20th from november 28 to december 2, 2022 SCIENTIFIC CONVENTION ON ENGINEERING AND ARCHITECTURE
HAVANA INTERNACIONAL CONFERENCE CENTER
58 ANNIVERSARY cujae

EXTENSIVE LARGE-SCALE EXPERIMENTAL CHARACTERIZATION OF DOWNBURST WINDS

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ABSTRACT

Meso-scale thunderstorms govern the severe wind climate of mid-latitude areas of Europe and many other parts of the world, particularly in the view of potentially dramatic impacts of climate change on our planet. The consequence of their actions on the natural and built environment are often catastrophic and fatal. This has led the wind engineering community to move its focus to the physical understanding of such phenomenon and, in civil engineering terms, to its effects on structures. From these premises, the project THUNDERR, developed at the University of Genoa (PI late Prof. Giovanni Solari), was awarded by the European Research Council (ERC) with an Advanced Grant 2016 to produce outcomes that can be transferred to design and standards to make structures wind-safer and cost-efficient. This paper describes the large experimental campaign carried out in the framework of this project at the WindEEE Dome, a large-scale wind simulator at Western University, in Canada. Here, a detailed picture of the dynamic behavior and spatiotemporal evolution of the downburst system formed by the non-linear superposition of different contributions, is obtained, and fulfills what cannot be retrieved from classical anemometric recording in nature. This represents the first link in the chain that takes from the understanding of the phenomenon to structural applications and implementation in design codes, as provided by THUNDERR.

KEY WORDS: THUNDERR Project, thunderstorm outflows, downburst, WindEEE Dome, impinging jet flow.

1. Introduction

The new long-term forecast models developed by atmospheric physicists and meteorologists are everything but optimistic in terms of intensification and frequency of occurrence of extreme events. Mass media production is nowadays often invaded by sad news of natural disasters and construction/infrastructure collapses related to natural hazards. Past events have repeatedly highlighted their potential impact in terms of economic losses, casualties and overall disruption (i.e., indirect loss). The in-depth analysis of risk-related aspects is of crucial importance. Many projects have emerged in the recent years with a dual approach towards loss-driven design and mitigation strategies and risk quantification (see, for instance, ERIES[1] [1]).

The wind is the most destructive natural phenomenon – over 70% of causalities due to natural hazards are caused by the wind [2, 3]. The wind climate at mid-latitudes in Europe and many other parts of the world is dominated by extra-tropical cyclones at the synoptic scale and thunderstorm outflows at the mesoscale. Whereas the former are well and widely known in the literature [4], thunderstorms are complex and still mostly unknown phenomena. Recent studies on climate change

[1] https://eries.eu

activity have predicted an increasing intensification of thunderstorms [5–7] with potentially catastrophic consequences on the natural and built environment.

Following these considerations, a completely new study stream on downburst winds has developed across the wind engineering community in the last few decades in order to characterize their occurrence and quantify their importance in terms of actions and effects on the society, environment and constructions [8].

The novelty in the investigation of thunderstorm winds, i.e., downbursts, lies in their unique spatiotemporal characteristics. Downbursts develop as cold descending currents of air (downdraft) from thunderstorm clouds (cumulonimbus). The vertical downward current has been proven to be crucial mainly for take-off and landing stages of flights, whereas the radially diverging wind that originates from the downdraft impingement on the ground can cause serious consequences on structures [9–11]. Downbursts are very localized phenomena both in space and in time: the strongest and dangerous outflows develop over only few kilometers on the horizontal, with 4 km being the extension that separates micro-bursts from macro-bursts according to Fujita [9, 10]; the wind speed and direction during the occurrence of the event can change drastically in very short time intervals of the order of tens of minutes [11–13]. These aspects make the recording of downbursts in nature by means of classically available anemometric instruments still very challenging and thus very limited in comparison to stationary synoptic winds [14]. Indeed, despite the punctual high-frequency-rate measurements of the phenomenon may capture well the time evolution of the recorded phenomenon, its spatial reconstruction is hardly retrievable in full-scale. This is even more restrictive in the view of understanding the physical interactions that form the final downburst system. Downbursts occur indeed embedded into the background Atmospheric Boundary Layer (ABL) wind and the horizontal outflow at the ground senses the effect of the upper-level storm motion. A decisive help in this sense comes from experimental simulations of the phenomenon in ad-hoc laboratories. In this context, the shortcomings above find answer in the extensive experimental campaign performed recently at the WindEEE Dome, at Western University in Canada, that will be the main focus of the present paper. The integration with advanced CFD simulations and analytical techniques will allow to achieve a refined model of the downburst wind field to be transferred to newly developed structural models for thunderstorm winds.

The physical characterization of the phenomenon shall always be the first crucial step towards the development of wind loading techniques of structures, tailored to the characteristics of the class of events considered. This is even more striking in the light of the significant differences between stationary Gaussian extra-tropical depressions and non-stationary non-Gaussian thunderstorms. A large number of studies in the literature deals with the separation of different wind events and assessment of maximum velocity distribution for each class of event. However, these distributions are eventually combined into one mixed distribution of the maximum wind velocity, from which a design wind velocity is obtained and put into calculation models typical of extra-tropical cyclones [15]. This approach leads to distort the reality and to force the use of concepts and rules definitely outside their correct application domain [16].

The Project THUNDERR [17], briefly described in Section 2, settles into this panorama and aims at implementing a codified design model based on the conjunction of the two contributions above that indeed form the two main sub-categories of the project itself: I) Thunderstorms and II) Structures. Section 3 describes the activity carried out at the WindEEE Dome and the main qualitative outcomes of the post-processing of the huge amount of experimental data. The reader is invited to refer to the papers recently published in the literature on this topic for a further and deeper understanding. Section 4 outlines the main conclusions and future prospects.

2. The ERC THUNDERR Project

The Project THUNDERR: "Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures"[2], is funded by the European Research Council (ERC) with an Advanced Grant 2016 to Prof.

[2] www.thunderr.eu

Giovanni Solari of the University of Genoa. The project aims at tackling the unknowns related to downburst winds and at creating regulatory schemes and models to share with both the atmospheric physics and civil engineering scientific communities. The first objective concerns the thunderstorm as a physical phenomenon. It aims at formulating a unitary and interdisciplinary model of downbursts with a dual purpose of achieving frontier knowledge for atmospheric sciences and a basis for realistic and simple wind engineering assessments of thunderstorm outflow actions on structures. This is pursued by strengthening the large wind monitoring network installed in the main ports of the Northern Tyrrhenian Sea withing the European projects "Wind and Ports" [18] and "Wind, Ports and Sea" [19] by new state-of-the-art instruments, conducting large-scale laboratory tests in the WindEEE Dome[3] at Western University, Canada, performing CFD simulations in collaboration with the Technical University Eindhoven[4], The Netherland, calibrating the results obtained by means of field measurements, studying the weather scenarios in which thunderstorms occur in collaboration with the European Severe Storm Laboratory[5]. Analytical techniques will provide decisive help in collecting and modelling the whole of this information. The second objective relates to the thunderstorm loading and response of structures. Towers and lighting poles have been equipped with anemometers, accelerometers, and strain-gauges. This will provide simultaneous measures of the outflow field and structural response to evaluate equivalent static loading through different techniques: time-domain analysis, response spectrum technique and evolutionary spectral method. An Independent Wind Loading technique will be developed to produce a novel set of partial and combination factors for thunderstorms.

The project[17] has been centered around the Giovanni Solari Wind Engineering and Structural Dynamics (GS-WinDyn) research group at the University of Genoa (Italy)[6]. The present paper deals only with the first objective of the program—that is, the experimental characterization of the downburst wind at the WindEEE Dome.

3. Experimental campaign at the WindEEE Dome

The study aims to quantitatively investigate the spatiotemporal evolution and interplay between the individual flow components that form the final downburst outflow DB (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.

The WindEEE Dome and case studies

The Wind Engineering Energy and Environmental (WindEEE) Dome is an innovative wind testing chamber part of the Western University, Canada [20]. It contains an inner chamber (Figure 1c) of hexagonal shape with equivalent diameter of 25 m and height $H = 3.8$ m. WindEEE is the first wind simulator worldwide capable of creating extreme wind events at large geometric scales and Reynolds numbers, Re. WindEEE generates an isolated downdraft as a large-scale impinging jet (IJ) (Figure 1b) using 6 fans located in an upper chamber (Figure 1a) that is connected to the main testing chamber (Figure 1c) through a bell mouth at the ceiling level. The opening of the bell mouth 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 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 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 2). This inclination is within the range of angles observed by Fujita [9] in full-scale observations of microbursts.

[3] www.windeee.ca
[4] www.urbanphysics.net
[5] www.eswd.eu
[6] www.gs-windyn.it

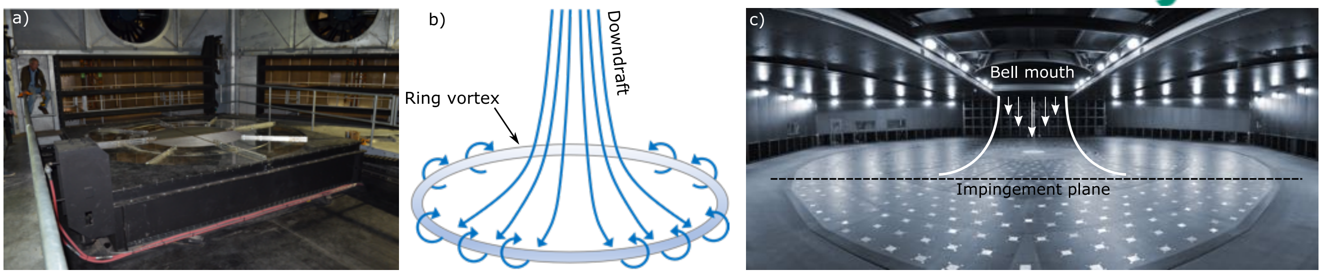

Figure 1. WindEEE Dome and downburst-like flow formation. (a) upper chamber; (b) Three-dimensional schematic of downburst (after [9]); (c) testing chamber with schematic of the downburst-like IJ. Figure from [21].

Figure 2 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.

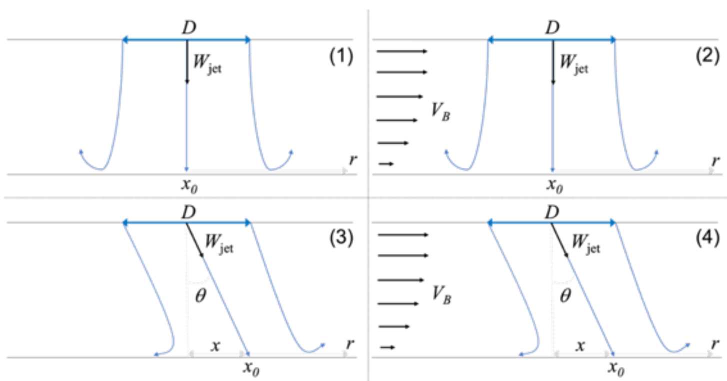

Figure 2. Downburst-like configurations (1–4) that were tested at the WindEEE Dome (side view). Here, W_{jet} and V_B are the jet centreline velocity and characteristic ABL wind velocity, respectively, D is the jet diameter, x_0 is the touchdown location of the jet axis, and θ is the jet-axis inclination.

Experiment 3D setup

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. The height locations in the result section will be normalized to z_{max} = 0.1 m, that represents the elevation of maximum wind speed for case (1). 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. 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.

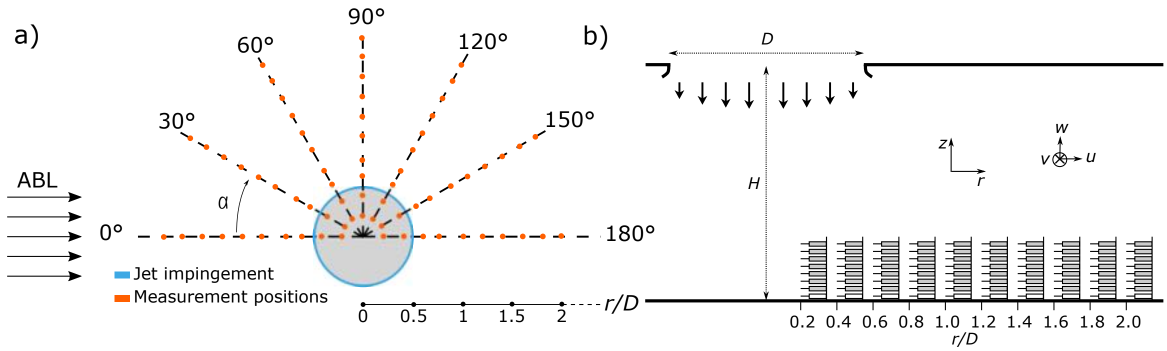

Figure 3. (a) Top and (b) side views of measurement locations, α and r/D are the azimuthal and radial locations of Cobra probes, respectively. Also, (b) shows the positive direction of the wind speed components (*u,v,w*). Figure from [21, 22].

Table 1. Experiment setup: Case name (Case); Jet diameter (*D*); Jet velocity (W_{jet}); Reynolds number (*Re*); ABL velocity (V_B); Equivalent translation velocity (V_t); Azimuthal locations (α); Radial locations (r/D); Experimental repetitions (Reps).

Case	*D* [m]	W_{jet} [m s^{-1}]	$Re \times 10^6$	V_B [m s^{-1}]	V_t [m s^{-1}]	α [°]	r/D	Reps
1	3.2	8.9 – 16.4	1.92–3.55	\	\	90	0.2:0.2:2.0	20
2	3.2	12.4	2.68	2.5 – 3.9	\	0:30:180	0.2:0.2:2.0	10
3	3.2	12.4	2.68	\	6.2	0:30:180	0.2:0.2:2.0	10
4	3.2	11.8	2.55	3.9	5.9	0:30:180	0.2:0.2:2.0	10

The large Reynolds numbers involved in the experiments allow to consider the flow in "fully-turbulent" regime [23] and thus to extend the results to real downburst occurrences. Furthermore, 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., O(~10^3). For a more comprehensive description of downburst generation at the WindEEE Dome, Cobra probe setup inside the chamber, and data analysis technique, the reader is referred to the article by Canepa et al. [21].

Main outcomes of the research

The main features of the isolated vertical downburst dynamics (case (1)) are depicted in Figure 4. Upon the jet exiting from the bell mouth, physically corresponding to the full-scale situation of downdraft released from the thunderstorm cloud (scenario 5), the flow widens in radial direction due to entrainment of ambient air (scenario 4) while travelling towards the ground. Vortical structures form due to the instability between the faster (also denser and colder in nature) column of downward air towards the ground and the calm (also lighter and warmer in nature) surrounding environment. The largest and most intense among these structures is the so-called primary vortex (PV) that, after the jet impingement on the ground, leads the horizontal outflow (scenario 1 to 3) and is the main contributor to the maximum horizontal wind speeds that are indeed observed at the boundary between the vortex lower end and the ground (scenario 2), in the full-scale range between approximately 50 to 150 m [13]. This scenario gives rise to the well-known nose-like shape velocity vertical profile, that profoundly differs from the logarithmic-like profile observed during larger-scale extra-tropical cyclones [13, 14, 16, 22, 24].

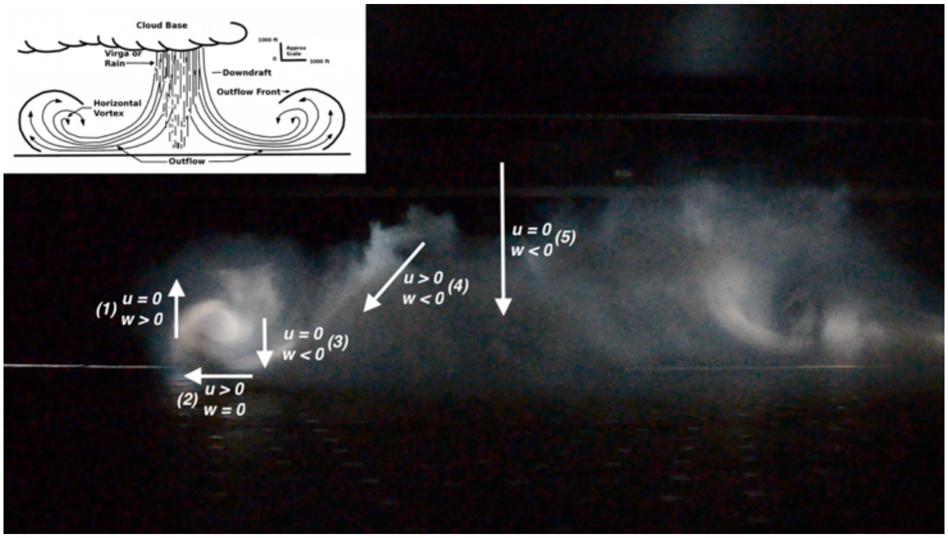

Figure 4. Flow visualization with smoke of a vertical IJ experiment (case (1)) at the WindEEE Dome. Scenarios (1) to (5) identify the main features of the outflow dynamics. Figure from [13].

Figure 5 shows the radial wind speed component as recorded at two different measurement positions in the flow field for case (1). Three different segments can be clearly distinguished and correspond to three distinct periods in the downburst outflows observed in real events [25, 14]: "PV", "plateau", and "dissipation" segments respectively corresponding to passage of the PV (peak wind speed), steady-state outflow with fairly-constant mean velocity over time, and phenomenon dissipation.

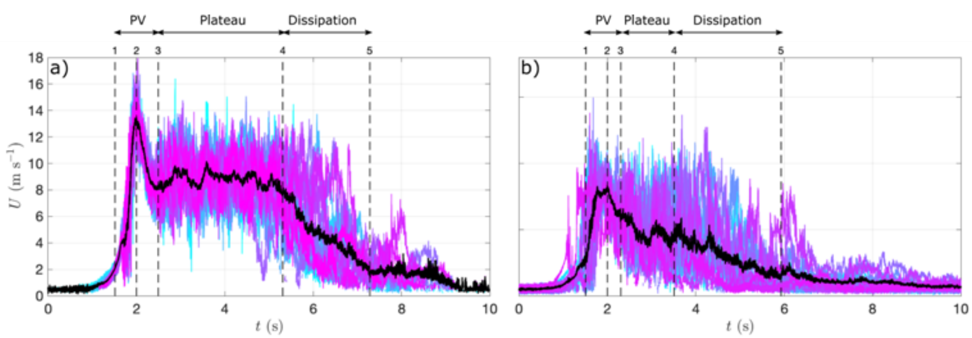

Figure 5. (a) 20 repetitions showing the radial wind speed component (colored lines) for case (1) measured at the position (r/D = 1.2, z/z_{max} = 0.4) and their ensemble mean (black line). (b) Same as (a) but for the position (r/D = 1.8, z/z_{max} = 2.7). Figure from [21].

The maximum horizontal wind speed V_{max} for case (1) are observed around r/D = 1.0, in agreement with other experiments in the literature [26, 27]. For radial positions away from the downdraft region (approximately r/D > 1.0), a secondary counter-rotating vortex (SV) is observed to form due to the air pushed outwards by the PV expansion and consequent detachment-reattachment of the boundary layer at the ground due to surface roughness. In this situation the maximum velocities develop at the boundary between PV and SV and are mainly directed upwards. This scenario is clear both qualitatively by looking at flow visualizations in Figure 6c,d and quantitatively by observing the onset of positive vertical wind speeds at the front of the PV right before its passage over the Cobra probe (scenario 1 in Figure 4) and also along the vertical profile (Figure 6e,f) during the PV segment. Figure 6g shows a sudden drop of the height of maximum radial speed $z(V_{max})$ concurrently with the passage of the PV, for the reasons mentioned above.

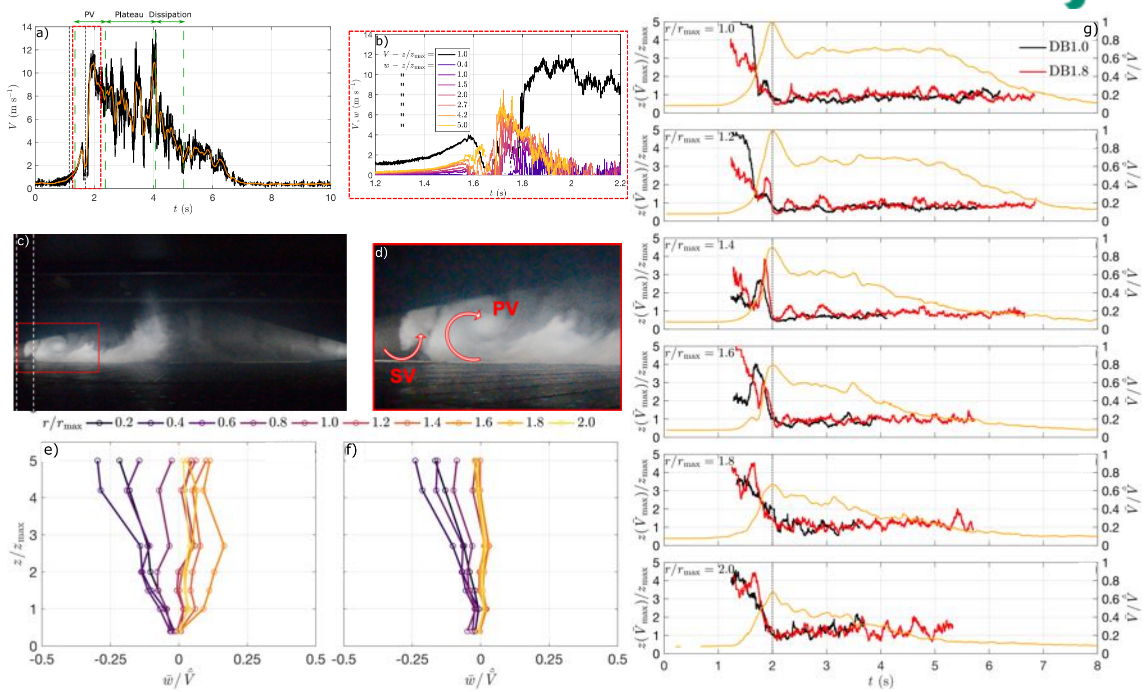

Figure 6. The SV that forms in front of the PV: (a) time series (black line) of the radial velocity at the position (r/D = 1.6, z/z_{max} = 1.0) and its moving average (orange line); (b) Zoom-in on the time interval between SV and PV with reported radial velocity (black line) and vertical velocities (colored lines) at all the instrumented heights and r/D = 1.6. (c) flow visualization of a downburst outflow a few seconds after touchdown; (d) Zoom-in on the frontal zone (red rectangle in (c)) with the indication of the PV and SV; (e,f) Vertical profiles of normalized vertical wind speed at the peak and plateau segments, respectively. (g) Time evolution of height of maximum wind speed (black and red lines) superposed with wind speed time series (orange line). Figure from [28].

Data of case (1) are publicly available [29] and can be further reused under Creative Commons license CC0 for metadata and CC-BY for data to widen the investigation.

The radial symmetry of the outflow in case (1) is significantly breached in the other three cases tested (2 to 4). The superposition of vertical IJ and ABL-like flow (case 2) unexpectedly generates maximum horizontal wind speeds at the interface between counter directed downburst outflow and ABL, as shown in Figure 7a,b. This may be explained as schematically outlined in Figure 7g: due to the same relative circulation (i.e., same vorticity sign) between the two flows at their interface, the radially-outgoing downburst PV entrains the counter-directed ABL-like wind and, as a result, rotational speed of PV and the horizontal flow underneath its structure intensify. In case (4), not shown here, where the ABL flow is supplemented to the inclined IJ, the structure of the PV at the front with the ABL flow is weakened by the particular experimental setup (downdraft tilted towards same direction of outgoing ABL). For this reason, the outflow assumes a typical elliptical-like shape with intensification of the flow in the rear region and weakening at the interface DB-ABL [9]. At the same time instant, the position of the PV and overall outflow changes accordingly to the azimuth measurement location in the flow field (see Figure 3a), namely to the mutual interaction between DB and ABL and to the elliptical shape caused by the jet tilt at the ground. To summarize, the PV is compressed at the front between DB and ABL, elongated in the region subjected to jet inclination and where the two flows have same direction, and with very similar structure at the boundary between the two regions.

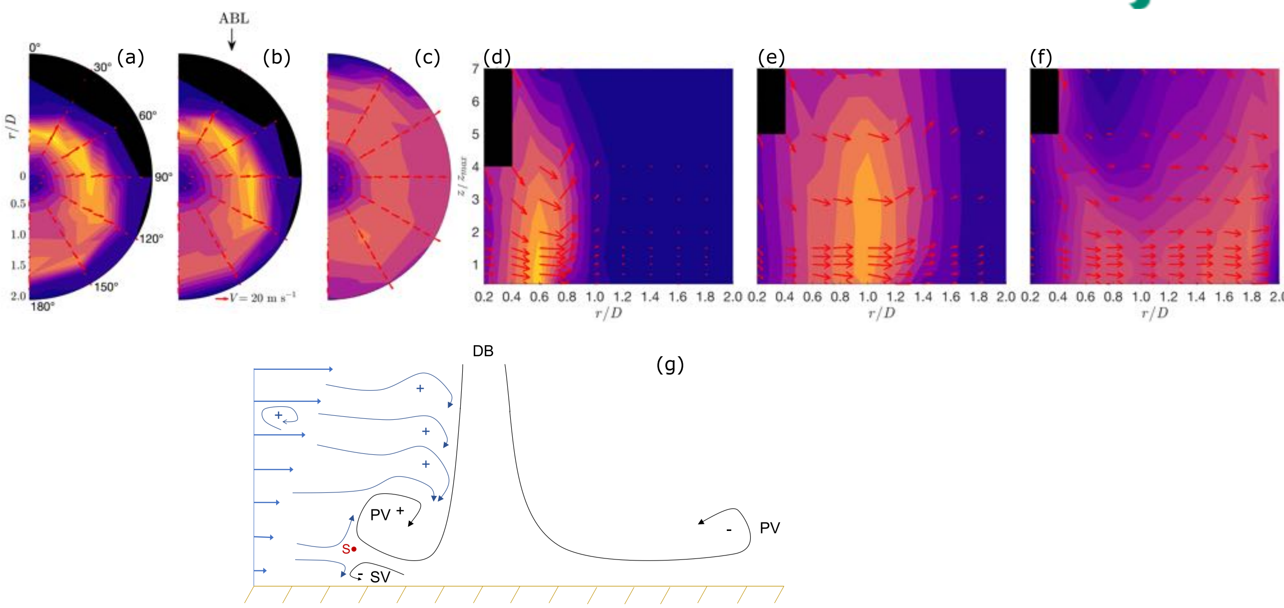

Figure 7. Case (2): (a-c) Horizontal view of wind speed field at z/z_{max} = 1.0 at the "PV" (a,b) and "plateau" (c) segments; (d-f) Vertical view of wind speed field at the same time instant and α = 0° (d), 90° (e), 180° (f) (for reference see Figure 3a); (g) Schematic of DB-ABL interaction for case (2). Figure from [22].

Turbulence intensity, not shown here, exhibits its maxima around *r/D* = 1.4–1.6, namely radially further from the touchdown position compared to the velocity maxima. Contrary to the usual hypothesis adopted in the literature of stationary turbulence intensity, its time series shows a peak few instant before that associated to the maximum wind speed.

4. Conclusions and future prospects

The very large experimental campaign performed at the WindEEE Dome and described in this paper, forms along with complementary on-going CFD simulations [30, 31], analytical approaches [32, 33], and full-scale measurements with state-of-the-art instrumentation [13, 34], the objective (I) Thunderstorms of the Project THUNDERR (Section 2).

The results shown in Section 3 represent a decisive step towards the physical and comprehensive characterization of downburst winds. The advanced properties of the WindEEE Dome laboratory allowed to investigate in detail the downburst flow field and its physical properties in time and 3D space coordinates at large geometric and kinematic scales, and thus Re, as it was never achieved before experimentally. For the first time, the interaction between the three main flow components (downburst wind, background ABL flow, storm translation) forming the final anemometric downburst recording has been described and quantified, thanks to the capability of the WindEEE Dome to reproduce independently and simultaneously the three contributions. We have therefore proved the non-linearity of the superposition between these contributions, and hence of the common over-simplistic assumptions adopted in the literature.

The joint effort among the techniques mentioned above to physically characterize the phenomenon will soon give important outcomes in the form of a downburst field model, able to include all the diversity and singularities inherent in the downburst occurrences in nature. In turn, its integration with a structural model (objective (II) Structures of the Project THUNDERR, [35–38]) will allow to characterize the downburst loading and effects on structures and implement a model to update the civil engineering design codes for thunderstorm wind actions.

Acknowledgments

The authors are deeply grateful to late Prof. Giovanni Solari for his invaluable contributions to the conceptualization and supervision of this research. This research is funded by the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Program (Grant agreement No. 741273) for the project THUNDERR – Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures – awarded with an Advanced Grant 2016. The support of the Canada Foundation for Innovation (CFI) WindEEE Dome Grant (No. X2281B38) is also acknowledged.

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