) thunderstorm cloud translation – independently and simultaneously at large geometric scales.

Keywords: Downburst; ABL; Storm motion; Inclined jet; Impinging jet.

1. INTRODUCTION

The falling hydrometeors from cumulonimbus clouds produce a downdraft of cold air. Eventually, the latent heat of evaporation and melting of hydrometeors inside and underneath the cloud further decreases the temperature of the descending air and promotes negative buoyancy of the downdraft. As it approaches the surface, the downdraft loses some of its vertical momentum due to the positive pressure perturbations (hydrostatic and nonhydrostatic contributions) close to the surface that accelerates flow horizontally and radially outwards from the impingement region. This produces a vigorous horizontal outflow with maximum wind speeds in the near-ground level underneath the leading primary vortex (PV). Shear instabilities between the denser downdraft and the calm surrounding environment trigger the formation of the PV as well as following vortical structures, named ‘trailing vortices’, which are of smaller sizes and weaker than the PV. The whole of this air motion is called a downburst (Fujita, 1985; Canepa, 2022). From the wind engineering perspective, the main focus is on the PV and related horizontal velocities which eventually are the major cause of potential damages to low- and mid-rise structures. Significant efforts have been made over the last few decades to assess and characterize the space and time characteristics of downburst winds. Major challenges arise from their very localized spatiotemporal structure and highly non-stationary properties. Downbursts have a horizontal scale of a few kilometres and their duration is 10–20 minutes. During this time, the event is characterized by significant variations of wind speed and direction. This short duration and small spatial scales of downbursts make anemometric records in

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field measurements inadequate to reconstruct the entire kinematics of a downburst outflow. Furthermore, it is challenging to retrieve reliable information on the relative position of the downburst downdraft with respect to the location of the anemometer, as well as to explore dynamical characteristics of a downburst that produced the measured flow field at the anemometer location. This research makes the assumption that the measured downburst outflow at the ground is a nonlinear superposition of three different flows, i.e.: (i) isolated downburst; (ii) background low-level atmospheric boundary layer (ABL) winds in which the isolated downburst is immersed; (iii) the translation of parent storm that results in the inclination of the initial downburst (Fujita, 1985). Full-scale records from field measurements are too complex and have insufficient spatiotemporal coverage to provide a clear understanding of this complex multi-flow superposition. While a simple vector summation of (i) and (iii) seems to be a satisfactory treatment of this flow interaction, recent studies (Romanic and Hangan, 2020; Canepa, 2022) have demonstrated that (i) and (ii) cannot be added as a linear combination of two isolated flows.

The WindEEE Dome, at Western University in Canada, is a novel, three-dimensional (3D) and large-scale wind simulator capable of independently and simultaneously reproducing the above three downburst outflow contributors. A comprehensive experimental campaign was recently performed in the WindEEE Dome in order to produce a unique database of downburst-like impinging jet measurements that are used to investigate the kinematics of downburst outflow. The analyses carried out returned understandings of the PV dynamics as developing from the different flow interactions, the dynamical behavior of the front between downburst and ABL winds as well as the effect of the parent cloud translation.

2. DOWNBURST-LIKE CASES AND EXPERIMENT SETUP

WindEEE generates an isolated downdraft (i.e., no ABL-like winds and no downdraft translation) as a large-scale impinging jet using 6 fans located in an upper chamber that is connected to the main testing chamber through a bell mouth at the ceiling level at H = 3.8 m above the floor. The upper chamber is pressurized by running the 6 fans while keeping the bell mouth louvers closed. Once the desired pressure difference between the upper chamber and the test chamber is reached, the opening of the louvers forms an impinging jet that travels downwards into the testing chamber and diverges radially as a wall jet upon impingement on the floor. The diameter of the nozzle is D = 3.2 m. The ratio H/D = 1.19 assures the fully formation of the PV at the ground in analogy to what is observed in actual downburst outflows at full scale. The inclusion of the background ABL winds is achieved by running a matrix of 4×15 fans placed in one of the six peripheral walls of the hexagonal testing chamber (the equivalent diameter of the testing chamber is 25 m). The effect of the storm translation is replicated by mechanically imposing an inclination of the impinging jet axis of 30° with respect to the vertical (Figure 1). This inclination is within the range of angles observed by Fujita (1985) in full-scale observations of microbursts in the United States. The tilt of the downdraft and the background ABL winds produce an outflow at the ground that breaks the radial symmetry of an undisturbed vertical jet (i.e., an isolated downburst). The inclusion of ABL winds and downdraft inclination results in an intensification of the front side and weakening of the rear side of the outflow. Here, the terms "front" and "rear" sides of the outflow refer to the locations downwind and upwind in the outflow with respect to the direction of ABL winds.

Figure 1 schematically shows 4 investigated cases of experimentally produced downburst-like flows: (1) vertical impinging jet that creates a radially symmetric outflow; (2) same as the case (1) with the inclusion of ABL-like winds; (3) inclined impinging jet (asymmetric elliptical outflow) without ABL-like winds; and (4) same as the case (3) with the inclusion of ABL-like winds.

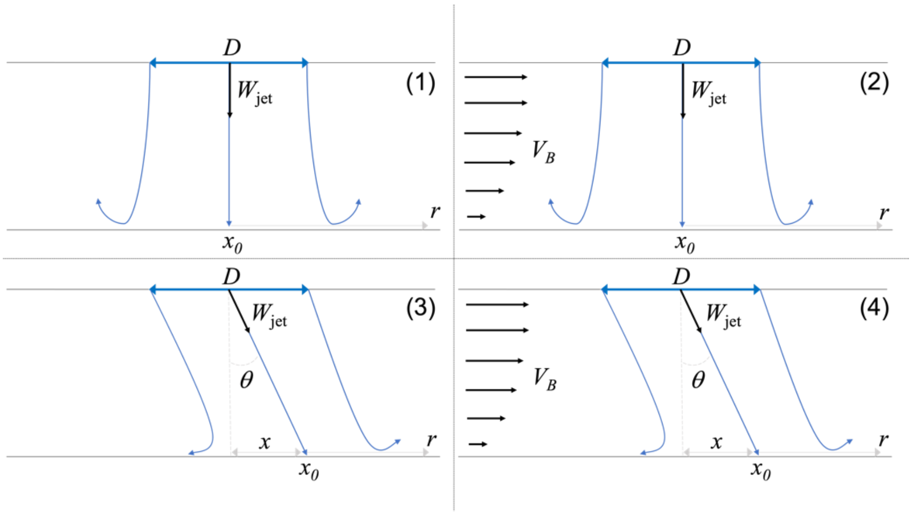

Figure 1. Downburst-like configurations (1–4) that were tested at the WindEEE Dome (side view). Here, W_{jet} and V_B are the jet centreline velocity and characteristic ABL wind velocity, respectively, D is the jet diameter, x_0 is the touchdown location of the jet axis, and θ is the jet-axis inclination.

Velocity measurements were performed using Cobra probes at a sampling frequency of 2500 Hz. For a given azimuth angle with respect to the direction of ABL winds, a total of 8 to 10 probes (depending on the case) were installed along a vertical stiff mast in the height range between z = 0.04 and 0.90 m from the floor. All Cobra probes pointed towards the jet impingement zone to record the radial component of the outflow. The mast was then displaced at 7 azimuthal locations, from α = 0° to 180° (0° corresponds to the direction of the incoming ABL flow) with incremental steps of $\Delta\alpha$ = 30°. Because of the symmetry, the results can be mirrored to the other half of the azimuthal domain, i.e., α = 180° to 360°. At each α, 10 radial positions were tested in the range between r/D = 0.2 and 2.0, where r/D = 0 corresponds to the geometric position of jet touchdown. Here, the radial increment was $\Delta r/D$ = 0.2 (Figure 2). An additional vertical mast with 2 to 4 Cobra probes was placed symmetrically to the first on the other side of the symmetry plane with respect to the direction of the incoming ABL wind. Here the Cobra probes' head was oriented towards the 60-fan wall to measure the ABL flow component. Each experiment with the Cobra probes' mast located at the specific measurement location (α, r/D) was repeated 10 to 20 times to study the deterministic mean part of the velocity signals and inspect the variability of the repetitions. The characteristic jet and ABL velocities used in the experiments are reported in Table 1, along with details on the geometric setup. The above velocities were measured respectively at the bell mouth section and 3 m downstream of the 60-fan wall at a height of 0.25 m. Table 1 also shows the additional horizontal velocity (V_t) that arises from the inclination of the jet axis (cases (3) and (4)) and that falls in the range of translation velocities of the parent thunderstorm observed in nature.

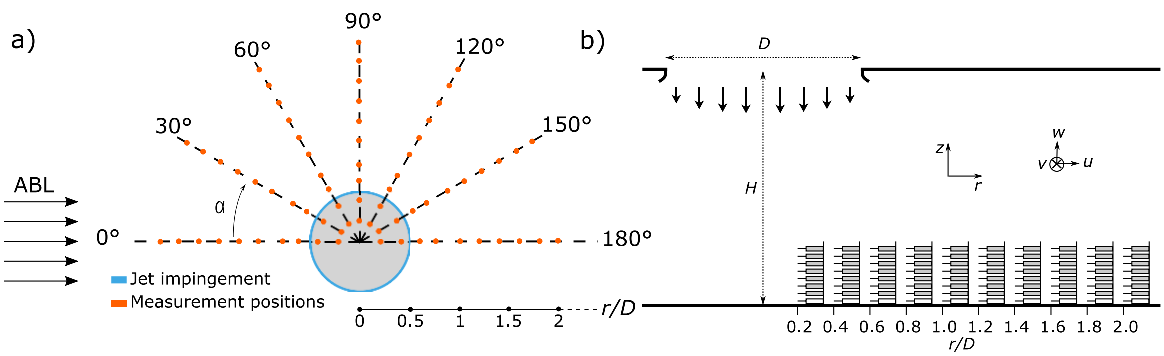

Figure 2. (a) Top and (b) side views of measurement locations, α and r/D are the azimuthal and radial locations of Cobra probes, respectively. Also, (b) shows the positive direction of the wind speed components (u,v,w).

Table 1. Experiment setup: Case name (Case); Jet diameter (D); Jet velocity (W_{jet}); ABL velocity (V_B); Equivalent translation velocity (V_t); Azimuthal locations (α); Radial locations (r/D); Experimental repetitions (Reps). Note that measurement heights are not reported due to large variation among the experimental cases; however, the range of measurement heights is reported in the text above.

Case	D [m]	W_{jet} [m s^{-1}]	V_B [m s^{-1}]	V_t [m s^{-1}]	α [°]	r/D	Reps
1	3.2	8.9 – 16.4	\	\	90	0.2:0.2:2.0	20
2	3.2	12.4	2.5 – 3.9	\	0:30:180	0.2:0.2:2.0	10
3	3.2	12.4	\	6.2	0:30:180	0.2:0.2:2.0	10
4	3.2	11.8	3.9	5.9	0:30:180	0.2:0.2:2.0	10

The experimental scenario reproduced at the WindEEE Dome is a satisfactory representation of full-scale downburst outflow also in terms of geometric scales when combining downburst- and ABL-like flows. The ABL boundary layer thickness (gradient height) and the height of the PV core, which is assumed to be representative of the size of downburst outflow, have the same geometric scaling between full-scale and WindEEE Dome, i.e., approximately 1:1000.

This abstract only describes the velocity measurements setup while the detailed analysis of the results will be presented at the conference.

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