Physical Investigation of Downburst Winds and Applicability to Full Scale Events

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A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Civil and Environmental Engineering
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Abstract

Thunderstorm winds, i.e. downbursts, are cold descending currents originating from cumulonimbus clouds which, upon the impingement on the ground, spread radially with high intensities. The downdraft phase of the storm and the subsequent radial outflow that is formed can cause major issues for aviation and immense damages to ground-mounted structures. Thunderstorm winds present characteristics completely different from the stationary Gaussian synoptic winds, which largely affect the mid-latitude areas of the globe in the form of extra-tropical cyclones. Downbursts are very localized winds in both space and time. It follows that their statistical investigation, by means of classical full scale anemometric recordings, is often inadequate in the view of accurately reconstruct the transient nature of the phenomenon. Wind tunnel tests in ad-hoc laboratories can fill this gap. Furthermore, downbursts never occur as isolated system in nature; they occur, in fact, embedded into the background Atmospheric Boundary Layer (ABL) flow and are influenced by the thunderstorm cell translation. In nature, the decomposition of the recorded downburst signals into component signals associated with the aforementioned contributions is often challenging or unfeasible. This study presents the results of the largest experimental campaign performed so far on downburst winds, where the physical behavior of downburst-like flows, simulated by means of the impinging jet technique, was thoroughly investigated in the spatiotemporal domain. The experiments were conducted in the Wind Engineering, Energy and Environment (WindEEE) Dome at Western University which allows the simultaneous generation of downburst and background ABL winds along with the simulation of the parent thunderstorm translation. For the first time, a clear understanding of the overall downburst dynamics and of the interactions that take place during the occurrence of the phenomenon is presented. Later, this study investigates, as a structural application, the aerodynamic behavior of two cylinders subject to the experimentally produced downburst winds at the WindEEE Dome. Finally, the thesis describes the vertical profile time-evolution of full-scale downburst events recorded by means of the state-of-the-art LiDAR profiler, installed within the large wind monitoring network developed along the northern Tyrrhenian coasts during the European Project “Wind and Ports”, with the aim of comparing the respective wind fields with those reproduced at the WindEEE Dome. Common characteristics concerning the transiency of the phenomenon in terms of mean and turbulent part of the wind speed signals are found and reported in statistical manner. It is found that the direction can be dealt as invariant with the height, the height of the time-dependent maximum velocity drops in correspondence of the absolute peak velocity produced by the passage of the primary vortex, and turbulence presents its maxima shortly before that. The implications of these findings in terms of structural response can be crucial.

This study is part of the wider project THUNDERR, whose Principal Investigator is Prof. Giovanni Solari, funded by an ERC Advanced Grant 2016. The project aims at finding a proper model of representation of
thunderstorm winds, from the joint combination of physical, numerical, and analytical investigations, to be implemented in the calculation framework to assess the loading and response of structures to thunderstorm winds. The inclusion of an independent model for thunderstorm winds in the structural design codes, where the wind-structure interaction is still evaluated based on the synoptic-scale extra-tropical cyclones, would indeed represent a decisive turn. The problem is even more crucial in the view of the severe climate changes that are affecting the earth planet, which induce, as a consequence, a rising intensification and sharp increase in frequency of the extreme wind events, such as thunderstorms.

Keywords
Downburst, Thunderstorm wind, Impinging jet, Background wind, ABL, Thunderstorm translation, Storm motion, Wind simulator, Turbulence, Vertical profile, Full Scale events.
Summary for Lay Audience

The wind is the most destructive natural phenomenon – over 70% of damages and casualties due to natural hazards are due to the wind. The wind climate of Europe and many other parts of the world at the mid-latitudes is dominated by extra-tropical cyclones and thunderstorm winds. The severe climate changes that have been affecting our planet in the last tens of years are producing a sharp increase in intensity and frequency of extreme wind events around the globe. Therefore, it is crucial to recognize the rising importance of these events and understand their physical behavior and dynamics on the natural and built environment. This appears even more fundamental considering that the current design codes provide calculation schemes based only on extra-tropical cyclones.

This thesis fits into the panorama of activities provided by the project THUNDERR, whose aim is indeed to implement a model to evaluate the wind actions due to thunderstorm winds and the response of structures to this phenomenon. To achieve this goal, it is first necessary to fully comprehend the dynamic evolution of downbursts, i.e. thunderstorm winds, in nature and to assess their characteristics relevant to the wind loading of structures. However, downbursts in nature are very transient phenomena, limited in both time and space dimensions. It follows that their recording by means of classical anemometric instruments is very challenging and the related databases of measurements of the phenomenon are still limited in the literature. This is even more remarked in the light of assessing the different flow contributions to the phenomenon that appear very difficult to discern in the final anemometric record. Wind tunnel testing in ad-hoc facilities can overcome these shortcomings by assess an experimental model able to characterize the behavior of downbursts to be later scaled up to the real world and validated by comparison with the available recordings in nature. This thesis tries to give a major step forward in this direction.
Co-Authorship Statement

The present thesis composes of article-like chapters, i.e., published/submitted/prepared journal papers slightly readapt in the form of thesis’ chapters.

Chapter II combines two articles recently submitted. The first part – accepted for publication in the Nature Scientific Data journal with the title “Downburst-like experimental impinging jet measurements at the WindEEE Dome” and under the co-authorship of Federico Canepa, Massimiliano Burlando, Djordje Romanic, Giovanni Solari and Horia Hangan – concerns the description of the database of experimental measurements on vertical-axis impinging jets published at the online repository PANGAEA, along with a detailed description of the experimental setup. The second part – submitted for publication in the Environmental Fluid Mechanics journal with the title “Experimental investigation of the near-surface flow dynamics in downburst-like impinging jets” and under the co-authorship of Federico Canepa, Massimiliano Burlando, Djordje Romanic, Giovanni Solari and Horia Hangan – concerns the post-processing analyses of the database of measurements.

Federico Canepa organized the data, prepared the database of measurements, performed data analysis, prepared the manuscripts and figures. Massimiliano Burlando conceptualized the study and methodology, performed wind tunnel tests, supervised the study and co-wrote the first part. Djordje Romanic conceptualized the study and methodology, performed wind tunnel tests and co-wrote the first part. Giovanni Solari conceptualized the study, found resources, was responsible for funding acquisition and supervised the study. Horia Hangan found resources and supervised the study.

Chapter III is submitted to the journal MDPI Atmosphere – special issue “Measurement, Analysis, Modeling and Prediction of Strong Winds in Atmospheric Boundary Layer” with the title “Experimental investigation of the near-surface flow dynamics in downburst-like impinging jets immersed in ABL-like winds” and under the co-autorship of Federico Canepa, Massimiliano Burlando, Horia Hangan and Djordje Romanic.

Federico Canepa performed wind tunnel tests and data analysis, prepared the manuscript and figures. Massimiliano Burlando conceptualized the study, the methodology, supervised the study, and co-reviewed the paper. Horia Hangan found resources, supervised the study, and co-reviewed the paper. Djordje Romanic conceptualized the study, performed wind tunnel tests, and co-reviewed the paper.

Chapter V is published in the Advances in Structural Engineering journal with the title “Aerodynamic coefficients and pressure distribution on two circular cylinders with free end immersed in experimentally
produced downburst-like outflows” and under the co-authorship of Djordje Romanic, Andrea Ballestracci, Federico Canepa, Giovanni Solari and Horia Hangan.

Djordje Romanic conceptualized the study and the methodology, performed wind tunnel tests and data analysis, prepared the manuscript and figures. Andrea Ballestracci performed wind tunnel tests and data analysis, and co-reviewed the paper. Federico Canepa performed wind tunnel tests and data analysis, prepared figures and co-reviewed the paper. Giovanni Solari supervised the study, co-reviewed the paper, found resources and was responsible for funding acquisition. Horia Hangan conceptualized and supervised the study, found resources and co-reviewed the paper.

Chapter VI is published in the Wind Engineering & Industrial Aerodynamics journal with the title “Vertical profile characteristics of thunderstorm outflows” and under the co-authorship of Federico Canepa, Massimiliano Burlando and Giovanni Solari. Federico Canepa performed the data analysis, prepared the manuscript and figures. Massimiliano Burlando co-supervised the study, co-reviewed the paper and was responsible for data collection. Giovanni Solari supervised the study and reviewed the paper.
Acknowledgments

It has been quite a journey!
I have lived happy, beautiful, exciting, inspiring, challenging, tough and sad moments along the way. I strongly believe that each of them has made me grow up, professionally but mostly personally.
I first want to thank all my friends and colleagues at the Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genoa (Italy). These past years have been disrupted by the Covid-19 pandemic which kept us away from our working environment and social life. I have always thought at the ‘University’ as the place where social interactions flow intensively and continuously, where people gather together to exchange ideas and build a community. We have missed conferences around the world, an important and enjoyable part of the Ph.D. life. Despite this, we have always been united, alive and dynamic, both inside and outside the department. Thank you!
I also want to thank all my friends at Western University (London ON, Canada), where I spent 6 beautiful months. I want to thank Andrea Ballestracci, who I co-supervised during the period in Canada, and later in Genoa. Looking after him somehow made me grow too. A special thanks goes to Prof. Djordje Romanic who helped me in building the base of my Ph.D. career, with whom I carried out the extensive experimental campaign at the WindEEE Dome and had great scientific discussions that enriched my mind. Thanks for the many rides that you gave me to WindEEE and back. And sorry, I was always late. An affectionate thanks to Gerry Dafoe, the legendary technician of WindEEE. His invaluable technical ability and experience were essential for the success of the experiments. Beside this, and more important, thank you for the joyful moments we spent together outside of work, for the unconventional and fascinating side of the Canadian culture and life that you showed me, for the speedway car racings, for the peace that I found at your home immersed in the nature, for the beers together and cigarettes outside of the WindEEE Dome during testing.
Thank you to Prof. Horia Hangan, for his invaluable scientific knowledge, for his capability to make complex things simple and clear to my mind, for his friendly and relaxed personality. At the end of each meeting things always seemed to have more sense to me.
Canada, London, Western and WindEEE will always have a special place in my heart.
Thanks to Prof. Massimiliano Burlando, who has followed me closely from the first day, for his constant availability to which I can always rely on to clear out any scientific doubt that I have. His great knowledge in physics has helped me not to lose sight of the motivations and purposes behind my research. His calm and friendly mood have surely contributed to make this journey smoother and pleasant.
I want to send an endless thank you up there to Prof. Giovanni Solari. You have been the guide, the beacon throughout my academic career. You changed the path of my career and hence of my life, gifting me with some of the best experiences that I have ever lived. Your personality, charism, integrity will always
accompany and support me. Your passion for wind engineering, the dedication to your Ph.D. students and to any student around the world willing for your help and scientific (and not) advice is something that I will never forget. We miss you, very much.

Another special thanks to my supervisors (Profs. Giovanni Solari, Horia Hangan, Massimiliano Burlando) who worked very hard and tirelessly for several long months to grant me the Dual Ph.D. title between the University of Genoa and Western University. They never gave up, even when the bureaucracy and paperwork seemed unsolvable they always found a way through it. Now this has become true, and I will be always grateful, proud and honoured for this recognition. It means a lot to me, and this title is also yours.

A heartfelt thanks to Flavia, who has stayed at my side and sincerely supported me throughout this journey. With whom I shared the deepest emotions of living this experience. We have been through a lot together, and beautiful memories are with me.

To conclude, a deep, loving thanks to my family, to my Mum Liuba, my Dad Gian Luigi and my brother Gabriele. They have been supporting me, my decisions, my desires for the entire life. They have always trusted and relied on me. When they tell me “we are proud of you” I feel fulfilled and, yes, I am also proud to have you guys as family.

Federico Canepa

This Ph.D. Thesis 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 – through an Advanced Grant 2016 (Principal Investigator: Prof. Giovanni Solari).
I dedicate this doctoral thesis to our Professor Giovanni Solari

“The answer, my friend, is blowin' in the wind”

-Bob Dylan
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Figure 6.12. 10-min slowly-varying mean standard deviation (a) and turbulence intensity (b): time histories at 120 m AGL (upper pictures); interpolated magnitude-maps as function of time and height (bottom pictures). Vertical dashed red lines indicate the time of the first and second peak of the horizontal mean wind speed. Horizontal dotted gray lines (bottom pictures) indicate the height at which the time histories are depicted (upper pictures).

Figure 6.13. Downburst in Genoa on 14 August 2015. 10-min horizontal (a) and vertical (b) slowly-varying mean wind speed: time histories (upper pictures); interpolated magnitude-maps as function of time and height (bottom pictures). Vertical dashed red lines indicate the time of the horizontal peak mean wind speeds, at which the vertical profiles of the horizontal and vertical slowly-varying mean wind speed are depicted (right-hand boxes). Horizontal dotted gray lines (bottom pictures) indicate the height at which the time histories are plotted (upper pictures).

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Figure 6.15. Same as Figure 6.13, but for the downburst in Genoa on 3 May 2016.

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IU as function of time and height (bottom pictures). Vertical dashed red lines indicate the time of occurrence of the horizontal peak mean wind speeds. Horizontal dotted gray lines (bottom pictures) indicate the height at which the time histories are depicted (upper pictures).

Figure 6.19. Vertical profile of the 20-min mean slowly-varying turbulence intensity $IU, Iu$ and $Iv$. Event names are given in terms of station, SS, year, YYYY, month, MM, and day, DD.
Chapter I

1 Introduction

1.1 General Introduction

Wind Engineering is a cross discipline of Mechanical Engineering, Civil Engineering, Meteorology and Applied Physics. It analyzes the effects of wind in the natural and built environment and possible damages, inconveniences or benefits resulting from it. Cermak (1975) defined wind engineering as “the rational treatment of the interactions between wind in the atmospheric boundary layer and man and his works on the surface of Earth”.

In the last few decades wind studies have increased considerably thanks to the great research development in this field. The technologic progress and consequent availability of state-of-the-art instruments has allowed to measure a multitude of atmospheric quantities in order to return a detailed picture of the wind characteristics above the earth surface within the well-known Atmospheric Boundary Layer (ABL).

The purpose of the last decades of Wind Engineering is to develop design methods for very complex, tall and slender buildings and bodies. The current methods and design codes focus the attention on the stationary and Gaussian extratropical cyclones at the synoptic scale. They are the most common type of wind event at the mid-latitudes around the globe and they last few days, developing over thousands of kilometers on the horizontal. Here, the wind velocity may be assumed as a stationary Gaussian process in a time interval between 10 minutes and 1 hour. Considering the turbulence as small and thus neglecting the effect of the quadratic term of the fluctuation by considering the quasi-steady theory, the wind velocity may be converted into an aerodynamic action which, in turn, is still a Gaussian process. Such aerodynamic loading is applied on a structure which is considered as linear. It follows that the dynamic response is also a Gaussian quantity. The resulting probability density function (PDF) is sharp and narrow, thus its mean value can be considered as representative of the maximum response. This process is well known as the Davenport chain (Davenport, 1967). It constitutes the foundation of the whole set of guidelines and codes to assess the wind actions on structures.

However, the nature and the built environment are often vulnerable to non-stationary winds, such as thunderstorms. Every year, 16 millions of thunderstorms strike the Earth’s surface. At any given time, there are 2000 thunderstorm cells active (Solari, 2019). Figure 1.1a depicts the global distribution of thunderstorms where the areas crossing the Equator are those most affected by the occurrence of thunderstorms due to the highly unstable atmosphere in this region. Figure 1.1b shows the global map of lightning which reflects the same concept of Figure 1.1a.
Figure 1.1. (a) Global thunderstorm climatology. Source: Electrical Engineering Portal (EPP)\(^1\);

(b) Global lightning activity in the period 1995-2013. Source: NASA\(^2\).

\(^1\) https://electrical-engineering-portal.com/11-major-causes-of-power-system-failures

\(^2\) https://earthobservatory.nasa.gov/images/85600/global-lightning-activity
Research about thunderstorms in Wind Engineering started about 40 years ago. They are very transient phenomena, developing in few tens of minutes over a very limited spatial area in the order of few kilometers. It follows that it is often very challenging to detect these phenomena by means of the classic measuring instruments and, therefore, the accurate reconstruction of the physical behavior of these events results poor in the view of building a suitable model to assess the structural response to their actions. In fact, despite an impressive amount of research, a shared model for thunderstorm-induced actions on structures is not available yet, mainly because the complexity of thunderstorms makes it difficult to establish physically realistic and simple models as in the case of extra-tropical cyclones (Solari, 2019); so, the methods currently applied to determine the wind actions on structures are still referred to the synoptic-scale extra-tropical cyclones-related Davenport chain mentioned above.

Unfortunately, thunderstorms present time-space characteristics completely different from extra-tropical cyclones and in many cases their intensity exceeds that of synoptic events. Thom (1968) first showed that one-third of the yearly peak wind velocities in the United States occur during thunderstorms, which are, in fact, the dominant wind type for structural design in many parts of the world (Gomes and Vickery, 1978; Letchford et al., 2002). Zhang et al. (2018) also showed that design wind velocities with mean return period greater than 10-20 years are often associated with thunderstorms. Literature now claims that, due to the totally different characteristics between synoptic and extreme winds, design methods have to be developed separately in order to consider the different nature and genesis of each phenomenon. Therefore, using a mixed statistics approach to evaluate the design velocity is even more striking in the light of the different structural behavior with regards to different wind exciting phenomena. Nowadays, the design models to evaluate the structural response due to thunderstorms are the Thunderstorm response spectrum (Solari et al., 2015b; Solari, 2016; Roncallo and Solari, 2020) and the Gust-front factor (Kwon and Kareem, 2009, 2011, 2013), in which the original gust factor technique was generalized from stationary to non-stationary wind actions. It follows that the classical unique wind loading conditions needs to be separated into a set of independent wind loading conditions, at least introducing a new set of partial safety coefficients and combination factors (Solari, 2014).

However, as mentioned above, the available data for thunderstorms are still very limited compared to synoptic events, pointing out the necessity to collect and analyzing as many thunderstorm records as possible. In this perspective, a crucial help in filling this gap may be given by the introduction of new measuring instruments, such as LiDAR (Light Detection and Ranging) profilers and scanners, capable of performing wide spatial scanning of the atmosphere. On the other hand, the spatiotemporal transiency of the phenomenon does not allow to depict a comprehensive picture of the dynamic of the phenomenon, also in structural engineering terms, by means of only full scale anemometric recordings. It follows that
advanced physical and numerical investigations are needed to obtain a clear and thorough understanding of the physical, dynamic and kinematic properties of the wind field generated by downbursts. Thunderstorm winds, i.e. downbursts, are defined in the next section in terms of historical background, meteorological scenario in which they develop along with the related meteorological classification, and wind engineering aspects. Finally, Section 1.3 describes the motivations behind this thesis and the framework of the ERC THUNDERR Project. The cited references are reported at the end of the chapter.

1.2 Definition of Downbursts

1.2.1 Historical background

Anaximandros of Miletos in 600 b.c. argued that “thunders in thunderstorms are due to the shear among clouds”. It was probably the first statement on thunderstorms ever pronounced. In the last years of his life, Leonardo da Vinci created a series of 11 drawings called Deluge or Visions of the End of the World, which were considered for many years just as visions of an old man no longer able to bring ideas and projects to completion. Recently, these drawings have been brought to light and, despite the obviously visionary nature of da Vinci’s scenes, clearly and accurately represent thunderstorm downburst that he had discovered through a combination of careful observation, experiments and reasoning (Gedzelman, 1990). He depicts a downburst pouring out from a cumulus or cumulonimbus cloud with strong intensity that causes huge parts of cliffs to fall into a river, sending out waves that spread radially outward across the land. The da Vinci’s downburst has an unmistakable vortex-ring structure which resembles what observed at the leading edge of downbursts, indeed. He also offered an explanation for these eddies based on the principle of conservation of motion. The scientific study on thunderstorms, however, began in 1946 with the Thunderstorm Project (Byers and Braham, 1948). The study of downbursts, such as other phenomena, took off from a tragic event. On June 1975, an aircraft from Eastern Airlines affronted with a rapid diverging wind while attempting to land at New York’s John F. Kennedy Airport (JFK) crashed and killed 112 people. This divergent wind pattern had already been observed previously and was later investigated by Fujita, who reported similarities between the measured data from the aircraft flight data recorder and the starburst outflow pattern of fallen trees observed in an aerial survey from the damages of “super-outbreak” of 148 tornadoes on 3–4 April 1974 (Fujita, 1974). From all these analyses, Fujita termed the event as “Downburst” and defined it as “A natural event that occurs due to thunderstorms produced by a cumulonimbus cloud causing a strong downdraft which induces an outburst of damaging winds on or near the ground” (Fujita, 1990). The radially divergent wind originated upon the downdraft impingement on the ground can impact the nature and the ground-mounted structures with high intensity causing immense damages. The strong developing winds are accompanied by potentially large amounts of precipitation, hail, and lightning.
Downbursts were thus redefined meteorologically as scientists reveal the scale and nature of the phenomenon (Fujita and Wakimoto, 1983).

1.2.2 Meteorological background and thunderstorm classification

Thunderstorms are defined as a cloud or cluster of clouds that produces thunder, lightning, heavy rain, and sometimes hail and tornadoes. They are also associated with near-surface severe winds and strong vertical currents (updrafts and downdrafts).

Thunderstorm clouds are cumulonimbus (Cb) clouds. Cb clouds are categorized into Cb calvus which is moderately developed Cb and Cb capillatus which is a powerful Cb cloud. A Cb capillatus has a hair-like top and the special subcategory of Cb capillatus is Cb incus, which is a Cb cloud that developed an anvil-like top (Figure 1.2).

The environmental factors of importance for thunderstorm development are:

- Wind shear and wind veer, i.e. change of wind velocity and direction with height, respectively.
- Convection
- Presence of ice nuclei
- Maintenance of these factors over time

An important indicator of thunderstorm development is the Convective Available Potential Energy (CAPE) which is the energy per unit mass available for a buoyantly rising parcel of air or, in other terms, the integrated amount of work that the upward (positive) buoyancy force would perform on a given mass of air (air parcel) if it rose vertically throughout the entire atmosphere. That is, positive CAPE will cause the air parcel to rise, while negative CAPE will cause the air parcel to sink. Therefore, CAPE quantifies the convective potential of an air parcel – high CAPE means high convective potential of the air parcel. This quantity can be obtained from thermodynamic diagrams; namely, it is the area disclosed by the ambient sounding of temperature and the moist adiabat after the LFC. The Level of Free Convection (LFC) is the
altitude in the atmosphere above which the temperature of the environment decreases faster than the moist adiabatic lapse rate of a saturated air parcel at the same level. The height at which the relative humidity (RH) of the air parcel reaches 100%, with respect to liquid water when it is cooled down by dry adiabatic lifting, is called Lifting Condensation Level (LCL); the cloud base begins from here when there is mechanical lift to saturation, e.g. due to a mountain/obstacle that forces the air to rise. When there is not mechanical lift, cloud base begins at the Convective Condensation Level (CCL), namely in the point where LFC and LCL eventually coincide; in this case, the heating from below the cloud causes spontaneous buoyant lifting to the point of condensation when the convective temperature is reached. The height at which moist adiabat crosses the ambient sounding is called the Limit of Convection (LOC).

Figure 1.3. Example of thermodynamic diagram recorded during a thunderstorm event. CAPE and CIN parameters are highlighted.

A value of CAPE between 1000 and 2500 m²/s² indicates moderate thunderstorms while the value above 3500 m²/s² is a precursor of a severe thunderstorm.

Figure 1.3 also reports the CIN quantity, referred as to the area where the air parcel is colder than its surroundings. Areas with high CIN are considered stable and with very little probability of developing thunderstorms. Indeed, CIN represents an obstacle, or lid, to updrafts necessary to produce convective weather. CIN greater than 200 J/Kg are usually sufficient to prevent convection in the atmosphere. When CIN is overcome, saturated parcels at LCL will rise to the LFC/CCL and then spontaneously rise until the parcel temperature is equal to the environment one (stable layer) at the LOC.

Another factor that plays a decisive role in the eventual development of thunderstorms is the atmospheric stability. Thunderstorms develop in either unstable or conditionally unstable atmosphere. Atmosphere is
unstable if, for instance, warm and moist air is located above surface and the air has high dew-point temperature (proportional to high relative humidity). One condition for unstable atmosphere is a negative gradient of potential temperature with height. Conditionally unstable atmosphere provides that the environment lapse rate is between dry adiabatic and moist adiabatic lapse rates. In other words, an unsaturated parcel is cooler than the environment and thus it will sink whereas a saturated parcel is warmer than the environment and therefore it will rise. This also means that we need to somehow “force” the air to saturation level and then the air will rise freely afterwards. In order to make the air unstable, the first option would be to decrease temperature of air aloft which usually happens when we have a cold air current at higher elevations or infrared cooling from clouds. Otherwise, we can also warm the earth’s surface which in turn will warm the air close to the surface. The earth’s atmosphere is predominantly heated from earth’s surface. Other option is to have warm air currents close to the surface (e.g., warm advection). Yet another option is to have cold close to the ground and moving over warm surface.

Meteorologically, thunderstorms are classified into three main classes with the following environmental conditions favorable for their development:

- **Single-cell thunderstorms**
  - Weak wind shear
  - Weak wind veer
  - Isolated convection
- **Multi-cell thunderstorms**
  - Strong wind shear
  - Weak wind veer
  - Pronounced convection
- **Supercell thunderstorms**
  - Strong wind shear
  - Strong wind veer
  - Very pronounced convection
According to Byers and Braham (1948), a single-cell thunderstorm evolves in three stages. In the first stage, named “Cumulus stage”, warm and humid air rises up vertically due to convection. The advection may also be of mechanical nature; in this latter circumstance, the air encounters an obstacle (e.g. mountain) and is “forced” to rise. Single-cell thunderstorms usually start as a cumulus congestus cloud. The word “cumulus” itself indicates that we need to have convection for this cloud to develop. The initial cumuliform clouds usually have a depth that is $1.5D$ where $D$ is the diameter of the cloud base. However, the dissipation of the first generation of clouds causes the environment to be less dry than it was before and therefore the entrainment process is less effective.

If the moist updraft exists after the evaporation of the previous cumuliform clouds, the new cumulus clouds will form in less dry environment. If the updraft continues to rise then the cumulus congestus will develop into cumulonimbus. Therefore, the main feature of the cumulus stage is that the whole cloud is dominated by updraft. Precipitation still did not reach the surface. The updraft can be about 10 m/s or even higher sometimes. The top of the cloud is frozen and has very low temperatures (around -40 and -50 °C) and the precipitation starts to form. The second stage, named “Mature stage”, usually begins when precipitation reaches the surface. The strong moist updraft still persists feeding the cloud with energy and water. However, the downdraft is also formed. The formation of the downdraft is due to the drag induced by the falling hydrometeors (e.g. rain, ice, graupel, etc.). The evaporation and/or melting of precipitation also contributes to the formation of downdraft. The main feature of this stage is the simultaneous existence of updraft and downdraft and precipitation that has reached the surface. This is also the most vigorous stage.
of a single-cell Cb. If the cloud is strongly vertically developed, the anvil will form at the top of the cloud due to the stable air (a lid) around tropopause and stratosphere. The last stage in a life cycle of a thunderstorm is the “Dissipation stage”. The cloud starts to lose the contributions of positive buoyancy and moist updraft because:

- The storm moves over a region where convection is not pronounced
- The downdraft cuts off the updraft
- Interaction between the updraft and downdraft diminishes the updraft

The downdraft still dominates the storm and precipitation still exists but diminishes with time. The dissipation stage is rapid because the cloud base is populated with small cloud droplets and the falling rain will quickly collect those small droplets. The anvil is the remnant that sometimes stays as cirrus cloud after the Cb has dissipated.

1.2.3 The Downburst in wind engineering

By definition, downbursts are downdrafts of cold air that emerges from a thunderstorm cloud and spreads out horizontally upon hitting the surface (Figure 1.6).
A schematic of downdraft and downburst outflow is shown in Figure 1.7a. The horizontal spread of the downdraft is formed by radially advancing vortices that are characterized with highly three-dimensional (3D) flow. The wind speeds in downburst can be very high and can pose a threat to the safety of people and objects. If the spatial extension of the radially diverging winds exceed 4 km the downburst is called *macroburst*, otherwise it is called *microburst* (Fujita, 1981, 1985). Generally, microbursts are more intense than macrobursts.

Three projects developed in the late seventies and eighties to increase the number of full scale measurements of thunderstorm outflows and gain knowledge on their behavior. These are named NIMROD (Northern Illinois Meteorological Research on Downburst, 1978), JAWS (Joint Airport Weather Studies, 1982), and MIST (Microburst and Severe Thunderstorms, 1986).

Fujita provided for the first time a fundamental link between meteorological aspects and wind field properties associated to thunderstorms. The time-history depicted in Figure 1.7b is highly different from what usually observed during synoptic wind events, being characterized by a strong non-stationarity. Furthermore, the intensity of wind speed reaches high magnitudes of about 149 mph.
Great contributions in the field of thunderstorm winds were also brought by Hjelmfelt. He provided articulated schemes of the wind field and outflow generated by the thunderstorm wind, furnishing average values for the main geometrical parameters involved in the phenomenon (Figure 1.8a) and focusing on the effects of a background wind speed (Figure 1.8b).
The outflow velocities during a downburst can exceed 75 m/s, which is comparable to a velocity in a strong tornado. However, the high wind speeds are not the only reason for downburst being dangerous. Namely, the velocity profiles in downbursts are profoundly different from the standard Atmospheric Boundary Layer (ABL) wind profile (Figure 1.9a). The former ones are characterized with a nose-like shape of velocity profile and therefore the maximum horizontal velocities occur close to the surface between about 50 and 120 m above the ground level (AGL), as reported first by Goff (1976) and later confirmed by Hjelmfelt (1988) (Figure 1.9b). The ABL winds are characterized with a standard logarithmic profile that grows with height, generating an atmospheric boundary layer with a depth in the order of 1-3 km.
Over the last few decades, the use of Doppler radar in aviation has allowed to drastically reduce the number of accidents and fatalities induced by downbursts on jets and flights. However, doppler radar cannot prevent the damages induced by thunderstorm outflows on the natural and built environment, as documented in Figure 1.10.
As shown by Figure 1.10, and for the particular vertical profile shape of the outflow wind speed, the structures that mostly suffer the wind action of thunderstorm outflows are low- and medium-rise structures (namely cranes, small turbines, light poles, towers, transmission lines, canopies, …).

1.3 Framework of the thesis

1.3.1 The ERC Project THUNDERR

Prof. Giovanni Solari was awarded with an ERC Advanced Grant 2016 after the outstanding results and contribution that he had been giving to the wind engineering community in the course of the last decades. The ERC AdG 2016 led to the project THUNDERR (Figure 1.11), “Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures” whose Principal Investigator is Prof. Giovanni Solari. The acronym THUNDERR stands for THUNDERstorm and the last R points out the Roar that the project wants to imprint to this research. The project aims at detecting thunderstorms, create a database of meteorological records and scenarios, conduct unprecedented laboratory tests and numerical simulations, formulate a thunderstorm model appropriate for both atmospheric sciences and structural design, change the format of wind actions, engineering practice and the codification system, make building safer and more sustainable, bring about a profound impact on society and its economy.
The project is a natural development of the research on thunderstorm outflows and their impact on structures carried out in the last years by the GS-WinDyn Research Group\(^3\) at the Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genoa. In particular, two European projects, named “Wind and Ports” (WP, Solari et al., 2012) and “Wind, Ports and Sea” (WPS, Repetto et al., 2018), paved the way to the study of thunderstorm winds at the University of Genoa. In fact, in the context of the two projects, an extensive in-situ wind monitoring network (Error! Reference source not found.) made up of 28 ultrasonic anemometers, three meteorological stations and three LiDAR profilers, was installed in the main commercial ports of the Northern Tyrrhenian and Ligurian Sea: Savona/Vado Ligure, Genoa, La Spezia, Livorno, Bastia and L’Île Rousse.

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\(^3\) Giovanni Solari – Wind Engineering and Structural Dynamics Research Group
While the main goal of the projects was to provide the port operators with an efficient and systematic tool for medium term (1-3 days) and short term (0.5-2 h) wind forecast for the safe management and risk assessment of port areas, it was surprisingly noted that some anemometric records exhibited very different characteristics from the typical observations of synoptic, i.e. stationary and Gaussian, events (Figure 1.13). Namely, the record showed strong non-stationary and non-Gaussian wind speed signals with high-magnitude peaks developing in a very short span of time. These records were soon associated to thunderstorm events (Figure 1.14) and a completely new strand of research raised from their observation.

Figure 1.13. Stationary Gaussian depression recorded on 22 November 2011 in the port of Savona. (a) 1-h wind speed time-history; (b) distribution of wind speed: histogram and Gaussian density function; (c) 1-h wind direction time history; (d) polar histogram of the wind direction. The figure is after De Gaetano et al. (2014).
Depressions are characterized by large mean wind velocities and small gust factors. The fluctuating part of the signal can be considered as a stationary and Gaussian process. The wind direction can be dealt as constant in time. On the other hand, thunderstorm outflows are associated with small mean wind speeds and large gust factors. Turbulence is a non-stationary and non-Gaussian process. The wind direction often exhibits strong variation during the occurrence of the event. It is worth noting that there is a third class of events, named intermediate events or gust front, which are stationary non-Gaussian and somehow complicate the separation and classification of events into subsets (Solari, 2014).

1.3.2 Motivation and purpose of the thesis

The present Ph.D. thesis arises from a strong collaboration between the University of Genoa (Italy) and the Western University (London ON, Canada). A cooperation agreement for research purposes has been established in 2015. The agreement between the two universities has recently given the opportunity to convert the Ph.D. program, of which this thesis shows the final research outcomes, into a dual Ph.D. degree between the two universities. The managers and directors of the agreement are Prof. Giovanni Solari (University of Genoa) and Prof. Horia Hangan (Western University).

The main purpose of the cooperation is to combine the innovative research and technological tools from the two parts into a common framework to investigate downburst winds and characterize their physical
behavior. In fact, on one hand, the Department of Civil, Chemical and Environmental Engineering (DICCA) at the University of Genoa is the only scientific partner of the two European projects mentioned above (WP and WPS, Figure 1.12) and can provide a very large and continuously updating database of full scale measurements of downbursts recorded from different instruments. On the other hand, Western University hosts the WindEEE Research Institute (Figure 1.15), namely the largest ad-hoc wind tunnel able to reproduce non-stationary wind events, such as tornadoes and thunderstorms.

![Figure 1.15. WindEEE Dome, testing chamber.](image)

The first aim of the THUNDERR Project is to gain a deep and thorough knowledge of the physical behavior of downburst winds in the spatiotemporal domain. This allows, in a second moment, to properly interpret its characteristics also in terms of wind-structure interaction. However, the current punctual anemometric instruments, on the one hand capture very well the time progress of the event but, on the other hand, lack to provide a precise spatial characterization. The limited spatial extension of the downburst and its rapid translation across the spatial domain make, indeed, the complete characterization of the phenomenon often very challenging. For this reason, full scale campaigns often miss to provide a detailed reconstruction of the event and of its evolution across space and time. This is even more enhanced by the fact that downburst in nature does not occur as isolated system but rather occurs as embedded into the background ABL flow (Figure 1.8) and influenced by the parent cloud (cumulonimbus) translation, or storm motion (Figure 1.16). The full scale recordings cannot distinguish and quantify the weight of each of the three components on the overall downburst outflow generated and impacting on structures. The WindEEE Dome bridges the above shortcomings. On the one hand, it provides a detailed reconstruction of the spatiotemporal wind field generated inside the laboratory thanks to a very refined grid of high-frequency instruments displaced in the
three-dimensional spatial domain. On the other hand, the laboratory is capable of replicating the effects of the downburst wind, the ABL-like flow and the storm motion, independently or combined.

The concept of spatially stationary or travelling downburst was firstly introduced by Byers and Braham (1948), who mentioned that when the storm is moving very slowly the resulting outflow is radial symmetric, whereas when it is moving with respect to the ground the outflow is not symmetric and the downstream flow velocities are substantially higher than in the upstream side. The same concept was later repeated by Fujita (1985) (Figure 1.16). The translation of the downdraft with respect to the ground determines a downward horizontal momentum flux from aloft towards the ABL and, as effect, the downdraft axis results inclined at the ground causing an intensification at the leading edge of the horizontal outflow. Hjelmfelt (1988) hypothesized the same effect on the jet axis when the downburst embeds into the low-level flow in the ABL. Furthermore, as discussed below in relation to recent experimental studies, the background horizontal flow interacts and modifies the developing downburst outflow in the near-ground region.

![Figure 1.16. Effect of the storm motion on the generated downburst outflow at the ground. Figure is after Fujita (1985).](image)

In literature, the contribution of the background ABL flow and storm motion on the overall downburst system is usually neglected in either physical, numerical or analytical models or treated in over-simplistic way, for example by a vector composition. For the first time in an analytical model, Holmes and Oliver (2000) recognized the importance of the contribution of parent cloud translation and background environmental wind on the resulting horizontal wind speed through a vector composition. Analogously, Le and Caracoglia (2017) reconstructed the horizontal wind velocity as the vector summation of the radial wind speed and the constant horizontal thunderstorm translation velocity which was assumed to coincide with the background environmental wind, which is often not the case. Abd-Elaal et al. (2014) noted that the downburst recordings are influenced by the position and time in which the downdraft touches down on the ground, as well as its translation speed and direction. Chay et al. (2006) and Kim and Hangan (2007) vectorially combined the downburst outflow and the background ABL flow. This was demonstrated to be
physically inaccurate by Romanic and Hangan (2020). Furthermore, all the papers above do not provide a clear distinction between the low-level environmental flow in the ABL and the motion of the thunderstorm cell. Deeper investigation is needed to understand the correlation between these two wind systems. Ponte and Riera (2007) and Miguel et al. (2018) argued that the most critical situations in terms of downburst-structure interaction occur when downbursts are generated during the passage of squall lines. Furthermore, they assumed that the squall lines generating the downburst are carried by a fully developed extratropical cyclone and thus the velocity and direction of the storm motion coincide with those of the low-level environmental wind. However, for most types of squall lines, the line motion is controlled by two factors: the advection motion of individual cells which tends to move with the mean environmental wind averaged in the 0-6 km layer and the discrete propagation due to triggering of new cells along the leading edge of the gust front. Squall line motion can also be affected by variations in the environmental conditions along the line and thus follows the direction with more favorable environmental condition. For these reasons, Xhelaj et al. (2020) conclude that the distinction between ABL wind and storm motion is essential. Hjelmfelt (1988) implicitly outlined the importance of this distinction by describing two downburst events as recorded by radar measurements: in one case, he described a nearly-stationary downburst (i.e. very low storm motion) embedded in strong low-level environmental winds while, in the second case, he reported a fast translating downburst embedded in a calm background ABL flow. Without such distinction, any analytical model would not be capable of describing these events. Therefore, the analytical model proposed by Xhelaj et al. (2020) assumed the wind velocity to be the vector summation of three independent velocity fields, namely the radial impinging jet, the translation velocity of the thunderstorm cell and the low-level ABL wind where the downburst wind near the surface is embedded. In fact, the storm motion induces downdraft translation/advection, while the near-ground downburst outflow is perturbed by the presence of the ABL wind. Considering the only downdraft translation as interacting with the downburst itself, this scenario may be reduced to a common rational mechanics problem connecting absolute and relative velocities with respect to the translation velocity of a moving observer. For instance, Burlando (2019) assumed the time-averaged value of the along-wind component to be equal to the storm motion. By subtracting this component from the overall wind field, already deducted from the boundary layer flow velocity (evaluated as the velocity measured before the onset of the downburst), he obtained the pure vertical jet velocity with radial symmetric wind field. However, while ad-hoc experimental analyses are needed to confirm the goodness of the vectorial superposition to describe the interaction between cell translation and downburst outflow, the low-level ABL field cannot be added linearly to the overall flow system, as mentioned above, but it rather depends on the mutual direction of background wind and downburst outflow at any given point in space. Therefore, the goal of the research presented in this thesis is to achieve a thorough understanding of the complex non-linear interaction involving the three above-mentioned flow components. This is made
possible by the innovative and unique characteristics of the WindEEE Dome, where the phenomenon is reproduced through the impinging-jet technique, whereas the contribution of the background ABL wind and of the thunderstorm translation is reproduced independently through the fans located at the 60-fan wall of the testing chamber and through the inclination of the impinging-jet axis, respectively, as deeply explained in the next chapters.

The largest experimental campaign on downburst winds performed thus far has recently taken place at the WindEEE Dome and is the main subject of this thesis. It is to be noted that so far the analyses have mostly concerned the slowly-varying mean part of the experimental wind speed records, namely the component characterizing the low-frequency range of the signals and hence the major contributor to the analysis of the overall physical dynamic of the phenomenon and of its evolution in structural engineering terms. Only the main properties of the turbulent component of the signals have been addressed in the following of this manuscript, while future post-thesis works will indeed focus deeply on this aspect.

The ultimate goal of the research is to provide a suitable and reliable experimental framework to model the downburst occurrences in nature. With this aim, the experimentally produced downburst fields at the WindEEE Dome have been qualitatively compared with few full scale events recorded within the WP and WPS wind monitoring network by state-of-the-art instruments, such as the LiDAR profiler, which provides a spatial reconstruction of the flow field in the vertical plane.

1.4 WindEEE Dome and Experimental setup

1.4.1 Testing chamber (WindEEE Dome)

The Wind Engineering Energy and Environmental (WindEEE) Dome is an innovative wind testing chamber part of the Western University, Canada [Hangan et al., 2017]. It contains an inner chamber of hexagonal shape with equivalent diameter of 25 m and height 4 m; this is surrounded by a return circuit of 40 m in diameter. WindEEE is the first wind tunnel worldwide capable of creating a variety of non-stationary wind systems, such as tornadoes and downbursts, as well as boundary layers winds, at large geometric scales and Reynolds numbers, $Re$. This is achieved by individually controlling the 106 fans in the dome. 100 of them are situated in the testing chamber and distributed as follows: 8 of them are situated at the bottom of 5 sides of the chamber while the remaining 60 make up the so called “60-fan wall”, i.e. the 6th wall of the chamber, and are organized in a matrix of 4 rows by 15 columns. Each fan here is 0.8 m in diameter and operates at approximately 25 m s$^{-1}$ at a nominal power of 30 kW. 6 other fans are located in an upper chamber, above the main one, and are of larger dimensions – 2 m in diameter – with nominal power of 220 kW. The 6 upper fans produce inflow to or reverse outflow from the upper plenum that communicates with the inner chamber through a 4.5 m wide bell-mouth opening.
WindEEE operates in two modes: (i) multi-fan wind tunnel mode with the 60-fan wall (14 m wide x 4 m high) pushing air inside the chamber which recirculates above the chamber itself. Each fan can be controlled individually and accelerated over 20% of their nominal rpm in 1 s or from 0 to 100% in 5 s (ii) axisymmetric mode in which 8 fans situated at the base of the 5 peripheral walls are coupled with the 6 larger fans situated in the upper chamber. In this mode WindEEE can generate tornadoes and downburst up to 4.5 m in diameter.

Boundary layer flows can be reproduced at various scales (defined as ratio between prototype and model quantities) ranging from 1/2000 to 1/1. This is made possible by putting in place contractions, spires and roughness elements, as well as active flow conditioning by varying the configurations of the fans of the 60-fan wall and manipulating them in a time-dependent manner. This means that the ABL-like profiles generated at WindEEE are not naturally developed as in the classic boundary layer wind tunnels but are rather mechanically triggered by varying the above-mentioned parameters. For this reason, the match with ESDU standard profiles cannot be accurately complied yet.

Downbursts at WindEEE are created as impinging jets by running the 6 upper fans while the bell-mouth is kept closed. The upper chamber is thus pressurized and, once reached the desired pressure of approximately 3.4 hPa above the pressure value in the testing chamber, the louvers of the bell-mouth are opened and the air is released into the chamber. The diameter of the bell-mouth can vary from the maximum value of 4.5 m to the minimum of 1.2 m, through a series of circular rings mounted at the bell-mouth, and therefore generating a range of $H/D$ ratios, where $H$ is the height of the chamber and $D$ is the diameter of the bell-mouth. WindEEE impinging jet can be operated in both continuous or dynamics modes by using a set of louvres at the bell-mouth that can be either open or be suddenly opened. For the first time ever, a laboratory has the capability to create the three components of a thunderstorm simultaneously: (i) the downburst itself as a continuous or dynamic impinging jet (ii) the background environmental winds by using the 60-fan wall (iii) the thunderstorm translation by setting the inclination of the louvres at the bell mouth, i.e. inclination of the jet axis, to non-zero angle in respect to the vertical. This latter configuration, in fact, replicates the parent thunderstorm translation in nature whose effect is to cause an inclination of the jet axis at the ground and consequent asymmetric radial outflow.

1.4.2 Test cases and Cobra probe 3D setup

The large experimental campaign performed at the WindEEE Dome consisted in 4 tested configurations which are schematically depicted in Figure 1.17: (1) reproduces the pure vertical downburst case (radial symmetric outflow); (2) is the same of case (1) but supplemented with background ABL-like flow; (3) investigates the inclination of the jet axis to replicate the effect of thunderstorm translation (Fujita, 1985); finally, (4) combines the three above contributions. The experiments setup is depicted in Figure 1.18 and
Table 1.1. The flow field was measured at seven different azimuthal ($\alpha$) and 10 radial ($r/D$) positions, where $D$ is the diameter of the bell-mouth, using Cobra probes mounted on a stiff mast that prevented vibrations of the instruments in the flow. Cobra probes are multi-hole pressure systems designed to resolve 3 components of velocity in real time at sampling frequency $f_s = 2500$ Hz. They acquire the incoming flow within a cone of $\pm 45^\circ$. The reported accuracy of the probes is $\pm 0.5$ m s$^{-1}$ and $\pm 1^\circ$ yaw and pitch angles up to approximately 30% of turbulence intensity. The $\alpha$ locations span a range from 0°, corresponding to the direction of the incoming background ABL flow, to 180° in clockwise direction and with incremental steps $\Delta \alpha = 30^\circ$. Due to the circular symmetry of the flow, the results can be mirrored to the other half of the circle ($\alpha = 180^\circ \div 360^\circ$). The radial measurement locations cover a range from 0.2 to 2.0 with increment $\Delta r/D = 0.2$; $r/D = 0$ identifies the position of jet impingement at the ground, i.e. $x_0$ in Figure 1.17.

Figure 1.17. Schematics of the downburst-like configurations tested at the WindEEE Dome (side view); $V_B$ is the ABL flow, $D$ the jet diameter, $x_0$ the touchdown of the jet axis, and $\theta$ the jet-axis inclination.
Figure 1.18. Schematics of measurement locations (top view); $\alpha$ and $r/D$ are the azimuthal and radial locations of Cobra probes, respectively.

Table 1.1. Experiment setups: Case name (Case); Jet diameter ($D$); Jet inclination ($\theta$); Jet velocity ($W_{\text{jet}}$); ABL-flow velocity ($V_{\text{ABL}}$); Azimuthal locations ($\alpha$); Radial locations ($r/D$); Cobra probe heights ($z/z_\text{max}$), where $z_\text{max} = 0.1$ m.

<table>
<thead>
<tr>
<th>Case</th>
<th>$D$ [m]</th>
<th>$\theta$ [$^\circ$]</th>
<th>$W_{\text{jet}}$ [m s$^{-1}$]</th>
<th>$V_{\text{ABL}}$ [m s$^{-1}$]</th>
<th>$\alpha$ [$^\circ$]</th>
<th>$r/D$</th>
<th>$z/z_\text{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1a)</td>
<td>3.2</td>
<td>\</td>
<td>8.9</td>
<td>\</td>
<td>90</td>
<td>0.2:0.2:2.0</td>
<td>0.4, 1.0, 1.5, 2.0, 2.7, 4.2, 5.0 (IJ)</td>
</tr>
<tr>
<td>(1b)</td>
<td>3.2</td>
<td>\</td>
<td>16.4</td>
<td>\</td>
<td>90</td>
<td>0.2:0.2:2.0</td>
<td></td>
</tr>
<tr>
<td>(2a)</td>
<td>3.2</td>
<td>\</td>
<td>12.4</td>
<td>2.3</td>
<td>0:30:180</td>
<td>0.2:0.2:2.0*</td>
<td>0.4, 0.7, 1.0, 1.25, 1.5, 2.0**, 3.0, 4.0**, 5.0, 7.0 (IJ)</td>
</tr>
<tr>
<td>(2b)</td>
<td>3.2</td>
<td>\</td>
<td>11.8</td>
<td>3.9</td>
<td>0:30:180</td>
<td>0.2:0.2:2.0*</td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>3.2</td>
<td>30</td>
<td>12.4</td>
<td>\</td>
<td>0:30:180</td>
<td>0.2:0.2:2.0*</td>
<td>0.4***, 1.0, 3.0***, 5.0 (ABL, cases (2) – (4))</td>
</tr>
<tr>
<td>(4)</td>
<td>3.2</td>
<td>30</td>
<td>11.8</td>
<td>3.9</td>
<td>0:30:180</td>
<td>0.2:0.2:2.0*</td>
<td></td>
</tr>
</tbody>
</table>

* The location $r/D = 0.8$ is moved to $r/D = 0.75$ due to a gap between turntable edge and chamber bare floor which does not allow proper positioning of Cobra probe mast.
** Only for Case 3 and Case 4
*** Only for Case 2

In Table 1.1 $\theta$ is the jet axis inclination in respect to the vertical, $W_{\text{ij}}$ is the jet velocity at the exit of the bell-mouth, $V_{\text{ABL}}$ is the ABL-like flow velocity at the exit section of the straight flow, i.e. 60-fan wall, and $z_\text{max} = 0.1$ m is the height at which the maximum horizontal velocity is, on average, experienced. In the test configurations supplemented with ABL-like wind, 4 Cobra Probes are displaced on the other side of the wind tunnel, i.e. $\alpha = 180^\circ \div 360^\circ$, symmetrically to those recording the DB flow and oriented towards the incoming direction of the ABL wind. Little variations in the heights of Cobra Probes among the experiment configurations will be discussed later. However, the above table returns an overall idea of the different experiment setup at WindEEE.
References


Chapter II

2 Physical investigation of vertical-jet axis downburst-like impinging jets

Abstract

Downbursts are strong downdrafts that originate from thunderstorm clouds and create vigorous radial outflows upon hitting the ground. The near-surface winds in downburst outflows can reach a velocity of a strong tornado. This study is part of the comprehensive experimental research on downburst-like outflows produced as large-scale impinging jets in the WindEEE Dome simulator at Western University, Canada. The 2800 tests of downburst-like outflows carried out inside the WindEEE Dome simulator represent the largest experimental campaign on downburst winds performed thus far. The experimental database of measurements is made available to the public in its whole and described in this study. Furthermore, the current chapter focuses on the outcomes of the post-processing and interpretation of such large collection of measurements. Impinging jets are here simulated as transient phenomena so that velocity records are characterized by a sudden ramp-up of velocity, followed by the velocity peak, a short statistically-stationary region, and the final velocity slowdown, as it is expected to occur in the real case. The dynamics and turbulence characteristics of the outflow are investigated with the particular focus on the primary vortex. A dominant velocity peak that was systematically observed in all velocity records is associated with the radial advection of the primary vortex. Depending on the radial distance from the downdraft, the primary vortex was sometimes preceded by a secondary vortex that forms ahead of the primary vortex and close to the surface. Vertical profiles of mean velocity and turbulence intensity are for the first time characterized through the extent of a downburst-like event in the spatiotemporal domain. This puts the foundations for an experimental model of non-stationary downburst outflows to come. The recorded profiles rapidly change in relation to the passage of the primary vortex and consequent variation of the surface layer thickness. The largest values in the moving mean profiles are observed at the lowest measurement heights and right beyond the outer edge of the jet impingement area. The largest values of turbulence intensities are observed shortly before the occurrence of the dominant velocity peak.

Keywords: Downburst; Impinging jet; Turbulence; Transient wind; Vortex structure; Database.

2.1 Introduction

Due to their importance in various fields of engineering and atmospheric sciences, impinging jets (IJs) have vastly been investigated over the last several decades (Glauert, 1956; Bakke, 1957; Brady and Ludwig,
1963; Gauntner et al., 1970; Bray and Knowles, 1990; Colucci and Viskanta, 1996; Landreth and Adrian, 1990). This study focuses on the investigation of experimentally produced IJs with application to downburst outflows in real atmosphere, with a critical eye to the current state of the art on IJs to provide the most accurate interpretation of the physics and dynamic of the phenomenon as observed in the current experiments. Downbursts develop as strong downward currents of cold air from thunderstorm clouds. Upon hitting the surface, the wind speeds in the radially expanding outflow can exceed 75 m s\(^{-1}\) (Fujita, 1981) in the first 50-100 m from the surface. Figure 2.1a represents a schematic of the downburst spatial evolution. These high wind speeds can pose a serious hazard to structure and environment. In addition, the increasing intensity and frequency of occurrence of downbursts in many parts of the world due to climate changes (Trapp et al., 2007; Allen, 2018; Rädler et al., 2019), leads to rethink their importance and to reassess both in qualitatively and quantitatively terms their actions on the built environment (Solari et al., 2020). The complexity in the characterization of downburst winds arises from their very limited temporal and spatial extension, respectively in the order of 10 min (Hjelmfelt 1988; Zhang et al. 2018) and few kilometers in diameter (Hjelmfelt 1988). This makes downburst small-scale, highly three dimensional and unsteady flows, and causes the full scale recording as well as the physical and numerical simulations of the phenomenon to be hardly practicable. Fujita (1985) classified downbursts into microbursts (< 4 km) and macrobursts (> 4 km) based on the spatial extent of the outflow. In particular, these characteristics make the simulation of downburst-like IJs in laboratory challenging because the limited dimensions of the usual test chambers. An IJ of O(~1) m, that translates in geometric scale ratios usually in the order of 1:1000 or less, leads to time scale ratios of 1:100 or 1:1000 for velocity scale ratios of 1:10 or 1:1, respectively. Therefore, adopting for example a velocity scale ratio of 1:1, the time scale of a transient downburst lasting 10 min would correspond to maximum 0.6 s in laboratory. Besides, for a geometric scale ratio 1:1000, if one were interested in the part of the outflow where maximum velocities occur, i.e. O(100) m, this would require taking measurements within 1 cm from the surface, which is technically very difficult using physical punctual sensors. These are the reasons why laboratory simulations of downburst-like flows using IJ are very limited both in time and space resolution.

The first field measuring campaigns (e.g., Wakimoto 1982; Fujita 1985; Hjelmfelt 1988; Atkins and Wakimoto 1991) used anemometers and Doppler radars to characterize the main dynamics of downburst outflows. However, full-scale measurements have become more frequent over the last years (e.g., Gast and Schroeder 2004; Solari et al. 2012; Gunter and Schroeder 2015; Repetto et al. 2017; Burlando et al. 2017; Canepa et al., 2020) and they have employed the latest generation of downburst measuring techniques such as LiDARs, multiple Doppler radars, and high-frequency anemometers, which allow to achieve a more refined spatial resolution of the measurements at the very local scale close to the ground. These new datasets (Zhang et al. 2018) enabled more thorough analysis of both mean and turbulent characteristics of downburst
flows and provided reliable climatological descriptions of these wind events. In parallel with the field measurements, downbursts have also been investigated computationally using IJ models (e.g., Kim and Hangan 2007; Sim et al. 2016), cloud and sub-cloud models (e.g., Lin et al. 2007; Mason et al. 2009b; Orf et al. 2012), as well as mesoscale weather forecasting models (Lompar et al. 2018). While numerical models offer large diversity of results, flexibility and repeatability of the experiments under the same or different conditions, they often lack the proper representation of turbulence, instabilities, and coarse spatial and time resolutions to accurately represent all aspects of downburst outflows.

Downburst’s reproduction in wind simulators is mainly based on two approaches: buoyancy-driven currents or momentum-driven IJs. The former are typically called gravity currents (Turner 1957; Simpson 1969, 1972; Charba 1974; (Jubayer et al., 2017; Hangan et al., 2019; Junayed et al., 2019; Romanic et al., 2020)Jones et al. 2015), while the latter are simply referred to as IJs (Gutmark et al. 1978; Sakakibara et al. 2001; Chay and Letchford 2002; Xu and Hangan 2008a; McConville et al. 2009). As expected, the literature survey indicates that the number of experimental studies on downbursts is smaller than the number of either numerical or full-scale research. This discrepancy is partially due to the limitations of traditional atmospheric boundary layer (ABL) wind tunnels to replicate highly three-dimensional (3D) and non-stationary wind systems, such as thunderstorm downburst winds. At the same time, the facilities that are capable of creating downburst-like IJs (Chay and Letchford 2002; Sengupta et al. 2008; McConville et al. 2009) are sometimes limited by small scales or, for instance, continuous impingement of the jet that creates a 3D, but steady-state outflow near the surface. In addition to being 3D and localized, downburst velocities are also pronouncedly non-Gaussian (De Gaetano et al. 2014; Burlando et al. 2017; Hangan et al. 2019).

A summary of several IJ studies with various applications to downburst outflows is presented in Table 2.1. The listed studies focused typically on the investigation of the flow field in downburst outflows and surface pressures on generic buildings. The prevalence of IJ over the gravity current methods in wind engineering is also exposed in Table 2.1. Gravity current experiments surely provide a more realistic physical representation and replicability of the downburst thermodynamic properties. However, from a wind engineering point of view, the low velocities and geometric scales involved in such experiments and the need to characterize the kinematic properties of the near-ground wind field interested by the flow-structure interaction, lead to favor the IJ approach. IJs experiments are also subdivided in continuous or pulsed, depending on the duration of the jet: continuous experiments simulate a steady jet flow that is less realistic in respect to the pulsed ones, according to the short duration of downburst in the real atmosphere. The terms translating and stationary refer to whether the nozzle that produces the jet is moving parallel to the plate that the jet impinges on or is fixed. This translation is adopted to simulate the movement of the cloud generating the downburst that often is advected by the tropospheric mean flow. Currently, the largest geometric scales of experimentally produced IJ downbursts are achieved in the Wind Engineering, Energy
and Environment (WindEEE) Dome (Hangan et al., 2017) at Western University (Canada). Here, geometric scales have been reported to be as large as 1:200 or more (Junayed et al., 2019; Romanic et al., 2020).

It is important to note that most of the studies presented in Table 2.1 used continues IJs to replicate downburst outflows. However, this approach suffers from the stationarity of the outflow after the passage of the primary vortex. Therefore, the current chapter focuses on the investigation of near-surface outflows in IJs in the case of rapid release and closure of the jet nozzle because this experimental scenario is more relevant to the real thunderstorm downbursts that are highly transient.

On the other hand, several studies opted to simulate downburst-like IJs by introducing certain modifications of the traditional ABL wind tunnel apparatuses (e.g., Lin and Savory 2006; Lin et al. 2007; Aboutabikh et al. 2019). In many cases these approaches managed to accurately replicate downburst velocity records at a particular point in the flow, but they inherently lack the complete 3D flow structure of the starburst outflow that is observed in real atmosphere (e.g., Hjelmfelt 1988; Gunter and Schroeder 2015). Also, recently Jubayer et al. (2019) used a stationary IJ in the WindEEE Dome with the goal to simulate intermediate winds which are characterized as stationary, but non-Gaussian wind systems (De Gaetano et al., 2014). The transient feature of the signal associated with the primary vortex passage was excluded from their analysis.

The experimental campaign here presented is composed of three different contributions: (1) the database of measurements itself that is published online in open-access mode (Canepa et al., 2021); (2) the description of the adopted methodology, instrumentation and grid of measuring points that originate the database; (3) the analysis and interpretation of the data. The aim of these experiments is to produce and analyze a laboratory data set that generically reproduces full scale observations and at the same time serves as a calibration set for numerical simulations and analytical models of downburst-like flows. The very large number of tests carried out, which comes from a very refined recording grid and a good number of repetitions per test, enables the detailed study of the spatiotemporal evolution of the downburst front over the measuring instruments. The emphasize is on the vortex dynamics aspects and turbulent flow field characterization. The outcomes of this study in the context of the project THUNDERR will allow to build a comprehensive, physically realistic, and simply applicable experimental model, to adopt in the structural design stage.
Table 2.1. Experimental studies on IJs with application to downburst outflows. While the list is not exhaustive, it indicates a wide range of experimental approaches and apparatuses used to reconstruct downburst-like IJs. The phrase “nr” stands for “not reported”.

<table>
<thead>
<tr>
<th>Study</th>
<th>Study’s main research focus</th>
<th>D [m]</th>
<th>$U_{jet}$ [m s$^{-1}$]</th>
<th>Continues (C) or Pulsed (P)</th>
<th>Translating (T) or Stationary (S)</th>
<th>Horizontal (H) or Vertical (V) impingement plane</th>
<th>Approximate geometric scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lundgren et al. (1992)**</td>
<td>Gravity current simulation of microbursts. Vorticity, turbulence and velocity analysis; as well as scaling methodology.</td>
<td>0.045</td>
<td>nr</td>
<td>P</td>
<td>S</td>
<td>H</td>
<td>1:22200*</td>
</tr>
<tr>
<td>Yao and Lundgren (1999)**</td>
<td>Investigation of flow field in experimentally produced gravity currents. They demonstrated that the velocity under the vortex is 4 times the velocity of vortex advancement.</td>
<td>0.045</td>
<td>nr</td>
<td>P</td>
<td>S</td>
<td>H</td>
<td>1:22200*</td>
</tr>
<tr>
<td>Wood et al. (2001)</td>
<td>Velocity characteristics investigated at various positions in the flow over flat terrain, and over simple topographic features.</td>
<td>0.31</td>
<td>20</td>
<td>C</td>
<td>S</td>
<td>V</td>
<td>1:1300–1:13000</td>
</tr>
<tr>
<td>Chay and Letchford (2002)</td>
<td>Simulating the flow structure in a stationary downburst and obtaining the pressure field on a cube immersed in the flow.</td>
<td>0.51</td>
<td>10</td>
<td>C</td>
<td>S</td>
<td>H</td>
<td>1:3000</td>
</tr>
<tr>
<td>Letchford and Chay (2002)</td>
<td>Simulating the flow structure in a moving downburst and obtaining the transient pressure field on a cube immersed in the flow.</td>
<td>0.51</td>
<td>10</td>
<td>C</td>
<td>T</td>
<td>H</td>
<td>1:3000</td>
</tr>
<tr>
<td>Reference</td>
<td>Description</td>
<td>Peak Velocity</td>
<td>Pulsation</td>
<td>Scale</td>
<td>Boundary</td>
<td>Inlet</td>
<td>Ratio or Conditions</td>
</tr>
<tr>
<td>---------------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>---------------</td>
<td>-----------</td>
<td>-------</td>
<td>----------</td>
<td>-------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Choi (2004)</td>
<td>Variation of wind velocity with height during real thunderstorms and IJ-like replica in the wind simulator.</td>
<td>0.1</td>
<td>nr</td>
<td>C</td>
<td>S</td>
<td>V</td>
<td>1:10000*</td>
</tr>
<tr>
<td>Mason et al. (2005)</td>
<td>Flow visualization, wind speed and surface pressure measurements from pulsed IJ.</td>
<td>0.51</td>
<td>9</td>
<td>P</td>
<td>S</td>
<td>V</td>
<td>1:3000</td>
</tr>
<tr>
<td>Sengupta and Sarkar (2008)</td>
<td>Transient loads acting on a cube-shaped building model.</td>
<td>0.203</td>
<td>10, 16</td>
<td>C</td>
<td>S</td>
<td>H</td>
<td>1:5000*</td>
</tr>
<tr>
<td>Xu and Hangan (2008a)</td>
<td>Investigating the sensitivity of the orthonormal impinging jets with respect to scale, boundary, and inlet conditions.</td>
<td>0.0381, 0.216</td>
<td>2.8, 6.8, 11</td>
<td>C</td>
<td>S</td>
<td>H</td>
<td>1:4600–1:26200*</td>
</tr>
<tr>
<td>Mason et al. (2009a)</td>
<td>Investigating the peak transient loading conditions on a cubic model submerged in the simulated pulsed downburst flow.</td>
<td>0.51</td>
<td>9</td>
<td>P</td>
<td>S</td>
<td>H</td>
<td>1:3000</td>
</tr>
<tr>
<td>McConville et al. (2009)</td>
<td>Three different methods are examined in order to generate the transient signature of a downburst.</td>
<td>1</td>
<td>11.1, 16.13</td>
<td>C, P</td>
<td>S, T</td>
<td>H</td>
<td>1:700–1:1000</td>
</tr>
<tr>
<td>Zhang et al. (2013)</td>
<td>Surface pressure distributions on two gable-roof building models of different roof angles and high-resolution particle image velocimetry (PIV) measurements.</td>
<td>0.6</td>
<td>6.9</td>
<td>C</td>
<td>S</td>
<td>H</td>
<td>1:1670*</td>
</tr>
<tr>
<td>Jesson et al. (2015)</td>
<td>Simulating the transient aspects of downburst-like flow and investigate pressure</td>
<td>1</td>
<td>13.7</td>
<td>P</td>
<td>S</td>
<td>H</td>
<td>1:1600</td>
</tr>
<tr>
<td>Study</td>
<td>Effects of the building position and orientation with respect to the location of the downburst-like IJ on the surface pressure distribution.</td>
<td>3.2</td>
<td>8.5</td>
<td>C</td>
<td>S</td>
<td>H</td>
<td>1:100</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
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<td>-----</td>
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<td>-------</td>
</tr>
<tr>
<td>Elawady et al. (2017)</td>
<td>Dynamic response of a transmission line structure subjected to simulated downburst wind field.</td>
<td>3.2</td>
<td>nr</td>
<td>C</td>
<td>S</td>
<td>H</td>
<td>1:50</td>
</tr>
<tr>
<td>Romanic et al. (2019)</td>
<td>Transient behavior in downburst-like IJs in crossflow.</td>
<td>3.2</td>
<td>8.9, 12.3, 16.4</td>
<td>C</td>
<td>S</td>
<td>H</td>
<td>1:320*</td>
</tr>
<tr>
<td>Junayed et al. (2019)</td>
<td>Mean and turbulent characteristics of several large-scale downburst-like IJs analyzed using Cobra probe and PIV measurements.</td>
<td>3.2, 4.5</td>
<td>6.0, 8.5, 8.8, 12.1, 13.5, 19.6</td>
<td>C</td>
<td>S</td>
<td>H</td>
<td>1:250–1:1500</td>
</tr>
<tr>
<td>Romanic et al. (2020)</td>
<td>Scaling of experimentally produced downbursts.</td>
<td>3.2</td>
<td>8.9</td>
<td>P</td>
<td>S</td>
<td>H</td>
<td>1:150–1:1500</td>
</tr>
<tr>
<td>Romanic and Hangan, (2020)</td>
<td>Interaction between downbursts and ambient winds.</td>
<td>3.2</td>
<td>8.9, 6.9</td>
<td>C</td>
<td>S</td>
<td>H</td>
<td>1:150–1:1500</td>
</tr>
</tbody>
</table>

* Geometric scale was not reported in the original paper, but estimated in this study using a diameter of downburst downdrafts of 1000 m.

** These studies used density driven gravity currents instead of IJs to replicate downburst-like flows.
The rest of this chapter is organized in the following manner. Section 2.2 describes the facility and experimental setup in the WindEEE Dome. In addition, Section 2.2 reports considerations on the kinematic, dynamic and geometric parameters involved in the downburst down-scaling to the laboratory environment. It also provides specifications of the flow visualization methodology used to visualize and qualitatively inspect the generated flow field inside the chamber. The data processing methodology and tools are reported in Appendix A at the end of the current chapter. Section 2.3 describes the typical sub-component segments of the experimental velocity records after the application of the procedure reported in Appendix A. Section 2.4 presents the results of this study together with their discussion. Here, the primary vortex dynamics as well as the transient features of the downburst outflows are discussed in relation to the position in the flow field and jet intensity. This is put in close relation with the flow characteristics observed in numerous IJ studies in literature. Statistical analyses on the outflow radial and vertical velocity profiles are provided with important insights on their rapid shift during the passage of the primary vortex. The space and time variation of the turbulence characteristics is also investigated. Finally, Section 2.5 provides the main conclusions of this research and outlines the prospects for future work.

2.2 Experiment setup

2.2.1 Facility

All experiments were carried out in the WindEEE Dome at Western University, Canada (Hangan, 2014). The capacity of the WindEEE Dome to replicate atmospheric boundary layer, shear, tornadic, and downburst wind flows was presented in Hangan et al. (2017). In short, the WindEEE Dome is a hexagonal chamber of 25 m in diameter surrounded by an outer return chamber of 40 m in diameter. The 25 m diameter testing chamber has 100 fans on the peripheral walls out of which 60 are mounted on one of the six walls in a matrix of 4 rows and 15 columns and the rest of 40 fans are distributed at the base of the other five peripheral walls. An upper hexagonal plenum sits above the testing chamber and it is instrumented with six larger fans. The test chamber and upper plenum communicate through the nozzle or bell mouth situated at the ceiling level of the test chamber. By coupling the action of the 100 fans in the main chamber and the upper larger six fans WindEEE can produce a large variety of atmospheric boundary layer (ABL) flows, gust flows, tornadoes and downburst like flows. Figure 2.1b is a photograph of the WindEEE Dome testing chamber.
2.2.2 Downburst-like wind generation and flow intensities

The IJs and various downburst-like flows in the WindEEE Dome are produced as schematically depicted in Figure 2.2. Here, downbursts are simulated as pulsed IJs through the rapid opening and closing of mechanical louvres installed at the bell-mouth level resulting in an IJ that runs through the bell mouth (maximum diameter $D = 4.5$ m) before impinging on the floor of the testing chamber. The process of creating a transient IJ has two steps. First, the upper chamber is pressurized using the upper fans and by closing the louvers on the bell mouth. Second, once the pressure reaches the desired pressure of approximately 3.4 hPa above the pressure value in the testing chamber (Romanic et al. 2019), the louvers of the bell mouth are opened, and the air is released into the testing chamber. The diameter of the bell mouth can vary from the maximum value of 4.5 m to the minimum of 1.2 m. A diameter of $D = 3.2$ m was used in this study. The corresponding $H/D$ ratio was 1.17, where $H = 3.75$ m is the ceiling height of the testing chamber. It is proven that for $H/D > 1$ confinement effects in IJ applications are negligible and thus the primary vortex leading the downburst outflow can develop fully (Behnia et al., 1999; Xu and Hangan,
In the present experiments, two different intensities of IJs were considered corresponding to centerline jet velocities, \( W_{\text{jet}} \), at the exit of the bell mouth of 8.9 and 16.4 m s\(^{-1}\) (Romanic et al. 2019) and, given their ratio of about 1.8, the two cases are hereafter referred to DB1.0 and DB1.8, respectively. The inflow characteristic velocities associated with the experiments are summarized in Table 2.2. The dynamics characteristics of various IJs at the exit of the bell mouth were recently investigated by Romanic et al. (2019) and Junayed et al. (2019).

Figure 2.2. (a) Top and (b) side views of the WindEEE Dome downburst mode.

### 2.2.3 Downburst scaling

When simulating a natural fluid mechanics phenomenon is critical to define kinematic, dynamic and geometric parameters that downscale the full scale occurrence to the laboratory simulations. The scales of velocity (\( \Lambda_v \)), time (\( \Lambda_t \)) and length (\( \Lambda_l \)) between real and simulated events are interconnected through the relation:

\[
\Lambda_v = \frac{\Lambda_l}{\Lambda_t}
\]  

(2.1)

Scale is here defined as the ratio between the full scale and the model quantities. It is enough to obtain two scales and calculate the third through Eq. (2.1).

The adopted scales depend on the related quantities invoked in their assessment. Indeed, wind tunnels for wind engineering applications do not generally provide a Reynolds number similarity and thus a dependency between geometric and kinematic scales. This would be achieved only for length scales of \( O(\sim 1) \) which lead to velocity scales of \( O(\sim 1) \) that are indeed feasible in wind tunnels. However, the length scales usually adopted of \( O(\sim 100) \) or larger would lead to a modeled wind speed hundred times or more
smaller than the one at full scale, which is technically impossible to satisfy. A particular way to achieve the Re similarity is to act on the viscosity term of the Re equation and hence to change the fluid that undergoes wind tunnel simulations. However, this is at least very challenging to realize and it is not common practice. Therefore, the two scales are independent each other and, in terms of downburst winds, they have been assessed as follows.

\( \Lambda_L \) was initially determined based on the downburst-jet diameter (Chay and Letchford, 2002; Letchford and Chay, 2002; Mason et al., 2005, 2009a; Kim and Hangan, 2007; McConville et al., 2009). However, estimating the full scale downburst “diameter” at the cloud base is at least challenging. Another option to evaluate the length scale is through the height of maximum horizontal velocity, which in nature is usually found in the range 50 to 120 m above the ground level (AGL) (Goff, 1976; Hjelmfelt, 1988; Lombardo et al., 2014; Canepa et al., 2020). It follows that in the common small-scale laboratories, \( \Lambda_L \) is in the order of few thousands. The velocity scale is usually defined according to the observed maximum horizontal velocities, which in full scale are often expressed as a 1-s or 3-s gust or as a 30-s or 40-s moving average (Holmes et al., 2008; Solari et al., 2015). According to this, \( \Lambda_V \) is generally found above 3 (Chay and Letchford, 2002; Mason and Wood, 2005; Mason et al., 2005; McConville et al., 2009). The time scale can be evaluated based on the ramping time, i.e. time elapsed between the beginning of the velocity ramp-up and the peak velocity, or the time interval between the maximum and minimum wind speeds registered (Hangan et al., 2017). Romanic et al. (2020) adopted a method that first detects the time scale comparing the \( \gamma \) function, where \( \gamma \) is defined as \( \gamma(t) = \bar{v}(t)/\bar{v}_{max} \) and the cross-bar indicates the slowly-varying mean wind speed. The proper averaging window for experimental data is the one that results in the best similarity between the \( \gamma \) functions of full scale and experiments. From here the time scale is evaluated. However, \( \Lambda_T \) is commonly derived from the other two by using Eq. (2.1). Regardless of the method adopted, the time scale is usually found in the order of \( \Lambda_T = 10^3 \).

Contrary to the usual small scales of previous experimental studies in the literature, WindEEE can reproduce downburst winds at the largest scales experienced thus far in a laboratory. As mentioned above, here the geometric scale is reported as little as 200 or less, while the velocity scale is usually determined in the range 1.5 to 4 (Jubayer et al., 2017; Hangan et al., 2019; Junayed et al., 2019; Romanic et al., 2020). Consequently, also the time scale results significantly smaller in respect to those reported above.

The resulting Reynolds number \( Re \) at WindEEE is in the order of \( 10^6 \), much larger compared to what usually experienced in any other wind tunnel. This aspect will be further discussed in the manuscript in relation to full scale downburst occurrences.
velocity measurements setup

The experiments setup is depicted in Figure 2.3. The flow was measured at different $r/D$ positions using Cobra probes mounted horizontally on a heavy and stiff vertical mast that prevented vibrations of the probes in the flow. As the flow is expected to be axis-symmetric, measurements were taken only at the azimuthal angle $\alpha = 90^\circ$ (see the rack position indicated in Figure 2.2a). The ten radial positions, $r/D$, of the mast were in the range 0.2–2.0 with an increment of 0.2. The heights ($z$) of the probes on the mast were 0.04, 0.10, 0.15, 0.20, 0.27, 0.42 and 0.50 m above the testing chamber floor. Table 1 reports the probe measurement positions. All probes' head was oriented towards the geometric position of jet touchdown, i.e., $r/D = 0$. The horizontal and vertical distances were normalized to the position of maximum slowly-varying radial velocity $\tilde{V}$ in the outflow, $r_{\text{max}} = D = 3.2$ m and $z_{\text{max}} = 0.1$ m, respectively. For every $r/D$ position, each IJ experiment with the same initial conditions was repeated 20 times to inspect the repeatability of the tests and to build more statistical significance of the results; including the analysis of their variability. Therefore, a total of 2 jet velocities $\times$ 20 repetitions $\times$ 10 radial locations $\times$ 7 measuring probes resulted in 2800 velocity records, which currently represents the largest open-access experimentally produced downburst-like IJ databases known to the authors. Table 2.2 summarizes the experiments setup. Cobra probes are 4-hole pressure probes designed to resolve three components of velocity in real time. The probes can measure incoming flows within a cone of 45°. The reported accuracy of the probes is ±0.5 m s$^{-1}$ in velocity measurements and ±1° yaw and pitch angles up to approximately 30% of turbulence intensity. The sampling frequency of all velocity measurements was $f_s = 2500$ Hz. It is worth pointing out that the data acquisition system embeds a digital filter that is applied by default to the recorded signal. In fact, the system captured data at a rate of 10000 Hz which was then filtered down to the desired sampling frequency mentioned above. The cut-off frequency and cut-off frequency factor were set to 250 Hz and 0.5, respectively. It follows that any frequency above 250 Hz was reduced by a factor of 0.5. This allows to reduce the data aliasing, disruption and interference from other objects. It also accounts for the mast vibration at high frequencies due to its stiff structure. All velocity magnitudes below 1 m s$^{-1}$ were removed and converted to NaN (Not a Number) from the online-published database due to accuracy of Cobra probes. Furthermore, some velocity values were reported null by the instruments likely due to the incoming flow being beyond the probe spatial cone of measurement and, for this reason, converted to NaN values in the database. During the testing, the air temperature and air density in the chamber were approximately 296 K and 1.148 kg m$^{-3}$, respectively. With the upper chamber being pressurized, the louvers of the bell mouth were opened and 3–5 s later closed to create transient downburst-like IJs. The closing procedure was manual and hence the uncertainty of approximately 2 s. This uncertainty is an additional motivation for conducting 20 repetitions of each test. Each time series of the experiments/repetitions lasted 20 s (Figure A1 in
Appendix A), but the velocity records saved in the final database uploaded in the PANGAEA repository (Canepa et al., 2021) are 10 s long (25000 samples) (Figure 2.4), corresponding to the part of the original time series containing the downburst signals, trimmed according to the procedure described in Appendix A to delete the null signals before and after IJs.

![Diagram](image)

**Figure 2.3.** (a) Downburst measurements experiment setup. $D = 3.2$ m, $H = 3.75$ m and the Cobra probe heights are 0.04, 0.10, 0.15, 0.20, 0.27, 0.42, and 0.50 m above floor; (b) Photo of Cobra Probe rack (the red rectangle in (a)) pointing the geometrical position of downburst touchdown (i.e. $r/D = 0$); (c) Zoom in on Cobra probe details.

**Table 2.2.** Experiment setup summary

<table>
<thead>
<tr>
<th>Case name</th>
<th>$D$ [m]</th>
<th>$W_{jet}$ [m s$^{-1}$]</th>
<th>$r$ [m]</th>
<th>$r/D$</th>
<th>$z$ [m]</th>
<th>$z/z_{max}$</th>
<th>Reps</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB8.9</td>
<td>3.2</td>
<td>8.9</td>
<td>0.64-6.4*</td>
<td>0.2–2.0**</td>
<td>0.04, 0.10, 0.15, 0.20, 0.27, 0.42, 0.50</td>
<td>0.4, 1.0, 1.5, 2.0, 2.7, 4.2, 5.0</td>
<td>20</td>
</tr>
<tr>
<td>DB16.4</td>
<td>3.2</td>
<td>16.4</td>
<td>0.64-6.4*</td>
<td>0.2–2.0*</td>
<td>0.04, 0.10, 0.15, 0.20, 0.27, 0.42, 0.50</td>
<td>0.4, 1.0, 1.5, 2.0, 2.7, 4.2, 5.0</td>
<td>20</td>
</tr>
</tbody>
</table>

* The radial increment was $\Delta r = 0.64$ m. ** The radial increment was $\Delta r/D = 0.2$. 

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2.2.5 Flow visualization specifications

Flow visualization using theatrical fog fluid was carried out in addition to the Cobra probe velocity measurements. This allowed to obtain an overall qualitative interpretation of the downburst flow evolution in space and time. The visualization smoke is a water-based substance known under the name dipropylene glycol (http://www.ultratecfx.com). The percentage concentration of the composition was always between 60% and 100%. This odorless fluid creates a white cloud of fog with a medium to long hang time. The same seeding material was also used in several other PIV measurements in the WindEEE Dome (Refan and Hangan 2018; Junayed et al. 2019). A fog machine (Power Fog Industrial 9D by Ultratec Special Effects) with a nozzle and a hose was used to release the fog particles with an average diameter of 1–5 μm into the WindEEE Dome testing chamber prior to the release of the downburst. Afterwards, the visualized outflow was captured using a full-frame digital single-lens reflex (DSLR) camera with the resolution of 1920 × 1080 pixels. The whole testing chamber was in dark with the exception of two light sheets that were used to illuminate one vertical cross section in the outflow. These two thin sheets of light were created using a couple of oppositely directed stroboscopic machines running in continues mode. The images were taken at approximately 8 m away from the targeted cross section of downburst outflows and the height of the camera was about 1.6 m above the floor.

2.3 Velocity signal description

As stated above, 20 repetitions of the downburst tests were carried out for each of 10 different \( r/D \) positions using 7 vertically displaced Cobra probes, which ultimately resulted in the total of 1400 measurements for each of the two jet velocities adopted. At a fixed position of \((r/D, z)\), each repetition represents one sample of a non-stationary random process (i.e., the downburst) and ensemble averages made from 20 repetitions can be used to analyze the properties of the signal that can be attributed to deterministic features. This is relevant because the exact time of the downburst onset and the outflow detection by a Cobra probe were slightly changing from one repetition to another in the 20 s time series, while all signals had to be synchronized prior to any further analysis. For every investigated position in the flow \((r/r_{\text{max}}, z/z_{\text{max}})\), the corresponding 20 repetitions were aligned as described in Appendix A. Figure 2.4a,b show the radial velocity, \( V \), of all 20 synchronized records recorded at the positions \((r/r_{\text{max}} = 1.2, z/z_{\text{max}} = 0.4)\) and \((r/r_{\text{max}} = 1.8, z/z_{\text{max}} = 2.7)\), respectively. Each velocity record was trimmed to have an overall length of 10 s with the starting point exactly 2 s before the primary peak. The black line represents the ensemble mean of all repetitions calculated as follows:

\[
\langle V(t) \rangle = \frac{1}{M} \sum_{i=1}^{M} V^{(i)}(t)
\]  

(2.2)

where \( M = 20 \) is the total number of repetitions, \( t \) is the time, and \( V^{(i)}(t) \) is the \( i \)-th measured time series.
The two records in Figure 2.4a,b are characterized by three different segments that correspond to three distinct periods in the downburst outflows observed in real events (e.g. Holmes et al., 2008; Burlando et al., 2017, 2018). The first segment is associated with the passage of the so-called primary vortex (PV) (i.e., the ring vortex shown in Figure 2.1a) by the probe and accordingly this portion of the record is called the “PV” segment. The PV segment, comprised between time instants 1 and 3 in Figure 2.4a,b, contains the ramp-up part of the signal (time instances 1 to 2), the first peak (time instant 2 is always the global maximum as well), and the velocity slowdown after the peak (time instances 2 to 3). After the PV segment, a steady state outflow—which is called the “plateau” segment in this study (time instances 3 to 4 in Figure 2.4a,b)—is characterized by a mean fairly-constant over time with Gaussian fluctuations superimposed. In this segment, the signal fluctuations have typically different phases in different repetitions. The third segment in experimental velocity records is called the “dissipation” segment and it represents the interval when the downburst dissipates. During this segment the velocity gradually decreases to a near-zero value (time instances 4 to 5 in Figure 2.4a,b). The intensity and duration of each of the three segments vary depending on the \((r/r_{max}, z/z_{max})\) position in the outflow, as clearly shown in Figure 2.4.

2.4 Results

2.4.1 Primary and secondary vortices

Figure 2.5a shows the time series from repetition #12 recorded at the position \((r/r_{max} = 1.2, z/z_{max} = 0.4)\) for DB8.9 and their ensemble mean (black line) calculated according to Eq. (2.4); (b) Same as (a) but for the position \((r/r_{max} = 1.8, z/z_{max} = 2.7)\).
passage of the PV (Junayed et al., 2019). The associated velocities and the size of the SV are smaller than those of the PV. The intensity of the secondary peak is proportional to the PV advection velocity, which according to Yao and Lundgren (1999) is about four times smaller than the maximum wind speed in the PV. The peak velocity of about 12 m s\(^{-1}\) is the result of the superposition of advection velocity and PV circulation relative to the primary vortex center. The secondary peak velocity is about 4 m s\(^{-1}\) considering the instantaneous times series, and about 3 m s\(^{-1}\) considering its moving average. The sharp decrease of radial wind speed between the time occurrences of SV and PV (see the dashed vertical line at about 1.7 s in Figure 2.5a) may be a consequence of the predominantly upward flow between the two vortices, as highlighted in Figure 2.5b, which results in the cancelation of the horizontal (radial) velocity component. The analysis of the velocity signals shows that the SV is detected for \(r/r_{\text{max}} \geq 1.2\) and \(z/z_{\text{max}} > 0.4\). With increasing radial distance, the signature of the SV is more evident at the higher elevations. Indeed, the opposite vorticity in the PV and SV augments the vertical velocity between the vortex pair (see Figure 2.5b), which consequently elevates the head of the PV and, in turn, the maximum velocities, to higher elevations. Furthermore, the SV is overall less evident in the case DB1.8 where the higher outflow velocities may flatten the SV and therefore make it difficult to be captured by the measurements.

The SV was also observed in the gravity current experiments of microbursts in Lundgren et al. (1992) and Yao and Lundgren (1999) and other impinging jet studies (e.g., van Hout et al., 2018; Junayed et al., 2019), as well as in the idealized numerical simulations of Mason et al. (2010). However, the presence of SV is not commonly observed in the real downbursts. A weak SV is observed by Sherman (1987) in his study of a weak downburst close to Brisbane, Australia. The presence of the SV, preceding the passage of the PV, was also reported by Canepa et al. (2020) in the downburst event recorded in Genoa on May 13, 2018 by means of a LiDAR vertical profiler. Due to the relative low elevation above the ground of the recorded profile in both these real events, the top part of the SV can be hardly captured and, even more so, that of the PV.
The secondary vortex (SV) that forms in front of the primary vortex (PV): (a) time series (black line) of the radial wind speed from the repetition #12 at the position ($r/r_{max} = 1.6$, $z/z_{max} = 1.0$) for the case DB1.0 and its moving average (orange line); (b) Zoom in on the time interval between SV and PV (red dashed rectangle in (a)) with reported radial wind speed (black line) and vertical wind speeds (colored lines) at all the instrumented heights and $r/r_{max} = 1.6$; (c) flow visualization of a downburst outflow a few seconds after touchdown; and (d) a zoom in on the frontal zone (the red rectangle in (c)) with the indication of the PV and SV.

The duration of ramp-up, plateau and dissipation segments are investigated in Figure 2.6, based on the ensemble means of all repetitions. The advection velocity of the approaching PV is proportional to the maximum wind speed in the PV itself. This latter is in turn proportional to the jet velocity. At the time of maximum outflow intensity, we found indeed that this dependency is described by the relation $V_{\text{max}} \approx 1.5 \times V_{\text{jet}}$. For this reason, the ramp-up period lasts longer in the DB1.0 case compared to DB1.8. Furthermore, the duration of ramp-up can be considered almost constant throughout the radial domain. Under the hypothesis that after the PV touchdown the spin of the PV core increases while expanding outwards because of vortex stretching, the translational speed has to initially decrease to keep the ramp-up duration constant. Afterwards, flow visualization shows that the size of PV tends to increase and the spin of the PV core to diminishes, in particular when $r/r_{max}$ is larger than $1.4 \div 1.6$, hence the advection velocity of PV ideally increases further from the touchdown position. From another point of view, the advection velocity of PV can be related to the potential flow model of a vortex ring in proximity to the
ground (see, for instance, Schultz, 1990), which explains the vortex evolution in space and time in terms of interaction between the real vortex and its image placed symmetrically below the ground plane. As the vortex expands outwards, it stretches and increases its rotational speed, while at the same time it also slowly dissipates due to surface drag, entrainment of ambient air, and turbulent viscosity. While stretching increases the rotational speed and hence the PV advection velocity, dissipation terms reduce the rotation and decelerate the PV. The present experiments seem to show that the former term governs this process up to $r/r_{\text{max}} = 1.4 \div 1.6$, whereas the latter contributor becomes more relevant beyond this $r/r_{\text{max}}$. This finding is in agreement with the experimental results of van Hout et al. (2018).

The plateau segment, which is the longest lasting part of the signals, presents a decreasing trend with a reduction factor of about -1.3 and -1.2 s every $D$ for the DB1.0 and DB1.8 case, respectively. This reduction, which is again due to the contribution of dissipation, means that the plateau is roughly halved along the overall distance of $r/r_{\text{max}} = 2$.

![Figure 2.6. Duration of ramp-up, plateau and dissipation segments.](image)

### 2.4.2 Radial and vertical velocity profiles

Figure 2.7 shows the radial and vertical profiles of the slowly-varying radial mean velocity $\bar{V}$, normalized by its maximum value over the entire flow $\bar{V}$ and calculated based on a time window $T = 0.1$ s (Junayed et al., 2019), at the peak (Figure 2.7a,c) and along the plateau (Figure 2.7b,d). In this latter segment of the records the velocity can be dealt as stationary, as mentioned above. In both cases, the maximum velocities
are observed at the lowest two measuring levels and afterwards show decreasing trend. The highest velocities are observed at \( r/r_{\text{max}} = 1.0 \), i.e., \( r/D = 1.0 \), which is in accordance with many other experimental studies (Chay and Letchford, 2002; Kim and Hangan, 2007; McConville et al., 2009). The wind speed magnitude increases at first with radial distance under the influence of the favorable pressure gradient and, afterwards, decreases because of the viscous dissipation and adverse pressure gradient (Tani and Komatsu, 1966; Didden and Ho, 1985). Interestingly, the maximum wind speed at the higher heights, i.e. \( z/z_{\text{max}} \geq 4.2 \), occurs earlier in the radial domain around \( r/r_{\text{max}} = 0.8 \). Nevertheless, during the plateau segment, \( \bar{V}_{\text{max}} \) occurs at \( r/r_{\text{max}} = 1.0 \) only at the lower levels, i.e. \( z/z_{\text{max}} \leq 1.5 \); by increasing the height, \( \bar{V}_{\text{max}} \) occurs radially closer to the jet touchdown position. Figure 2.8 provides an interpretation of this aspect. It shows the vertical profiles of the vertical wind speed \( \bar{w} \) at the time of the horizontal velocity peak \( t(\bar{V}_{\text{max}}) \) (Figure 2.8a,c) and averaged along the plateau segment (Figure 2.8b,d). A quite strong downward flow component is observed along the vertical profiles for \( r/r_{\text{max}} \leq 0.8 \). The sharp decrease of \( \bar{w} \) from \( z/z_{\text{max}} = 5.0 \) to 0.4 clearly indicates that this area is still inside the downdraft. Indeed, upon exiting from the bell mouth, the jet widens in the radial direction beyond its geometric apex, defined by \( r/r_{\text{max}} = 0.5 \), due to the entrainment of ambient air and tangential shear with the surrounding (Gauntner et al., 1970; Cao et al., 2009). As the jet approaches the ground, the vertical velocity decreases rapidly while the flow streamlines are forced to spread in the radial direction due to the pressure gradient (Tani and Komatsu, 1966; Colucci and Viskanta, 1996). This region, where the jet’s momentum changes from vertical to horizontal, was named “deflection zone” by Bradshaw and Love (1959). Accordingly, the primary vortex forms at the edge of the downdraft as consequence of the high shear stress with the quiescent and overlying flow, and changes its propagation direction from vertical to horizontal upon the impingement (Landreth and Adrian, 1990). Therefore, the maximum radial velocities at the higher elevations (Figure 2.7), which are observed at \( r/r_{\text{max}} \leq 0.8 \), are not associated with the passage of the primary vortex; they are rather related to the flow in the downdraft region that in proximity to the ground, i.e. in the deflection zone, induces quite significant horizontal components as well. In the wall-jet region after the impingement, the surface layer thickness is confined underneath the primary vortex (Tani and Komatsu, 1966) and the top measurement heights record a sharp decrease of the velocity magnitude clearly detected in Figure 2.7a,c and corresponding to the flattening of the top part of the nose-shaped vertical profiles, characteristic of this stage of the phenomenon. According to the experimental findings of Didden and Ho (1985) and Landreth and Adrian (1990), the vertical flow reversal highlighted by the positive values (upward component) of the vertical velocity for \( r/r_{\text{max}} \geq 1.0 \), indicates the onset of surface layer separation near this point, which corresponds to the advancing side of the PV and the formation of the SV. In fact, the highest vertical wind speeds observed at the peak (Figure 2.8a,c) at \( r/r_{\text{max}} = 1.6 \) are the result of the strong interaction between
the inner-region vortex, i.e. secondary vortex, formed as consequence of the separation-reattachment of the surface layer, and the outer-region vortex, i.e. primary vortex. By moving downstream, the size of the SV increases in height and decreases in the streamwise direction; the coupling with the primary vortex provides a strong upward induction on the secondary vortex (Gogineni and Shih, 1997) and high upward flow velocities at the boundary between the two vortex structures (see Figure 2.5), which can eventually induce the SV ejection from the surface. Furthermore, \( \vec{w} \) decreases and is very close to 0 for \( r/r_{\text{max}} = 1.8 \) and 2.0. This is consistent with the increasing size of the PV as it spreads out from the touchdown position, which reduce the PV circulation and therefore both the \( \vec{V} \) and \( \vec{w} \) velocity components. In the plateau segment, \( \vec{w} \) is zero for all heights when \( r/r_{\text{max}} \geq 1.0 \), because this region is dominated by smaller-scale random vortices and the mean flow is along horizontal streamlines.

Figure 2.7. Normalized wind speed variation along the radial and height domain: DB1.0 (a,b) and DB1.8 (c,d) at the peak (a,c) and plateau (b,d) segments. \( \vec{V} \) is the maximum value of the slowly-varying radial velocity \( \vec{V} \) over the entire flow.
Figure 2.8. Vertical profiles of normalized vertical wind speed: DB1.0 (a,b) and DB1.8 (c,d) at the peak (a,c) and plateau (b,d) segments of the radial wind speed. $\bar{\nu}$ is the maximum value of the slowly-varying radial velocity $\tilde{\nu}$ over the entire flow.

Figure 2.9 shows the time history of the height of maximum radial slowly-varying mean wind speed $z(\bar{\nu}_{\text{max}}(t))$ along the profile, nondimensionalized with the height $z_{\text{max}} = 0.1$ m at which the maximum velocity over the entire flow is observed. $z(\bar{\nu}_{\text{max}}(t))$ is calculated as the ensemble over the 20 repetitions at each radial location $r/r_{\text{max}} > 0.8$. Since the main purpose here is to investigate the effect generated by the passage of PV on the height of maximum wind speed, the analysis is extended only to those radial positions outside of the downdraft region (see Figure 2.8). While the downburst outflow is approaching the instrument ($t < t(\bar{\nu}_{\text{max}})$), the ambient air pushed outwards by the vortex expansion is subjected to an unsteady adverse pressure gradient. Strong viscous effects arise in the near-surface region due to the adverse pressure gradient and, hence, provoke the retardation of the flow at the lower levels. At the same time the flow accelerates in the inviscid region farther from the surface and shows rather high velocity gradients (Didden and Ho, 1985). Therefore, the highest wind speeds at the beginning of the velocity ramp-up are usually experienced at rather high heights above the ground (Brady and Ludwig, 1963). However, the ramp-up of the velocity time series (orange dotted lines in Figure 2.9) is dominated by the subsequent local minimum and maximum of $z(\bar{\nu}_{\text{max}})$ which are related to the formation of the secondary vortex in the inner layer of the outflow and to its interaction with the outer layer, characterized by the presence of the primary vortex. In this situation, in fact, the maximum velocities develop at the boundary between the two layers.
(Gauntner et al., 1970). Accordingly, the minimum of $z(\bar{V}_{\text{max}})$ increases as the height of SV increases throughout the radial domain of measurements; this corroborates the observations above on the increase of the surface layer thickness by moving away from the jet touchdown. At $r/r_{\text{max}} > 1.6$, the signature of the interaction between PV and SV is experienced almost at the top of the profile, suggesting that the SV is likely to be ejected from the surface. From here, the height of $\bar{V}_{\text{max}}$ decays abruptly and reaches the minimum value of about $z(\bar{V}_{\text{max}})/z_{\text{max}} = 0.5$ after the time of the peak velocity, $t(\bar{V}_{\text{max}})$. Analogously to before, however, $z(\bar{V}_{\text{max}})$ appears higher on the ground at radial positions $r/r_{\text{max}} \geq 1.6$ due to the increase of the surface layer height. This behavior reflects the transient nature of the downburst outflow and particularly of the travelling PV which, during its passage, constrains the flow in the area at the boundary between the vortex lower end and the ground. Our findings demonstrate that the thickness, i.e. height, of the surface layer is a function of the time other than of the radial coordinate. The theoretical models developed in the literature on this topic neglect the time-dependency of the surface layer thickness and assume the height at which the velocity equals half of the maximum radial velocity as the surface layer characteristic height, constant in time (Bakke, 1957; Brady and Ludwig, 1963; Poreh et al., 1967; Oseguera and Bowles, 1988; Xu et al., 2008).
Figure 2.9. Ensemble average of 20 experiment repetitions of the height of maximum velocity $z(\bar{V}_{\text{max}})$, normalized by $z_{\text{max}} = 0.1$ m, for $r/r_{\text{max}} \geq 1.0$ and the cases DB1.0 (black line) and DB1.8 (red line). Orange lines show the ensemble average of the 20 mean wind speed time series at $z/z_{\text{max}} = 1.0$ for the case DB1.0 (shown as reference signal). Vertical gray dotted lines show $t(\bar{V}_{\text{max}})$ for the case DB1.0.

Figure 2.10 and Figure 2.11 provide a thorough characterization of the slowly-varying radial mean wind speed field $\bar{V} = \bar{V}(r,z,t)$, calculated as ensemble average across the 20 repetitions, in the form $\bar{V} = \bar{V}(z,t)$ as function of radial positions $0.6 \leq r/r_{\text{max}} \leq 1.6$. The remaining $r/r_{\text{max}}$ locations are not shown here for sake of space but are available in the published database of measurements (Canepa et al., 2021). The maps of $\bar{V}(z,t)$ show a clear maximum slightly before 2 s, aligned in time throughout the radial dimension, that reaches the highest intensity at $r/r_{\text{max}} = 1.0 - 1.2$. All these maxima correspond to vertical profiles with a clear nose shape which for these radii covers most of the vertical axes. Moving radially outwards, the
nose and maximum velocities are gradually constrained to the ground. This is mostly evident in the case DB1.0 for which the PV segment lasts longer because of the lower vortex advection velocity (see Figure 2.6). In analogy to Figure 2.6, the duration of the plateau segment is observed to decrease with radial distance due to flow dissipation. The transition to dissipation occurs faster in the case DB1.0 due to the lower flow speeds involved.

The spikes in the plateau segment of the velocity profiles track the passage of the trailing vortices. At the bell mouth outflow, the Kelvin-Helmholtz instability in the shear layers leads to the formation of vortices with a natural frequency $f$ characterized by a Strouhal number $St$ defined in terms of jet velocity $V_{\text{jet}}$ and diameter $D$:

$$St = \frac{f D}{V_{\text{jet}}} \quad (2.3)$$

In an impinging jet, $St$ also depends on the Reynolds number $Re$ and nozzle-to-plate height $H/D$, other than on the initial velocity profile, turbulence state and other factors (Hadžiabdić and Hanjalić, 2008). In the literature on impinging jets at low $Re$ ($O(10^4 - 10^5)$) and scales, $St$ is usually found between 0.35-0.65 depending on the parameters above (Yule, 1978; Tsubokura et al., 2003; Han and Goldstein, 2003). To the author’s knowledge, there are no impinging-jet studies in the literature assessing $St$ for larger $Re$ similar to those tested in the experiments here described (Section 2.4.3) Considering this range of $St$, $D = 3.2 \text{ m}$ and $V_{\text{jet}} = 8.9 \text{ m s}^{-1}$ and $16.4 \text{ m s}^{-1}$, we obtain a range of vortex shedding frequency $f = 0.97 - 1.81 \text{ Hz}$ and $1.79 - 3.33 \text{ Hz}$ for DB1.0 and DB1.8, respectively, which, despite being rather wide, qualitatively matches with the occurrence rate of velocity spikes observed in Figure 2.10 and Figure 2.11. The wiggles in the velocity vertical profiles may also be intrinsically due to the limited number of experimental repetitions which may not provide statistical convergence of the results and a thorough description of the standard deviation of the experiments, whereas the mean part and deterministic features of the wind speed signals are well retained and modeled. It follows that spurious oscillations might arise in the reconstruction of the ensemble wind speed signal. However, an extension of repetition numbers would have overly increased costs and duration of the experimental campaign.
2.4.3 Turbulence intensity and statistical properties of downburst-like outflows

Several studies reported non-Gaussian properties of full scale thunderstorm flow fields (see for instance De Gaetano et al., 2014). Figure 2.12 shows the values of skewness and kurtosis as function of the radial and height position for the plateau segment of the records. Because the plateau segment represents the steady-state phase of the outflow, the ensemble mean of multiple repetitions filters out fluctuations around the
mean resulting in a nearly Gaussian statistics. The radial location $r/r_{\text{max}} = 0.2$ is horizontally located in proximity of the geometrical downdraft center where the flow has a predominant vertical component; the very little radial velocities detected here cause the related distribution to deviate from the reference Gaussian properties. The same partly holds at the larger radial locations and higher heights of measurements, where the flow loses momentum and disperses in a more three-dimensional pattern. The larger velocity dispersion from $r/r_{\text{max}} = 1.0$ causes the kurtosis to assume values below 3 and a decreasing trend up to $r/r_{\text{max}} = 2.0$ where $\kappa = 2.5$.

![Figure 2.12](attachment:image.png)

Figure 2.12. Dependency of skewness ($\gamma$) and kurtosis ($\kappa$) on height and radial position in the outflow.

The velocity histograms for the PV segments are depicted in Figure 2.13. Here, the differences in respect to the Gaussian distribution are more pronounced than in the plateau segment. As expected, velocity PDFs are asymmetric towards the high values ($\gamma < 0$) in the area subjected to the high radial wind speeds produced by the passage of PV, i.e. $0.8 \leq r/r_{\text{max}} \leq 1.8$ and $0.4 \leq z/z_{\text{max}} \leq 2.7$. Outside this region, wind speeds are more concentrated at low values ($\gamma > 0$) due to the loss of momentum of the flow. The velocity distributions tend towards the Gaussian distribution at the radial locations closer to the jet touchdown. However, no clear radial trend can be identified.
Figure 2.13. DB1.0 case: velocity histograms of the PV segment (0.25 s on each side of the peak) of 20 downburst outflows for all heights \( z/z_{\text{max}} \) and all radial positions \( r/r_{\text{max}} \). The values of kurtosis \( k \) and skewness \( \gamma \) are included.

Turbulence intensity characteristics are well modeled and retained thanks to the high sampling frequency of the experimental measurements, i.e., \( f_s = 2500 \text{ Hz} \).

Table 2.3 shows the main turbulence properties, averaged along the vertical profile, at all radial locations in the outflow. The calculated parameters are:

Temporal mean \( \bar{I}_V(r,z) \) of the slowly varying turbulence intensity \( I_V(r,z,t) \) given by:

\[
I_V(r,z,t) = \frac{\sigma_V(r,z,t)}{\bar{V}(r,z,t)}
\]

\( \bar{V} \) is the slowly-varying radial mean velocity extracted applying a moving average period of \( T = 0.1 \text{ s} \) (Junayed et al., 2019), and \( \sigma_V \) is the slowly-varying standard deviation of the residual turbulent fluctuations, \( V' \), given by \( V'(r,z,t) = V(r,z,t) - \bar{V}(r,z,t) \). The temporal mean of \( I_V(r,z,t) \) was performed over the time interval included between the beginning of the velocity ramp-up period in the PV segment and the final part of the dissipation segment (instances “1” to “5” in Figure 2.4a,b).

Skewness \( \gamma_{V'} \) and kurtosis \( \kappa_{V'} \) of the reduced turbulent fluctuation \( \tilde{V}'(r,z,t) \) given by:
\[
\bar{V}'(r, z, t) = \frac{V'(r, z, t)}{\sigma_V(r, z, t)}
\]  

(2.5)

Similar to Zhang et al. (2019) and Canepa et al. (2020), extremely large and unphysical values of the turbulence intensity \( I_V > 0.2 \) corresponding to very low values of the slowly-varying mean velocity \( \bar{V} < 5 \text{ m s}^{-1} \) are removed from the analysis.

Table 2.3. Mean slowly-varying turbulence intensity \( \bar{I}_V \); skewness \( \gamma_{V'} \); kurtosis \( \kappa_{V'} \). The reported values are averaged over all heights.

<table>
<thead>
<tr>
<th>Case</th>
<th>( r/r_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>( \bar{I}_V )</td>
<td>DB1.0</td>
</tr>
<tr>
<td></td>
<td>DB1.8</td>
</tr>
<tr>
<td>( \gamma_{V'} )</td>
<td>DB1.0</td>
</tr>
<tr>
<td></td>
<td>DB1.8</td>
</tr>
<tr>
<td>( \kappa_{V'} )</td>
<td>DB1.0</td>
</tr>
<tr>
<td></td>
<td>DB1.8</td>
</tr>
</tbody>
</table>

The high flow mixing in the jet impingement area contributes to the flow turbulence. Outside the downdraft region, i.e. starting from \( r/r_{\text{max}} = 0.8 \), \( \bar{I}_V \) increases almost linearly with radial location. At first, in fact, the radial flow component becomes predominant, the primary vortex leads the downburst outflow and its downward induction has a stabilizing effect on the wall-jet flow (Shih and Gogineni, 1995). However, in analogy to what was commented for Figure 2.12, from \( r/r_{\text{max}} = 1.0 \) complex three-dimensional structures emerge and the turbulence intensity increases until the breakaway of the surface layer at large radial distances from the touchdown. \( \bar{I}_V \) appears overall greater in the case DB1.8. The ratio between DB1.8 and DB1.0 (not shown here) increases as well with a quasi-linear trend outside the impingement region up to \( r/r_{\text{max}} = 1.4 \), where the ratio is equal to 1.53. Overall, the turbulence intensity values are in good agreement with those generally found in literature on full scale downburst events. The recent findings by Canepa et al. (2020) on downburst vertical profiles showed that the values of \( \bar{I}_V \), averaged along the height, are in the range 0.08–0.09. Solari et al. (2015) and Zhang et al. (2018, 2019) reported \( \bar{I}_V = 0.12 \) averaged over a large set of downburst outflows extracted from ultrasonic measurements. In our study, \( \bar{I}_V \) averaged along both the height and radial dimensions assumes values of 0.094 and 0.124, respectively for DB1.0 and DB1.8, which is in the range of values obtained for the actual events in the above studies.

Figure 2.14 shows the parameter \( \mu(r, z, t) \) evaluated as ensemble average of the 20 single time series, i.e. experimental repetitions, of \( \mu \) at each position \( r/r_{\text{max}} \geq 1.0 \) and \( z/z_{\text{max}} = 0.4, 1.0, 2.0 \) and 4.2.

\[
\mu(r, z, t) = \frac{l_V(r, z, t)}{\bar{I}_V(r, z)}
\]  

(2.6)
While it is usual in the literature to assume $\mu = 1$, Solari et al. (2015) and Zhang et al. (2018, 2019) noticed asymmetry of $\mu(t)$ around the main velocity peak, i.e. the PV. This asymmetry is more pronounced in the present experiments due to the smoother surface compared to the fully turbulent environment in nature as well as to the different Reynolds numbers involved and defined as:

$$Re = \frac{V_{\text{jet}} D}{\nu}$$

(2.7)

where $\nu = 1.48 \times 10^{-5}$ m$^2$s$^{-1}$ is the kinematic viscosity of air at $15^\circ$C, $V_{\text{jet}}$ and $D$ are the jet velocity and diameter, respectively, of either full scale or experimentally produced downburst. The two cases here investigated, i.e. DB1.0 and DB1.8, provide Reynolds numbers $Re = 1.92 \times 10^6$ and $3.55 \times 10^6$, respectively, whereas full scale downbursts typically present $Re$ in the order of $10^9$. The same holds if $Re$ is evaluated as function of the maximum velocity over the entire flow and its height of occurrence, $\hat{V}$ and $z_{\text{max}}$, respectively.

Concurrently with the increase of velocity in the PV segment, $\mu$ drastically increases and reaches the related maxima shortly before the occurrence of $\bar{V}_{\text{max}}$ (vertical gray dotted lines). The maximum value $\mu = 3.28$ is detected at $r/r_{\text{max}} = 1.2$ and $z/z_{\text{max}} = 0.4$ for the case DB1.8, which shows overall greater values in respect to DB1.0, as expected. In general terms, $\mu$ at the peak increases with the radial distance up to $r/r_{\text{max}} = 1.4$ and decreases afterwards, while is found to decrease along the height. Furthermore, a first spike of $\mu$, sometimes higher than that related to $\bar{V}_{\text{max}}$, is observed at the beginning of the velocity ramp-up in the range of measurement positions $1.4 \leq r/r_{\text{max}} \leq 1.8$ and $0.4 \leq z/z_{\text{max}} \leq 2.0$. The temporal and spatial occurrence suggest the correlation of the first peak with the high shear developed at the boundary between primary and secondary vortex. Upon reaching the maximum, $\mu$ decreases to a local minimum below the unity, which is recorded in correspondence of $t(\bar{V}_{\text{max}})$ or slightly later. The plateau segment is the longest segment in the velocity records and thus represents the main contribute to the evaluation of $\bar{I}_V$. Accordingly, $\mu$ is here close to the unity.

Therefore, in analogy to the full scale measurements carried out by Zhang et al. (2019) and Canepa et al. (2020), a sharp peak of the turbulence intensity is observed slightly before the occurrence of the peak velocity. This behavior of $\mu$, observed in both full scale and controlled conditions, surely represents an important signature of the passage of the primary vortex during the downburst outflow. The radial and height locations where the asymmetry of $\mu$ is clearly recognizable corroborate this observation. As reported above, the maximum values of $\mu$ are observed at the radial positions $r/r_{\text{max}} = 1.2 - 1.4$, namely radially further from the location of the recorded maximum wind speed, i.e. $r/r_{\text{max}} = 0.8 - 1.0$ (see Figure 2.7). Hjelmfelt (1988) first demonstrated that the maximum velocities underneath the vortex follow the vortex center in time and are thus recorded spatially behind its radial location. The same findings are also found
in experimentally produced downbursts (Alahyari and Longmire, 1995; Junayed et al., 2019) and seem to be confirmed in our analysis by assuming that the maxima of $\mu$ occur in correspondence of the passage of PV. For $z/z_{\text{max}} > 2.0$, where the trace of the travelling PV has basically disappeared, the asymmetric trend of $\mu$ is almost lost and the entire signal fluctuates around the mean (i.e. $\mu = 1$).

**Figure 2.14.** Ensemble average of 20 experiment repetitions of $\mu$ (2.6), for $r/r_{\text{max}} \geq 1.0$ and $z/z_{\text{max}} = 0.4, 1.0, 2.0, 4.2$ and the cases DB1.0 (black line) and DB1.8 (red line). Orange dotted lines show the ensemble average of the 20 mean wind speed time series for the case DB1.0 (shown as reference signal). Vertical gray dotted lines show $t(V_{\text{max}})$.

In analogy to Figure 2.9, Figure 2.15 shows the variation of the height of maximum radial turbulence intensity along the velocity record for the radial positions outside the impingement zone that are actually affected by the passage of the PV, i.e. $r/r_{\text{max}} > 0.8$. At the beginning of the velocity ramp-up and for radial positions $r/r_{\text{max}} \leq 1.4$, turbulence is convected to the higher levels in the free-shear layer due to the viscous-inviscid interaction (Gogineni and Shih, 1997). From approximately $r/r_{\text{max}} = 1.4 - 1.6$ the SV forms and turbulence mostly concentrates at the boundary with PV. Concurrently with the passage of the primary vortex, few instances before the occurrence of the peak velocity (vertical gray dotted lines), $z(l_{V_{\text{max}}})$ decrease quite rapidly to the height of occurrence of the maximum $\mu$ observed in Figure 2.14, i.e. $z(l_{V_{\text{max}}})/z_{\text{max}} < 2$. In correspondence of $t(V_{\text{max}})$, as a result of the unsteady adverse pressure gradient induced by the passage of the primary vortex (Didden and Ho, 1985), the height of maximum turbulence intensity suddenly switches to higher levels and remains fairly constant around $z(l_{V_{\text{max}}})/z_{\text{max}} = 4$ throughout the plateau segment of the velocity due to the increase of the surface layer thickness. However, the same behavior is only partly detected at larger radial positions $r/r_{\text{max}} > 1.6$, where the change of $z(l_{V_{\text{max}}})$ is less pronounced and the maximum turbulence intensity settles at lower heights.
Overall the height of maximum turbulence intensity shows a sudden switch in relation to the peak velocity, similarly to what was observed for $z(\bar{V}_{\text{max}})$ (Figure 2.9). Contrary to $z(\bar{V}_{\text{max}})$, however, the switch here is from the lower to the upper heights.

![Graphs showing the height of maximum turbulence intensity](image)

Figure 2.15. Ensemble average of 20 experiment repetitions of the height of maximum turbulence intensity $z(I_{V_{\text{max}}})$, normalized by $z_{\text{max}} = 0.1$ m, for $r/r_{\text{max}} \geq 1.0$ and the cases DB1.0 (black line) and DB1.8 (red line). Orange lines show the ensemble average of the 20 mean wind speed time series at $z/z_{\text{max}} = 1.0$ for the case DB1.0 (shown as reference signal). Vertical gray dotted lines show $t(\bar{V}_{\text{max}})$.

Figure 2.16 and Figure 2.17 show the profiles of the slowly-varying standard deviation and turbulence intensity, $\sigma_V(r, z, t)$ and $I_V(r, z, t)$. The peak of the turbulence intensity, mirrored in the diagrams of the standard deviation, is again observed shortly prior to the occurrence of the maximum radial velocity, confirming the assumption made above. These peaks grow radially in magnitude, particularly for $r/r_{\text{max}} >$
1.0. The vertical profile of $I_V$, at the time of maximum intensity, shows a nose shape that covers a larger vertical extension by moving along the radial direction. The higher values of $I_V$ at the top of the profile, that are clear for $r/r_{\text{max}} > 1.0$, are caused by the decrease of the radial velocity at those elevations following the nose-like vertical shape.

Figure 2.16. Profiles of $\sigma_v(z/z_{\text{max}}, t)$ for $0.6 \leq r/r_{\text{max}} \leq 1.6$ and DB1.8.

Figure 2.17. Same as Figure 2.16 but for $I_v(z/z_{\text{max}}, t)$.

Figure 2.18 shows the maps of the second-order moment Reynolds stress $\overline{u'w'} = \overline{u'w'}(z, t)$ as function of the radial coordinate, in analogy to Figure 2.10 and Figure 2.11, for the case DB1.8. This analysis is carried
out in order to evaluate the momentum flux across the vertical section and provide insights into the flow direction at the different elevations above the ground. The change of sign of this parameter eventually identifies the separation between inner and outer surface layer correlated with the location of the nose tip of the velocity vertical profile.

The ambient air pushed outwards by the vortex expansion, before the PV segment of the velocity records, is slowed down at the lower elevations because of friction with the ground and assumes a logarithmic-type vertical profile, as shown in Figure 2.9. Consequently, the momentum flux is directed downward along the whole vertical extension. With the passage of the PV and of the subsequent trailing vortices, the surface layer depth reduces and the tip of the nose-shaped profile moves gradually closer to the ground as the vortex advances radially outwards. The red area indeed defines the elevation range above the nose of the vertical profile where the velocity gradient is reversed with respect to a boundary layer flow.

![Figure 2.18. Profiles of $u'\bar{w}'(z/z_{max}, t)$ for $0.6 \leq r/r_{max} \leq 1.6$ and DB1.8.](image)

The Gaussian and stationary properties of the reduced turbulent fluctuations, $\bar{V}'$, (Solari et al., 2015; Zhang et al., 2018), are well retained in the flow generated during our experiments. $\bar{V}'$ has always nearly zero mean and unit standard deviation; whereas the skewness and kurtosis are close to $\gamma_{\bar{V}'} = 0$ and $\kappa_{\bar{V}'} = 3$, respectively. The kurtosis is found to be higher in the case of DB1.8, where it shows a quasi-periodic trend with maximum of $\kappa_{\bar{V}'} = 3.211$ at $r/r_{max} = 0.6$, while it remains approximately constant around $\kappa_{\bar{V}'} = 2.9$ for DB1.0. The skewness assumes values $\gamma_{\bar{V}'} > 0$ within the impingement region while, outside of that region it fluctuates around zero.

The Kolmogorov’s similarity proves that the energy cascade in the inertial subrange is proportional to $\pi^{-\frac{5}{3}}$, where $\pi$ is the frequency. In analogy to synoptic ABL winds, several studies in literature on full scale
downburst events demonstrate that the power spectral density (PSD) of $\tilde{V}'$ follows the law $n^{\frac{5}{3}}$ (Holmes et al., 2008; Solari et al., 2015; Burlando et al., 2017). Furthermore, Junayed et al. (2019) investigated parametrically a set of experimentally produced downburst flows at the WindEEE Dome varying the Reynolds number $Re$ and the ratio $H/D$, where $H$ is the height of the testing chamber and $D$ the jet diameter. They found that the high frequency end of the spectra of the reduced turbulent fluctuation matches well with the full scale observations. In particular, the slope $n^{\frac{5}{3}}$ finds a very good fit for the higher values of $Re$ and for $H/D > 1$. In this situation, in fact, the vortex forms fully and the larger range of scales allows a better match with the typical inertial subrange behavior. Figure 2.19 shows the PSD of $\tilde{V}'$ for DB1.0 which again corroborates the observations above.

![Figure 2.19](image)

Figure 2.19. PSD of the reduced turbulent fluctuation $\tilde{V}'$ for DB1.8, matched with $n^{\frac{5}{3}}$ profile (dashed lines). Note that the repetition #18 at the radial position $r/D = 0.2$ was excluded from the analyses due to false readings in the measurement record.
2.5 Conclusions and prospects

This chapter is an in-depth analysis of a large set of experiments on downburst winds performed at the WindEEE Dome, at Western University in Canada, as part of the project THUNDERR (Solari et al., 2020). The aim of these experiments is to produce and analyze a laboratory data set that generically reproduces full scale observations and at the same time serves as a calibration set for numerical simulations of downburst-like flows. The dynamic characteristics of spatially-stationary, non-steady vertical downburst winds are investigated by means of a refined spatial and temporal grid of Cobra probes measurements at 10 radial positions, 7 vertical positions repeated 20 times to achieve some statistical significance. The database containing the whole of the experimental measurements at the base of this chapter is published at the online repository PANGAEA (Canepa et al., 2021) and described here along with a new procedure adopted to synchronize the velocity time series among the experimental repetitions.

In order to facilitate comparison with the full scale data collected under the same THUNDERR Project, the wind speed records were decomposed into three main segments corresponding to three different time phases observed during full scale downburst outflows and associated to: (1) passage of the primary vortex; (2) steady state condition, i.e. plateau stage, of the velocity signal; (3) dissipation stage of the downburst. (1) mainly presented asymmetric PDF velocity distributions concentrated towards high values, while (2) showed mostly gaussian properties with the exception of the downdraft region. Vortex shedding frequency peaks are identified as a result of the jet exit shear layer instability and can be expressed as a function of the Strouhal number $St$. The high mixing and three-dimensionality of the flow in the downdraft region and at the larger radial locations due to the surface layer separation, provide an increase of turbulence.

The primary vortex advection velocity is dependent on the jet intensity and, consequently, the duration of the ramp-up period changes accordingly. Lower inflow wind speeds cause less energetic primary vortices that dissipate earlier. The secondary vortex often forms ahead of the outflow at higher radii as consequence of the dynamic separation-reattachment of the surface layer due to the passage of the primary vortex. The large number of experiments allows to statistically address the time evolution of the outflow radial and vertical profiles. At the beginning of the ramp-up, the maximum wind speed occurs at the higher heights due to the viscous-inviscid interaction; $z(\bar{V}_{\text{max}})$ is then found to increase with radial distance due to the increase in height of the interface between primary and secondary vortices. During the primary vortex passage $z(\bar{V}_{\text{max}})/z_{\text{max}}$ decreases very rapidly to values below 1 and fluctuates around it during the plateau segment. The rapid variation of $z(\bar{V}_{\text{max}})$ is thus a consequence of the time-dependency of the surface layer thickness which, at first, is driven by the interaction between the primary and secondary vortex and, later, is constrained underneath the vortex due to the suction produced by it on the surface. At the larger radii, the surface layer detaches from the surface due to the change of surface-pressure gradient upon the passage
of the primary vortex. The theoretical models provided by literature on downburst outflows neglect the time-dependency of the surface layer thickness. The implications of this rapid change of $z(\bar{V}_{\text{max}})$ on the structural dynamics definitely deserve future studies.

The values of turbulence intensity found in the experimental signals match to a very good extent those observed for large datasets of real thunderstorm events (Solari et al., 2015; Zhang et al., 2018, 2019; Canepa et al., 2020). The highest values are found shortly prior to the occurrence of the peak wind speed. The peak values of $\mu(t) = I_V(t)/\bar{I}_V$ are observed at radial locations and heights correlated with primary vortex passage. The maximum values are observed at $z(I_{V_{\text{max}}})/z_{\text{max}} < 2$ and $r/r_{\text{max}} > 1.0$. These maxima correspond to vertical profiles with a nose-like shape extending higher by moving outwards in the radial direction. From here, the occurrence of $I_{V_{\text{max}}}$ is observed to switch to higher heights due to the unsteady pressure gradient upon the passage of the primary vortex. A first peak of the turbulence intensity is sometimes observed at the beginning of the velocity ramp-up and is likely to be related to the primary-secondary vortex interaction. The rapid change in magnitude of the turbulence intensity reflects the recent findings of Zhang et al. (2018, 2019) and Canepa et al. (2020) on full scale events where a similar increase and decrease of $I_V$ was still observed immediately before and after the time occurrence of $V_{\text{max}}$, respectively. This makes again questionable the usual hypothesis $I_V = \bar{I}_V$ adopted in literature, namely turbulence intensity invariant with time, and may have significant implications on the analysis of the dynamic response of structures to thunderstorms. Furthermore, the rapid change of the vertical profiles of $I_V$ in correspondence of the passage of the primary vortex emphasizes once again the transient behavior of downburst winds in terms of wind engineering aspects. The asymmetric behavior of $\mu$ is also found in controlled conditions other than in nature as it had already been demonstrated. This may have benefits on the procedures adopted for the systematic detection and extraction of thunderstorm records from large databases of wind measurements. We suggest, therefore, the implementation of $\mu$ as well as $z(I_{V_{\text{max}}})$ in these techniques.

For the first time, a spatiotemporal $(r,z,t)$ characterization of the spatially-stationary non-steady downburst flow field has been presented, with focus on the slowly-varying mean wind speed and turbulence intensity. The database of measurements uploaded to PANGAEA (Canepa et al., 2021) is here investigated and will form, in addition to parallel CFD and analytical solutions, the skeleton of a refined experimental model to reassess the design codes in terms of fluid-structure interaction.

Future work in the context of the experimental campaign at the WindEEE Dome will address other important aspects of downburst winds. The present experiments are limited to a 2D axisymmetric flow field. In future studies we aim to expand the investigation to 3D by incorporating large scale PIV measurements. A future goal will be to reconstruct the complex mechanisms that take place during the occurrence of real downburst events, where the downburst is not an isolated system but rather interacts with
the background ABL wind and thunderstorm cloud translation. This complex interaction is expected to have important effects on the near-surface outflow impacting on structures. Furthermore, the future work will also quantify the effects produced by the terrain roughness on downburst winds to achieve the most refined and complete physical characterization of this phenomenon.

Data availability

The experimental data presented and processed in this research are made available using the data publisher for Earth & Environmental Science PANGAEA (https://www.pangaea.de) (Canepa et al., 2021).

Appendix A

Data synchronization was performed through a time-dependent spectral analysis of the times series. To describe this methodology, Figure A1a,d depict the time-series (black line) of the radial wind speed and the corresponding moving average (orange line) evaluated over a time window of 500 samples (i.e., 0.2 s). Figure A1b,e are the periodogram power spectral density (PSD) of the velocity records calculated using $2^7$ points in the segmented windows. The goal here is to divide a velocity record into shorter portions and then independently compute the fast Fourier transform on each of the segments. The spectra ($S_k$) at the frequency $k$ is computed using the short-time discrete fast Fourier transform in the form of modified periodograms as follows:

$$S_k = \sum_{n=0}^{N-1} h_n V_n e^{-i2\pi k n N}$$

where $N$ is the number of velocity readings in each spectral window, $V_n$ is the wind speed at the $n$-th reading in the window, $k \in (0,1,2,\ldots,N-1)$, $h_n$ is the periodogram modifier in the form of Hamming window and $i = \sqrt{-1}$. This study uses a 50% overlap between adjacent windows to reduce the effects of windowing near the frame edges. The power spectral density ($P_k$) is obtained as:

$$P_k = \frac{1}{f_s} \frac{2|S_k|^2}{H}$$

where $H = \sum_{n=0}^{N-1} h_n^2$ is the window normalization constant and $f_s = 2500$ Hz is the sampling frequency.

Lastly, the normalized power content ($P_t$) in Figure A1c,f, i.e. the red line, is calculated as:

$$P_t = \frac{1}{\bar{P}} \sum_{k=0}^{f_s/2+1} P_{k,t}$$

where $\bar{P} = \max_t (P_t)$ and $t$ is the time. The proposed methodology for aligning the velocity signals uses the moving average of $P_t$ calculated every 10 samples (which correspond approximately to 0.5 s), hereafter $\tilde{P}_t$, with the threshold value of $\tilde{P}_t = 0.1$ as the starting pivot point for all 20 experiment repetitions. Then, the first local maximum after this point corresponds to the primary peak (time instant 2) and the end of the
primary peak is the first local minimum after the peak itself (time instant 3). Afterwards, the plateau segment starts and ends with the last local maximum in the record (time instant 4). Finally, the end of downburst record is when $\tilde{P}_r$ crosses the threshold value for the last time (time instant 5).

In repetition #9 (Figure A1a), the nozzle releasing the jet was opened at about 7 s into the sampling. After the bell mouth louvers opened, the vortex ring produced by the downdraft in the form of a PV hit the ground, expanded radially, and reached the Cobra probe (time instance 1 in Figure A1a). The measurements continued until the downdraft was terminated approximately 5–6 s from the bell mouth opening. The passage of the PV by the Cobra probe is marked by the first peak in the time series which also corresponds to the time instant “2” in Figure A1a. Since the first peak occurs systematically in all analyzed velocity records, this dominant feature of the flow was used to shift the signals in time domain and synchronize them. Therefore, the time instant at which the power content (Figure A1c,f) is the maximum was used as a reference time for the alignment of velocity records from multiple repetitions of the same experiment.

Figure A1. Downburst test repetitions #9 and #20 at the position ($r/r_{max} = 1.0, z/z_{max} = 1.0$) and for the case DB8.9: (a,d) time series of radial wind speed (black line) and its moving average (orange line); (b,e) periodogram of power spectral density as $10\log_{10}(P_k)$; and (c,f) normalized power content.
References


Chapter III

3 Physical investigation of vertical-jet axis impinging jet embedded in ABL wind

Abstract

Research on thunderstorms has been one of the main topics in wind engineering for the last few decades. Downburst winds are highly transient and three-dimensional phenomena. Their limited spatiotemporal structure makes the anemometric measurements in nature inadequate for reconstructing their complex flow fields. As a result physical simulation are often the only tool capable of investigating the influence of the individual flow components on the resulting near-ground wind impacting on structures. In the framework of the project THUNDErr, an experimental campaign has been carried out at the WindEEE Dome at Western University, Canada. The present study analyzes for the first time the three-dimensional interaction between downburst (DB) outflows, produced as large-scale impinging jets, and background atmospheric boundary layer (ABL) winds. It is found that the generated near-surface outflow is asymmetric, and a zone of maximum wind speeds develops at interface between DB and ABL winds. The overall highest outflow intensities are observed at the front between the counter directed flows. The time variability of the front is investigated using the synchronization of all signals across the chamber based on the opening time of the upper bell mouth releasing the jet. The three-dimensional structure of the flow is studied thanks to a refined spatiotemporal grid of measuring Cobra probes. 10 repetitions per each experiment were conducted in order to build minimum statistical relevance of the results. The passage of the primary vortex produces a drastic drop of the height of maximum radial velocity, predominantly in the ABL-streamwise direction. Finally, turbulence properties are characterized with important findings on their behavior along the vertical profile; here, a sudden spike occurs right before the occurrence of the maximum wind speed and is well recognizable at the lower heights, affected by the passage of the primary vortex. Turbulence intensities are overall higher where DB and ABL collide against each other.

Keywords: Downburst; Impinging jet; ABL wind; Background wind; Crossflow; Flow interaction; Wind simulator; Transient wind; Turbulence; Vertical Profile.

3.1 Introduction

Downbursts are cold descending winds from cumulonimbus clouds which, upon hitting the ground, diverge radially in strong outflows that impact low- and mid-rise structures (Solari et al., 2015). They are non-stationary phenomena that occur under mesoscale convective conditions and develop over few kilometers
and over very limited time of tens of minutes. However, their space and time characteristics are highly susceptible to atmospheric conditions and dependent on the particular climatic regime in the different regions of the world (Burlando et al., 2018). For this reason, their characterization and standardization in design codes steered discussions inside the wind engineering community for the last few decades. Design codes are, indeed, still based on the Davenport chain, built to determine the wind loading and response of structures subjected to large scale cyclones (Davenport, 1961, 1967).

Furthermore, the traditional anemometric instruments capture very well the time evolution of the phenomenon, whereas they lack to reconstruct accurately their spatial structure. On the one hand, in fact, the transient and dominant feature of a typical downburst record, i.e. the peak of the signal, is usually well defined and represents the passage of the so-called primary vortex (PV) over or nearby the measuring instrument. The PV forms at the level of the parent thunderstorm cloud, triggered by the strong instability between the cold and dense buoyancy-driven downdraft and the surrounding environment. Upon reaching the surface, the PV changes its travelling direction from vertical to horizontal and propagates radially. The strong vorticity inherent in the vortex core produces the well-known nose-shaped profile with maximum horizontal velocities underneath the vortex itself, in the range 50-120 m AGL, and decreasing velocities above (Goff, 1976; Hjelmfelt, 1988). On the other hand, however, the punctual measurements completely miss to provide information on the physical interactions in the flow. Therefore, that the spatial evolution of the outflow can be addressed only by integrating such measurements with advanced measuring techniques, such as new generation doppler radars or LiDAR profilers and scanners, which can provide a picture of the generated transient outflow field. However, the poor time resolution of measurements and technical issues that, for instance, prevent the instrument to acquire useful information in rainy conditions (Chapter 6), often limit the related investigations. The project THUNDERR (Solari et al., 2020) aims at tackling these shortcomings by means of advanced physical and numerical investigations that rely on an very large database of downburst measurements, mostly acquired in the context of the two European projects “Wind and Ports” (WP, 2009-2012) (Solari et al., 2012) and “Wind, Ports and Sea” (WPS, 2013-2015) (Repetto et al., 2018).

Over the last years, several laboratories have emerged with the goal of reproducing the transient dynamics of downburst winds (Letchford and Chay, 2002; Xu and Hangan, 2008; McConville et al., 2009). To date, the largest geometric scales to replicate downburst-like winds are achieved at the WindEEE Dome simulator at Western University in Canada (Hangan et al., 2017). The present experiments use the impinging jet (IJ) technique, widely adopted in the research community due to the simple mechanism of downburst-like flow generation, suitability to produce high wind speeds, easy scalability and capability to replicate accurately the vortex structures of real downbursts (Wood et al., 2001; Chay and Letchford, 2002; Xu and Hangan, 2008; Sengupta and Sarkar, 2008; Mason et al., 2009a; McConville et al., 2009; Junayed
et al., 2019; Romanic et al., 2019). Nevertheless, the impinging jet approach is not able to capture the buoyancy-driven nature of the phenomenon and thus partially misses the full physical representation of it. In wind engineering terms, however, the focus is on the characterization of the flow field in the first layers (order of hundred meters) of the atmospheric boundary layer (ABL) and, thus, the thermodynamic generated downdraft is reproduced mechanically to produce the mean and fluctuating components of the velocity field.

Thunderstorm winds are a non-linear superposition of processes at various scales which can be summarized in mainly three components: the DB wind, the background ABL flow and the parent cloud translation. Little research has been conducted so far on how to properly account for these interactions. The non-linear interplay of the three effects is often neglected in literature or treated as the vector superposition in either analytical or numerical models (Holmes et al., 2008; Chay et al., 2006; Kim and Hangan, 2007; Abd-Elaal et al., 2014). The translation velocity of the thunderstorm cloud affects the intensity and direction of surface winds and, consequently, the resulting outflow assumes an elliptical shape with intensification of the wind speed vectors at the upwind side and weakening at the downwind side (Fujita, 1981, 1985). Furthermore, the translating downburst system is always released into the already developed ABL flow characterized by pronounced wind shear and directional change with height, favorable for the development of thunderstorms (Burlando et al., 2017). Literature provides a large number of studies on impinging jets through cross flows (Romanic et al., 2019). However, only very few of them apply to downburst winds. The embedment of impinging jets in crossflows gives rise to three different flow regions: (1) The potential core zone, which is the closest area to the nozzle where the interaction between the two flows is only minor; (2) The zone of maximum deflection, characterized by high flow shear; and (3) the wall-jet zone, where the flow is far from the source and dissipates horizontally onto the surface. Under high jet-to-crossflow velocity ratios $V_j/U_0$ and jet heights above the surface, typical of thermal and thermodynamic applications, a number of studies (e.g. Bray and Knowles, 1990; Barata et al., 1992; Barata and Durão, 2004) have found that the interaction between the wall jet and the cross flow results in the formation of a ground vortex which wraps around the jet like a scarf and is highly dependent on $V_j/U_0$. The flow here resembles the horseshoe structure observed as a result of the deflection of a boundary layer by a solid obstacle despite its main origin is the upstream wall jet and not the cross flow. However, all these studies take into consideration a jet-to-crossflow velocity ratio in the range $V_j/U_0 = 20 − 50$ which is way larger from what is experienced during a downburst event.

Only recently the interaction between impinging jet and cross flow has been addressed in relation to the superposition between DB and ABL winds. In a first study, Mason et al. (2009b) numerically simulated an intense spatially stationary downburst using a sub-cloud model and a simplified cooling source to approximate the evaporative processes that trigger the formation of the phenomenon. Using the same numerical approach, Mason et al. (2010) later studied stationary, tilted and translating downdrafts in calm
environment and embedded in background winds. Deeper outflows on the surface were observed as the tilt angle increases. The asymmetric outflow and the presence of environmental winds broke the formation and development of the secondary vortex (SV), which typically forms ahead of the PV and is observed in the case of spatially stationary isolated downburst, and thus the associated lifting of a high wind speed area at the boundary between inner and outer outflow regions (Chapter 2). Physical experiments on the interaction between downburst gust-fronts and ABL-like winds were recently performed by Richter et al. (2018), who conducted experiments at the Laboratory of Building and Environmental Aerodynamics at the Karlsruhe Institute of Technology, Germany. The authors used both continuous (steady) and pulsed (non-steady) jets to simulate a down-gust immersed in ABL flow and impinging on a street canyon model. They found horizontal velocities aligned with the background flow exceeding those orthogonal to it by up to 77%. In case of pulsed jet, a ring vortex is formed ahead of the outflow which, during its passage, produces peak velocities up to three times higher than those of the steady case. However, due to the nature of their experiments, the measured flow field was highly affected by the presence of the buildings and orientation of the street canyon. Moreover, the small geometric scales involved in the study make the flow fields more representative of small-scale gusts rather than of downburst winds.

In this regard, WindEEE Dome is also capable of producing straight and steady flows, such as ABL flows, that are representative of synoptic winds in nature. One of the advanced modes of WindEEE enables the simultaneous generation of DB-like impinging jets and ABL-like straight flows at large geometric scales, various Reynolds numbers, and momenta ratios of the two flows (Romanic et al., 2019). Here, the interaction was investigated by Romanic and Hangan (2019, 2020) who demonstrated that the simple superposition as either vector or algebraic sum is physically wrong. Their study showed that the interaction between the two flows highly depends on the position in the outflow. For instance, in analogy to the findings of Richter et al. (2018), combined DB and ABL outflow is stronger than the pure DB (without ABL wind) at the azimuth angle of 180° measured from the incoming ABL wind. Also, at the front between DB and ABL and close to the undisturbed downdraft touchdown, the same sign vorticity between primary vortex and ABL wind intensifies the wind in the upper regions of the vortex which, in turn, are brought down following the vortex circulation. It follows that the associated horizontal velocities increase as well. The concordant vorticity between the counter-directed flows also elevates the vortex above the ground and, consequently, extends the high-velocity region below the vortex itself. This, in turn, returns quite clear nose-shaped velocity profiles. However, their roundness is more pronounced for the undisturbed downburst. The authors investigated only four radial positions. This study takes over from it and extends the number of radial positions to 10 as well as the number of simultaneous along-height measurements, facing both the outflow and ABL directions, by deploying a larger number of Cobra probes. The evolution of the front between the two wind systems is here analyzed in detail and compared to the case of isolated DB discussed.
in Chapter 2. One of the novel features of the WindEEE laboratory is the possibility to record the time of opening and closing of the bell mouth installed on the ceiling of the testing chamber or, in other words, the moment of jet releasing. Based on this, all signals across the chamber are synchronized to draw a detailed investigation of the spatial and temporal development of the phenomenon. This allows, on one hand, to study the ensemble averages and variability of the test repetitions in deterministic manner and, on the other hand, to eventually inspect the time scales of the experimentally produced downbursts, for instance in terms of travelling time of the primary vortex leading the DB outflow. Furthermore, the abrupt changes of the flow features of wind profiles and turbulence fluctuations concurrently with the embedment of the DB into the ABL flow can be addressed in detail.

Junayed et al. (2019) performed PIV analyses, in addition to Cobra probes measurements, to study the evolution of experimentally produced DB outflows at the WindEEE Dome. They reproduced six spatially-stationary DB-like impinging jets related to different Re numbers and thus to different combinations of jet diameter $D$ and velocity $V_j$. The ratio $H/D$, where $H$ stands for the testing chamber height, was another important parameter characterizing the different experimental cases. The focus of the PIV analysis was to capture the parent vortex dynamics in a vertical section of the outflow and to compare it with different full-scale scenarios. The maximum radial velocities were experienced underneath the center of the vortex and followed the vortex center in time, in analogy to what observed by Hjelmfelt (1988) during full scale downburst occurrences. The density of flow streamlines, in fact, increases at the boundary between the vortex and the ground and this results in flow speedup. The primary vortex was observed, at first, to move down to a position of minimum height and, afterwards, to move upwards creating an arch-like trajectory. The comparison with full scale downburst records showed a good match in terms of height and trajectory of the vortex center throughout the event. The authors also noted the formation of a bubble below and in front of the vortex, due to the separation-reattachment of the flow. This bubble is commonly referred as to secondary vortex and is often observed during impinging jet experiments (Gauntner et al., 1970; Didden and Ho, 1985; Gogineni and Shih, 1997; Chapter 2) as well as in real downbursts (Sherman, 1987; Chapter 6) where, however, the large variability of parameters involved in the event and the poor spatial resolution of measurements do not always allow to clearly record its passage.

The rest of this chapter develops in the following manner: Section 3.2 describes the WindEEE Dome, with focus on the simultaneous generation of impinging jets and ABL flows, along with the experimental setup. The results of this study and their discussion is presented in Section 3.3. The transition of the outflow vertical profiles due to the combination of DB and ABL winds as well as the evolution of the front between the two systems are critically interpreted in terms of mean wind velocity and turbulence intensity. The main findings of this research, along with the future steps to be presented in upcoming studies, are outlined in Section 3.4.
3.2 Experiment setup

As mentioned in Section 3.1, the large experimental campaign provided by the project THUNDERR was conducted at the WindEEE Dome simulator, at Western University in Canada. The detailed description of the facility and the capability to produce large-scale non-stationary three-dimensional wind fields, such as downburst winds and tornadoes, are provided in Hangan et al. (2017), whereas Romanic et al. (2019) analyzed several combinations of DB-like impinging jets in ABL-like flows when produced simultaneously at the laboratory.

In the current study, the flow has been analyzed with the use of high-sampling-rate sensors, i.e. Cobra probes, deployed in a three-dimensional grid of measurement positions (Section 3.2.2). This allows high spatial and temporal resolution in the near-surface region.

3.2.1 DB in ABL mode and flow intensities

The impinging jet is created by running the six fans of 2 m diameter and nominal power 220 kW, displaced in an upper room that communicates with the main testing chamber through a moving bell mouth of 4.5 m in diameter $(D)$. In the first stage the upper room is pressurized by keeping the louvers at the bell mouth in closed position. Upon the sudden opening of the louvers, the pressure differential between upper and testing chambers produces a dynamic impinging jet that travels downward and, upon hitting the chamber floor, expands radially. The diameter of the bell mouth can vary from a minimum of 1.2 m to a maximum of 4.5 m but, in the current study, only $D = 3.2$ m was used. The WindEEE simulator can produce DB-like winds at large scales from 1:100 to over 1:500 (Junayed et al., 2019; Romanic et al., 2019, 2020) and different $H/D$ ratios ($H = 3.8$ m is the testing chamber height). In our experiments the ratio was set at $H/D = 1.19$ for which the confinement effects in impinging jet applications are proven to be negligible (Behnia et al., 1999; Xu and Hangan, 2008). Junayed et al. (2019) tested different $H/D$ ratios and demonstrated that the primary vortex leading the downburst outflow fully develops only for $H/D > 1$; the corresponding vertical profiles have a more pronounced “nose” shape and, overall, show better comparison with existing full-scale measurements.

In the present experiments the DB wind always embeds into the already developed ABL-like flow. This latter is produced in “straight-flow” mode by the 60 fans displaced in a matrix of four rows and 15 columns on one of the six peripheral walls of the hexagonal testing chamber, i.e. the “60-fan wall”. Conversely to classical boundary layer wind tunnels, where the ABL-like profile is naturally developed over the length of the tunnel, the WindEEE Dome mechanically reproduces the shape of the profile by controlling the rpm configuration of the 60 fans. It follows that the reproduced profiles do not match perfectly the ESDU standards for neutral atmosphere. Nevertheless, Romanic and Hangan (2020) found that the mechanically generated ABL-like profile at the WindEEE Dome resembles more accurately the unstable atmospheric
conditions typical of downburst occurrences. Figure 2.2 shows the schematic of downburst in ABL wind mode at the WindEEE Dome. The different flow intensities are given in terms of percentage of the nominal power per minute (% rpm) of the respective fans. With this nomenclature, the intensity of the six upper fans generating the impinging jet was set to 30%, referred to as IJ30 (impinging-jet-30), whereas the two homogeneous intensities of the 60 ABL-related fans were 20% and 30%, referred as to SF20 and SF30 (straight-flow-20 and 30). This latter setup choice was adopted to replicate the ratio between peak and mean wind speed of respectively downburst and ABL outflows ($v_{DB,max}/\bar{v}_{ABL}$) that in nature is usually found in between 3 and 5 (Burlando et al., 2017; Solari et al., 2015; Romanic et al., 2020a). The corresponding centroid jet velocities at the exit of the bell mouth can be found in Romanic et al. (2019); the inclusion of the background wind produces the centroid jet velocity of the case supplemented with higher ABL flow (SF30) to decrease to 11.8 m s$^{-1}$ from that in absence of background wind, 12.4 m s$^{-1}$. Such variation is due to the nature of the closed-circuit simulator which produces a deficit in the momenta of both flows when they are produced simultaneously. Instead, the jet velocity in the lower-ABL case (SF20) is not reported in Romanic et al. (2019). However, as the mean wind speed of SF20 is much lower than the corresponding speed of SF30, the centroid jet velocity is not expected to have significant change in respect to the base case without straight flow. The mean wind speeds of the ABL-like flow 3 m downstream of the outlet section, i.e. 60-fan wall, and at $z = 25$ cm are 2.5 m s$^{-1}$ and 3.9 m s$^{-1}$ for the SF20 and SF30 cases, respectively. The two jet-to-crossflow velocity ratios are respectively $V_j/U_0 = 5.0$ for IJ30-SF20 and $V_j/U_0 = 3.0$ for IJ30-SF30. Consistently with the literature on impinging jets in crossflow, the two cases will be named accordingly DBABL5.0 and DBABL3.0. The characteristic wind speeds involved in the experiments are summarized in Table 3.1.

![Figure 3.1: DB in ABL wind mode in the WindEEE Dome: (a) Top and (b) side views.](image)

Figure 3.1. DB in ABL wind mode in the WindEEE Dome: (a) Top and (b) side views.
3.2.2 Cobra probes setup

The flow field produced by the interaction between DB and ABL flows was measured at seven different azimuthal ($\alpha$) and 10 radial ($r/D$) positions using Cobra probes mounted on a stiff mast that prevented vibrations of the instruments in the flow. Cobra probes are multi-hole pressure systems designed to resolve 3 components of velocity in real time at sampling frequency $f_s = 2500$ Hz. They acquire the incoming flow within a cone of $\pm 45^\circ$. The reported accuracy of the probes is $\pm 0.5$ m s$^{-1}$ and $\pm 1^\circ$ yaw and pitch angles up to approximately 30% of turbulence intensity. Due to their accuracy, all velocity measurements $V < 1$ m s$^{-1}$ were removed from the analyses. The $\alpha$ locations span a range from $0^\circ$, corresponding to the direction of the incoming background ABL flow, to $180^\circ$ in clockwise direction and with incremental steps $\Delta \alpha = 30^\circ$. Due to the assumed symmetry of the flow, the results can be mirrored to the other half of the circle ($\alpha = 180^\circ + 360^\circ$). The radial measurement locations cover a range from 0.2 to 2.0 with increment $\Delta r/D = 0.2$; $r/D = 0$ identifies the position of jet impingement at the ground. For sake of precision, the radial location $r/D = 0.8$ is actually moved to $r/D = 0.75$ due to a small irregularity in the floor corresponding to the edge of the turntable, which coincides exactly with $r/D = 0.8$, that did not allow a proper positioning of the Cobra probe mast at that location. For $30^\circ \leq \alpha \leq 150^\circ$, eight Cobra probes were installed along the mast at heights $z = 0.04, 0.07, 0.10, 0.125, 0.15, 0.30, 0.50$ and 0.70 m. Figure 3.2 shows top (panel a) and side (panel b) view schematics of the experimental setup, along with a photograph of the testing chamber during the experiments at ($\alpha = 120^\circ$, $r/D = 1.4$) (panel c) and a zoom-in on the Cobra probes’ mast (panel d). As highlighted by Figure 3.2b,d, in this configuration all Cobra probes’ heads were oriented radially towards the downburst touchdown location identified by $r/D = 0$. However, in addition to this and on the other side of the symmetry plane in respect to the direction of the incoming ABL wind, four Cobra probes (not shown) were installed at heights 0.04, 0.10, 0.30 and 0.50 m above the floor and pointed towards the 60-fan wall to measure the ABL component before the DB release and as embedded in the DBABL outflow. For $\alpha = 0^\circ$ and $180^\circ$, additional probes pointing the DB touchdown were added at $z = 0.20$ and 0.40 m, as well as at $z = 1.00$ m for $\alpha = 180^\circ$. At this latter azimuthal location of measurement, all probes installed on the vertical mast measure also the ABL flow component due to its coincident direction with the radial DB outflow. Conversely, no ABL flow measurements were taken at $\alpha = 0^\circ$ being all probes oriented towards the DB touchdown position. Furthermore, at this location the Cobra probe located at $z = 0.50$ m was removed from the analyses due to malfunctioning. In the following paragraphs the results will be referred to radial and height locations normalized, respectively, by the diameter $D = 3.2$ m and $z_{\text{max}} = 0.10$ m. This choice is convenient in the light of comparing the outcomes of the analyses hereafter reported with those on isolated vertical-jet case (Chapter 2), where the approximate position of the maximum slowly-varying radial velocity was indeed found at $r_{\text{max}} = D = 3.2$ m and
For every \((\alpha, r/D)\) position, each experiment is repeated 10 times in order to inspect the repeatability of the tests and draw limited statistical analyses of the results. Therefore, the overall number of velocity records acquired in this set of experiments is 16000 (2 velocity setups \(\times 7 \alpha \times 10 r/D \times (9 \text{ to } 12)\) probes \(\times 10\) repetitions).

Table 3.1. Experiment setups: Case name; Jet diameter \((D)\); Jet velocity \((W_{\text{jet}})\); Straight flow velocity \((V_{\text{ABL}})\); Azimuthal locations \((\alpha)\); Radial locations \((r/D)\); Cobra probe heights \((z/z_{\text{max}})\); Repetitions per experiment \((\text{Reps})\). The ditto mark (*) indicates that Cobra probe heights are to be considered the same of the case above. IJ identifies probes facing jet touchdown, SF those facing incoming ABL direction.

<table>
<thead>
<tr>
<th>Case</th>
<th>(D) [m]</th>
<th>(W_{\text{jet}}) [m s(^{-1})]</th>
<th>(V_{\text{ABL}}) [m s(^{-1})]</th>
<th>(\alpha) [°]</th>
<th>(r/D) [l]</th>
<th>(z/z_{\text{max}}) [m]</th>
<th>Reps</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBABL5.0</td>
<td>3.2</td>
<td>12.4</td>
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<td></td>
<td>10</td>
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</tr>
<tr>
<td>DBABL3.0</td>
<td>3.2</td>
<td>11.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

* \(r/D = 0.8\) is moved to \(r/D = 0.75\) due to irregularities of chamber floor.
3.2.3 ABL profiles and DB-ABL scaling

Figure 3.3 reports the vertical profile of the ABL-like velocity at each measurement position in the horizontal plane (Figure 3.2). Here the wind speed is averaged over the time interval preceding the release of the IJ, corresponding to the ABL portion of the velocity signal. Differences are observed among the measured profiles; the velocity tends to decrease by moving away from the outer section (60-fan wall) of the incoming ABL wind, i.e. back-wind side, to the forward-wind side because of the loss of horizontal momentum of the flow itself and the widening of the chamber due to its hexagonal shape. The radial positions closer to the center of the jet impingement reasonably record similar velocity profiles among the tested azimuth locations, while the deviation appears larger at further distances from the IJ touchdown because the distance among the different azimuth lines increases.

Figure 3.3 shows that the boundary layer thickness, namely the ABL gradient height $z_G$ above which the wind speed can be considered as approximately constant, is reached approximately at $z_{G,exp} = 0.5$ m or likely slightly above. The lack of measurements above this level cannot confirm this aspect. In nature at full-scale (FS), $z_{G,FS}$ has an order of magnitude $O(10^3)$ m. If we now consider the height of the primary vortex (PV) core as representative of the size of the downburst outflow, this is found to lay at $z_{PV,exp} =$
0.6 – 0.8 m in the experimental measurements at WindEEE (Junayed et al., 2019), while at \( z_{\text{PV,FS}} = 700 – 1200 \) m in full scale occurrences (Wakimoto, 1982; Hjelmfelt, 1988), which is again \( O(10^3) \) m. The respective surface layers related to the background ABL wind and to the downburst outflow appear thus of comparable size both in nature and in their experimental modelling at the WindEEE Dome.

![Figure 3.3](image_url) ABL-like wind speed vertical profiles at each azimuth and radial position of measurement for the case DBABL3.0. Wind speed is normalized by \( V_{\text{ABL}} \) (Table 3.1) while height is normalized by \( z_{\text{max}} = 0.10 \) m.

### 3.3 Results

This section analyzes the effects of the interaction between the produced DB and ABL winds. Upon the bell mouth opening, the descending jet embeds into the background flow (Section 3.2.1) which deflects the jet and distorts the natural radial expansion of the outflow generated upon the impingement. Section 3.3.1 focuses on the velocity time histories recorded at different measurement positions in the flow field by the Cobra probes. Starting from here, Section 3.3.2 reconstructs the resulting downburst outflows on both the horizontal and vertical plane. The spatiotemporal evolution of the front between the two flows is thus analyzed with regards to the punctual Cobra probe measurements (Section 3.3.3). The propagation of PV in the radial and azimuthal plane is thus investigated in Section 3.3.4 by tracking its convective velocity thanks to the new synchronization system at the WindEEE Dome. Section 3.3.5 statistically analyzes the rapid transition of the outflow vertical profiles and the effects produced by their embedment into the background wind. Finally, Section 3.3.6 discusses the main turbulence properties of the reproduced DB outflows, their time correlation with the evolution of the wind speed and variation along the profile.

For sake of simplicity, the results presented in the following of this chapter will be mainly referred to two spatial areas corresponding to the rear-wind region (\( \alpha = 0^\circ: 90^\circ \)) and to the forward-wind region (\( \alpha = \))
90°; 180°), following the ABL flow direction of propagation in the chamber, and characterized respectively by the opposite and equally directed DB and ABL winds. Unless otherwise specified, the analyses hereafter reported will refer to the radial component of the wind speed $V$ (Figure 3.2b).

### 3.3.1 Wind speed time histories

Figure 3.4 shows the radial velocity $V$ time series at $r/D = 1.0$, three different $z/z_{\text{max}}$ as well as $\alpha$ measurement positions. The diagrams are shown in terms of ensemble means (thick lines) and variability (error bars) of the related 10 repetitions.

![Figure 3.4: Velocity time series of the DB-like outflow for DBABL5.0 (blue) and DBABL3.0 (red) cases at $r/D = 1.0$, $z/z_{\text{max}} = 0.4, 1.0, 3.0$ and $\alpha = 0°, 90°, 180°$. Thick lines and error bars represent the ensemble mean and standard deviation of the 10 repetitions, respectively.](image)

The maximum wind speeds are observed close to the surface at $z/z_{\text{max}} = 0.4$ and 1.0 with no significant differences, while a relevant velocity decrease occurs above at $z/z_{\text{max}} = 3.0$. This confirms what observed in other experiments (see for instance Junayed et al., 2019; Romanic and Hangan, 2019; Chapter 2) and resembles the nose-like shape profile typical of full scale downburst signals (Goff, 1976; Hjelmfelt, 1988; Lombardo et al., 2014; Chapter 6). When the DB is simulated without the inclusion of the ABL flow, Chapter 2 shows that each experimental DB-like signal contains three different time phases in analogy to what observed in real downburst events (e.g. Holmes et al., 2008; Burlando et al., 2017, 2018): (1) PV phase, associated with the passage of the primary vortex PV by the Cobra probe and, in turn, containing
(1.1) the velocity ramp-up – PV approaching the instrument, (1.2) the velocity peak – PV just passed over the instrument (Hjelmfelt, 1988; Alahyari and Longmire, 1995; Junayed et al., 2019), and (1.3) the ramp-down of the velocity as PV moves away from the Cobra probe; (2) plateau phase, namely a steady-state condition of the velocity signal characterized by ensemble velocities rather constant in time and fluctuations symmetric around the mean; (3) dissipation stage, corresponding to when the downburst system moves away from the instrument, or dissipates, and velocities gradually return to near-zero values. However, the three different stages are not clearly detectable anywhere in the spatial field when the DB outflow is embedded in the ABL flow. The azimuth location $\alpha = 90^\circ$ (panels d-f) is perpendicular to the direction of the incoming background flow and the velocity records here are those apparently less affected by the interaction between the two flows. Consequently, the three phases of the DB-like outflow are well retained, and the variability of the repetitions seems rather limited. The wind speeds here are of comparable magnitude among the three heights with the exception of the velocity plateau stage at $z/z_{\text{max}} = 3.0$, weaker because of the flattening of the vertical profiles at those heights (Chapter 2). Furthermore, the peak wind speeds here are clearly higher in respect to the other two azimuth locations. The scenario changes at the other two azimuth angles depicted in Figure 3.4. At $\alpha = 0^\circ$ (rear-wind region; panels a-c) the head-on collision between the two flows provokes high mixing. Consequently, the peak stage of the wind speed does not appear as pronounced as in the pure DB-like environment but rather more time-shifted to smoothly merge in the plateau phase. Indeed, the velocity slowdown after the peak is practically absent. This is clearly visible in the case DBABL3.0 and even enhanced by the comparison with DBABL5.0 where the weaker background flow does not affect the outflow in same proportions: at $z/z_{\text{max}} = 0.4$ and 1.0 (panels a,b) the peak of the ensemble wind speed of DBABL3.0 appears about 3 m s$^{-1}$ lower and rather delayed ($\Delta t \approx 0.3$ s) in respect to DBABL5.0 due to the opposite directed and stronger ABL. However, at $z/z_{\text{max}} = 3.0$ (panel c) the peaks of the ensemble wind speeds are more aligned ($\Delta t \approx 0.1$ s) but, at the same time, more dissimilar in terms of wind speed magnitude ($\Delta V \approx 6$ m s$^{-1}$). This suggests that the DB front of the case DBABL3.0 is stopped by the opposite approaching ABL-like wind around $r/D = 1.0$, which is closer to the DB touchdown in respect to DBABL5.0, corroborating the observations provided by Romanic and Hangan (2020). However, in their study the authors adopted a weaker jet velocity, and thus a lower jet-to-crosflow velocity ratio that corresponds approximately to DBABL2.2 in our notation. Interestingly, the case DBABL5.0 shows at $z/z_{\text{max}} = 3.0$ an ensemble peak velocity $V_{\text{max}} = 17.7$ m s$^{-1}$ of about 2 m s$^{-1}$ higher than that at the bottom two heights. Similar behavior is observed at $\alpha = 90^\circ$ for the case DBABL3.0. This suggests that the vortex is lifted up by the counter directed ABL wind in this region (Romanic and Hangan, 2020), provoking maximum velocities still underneath the PV structure but at higher heights; the next sections will discuss this aspect in detail. As result of the flow mixing, we notice a high dispersion of the repetitions in the plateau stage and somehow at the PV phase in a lesser extent. At $\alpha = 180^\circ$ (forward-
wind region; panels g-i) where DB-like outflow and background ABL wind point the same direction, the velocity peak is of comparable magnitude to that of the plateau stage. At the higher heights, in fact, the ABL-like flow does not collide against the counter propagating low-level downburst outflow in the rear region but it rather hits the descending jet causing its deflection in the forward region towards $\alpha = 180^\circ$, as explained in the following sections. The stretching of PV and the deepening of the outflow depth in the forward region was already observed in the numerical simulations by Mason et al. (2010) and in the experiments by Romanic and Hangan (2020). Consequently, the development of the PV and the related velocity peaks are only appreciable starting from $r/D = 1.2$ (not shown here). However, the steady-state velocity in the plateau stage does not show any relevant change in respect to that at $\alpha = 90^\circ$. The following of this chapter will critically interpret the influence of the ABL on the produced DB-like outflow based on the mutual direction of the two flows.

3.3.2 Spatial reconstruction of the wind field

Figure 3.5 shows the downburst outflow field at $z/z_{\max} = 1.0$ and three different time frames on the horizontal plane $r - \alpha$: (1) $t = 1.67$ s (Figure 3.5a,d) – namely the time occurrence of the absolute maximum of the slowly-varying mean wind speed $\overline{V}_{\max}$ among all $\alpha$ and $r/D$ positions in the chamber for the case DBABL5.0; (2) $t = 1.74$ s (Figure 3.5b,e) – same as (1) but for the case DBABL3.0; (3) $t = 2.88$ s (Figure 3.5c,f) – generic time during the plateau phase when the most intense phase of the DB outflow is gone. $t = 0$ s corresponds to the instant of opening of the bell mouth at the ceiling releasing the jet. The radial symmetry, characteristic of the isolated DB flow (Chapter 2), appears here completely lost. This is very clear in the two scenarios shortly after the jet impingement (panels a,d and b,e) where the outflow results hindered by the opposite directed ABL-like flow in the rear region ($0^\circ \leq \alpha \leq 90^\circ$), while it expands further in the forward region ($90^\circ < \alpha \leq 180^\circ$), where the two flows point in the same direction. In terms of wind speed, both cases show the occurrence of $\overline{V}_{\max}$ around at $\alpha = 30^\circ$ and $r/D = 0.75$ with very similar magnitudes of 21.2 m s$^{-1}$ for DBABL5.0 and 21.0 m s$^{-1}$ for DBABL3.0. Also supported by recent and parallel CFD simulations reproducing the same experimental conditions at the WindEEE Dome, as well as by the recent study of Romanic and Hangan (2020), we believe that the occurrence of the absolute maximum wind speed in the region where the incoming ABL wind opposes the downburst outflow, may be explained as schematically outlined in Figure 3.6: due to the same relative circulation (i.e. same vorticity sign), the radially-outgoing downburst PV entrains the counter-directed ABL-like wind and, as a result, the flow at the top of the PV structure is intensified. Consequently, following the vortex circulation, the enhanced wind first travels vertically downward and then horizontally outward with increased momentum (Romanic and Hangan, 2020). As a result, the maximum horizontal velocities intensify in magnitudes at the boundary between the vortex lower end and the ground. The same dynamic effect would not be
happening considering the SV, which is formed ahead of the radially advancing PV and has opposite circulation in respect to this latter (Chapter 2). However, as mentioned above, the PV entrains the ABL flow at the top of its structure. The SV is squeezed to the ground under the leading edge of the outgoing PV and has limited interaction with the counter directed ABL. Furthermore, as reported by Mason et al. (2010), the asymmetric outflow and the presence of background ABL wind may break the formation of the SV. Despite the downburst outflow may eventually overcome the opposed ABL forcing (Figure 3.5c), the PV structure appears deteriorated for \( r/D > 1.0 \) and so the related maximum in the velocity time histories. It follows that the PV likely remains in a “locked-in” regime around \( r/D = 1.0 \) which explains the maximum radial velocities experienced at \( r/D = 0.75 \), spatially behind the actual vortex location, as mentioned above in relation to literature studies. The DB outflow finally penetrates through the ABL wind but the structure of both flows appears lost. Despite \( \overline{V}_{\text{max}} \) occurs at the same location for the two cases, a short time delay (\( \Delta t = 0.07 \) s) between them is noticed and caused by the more intense background flow, i.e. SF30, acting as a stronger oppositely directed force to the expansion of the downburst PV. Accordingly, the comparison between panel (a) and (d) as well as panel (b) and (e) shows a radial shift \( \Delta r/D \) between the location reached by the primary vortex: at the time of the maximum wind speed for DBABL5.0 (panel a), PV appears located still at \( r/D = 0.6 \) in DBABL3.0 (panel d); when the absolute maximum occurs for this latter case (panel e), instead, the PV in the case DBABL5.0 has already reached \( r/D = 1.0 \) (panel b). Analogous but reverse reasoning can be addressed to the forward-wind region of measurements, i.e. \( 90^\circ < \alpha \leq 180^\circ \), where at both times (panel a,d and b,e) the outflow reaches further radial locations in the case DBABL3.0. This is due to the stronger ABL flow acting as a horizontal cross-force on the descending downdraft and causing a shift of the touchdown center beyond \( r/D = 0 \) in the direction of \( \alpha = 180^\circ \) (Barata et al., 1992; Barata and Durão, 2004). The radial outflow shifts consequently. Accordingly, the time evolution of the flow field shows the occurrence of a high velocity region, associated with the recording of the PV, at \( r/D = 1.2 \) and at about 1.48 s (not shown here), namely earlier in respect to the occurrence of maximum velocities in the other parts of the spatial flow field. When the intense phase of the downburst signal is over, the outflow is mainly governed by trailing vortices developing in the wake of the PV and producing lower and rather stationary velocities (plateau segment of the velocity records). However, Figure 3.5c,f shows that the radial symmetry of the outflow is still not achieved and, while in the rear area the flow field assumes a very similar behavior between panel (c) and (f), the same does not occur in the forward region. Here, in fact, the outflow in the case DBABL5.0 (panel c) reaches the boundary of the radial domain across almost every azimuthal position while the ABL-like flow in the case DBABL3.0 (panel f) still constrains the DB flow to assume an asymmetric beam-shape with velocity magnitudes gradually decreasing towards the touchdown position from \( \alpha = 60^\circ \) to \( \alpha = 0^\circ \).
Figure 3.5. Downburst outflow field at $z/z_{max} = 1.0$ (horizontal plane $r - \alpha$) and $t = 1.67\ s$ (a,d), $1.74\ s$ (b,e) and $2.88\ s$ (c,f) for DBABL5.0 (a-c) and DBABL3.0 (d-f) cases. Black spots identify regions where velocity is below $1\ m\ s^{-1}$ (not considered due to accuracy of probes). Red vectors represent the actual punctual measurements of Cobra probes.

Figure 3.6. Schematics of the DB-ABL interaction and entrainment of ABL flow into the PV (vertical plane as seen from $\alpha = 270^\circ$). +/- indicate the sign of vorticity.
Figure 3.7 replicates the same concept of Figure 3.5 in the vertical $r - z$ plane where, however, the flow field is shown only at the time $t = 1.74$ s (Figure 3.5b,e) but at three different azimuths $\alpha = 0^\circ, 90^\circ$ and $180^\circ$. As explained in the context of Figure 3.5, PV reaches higher radial positions by moving from the rear- to the forward -wind region, i.e. from $\alpha = 0^\circ$ to $180^\circ$. At $\alpha = 0^\circ$ the vortex in the case DBABL5.0 (panel a) is above $r/D = 0.75$ while still at $r/D = 0.6$ for DBABL3.0 (panel d). At $\alpha = 90^\circ$ PV in DBABL5.0 (panel b) is still ahead compared to DBABL3.0 (panel e), respectively at $r/D = 1.2$ and $r/D = 1.0$. At $\alpha = 180^\circ$, the concordant direction of ABL and downburst outflow makes this latter expanding further in the case DBABL3.0 for the reasons above. The outflow here seems to reach the boundary of the domain. Earlier in time and in accordance with Figure 3.5, a high-velocity region that corresponds to the recording of the PV passage lands at the surface only at $r/D = 1.2$ (not shown here), confirming the deflection of the jet towards $\alpha = 180^\circ$. To summarize the overall DB-ABL wind interaction, the PV is compressed at the front between the two flows (rear-wind region), elongated in the forward-wind region where the two flows have same direction, and with very similar structure and kinematic features in respect to the isolated vertical DB at the boundary between the two regions ($\alpha = 90^\circ$).

The velocity vectors in Figure 3.7, identifying the punctual Cobra probe measurements, clearly depict the descending jet at low radial locations ($r/D < 0.6$) and the passage of the PV. In fact, we observe the respective downward and upward components of the annular vortex right before and after the recording of the maximum horizontal velocity (Chapter 2, Chapter 6). Ahead of the outflow front, where the vortex has not passed yet, the flow is in calm condition with near-zero velocities or slightly positive due to the air being pushed outwards by the expanding outflow.
3.3.3 Gust front evolution

Figure 3.8b depicts the rear-wind region of the outflow at \( z/z_{\text{max}} = 1.0 \), namely the region subjected to the front between DB and ABL flows. Each colored line in panel (b) refers to a specific instant in time (see panel a) and interpolates four observations, one per azimuthal location starting counterclockwise from \( \alpha = 90^\circ \) to \( \alpha = 0^\circ \). Each observation identifies the first radial position \( r/D \) (from \( r/D = 0.2 \)) at which the wind speed decreases of 30% or more in respect to that at the previous \( \alpha \) and same \( r/D \). Therefore, Figure 3.8 highlights the asymmetric nature of the outflow when produced in combination with ABL flow. The whole of the diagram suggests the 2D time evolution of the front.
The interaction appears to weaken as we move forward in time, namely the DB gains more power and overcomes the influence of the ABL. During the PV segment, in fact, we observe a change of the curves from the reference form of the arc of circumference characteristic of the radial symmetry. The decrease of wind speed for 30% or more between subsequent azimuthal locations occurs radially closer and closer to the ideal touchdown position \( r/D = 0 \) by moving towards \( \alpha = 0^\circ \) in counterclockwise direction. This means that the DB outflow is increasingly hindered by approaching the direction of the incoming ABL flow. During the plateau of the velocity signal and spatially far from the touchdown position, the 30% velocity decrease often occurs at the same radial location between subsequent azimuths. This implies that, at least for that specific portion of domain, the radial symmetry is retrieved. In this latter condition, in fact, the outflow has mostly overcome the influence of the opposed ABL flow and can expand up to the last radial location of measurements, i.e. \( r/D = 2.0 \), with the exception of \( \alpha = 0^\circ \) and \( 30^\circ \).

Figure 3.9 shows the DB slowly-varying radial mean wind speed as function of \( r/D \), captured at different time instants (with reference to Figure 3.8) and for azimuth locations \( 0^\circ \leq \alpha \leq 90^\circ \) (rear-wind region). From a different perspective, it shows the time evolution of the DB outflow at the front with the counter directed ABL flow. The drastic drop of the DB velocity can be considered as representative of the location of collision with the ABL wind, which blocks the radially outgoing DB outflow and, consequently,
diminishes the related horizontal velocity. A common trend, at least in the PV phase, is highlighted up to approximately $t = 1.92$ s (panels a-e): the wind speed increases up to a certain radial location where, upon reaching its maximum value, is followed by an abrupt decrease of magnitude. Indeed, the recording of the passage of PV over the generic radial location $(r/D)_i$ produces: peak wind speed at $(r/D)_i$; ramp-up signature of the velocity at locations $r/D < (r/D)_i$ where PV has already passed through; velocity slowdown at locations $r/D > (r/D)_i$ where PV has not reached yet. The shift $\Delta r/D$ in the radial occurrences of $V_{\text{max}}$ between the investigated $\alpha$ locations corroborates again the non-symmetric behavior of the outflow. At $t = 1.44$ s (panel b) the jet has just impinged down to the ground into the background flow which prevents the outflow to spread out freely. Here, the maximum radial velocities for $0^\circ \leq \alpha \leq 60^\circ$ are all confined within the ideal geometrical boundaries of the downdraft, i.e. $r/D \leq 0.5$, and thus are not due to the travelling PV. However, at $\alpha = 90^\circ$ the two flows are perpendicular each other and the outflow expands further due to the less resistance encountered in this condition. $V_{\text{max}}$ is here recorded at $r/D = 0.6$. Later on (panels c-d), the passage of PV is recorded at every $\alpha$. However, on one hand, $\Delta r/D(V_{\text{max}})$ is conserved with rather the same clockwise order: in terms of $r/D$, $V_{\text{max}}$ occurs first at $\alpha = 0^\circ$ and last at $\alpha = 90^\circ$; on the other hand, the azimuthal location $\alpha = 30^\circ$ records the highest values of wind speed as observed in Figure 3.5. Nevertheless, this implies that the two flows cannot be superimposed vectorially or algebraically, as mentioned in Section 3.1. The more oppositely directed are DB and ABL flows and the closer to the jet touchdown ($r/D = 0$) $V_{\text{max}}$ occurs. Panel (e) and panel (f) still record the passage of PV which has now reached higher radial positions. In this time frame, $\alpha = 90^\circ$ records the maxima of the wind speeds among the azimuth locations. Here, in fact, PV has lost its symmetric structure and thus the benefits of the entrainment of background air in terms of velocity speed-up at the front between the two wind systems. During the plateau stage (panels g-h) the wind speed becomes steadier after the initial ramp-up in the touchdown region. Here, analogous velocity magnitudes are recorded across the azimuthal locations for $r/D > 0.5$ and are produced by trailing vortices following the PV. Depending on $\alpha$, however, such velocity is reached at different $r/D$s following rather accurately the same pattern observed above. Analogously, after the plateau the wind speed decreases starting from $\alpha = 0^\circ$ and in clockwise order. Indeed, the wind speed at $\alpha = 90^\circ$ does not decrease as drastically as for $\alpha < 90^\circ$, at least until the end of the radial domain of observations.
3.3.4 Primary vortex propagation

The synchronization of all signals across the chamber allowed the evaluation of the convective velocity (or travelling time) of the primary vortex. To do so, at each $r/D$ and $\alpha$ location the first velocity peak of the ensemble mean of all repetitions at $z/z_{\text{max}} = 1.0$ was here assumed to occur simultaneously to the passage of PV (Section 3.1). The calculation of the PV convective velocity is thus straight-forward: the distance between two subsequent radial locations is known ($\Delta r/D = 0.2$) and dividing this quantity by the time difference between the respective velocity peak occurrences, we obtain $U_{PV}$:

$$U_{PV} = \frac{\Delta r \cdot D}{t_{r|l} - t_{r|l-1}}$$ (3.1)

The estimation error in the evaluation $U_{PV}$ is assumed to be very little given the negligible relative errors of the quantities involved in its assessment, i.e., $O(1)$ cm for the Cobra probes’ mast positioning ($\Delta \frac{r}{D}$) and $O(10^{-3})$ s in terms of time occurrence of the wind speed peak (acquisition frequency $f_s = 2500$ Hz).

The procedure was applied starting from $r/D = 0.6$. In fact, the primary vortex PV forms at the edge of the bell mouth outlet section as consequence of the high shear between downdraft and environment flow. Lower radial locations are still within the jet (downdraft) width and the annular vortex, which travels vertically to the ground and changes its propagation direction to radial as soon as the jet hits the ground, is not appreciable yet. In the case of vertical isolated DB (Chapter 2), the jet widens in the radial direction upon exiting the bell mouth and the radial positions up to $r/D = 0.8$ are thus still inside the downdraft.
area. In the case investigated here, however, the jet is deflected towards $\alpha = 180^\circ$ by the cross ABL-like flow and, on the one hand, the rear boundary of the jet moves closer to $r/D = 0$ while, conversely, the forward part of the downdraft edge moves away from $r/D = 0$ in the direction of the ABL wind (i.e., $\alpha = 180^\circ$). This is clearly portrayed in Figure 3.10 that shows the variation of $U_{PV}$ across the radial positions $r/D$s as function of the azimuth angle $\alpha$ for the case DBABL5.0. Note that the velocities here are normalized by the maximum convective velocity $U_{PV_{\text{max}}}$ at each azimuthal location in order to draw a better comparison of the PV evolution along the radial direction irrespective of the case considered. Due to the reasons mentioned above, the PV in the rear-wind region ($0^\circ \leq \alpha \leq 90^\circ$) exhibits maximum translational speeds at $r/D = 0.75$ while, moving to the forward-wind region ($90^\circ \leq \alpha \leq 180^\circ$), $U_{PV_{\text{max}}}$ occurs further away from the geometric jet touchdown position in the case of isolated DB, i.e. $r/D = 0$ (Chapter 2). For $\alpha = 150^\circ$ and $180^\circ$ the PV velocity at the radial location $r/D = 0.75$ theoretically assumes negative and unphysical values (removed from the graph) which clearly indicate that such position is still inside the jet downdraft area and, therefore, the related measurements are strongly influenced by it. Therefore, the analysis reported in Figure 3.10 can also serve as a qualitative measure of the position of the downdraft at the ground at the different azimuth locations.

In the rear-wind region, upon the occurrence of $U_{PV_{\text{max}}}$ at $r/D = 0.75$ the downburst front is observed to slow down considerably, which suggests that the two wind systems are “competing” against each other. PV maintains a quite low travelling velocity and is blocked by the counter directed ABL flow. Indeed, as mentioned above, the larger radial locations of measurements do not record its actual passage. Consequently, the PV appears in a sort of “locked-in” position. This is also clearly detected from flow visualizations (not shown here) where the camera pointed the area of impact between the two opposing wind systems and shows the vortex locked above the approximate same radial position. However, the Cobra probes here still record positive velocity values, and it is hence tricky to accurately distinguish and attribute these wind speed measurements to the passage of PV or, more likely, to random fluctuations in the flow that loses its coherent structure far from the DB touchdown. For this reason, the related values of $U_{PV}$ are not removed from the analysis.

By moving to the forward-wind region $90^\circ < \alpha \leq 180^\circ$, the location of $U_{PV_{\text{max}}}$ appears shifted to higher radii due to the jet impingement that is shifted beyond $r/D = 0$ in the downwind direction. As expressed above, the inclusion of the ABL flow produces an inclination of the downdraft at the touchdown, similarly to what observed in the case of travelling downburst (Fujita 1985). Here, $U_{PV}$ is maintained rather high, although gradually decreasing, throughout the radial direction due to the speed-up effect produced by the ABL flow on the travelling PV in this area.
3.3.5 Vertical profiles of radial wind speed

Figure 3.11 provides a characterization of the slowly-varying mean wind speed field $\bar{V} = \bar{V}(\alpha, r, z, t)$ evaluated as $\bar{V} = \bar{V}(z, t)$ at $\alpha = 0^\circ, 90^\circ, 180^\circ$ and $r/D = 0.6, 1.0, 1.4, 1.8$. The analysis is shown only for DBABL3.0 and the remaining spatial positions of measurement are omitted for sake of briefness. By moving from the rear- to the forward- wind region, i.e. from $\alpha = 0^\circ$ to $180^\circ$, the interaction between DB and ABL flows changes drastically, as reported above. The stagnation condition at the front between the two wind systems leads to observe maximum velocities for $r/D < 1.0$; conversely, the same direction of propagation of DB and ABL outflows in the forward region of the domain, and the consequent effects, shift the region of absolute maximum wind speeds at $r/D > 1.0$. At $\alpha = 90^\circ$, where the ABL seems to have the least influence on the DB outflow, the velocity vertical profiles are observed to resemble the case of isolated DB (Chapter 2) to a very good extent and maximum velocities are still observed around $r/D = 1.0$ as widely found in literature in case of axisymmetric downburst outflow (Chay and Letchford, 2002; Kim and Hangan, 2007; McConville et al., 2009). Overall, therefore, the region of maxima of the wind speed is observed at further radial distances by moving from the rear to the forward region of the interaction DB-ABL. Moreover, due to the different and somehow opposite action of the ABL between the rear- and forward- wind region of the outflow, the time at which the Cobra probes start to record non-zero velocity values changes accordingly: the DB outflow reaches first the forward region and later the rear region. This is very evident at the location $(\alpha, r/D) = (0^\circ, 1.8)$ where the signature of the passage of the DB outflow is basically absent. Throughout the evolution of the event, and outside of the downdraft region, the DB vertical profile is always nose-shaped, in agreement to the observations in Chapter 2 on the isolated DB case: at the time of the passage of PV, the vertical extension of the area of observation of $\bar{V}_{\text{max}}$ is quite high on the
ground while during the plateau segment of the velocity records, where the outflow is dominated by smaller trailing vortices following PV, the nose of the vertical profile is more constrained to the ground. The spikes in the vertical profiles of $\overline{V}$ are inherently related to the frequency of the vortex detachments from the nozzle (Chapter 2). The large values of $\overline{V}$ at $\alpha = 180^\circ$ during the dissipation stage of the velocity are due to the asymmetrical closing of the bell mouth and thus are not related to any meaningful physical interpretation.

![Figure 3.11](image)

Figure 3.11. Profiles of $\overline{V}(z, t)$ at $\alpha = 0^\circ, 90^\circ, 180^\circ$ and $r/D = 0.6, 1.0, 1.4, 1.8$ for DBABL3.0.

Figure 3.12 reports the time variation of the height of maximum slowly-varying mean speed, $z(\overline{V}_{\text{max}})$, at $\alpha = 0^\circ, 90^\circ$ and $180^\circ$. All wind speed signals were first synchronized based on the time occurrence of the absolute maximum velocity along the vertical profile, for each repetition performed. Hence, the ensemble average was calculated as the mean across all 10 repetitions at each azimuth angle and each radial position $r/D \geq 1$. The ensemble average across the repetitions of $z(\overline{V}_{\text{max}})$ was evaluated separately over each radial location since the length of the segments composing the velocity signal is strictly correlated to the measurement position in the outflow and changes according to this. The diagrams also report the ensemble average of the slowly-varying mean speed at the respective $(\alpha, r/D)$ location and at $z/z_{\text{max}} = 1.0$, in order to qualitatively inspect the correlation between the observed $z(\overline{V}_{\text{max}})$ and the different time phases of the velocity time series. The comparison with the case of vertical DB (green dots) (Chapter 2), i.e. without the inclusion of the ABL wind, clearly highlights the role played by this latter on the resulting outflow. Figure
3.12 shows that at $\alpha = 0^\circ$ the decrease of $z(V_{\text{max}})$ related to the passage of the PV is generally not as pronounced as at the other two azimuths. Here, the same vorticity sign of the propagating PV and counter directed ABL flow makes this latter being entrained in the vortex structure (Figure 3.6). Consequently, the vortex is likely to raise up above the ground, as mentioned before. However, $z(V_{\text{max}})$ does not seem to increase significantly in respect to the isolated DB case at least until $r/D = 1.6$. Beyond this location, the interaction between DB and ABL flows produces a decrease in radial velocities towards zero. At $\alpha = 90^\circ$ (mid column of Figure 3.12), the evolution of $z(V_{\text{max}})$ resembles to a good extent that of the case without the inclusion of background wind. However, at larger radial locations and particularly at the beginning of the velocity ramp-up before the passage of PV, $z(V_{\text{max}})$ assumes higher values possibly due to the detachment of the boundary layer and consequent formation of the SV. At this stage the maximum horizontal velocities occur at the boundary between PV and SV (Chapter 2). The right columns of Figure 3.12 shows very high $z(V_{\text{max}})$, close to the top measurement height, before and after the embedment of the DB into the developed ABL wind, in agreement to the ABL logarithmic-like profile. Here, therefore, the transition of $z(V_{\text{max}})$ appears much more remarked. However, the height of maximum wind speed matches well with that of the isolated DB case in correspondence of the passage of the PV and in the plateau segment. This suggests that the height of the vortex core does not increase due to the opposite vorticity between the two flows and to the downward momentum exerted by the ABL flow on the PV expansion at $\alpha = 180^\circ$ which prevents the detachment of the surface layer from the ground.
Figure 3.12. Ensemble averages of 10 time series (experiment repetitions) of the height of maximum velocity $z(\bar{V}_{\text{max}})$, normalized by $z_{\text{max}} = 0.1$ m, at $\alpha = 0^\circ, 90^\circ$ and $180^\circ$ and $r/D \geq 1$ for DBABL5.0 (black dotted line), DBABL3.0 (red dotted line) and isolated vertical DB (Chapter 2) (green dotted line) cases. Orange dotted lines show the ensemble average of the 10 mean velocity repetitions at $z/z_{\text{max}} = 1.0$ for the case DBABL3.0. Vertical gray dotted lines show $t(\bar{V}_{\text{max}})$.

Figure 3.13 shows $z(\bar{V}_{\text{max}})$ at the time of the absolute maximum of $\bar{V}$, namely in correspondence of the passage of PV at different radial and azimuth locations. Each height depicted in the diagrams is the result of the ensemble of the 10 test repetitions at the occurrence of the maximum wind speed at the particular ($\alpha, r/D$) position. A stagnation zone forms at the front between DB outflow and ABL wind (panel a,b) at $r/D = 1.0$. This, in addition to the modified inclination of the jet at the ground due to the acting horizontal ABL-cross force, causes the PV to elevate over the surface (Orf and Anderson, 1999; Barata and Durão, 2004). As consequence, the related maximum velocities are experienced at higher levels and the nose-like
curvature is more clear (Romanic and Hangan, 2020). The abnormal large values of \( z(\bar{V}_{\text{max}}) \) at \( \alpha = 0^\circ \) and \( 30^\circ \) starting from \( r/D = 1.6 \) are again to be related to the very low velocities at these locations, analogously to what discussed in Figure 3.10. The trend of \( z(\bar{V}_{\text{max}}) \) appears somehow more regular and similar to the one of isolated DB (gray dots) (Chapter 2) at \( \alpha = 60^\circ \) and \( 90^\circ \). At this latter azimuth, however, the heights throughout the radial coordinate are shifted up to the range \( z(\bar{V}_{\text{max}})/z_{\text{max}} = 2 \div 3 \) for DBABL3.0. Indeed, the deflection of the impinging jet beyond the horizontal axis \( \alpha = 90^\circ - 270^\circ \), namely towards the forward-wind region, might somehow cause the same effect observed at \( \alpha = 0^\circ \) on the vortex uplifting. In the forward area of the outflow, \( z(\bar{V}_{\text{max}}) \) related to the cases of DB supplemented with ABL flow is even below in respect to the isolated outflow case. As mentioned above, this behavior is due to the opposite vorticity sign of the two flows in this region. In other terms, the ABL-like flow at the higher levels runs into the vertically descending impinging jet, gains downward momentum, and thus partly acts as a downward force on the expanding PV in the area \( 90^\circ < \alpha < 180^\circ \). PV is thus lowered down and so are the related heights of maximum wind speed. Nevertheless, as mentioned above, at \( \alpha = 180^\circ \) the ABL flow acts also as a horizontal force to tilt the descending downdraft. This causes the jet impingement as well as the generated DB outflow to shift further beyond \( r/D = 0 \), i.e. the geometric touchdown location of the isolated DB case (Chapter 2). The radial locations \( r/D < 0.8 \) are thus still included in the jet projection to the ground and the stronger downward component of the wind speed at the higher elevations provoke here the highest horizontal velocities as well, as explained in detail in Chapter 2. At \( r/D = 1.2 \div 1.4 \), \( z(\bar{V}_{\text{max}}) \) reaches its minimum and increases again afterwards, partly following what observed in the isolated DB case.
3.3.6 Turbulence properties

Chapter 2 analyzed a large set of experimentally produced downburst outflows and found that the usual hypothesis adopted in literature, i.e. turbulence intensity assumed constant in time $I_v = \overline{I}_v$ (where $\overline{I}_v$ is the temporal mean of the slowly-varying turbulence intensity $I_v$), loses validity in controlled conditions. However, this was also noticed in the full scale environment by several authors (Solari et al., 2015; Zhang et al., 2018, 2019; Chapter 6) who found an asymmetry of the parameter $\mu(t) = I_v(t)/\overline{I}_v$ in correspondence of the peak velocity occurrence or, in other words, concurrently with the passage of PV by the measuring instrument. Specifically, $\mu$ shows a local maximum and minimum respectively before and after the recording of the maximum velocity. Despite this behavior is experienced in both full scale and controlled conditions, the experiments described in Chapter 2 enhance this aspect much more. The three orders of magnitude or so lower Reynolds numbers $Re$ involved in the experiments at the WindEEE Dome return a much smoother environment compared to full scale conditions and thus the off-mean values of the turbulence intensity are overall magnified. The current study shows that the overall time evolution pattern of the turbulence intensity, particularly in the neighborhood of the velocity maximum (grey dotted line in Figure 3.14), is often analogous to that of the isolated jet case (Chapter 2). Figure 3.14, however, shows that $\mu$ generally assumes values below 1 at the beginning of the velocity signal, i.e. before the DB release into the developed ABL flow. Therefore, the diagrams show that the embedment of the DB wind actually contributes to add turbulence to the ABL-like environment. As a general observation, when the DB outflow embeds into the ABL-like flow, i.e. during the PV phase, $\mu$ increases rapidly and assumes,
with few exceptions, the maximum value slightly before the occurrence of the maximum wind speed, \( t(\overline{V}_{\text{max}}) \). The maximum of \( \mu \) is followed by a local minimum few instants later than \( t(\overline{V}_{\text{max}}) \) and by a plateau of roughly constant \( \mu = 1 \) during the plateau segment of the velocity. At \( \alpha = 0^\circ \), the strong flow mixing between ABL and DB outflows causes the parameter \( \mu \) to fluctuate significantly. Here, the maximum values are observed in correspondence of the top measurement height \( z/z_{\text{max}} = 7.0 \) for \( r/D < 1.4 \) likely due to the embedment of the ABL air into the vortex structure. At \( \alpha = 90^\circ \), where the outflow fairly conserves the radial symmetry, the asymmetric behavior of \( \mu \) becomes evident and is highlighted at the lowest heights where the maximum velocities during the passage of PV are recorded, in analogy to what found in Chapter 2. Starting from \( r/D = 1.6 \), the maximum of \( \mu \) is observed earlier in the time history; the time occurrence suggests its correlation with the detachment of the boundary layer from the surface and consequent formation of the SV. Here, the interaction and friction between PV and SV increases the turbulence level significantly. At \( \alpha = 180^\circ \), where the DB and ABL flows have opposite vorticity sign, the ABL acts as a downward and stabilizing force on the developing PV. Moreover, the passage of the PV is only evident from \( r/D = 1.2 \) due to the deflection of the jet at the ground. It follows that the spike of \( \mu \) ahead of that associated to \( V \) is not observed for \( r/D < 1.4 \). Here, the spike of \( \mu \) is observed slightly after the occurrence of the maximum velocity. This effect slowly vanishes with the near-surface onset of the SV beyond \( r/D = 1.4 \) and the trend of \( \mu \) appears thus retrieved. Therefore, the influence of the passage of the PV on the asymmetric trend of \( \mu \) is again corroborated.
Figure 3.14. Ensemble averages of 10 time series (experiment repetitions) of $\mu$ at $\alpha = 0^\circ$, $90^\circ$ and $180^\circ$, $r/D \geq 1$ and $z/z_{max} = 0.7, 1.5, 3.0$ and $7.0$ for the DBABL3.0 case. Orange dotted lines show the ensemble average of the 10 mean velocity repetitions at $z/z_{max} = 1.0$ for the case DBABL3.0. Vertical gray dotted lines show $t(\bar{V}_{max})$.

Figure 3.15 shows distributions of the slowly-varying turbulence intensity $I_V = I_V(\alpha, r, z, t)$ for the case DBABL3.0 and same measurement locations shown in Figure 3.11. The maximum values are found at $\alpha = 0^\circ$, i.e. at the front between DB and ABL flows. This is thought to be consequence of the high flow mixing that develops from the interaction between the DB PV and the ABL flow. Quite large turbulence values are found in the forward area of the flow far from the DB touchdown, likely due to the PV losing its symmetric and coherent structure at these locations. Due to the modulation of the mean wind speed and to its large values at the bottom heights (see Figure 3.11), $I_V$ is usually observed to assume lower values at the bottom levels compared to the rest of the vertical profile.
Figure 3.15. Profiles of $I_V(z, t)$ at $\alpha = 0^\circ, 90^\circ, 180^\circ$ and $r/D = 0.6, 1.0, 1.4, 1.8$ for DBABL3.0.

Figure 3.16 shows the time evolution of the height of maximum turbulence intensity at the different $(\alpha, r/D)$ locations, in analogy to Figure 3.12, for both DBABL3.0 and DBABL5.0 cases in respect to the case of isolated vertical DB. In agreement to the observations in Chapter 2, the rapid shift of $z(I_{V_{\text{max}}})$ concurrently with the passage of the PV appears from the lower to the higher heights. At $\alpha = 0^\circ$, however, the rapid transition of $z(I_{V_{\text{max}}})$ is only slightly noted for $r/D \leq 1.4$ due to the PV being deteriorated by the opposed ABL flow at further radial locations. Overall, at this azimuth location, the maximum turbulence intensity settles and fluctuates around $z/z_{\text{max}} = 3.0$, which is slightly less than observed in the case of isolated vertical DB. At $\alpha = 90^\circ$ and $180^\circ$, the change of $z(I_{V_{\text{max}}})$ is much more remarked and follows the observations pointed out in Chapter 2. Here, the maximum of $I_{V_{\text{max}}}$ is observed close to the top measurement heights around $r/D = 1.0$ while decreases beyond. At $\alpha = 180^\circ$, the higher heights of occurrence of the maximum turbulence intensity at the beginning of the velocity ramp-up are likely due to the interaction between inner and outer layers of the outflow as consequence of the separation and reattachment of the boundary layer to the surface. The higher values of $z(I_{V_{\text{max}}})$ in the last part of the plateau segment of the velocity are, instead, to be related to the mechanical asymmetric closing of the bell mouth louvers which causes the velocity, and the turbulence intensity, to increase at these azimuths and at the higher heights.
Figure 3.16. Ensemble averages of 10 time series (experiment repetitions) of the height of maximum turbulence intensity \( z(I_{V_{max}}) \), normalized by \( z_{max} = 0.1 \) m, at \( \alpha = 0^\circ, 90^\circ \) and \( 180^\circ \) and \( r/D \geq 1 \) for DBABL5.0 (black dotted line), DBABL3.0 (red dotted line) and isolated vertical DB (Chapter 2) (green dotted line) cases. Orange dotted lines show the ensemble average of the 10 mean velocity repetitions at \( z/z_{max} = 1.0 \) for the case DBABL3.0. Vertical gray dotted lines show \( t(V_{max}) \).

Figure 3.17 shows the azimuthal development of the vertical profiles of \( \bar{T}_V \) for the case of DB supplemented with stronger ABL-like wind (DBABL3.0). Only radial positions \( r/D \geq 0.6 \) are considered as these positions are likely to be affected by the actual passage of the PV. \( \bar{T}_V \) is evaluated as the mean over the duration of the DB-like flow, i.e. from the opening till the closing of the bell mouth releasing the jet. The magnitude of \( \bar{T}_V \) is observed to generally increase along the first few radial locations and to remain approximately constant when \( r/D \) increases. In the area \( 120^\circ \leq \alpha \leq 180^\circ \) (panels e-g), however, a decrease of \( \bar{T}_V \) along the profile is observed starting from lower heights, usually around \( z/z_{max} = 3.0 \) for greater \( r/D \) values. Also, at \( r/D = 2.0 \) \( \bar{T}_V \) is generally found lower at the higher heights compared to the
previous radii. At $\alpha = 0^\circ$ (panel a) and for $r/D > 1.4$, the vertical profiles of $\tilde{I}_V$ show clear off-mean maximum values at $z/z_{\text{max}} = 2.0$. The large radial locations of observation suggest that these spikes may be caused by the interaction between PV and SV; this latter, indeed, develops only at radial locations further from the jet touchdown where the boundary layer separation may occur (Gauntner et al., 1970; Gogineni and Shih, 1997; Chapter 2). The spike in the vertical profile of $\tilde{I}_V$ appears weaker in magnitude and located at $z/z_{\text{max}} = 1.25$ for the remaining $\alpha$ positions. The entrainment of ABL air into the PV structure at the colliding front between DB and ABL flows (Figure 3.6) causes the vortex to rise over the ground and, consequently, the interaction with the inner-region vortex, i.e. secondary vortex, occurs at a higher height. Accordingly, where the effect of the ABL entrainment partly vanishes, the interaction between inner- and outer-region vortices is experienced at lower elevations. Therefore, we believe that this aspect might cause the lowering of the height of off-mean values of $\tilde{I}_V$ at the locations that does not directly experience the front between the opposite directed flows. Furthermore, the overall values of $\tilde{I}_V$ appears higher in the first quadrant $0^\circ \leq \alpha \leq 90^\circ$ (rear region; panels a-d), where they are generally found between 0.1 and 0.2, while they decrease even below 0.1 in the region $120^\circ \leq \alpha \leq 180^\circ$ (forward region; panels e-g), for the reasons mentioned above. Finally, the turbulence intensity magnitudes are overall found in good agreement with those found for large sets of downburst records from ultrasonic measurements (Solari et al., 2015; Zhang et al., 2018, 2019) and also in relation to the vertical profiles evaluated by means of LiDAR profiler measurements (Chapter 6), as well as to the experimental investigation on vertical isolated DB (Chapter 2).
The statistical properties of the reduced turbulent fluctuation $\tilde{V}'(t) = V'(t)/\sigma_V(t)$, being $V'(t)$ the residual fluctuation ($V'(t) = V(t) - \bar{V}(t)$) and $\sigma_V(t)$ its mobile standard deviation, confirm that this quantity can be reasonably treated as a stationary random process with zero mean and unit standard deviation, as widely proved by literature. In accordance with the experimental investigation on vertical isolated impinging-jet downbursts (Chapter 2), the power spectral density (PSD) of $\tilde{V}'$ (not shown here) provides that its trend follows the law $n^{-5/3}$ (where $n$ is the frequency) in analogy to full scale synoptic-scale ABL winds and also to real downburst occurrences (Holmes et al., 2008; Solari et al., 2015; Burlando et al., 2017).

### 3.4 Conclusions and prospects

This chapter presents a comprehensive analysis of a large and unique set of experiments performed at the WindEEE Dome, at Western University in Canada, on the interaction between downburst (DB) and background ABL winds. The analysis of the combination between the two flows has only recently been addressed in literature where, however, the superposition is usually dealt through a simple vector summation. Our findings confirm what already concluded by Romanic and Hangan (2019, 2020) on the unfeasibility of this hypothesis and discuss in detail the evolution of this interaction. In our experimental study, velocity measurements were carried out on a highly refined spatial and temporal grid in order to
reconstruct the detailed flow field and dynamic mechanism involved during the occurrence of the reproduced phenomenon.

The new integrated system installed at the WindEEE Dome enabled the recording of the time of opening and closing of the bell mouth releasing the jet into the testing chamber. This allowed to synchronize all signals across the chamber and among the repetitions in order to faithfully reconstruct the time evolution of the front between DB and ABL flows. The maximum radial velocities are surprisingly found at the front between the colliding flows where the radially advancing vortex, upon the jet impingement on the ground, entrains the counter directed ABL air taking advantage of the same sign of horizontal vorticity (Figure 3.6). This causes the vortex to increase its momentum and vorticity and the horizontal flow constrained underneath the vortex structure to accelerate accordingly. In general terms, we noticed a highly asymmetric behavior of the expanding outflow. In the rear-wind region where the two fronts collide against each other, in fact, the outflow results hindered and convectively slowed down by the ABL flow up to an azimuth angle approximately equal to $\alpha = 60^\circ$ in respect to the ABL incoming direction. On the other hand, in the forward region, the background ABL distorts the embedded vertical downdraft provoking an inclination of its axis with respect to the vertical. This causes the jet touchdown position to shift further from the geometric vertical axis of the jet, identified by $r/D = 0$, in the streamwise direction of the ABL flow. Overall, this results in a “locked-in” outflow at the front between DB and ABL systems, i.e. for $0^\circ \leq \alpha \leq 90^\circ$ (rear-wind region), while the development of the PV and the DB outflow in the forward-wind region, i.e. $90^\circ < \alpha \leq 180^\circ$, is translated to larger radial distances and speeded-up compared to the pure DB mode analyzed in Chapter 2. The DB outflow is therefore shifted in time and along the radial coordinate based on the mutual interaction between DB and ABL which in turn depends on the azimuth location of observation.

The time variation of the height of maximum radial velocity is observed to change abruptly at the passage of the primary vortex (PV), marked by the absolute maxima of the horizontal wind speed, in analogy to what observed in Chapter 2. The “locked-in” location generated by the collision between the two flows is likely to raise the vortex up above the surface. This might explain the more gradual drop of $z(\bar{V}_{\text{max}})$ at the time of the PV passage in respect to the other azimuths, despite during the plateau segment of the velocity it is not higher compared to the case of isolated DB. At $\alpha = 90^\circ$, where the DB outflow is less influenced by the ABL wind, $z(\bar{V}_{\text{max}})$ shows a spike at the beginning of the velocity ramp-up and that is an indicator of the formation of the SV due to the detachment-reattachment of the surface layer at the surface. In this situation, indeed, the maximum velocities occur at the boundary between inner and outer layers of the outflow. The decrease of $z(\bar{V}_{\text{max}})$ is much more pronounced in the ABL-streamwise direction due to the velocity vertical profile that switches from the logarithmic-like shape, typical of the ABL wind, to the nose-like shape, associated to downburst outflows. However, at the passage of the PV and during the plateau segment of the velocity, the height of $\bar{V}_{\text{max}}$ resembles to a very good extent that observed in the vertical
isolated DB case (Chapter 2). Overall, the nose-like shape of the velocity vertical profile is observed throughout the occurrence of the phenomenon. While the area of maximum velocities covers a wider range of heights during the passage of PV, the surface layer is more constrained to the ground during the plateau segment of the velocity characterized by the presence of trailing vortices of smaller size in respect to PV. In the rear region of the outflow, the ABL downward momentum squashes the radially outgoing PV to the ground up to a certain radial location, that is dependent on the azimuth location of measurement, where the front between DB and ABL flow forms and this latter is entrained in the PV structure causing an increase of the surface layer depth over the ground.

Turbulence characteristics of the flow were found to be in good agreement with those evaluated for large datasets of real thunderstorm events (Solari et al., 2015; Zhang et al., 2018, 2019) and also with reference to their vertical profiles (Chapter 6). We found higher turbulence in the region subjected to the front between DB and ABL due to the high flow mix generated by the collision. The along-height temporal evolution of the turbulence intensity \( I \) shows a sudden peak shortly prior the maxima of the wind speed. The maxima of the turbulence intensity generally occur at the bottom heights and are thus associated to the passage of the PV by the instrument and to its interaction with the outer layer of the outflow. Overall, the embedment of the downburst wind into the already developed ABL causes an augmentation of the turbulence intensity.

Analogous observations are reported in the analysis of full scale events by Zhang et al. (2018, 2019) and Chapter 6 as well as in controlled conditions (Chapter 2). In terms of structural response, the effect of denying the usual assumption \( I = \bar{I} \) usually adopted in literature, namely turbulence intensity invariant with time, may have significant implications.

This study is part of a large and unique experimental campaign performed at the WindEEE Dome in the context of the project THUNDERR (Solari et al., 2020). A complementary study will make a further and decisive step in the reconstruction of the detailed physical scenario that emerges during full scale downburst occurrences. This will be accomplished by investigating the effect of the parent thunderstorm translation and its superposition with the DB and background ABL winds. Comparison with full scale data will be later discussed with the aim of achieving the most appropriate model of this extreme phenomenon and, in a wider perspective, of implementing the outcomes of experimental, numerical and theoretical models into the structural design codes.

References


Chapter IV

4 Physical investigation of inclined-jet axis impinging jet and interaction with ABL wind

Abstract
Thunderstorm winds are cold descending gravity currents which upon the impingement on the ground create strong radial outflows with maximum wind speeds in the range 50-120 m above the ground. They represent one of the greatest hazards for both natural and built environment as well as one of the deadliest phenomena all over the world. This study carries on the analyses of the downburst experimental campaign performed at the WindEEE Dome, part of the Western University in Canada, in the context of the ERC project THUNDERR. While a former study presented the interaction between downburst and atmospheric boundary layer winds, here the focus is on the influence exerted by the thunderstorm cell translation on the overall downburst dynamics in both the downdraft and outflow stages. This was physically replicated at large-scale by means of the impinging jet technique where the jet axis was inclined to a non-zero angle with respect to the vertical. Finally, the influence of the thunderstorm cloud dynamics was combined with the effect of the background ABL wind to reconstruct the complete three-dimensional nature and evolution of real downburst events. The radial symmetry of the outflow, observed for vertical impinging jet case, is lost in the case of inclined jet-axis. This leads to an intensification of the forward-wind side and weakening of the back-wind side, where the entrainment of the counter-directed ABL wind, and consequent flow speed-up, is not as pronounced as in the vertical-axis case. Turbulence characteristics are in line with the findings reported in the previous chapters, highlighting the turbulence asymmetric behavior around the occurrence of the velocity, with highest values at the lowest heights.

Keywords: Downburst; Impinging Jet; Background wind; ABL; Thunderstorm translation; Storm motion; Turbulence; Wind simulator.

4.1 Introduction
Thunderstorm downbursts are non-stationary and vigorous winds at the meso-γ scale (2–20 km) that occur in particular convective conditions and present characteristics completely different from those that are typical of extra-tropical cyclones at the synoptic scale. The evaporation and melting of hydrometeors inside and underneath the cumulonimbus cloud in the subsaturated environment, as well as the drag due to the falling raindrops or ice, are the main contributors for the negative buoyancy which drives the downdraft to the surface. The extracted latent heat of evaporation/melting/sublimation cools the column of air in the
precipitation region and the resulting downdraft creates an intense radial outflow with nose-like vertical velocity profile (Fujita, 1981, 1985). In contrast to the logarithmic-like atmospheric boundary layer (ABL) winds, the maximum radial velocities in downburst outflows are experienced in the near-surface region where the formation of ring vortices takes place. Downbursts are spatially classified into macrobursts and microbursts depending on whether the horizontal size of the outflow is greater or smaller than 4 km, respectively (Fujita, 1985). The diameter of thunderstorm downdrafts typically varies from approximately 400 m to several km (Hjelmfelt, 1988; Mason et al., 2009a; Zhang et al., 2013).

The complexity in the study of thunderstorms is mainly due to two factors. Firstly, downbursts are highly transient phenomena; they occur over a very short time interval of 2 to 10 minute duration and develop over only few kilometers on the horizontal. This limits the available full scale measurements and, consequently, makes it difficult to build physically realistic and reliable models as in the case of extra-tropical cyclones (Davenport, 1961). Despite the time evolution of the phenomenon being characterized in detail by deploying state-of-the-art high-sampling sensors, there is still a lack in reconstructing the spatial field due to the limited number of measuring stations. Secondly, and more relevant to this study, downburst outflows are influenced by the translation velocity of the parent cloud, which inherently affects the intensity and direction of surface winds. Hjelmfelt (1988) and Proctor (1988) suggest that a tilted downdraft core may occur when momentum from the surrounding flow is transferred to the downdraft column. Holmes (1999) corroborates that downdrafts retain large amounts of the translational momentum of the parent cloud whose speed can be up to a third of the speed of the downdraft itself. Hjelmfelt (1988) concluded that the superposition of the low-level environment winds with the normal impinging downdraft can explain adequately the resulting outflow pattern. Fujita (1985) first reported that the travelling motion of a microburst distorts the radial symmetry of the outflow, observed in the stationary case, due to the downdraft tilting at the impingement stage; the forward-side wind intensifies while the back-side wind weakens and, consequently, the outflow assumes an elliptical shape (Figure 4.1). One of the most clear case of tilted downburst is the Andrews Air Force Base microburst that was reported to have a jet-axis inclined to approximately 23° and very high horizontal wind speeds in the near-ground level (Fujita, 1983).
Letchford and Chay (2002) used The Moving Jet Wind Tunnel at the Texas Tech University (TTU) to study the effect of the storm motion on a model cube (side length 30 mm) for jet translation speeds in excess of 20% of the downdraft speed. The length scale of the simulation was estimated to be 1:3000 based on the geometric characteristics of the facility and on full scale observations from Hjelmfelt (1988); this latter study, in fact, reported that the parent downdraft of a typical microburst has a diameter of about 1.8 km and that the maximum radial wind speeds are experienced at about 1.5 km ($\approx 0.83D$) from the downdraft touchdown. In Letchford and Chay (2002), the 0.51 m diameter jet ($D$) blew against an extensive flat surface positioned 870 mm ($1.7D$) above its outlet, producing an inverted downburst simulation. The blower sat on a carriage which could be translated manually on rails at approximately constant velocity of up to 2 m/s. A pair of switches positioned 5 m apart on the rails allowed the calculation of the jet translational speed and also provided an exact temporal and spatial reference for the jet in the velocity and pressure measurements. The authors found that for translation speeds lower than 20% of the downdraft speed, no gust front was evident and the resulting outflow was very similar to a stationary wall jet. In these conditions the smoothed velocity profile as well as the surface pressures over the cube were well approximated by a quasi-steady approach using the data from the stationary jet experiments. For higher jet translation speeds, instead, the transient characteristics significantly exceeded the quasi-steady estimates. Fujita (1985) gave many examples of recorded microbursts where the angle of impact at the ground is between 45° and 90° to the surface due to the travelling motion of the parent storm. Mason and Wood (2005) reproduced this condition at the steady jet wind tunnel of the University of Sidney. By means of a 1.82 m long horizontal settling chamber and a circular nozzle of diameter $D = 0.31$ m connected to the rectangular outlet, they produced an impinging air jet on a vertical flat surface positioned 1.5$D$ away from the outlet. The length scale was set to 1:3250 based on the nozzle diameter in order to draw comparisons with full scale events. They performed both steady state and pulsed flow simulations where, for this latter,
they used a punctured latex membrane to produce the vortex ring at the leading edge of the flow. Finally, the jet inclination was replicated by varying the angle of the testing surface from the vertical position since the jet itself was unable to rotate. The authors simulated the flows over a model cube with side length of 20 mm and found that inclining the jet generally decreases the design pressures, except for pulsed flow with the model located downwind or to the side where pressures were increased by about 5%. Later, Mason et al. (2009b) measured the outflow produced by setting the impinging jet-axis inclination to five non-normal angles from $0^\circ$ to $35^\circ$ and found that, as the angle of the jet tilt increases, the radial extent over which high wind speeds develop increases as well. Maximum wind speeds were found to be relatively independent of jet tilt, but their radial locations were observed to shift away from the jet touchdown with increasing the jet tilt. The elevation of maximum wind speeds was also found to be dependent of the jet-axis angle. The authors concluded that, in terms of structural loading, tilted downbursts have the potential to cause larger loads than surface-normal events.

Despite this set of physical simulations gives good indications on the behavior of tilted (or travelling) downbursts, the small-scale characteristics involved in all experiments mentioned above along with the use of technically restricted expedients to modify the available equipment in order to properly replicate the phenomenon, leave some uncertainties on the accuracy of the results to address the actual nature of downburst winds.

In addition to the role exerted by the moving parent cloud, downbursts in nature always occur embedded in the atmospheric boundary layer (ABL) winds. Indeed, ABL winds present pronounced velocity shears favorable for the development of thunderstorms (Burlando et al., 2017). In literature the combination of downburst with background wind has mostly been dealt as the vector superposition of the two wind systems (Holmes and Oliver, 2000; Chay et al., 2006; Kim and Hangan, 2007; Abd-Elaal et al., 2014). This has been demonstrated to be physically inaccurate and only recently the non-linear interplay has been addressed experimentally (Romanic and Hangan, 2019; Chapter 3). Chapter 3 shows that the interaction with the ABL-like flow produces maximum velocities of the downburst outflow at the front between the opposing flows in the position $\alpha = 30^\circ$ and $r/D = 0.75$, where $\alpha = 0^\circ$ corresponds to the direction of the incoming ABL wind while $r/D$ is the radial distance from the jet touchdown normalized by the jet diameter $D = 3.2$ m. In this region, in fact, the logarithmic-like ABL profile produces horizontal vorticity concordant to that of the downburst (DB) primary vortex (PV). This leads the ABL air to be entrained into the radially advancing PV and, consequently, the horizontal flow to speed-up between the lower vortex filaments and the ground, where the maximum wind speeds are experienced (Goff, 1976; Hjelmfelt, 1988; Lombardo et al., 2014). The findings discussed in Chapter 3 confirm the unfeasibility of the vector superposition between the two flows and described, in both qualitative and quantitative terms, the spatial and temporal evolution of the related gust front. It resulted that, in the neighborhood of $\alpha = 0^\circ$, the ABL-like flow hinders the
natural expansion of the radial outflow. This occurs particularly upon the jet touchdown on the ground, namely in the most intense phase of the outflow captured by the passage of the radially developing PV which maintains its symmetric structure and runs into the counter directed ABL wind. PV travelling velocity is thus reduced while, at the same time, the entrainment of ABL air leads to what mentioned above. On the other hand, the vertical jet that approaches the ground is tilted by the horizontal cross-ABL flow and thus the touchdown position results slightly shifted downwind accordingly to the ABL direction. Despite the physics behind is different, the overall outflow embedded into the ABL flow assumes an elliptical shape similar to that triggered by the parent thunderstorm translation.

As expressed above, the advanced modes of the state-of-the-art WindEEE simulator allow to couple and reproduce simultaneously DB and ABL flows. In this study, in analogy to Mason et al. (2009b), we first addressed the effect of the moving parent thunderstorm on the generated DB field by setting the inclination of the jet axis at the outlet to \( \theta = 30^\circ \) in respect to the normal to the ground; it corresponds to a jet that impacts the surface at \( 60^\circ \) and falls in the range of angles observed by Fujita (1985) during most of his full scale observations on microbursts. The decomposition of the inclined jet velocity (\( V_J \)) into vertical downdraft velocity (\( V_d \)) and horizontal translation velocity (\( V_t \)) components, respectively evaluated through \( V_d = V_J \times \cos(\theta) \) and \( V_t = V_J \times \sin(\theta) \), leads to \( V_t = 0.58 \times V_d \) which is abundantly in the range of values \( V_t > 0.2 \times V_d \) estimated by Letchford and Chay (2002), where the transient features of the phenomenon become significant and cannot be assessed through the quasi-steady theory. Finally, we coupled the contributions and effects of inclined jet and background ABL-like flow to investigate the whole downburst system and thus reconstruct the most realistic scenario of full scale downburst occurrences. To date and to our knowledge, the presented physical investigation represents the largest, most thorough and exhaustive experimental campaign on downburst winds. Furthermore, the geometric scale of the experiments performed at the WindEEE Dome is by an order of magnitude or so larger than in all previous studies; this surely allows a more accurate and careful analysis of the dynamic processes involved in the simulations.

The chapter is organized in the following manner: Section 4.2 briefly describes the WindEEE Dome and the impinging jet (IJ) modes to generate the investigated DB-like flows; it also provides a detailed description of the experimental setup. The effects of the IJ-axis inclination on the DB flow field with and without background ABL wind, is analyzed in Section 4.3. Here the main results are shown in terms of spatiotemporal evolution of the three-dimensional downburst outflow in relation to the vertical (i.e. spatially stationary) DB cases presented, without and with the inclusion of the ABL wind, here named vertDB (Chapter 2) and vertDBABL (Chapter 3), respectively. Important considerations on the time transition of the wind speed vertical profiles across the DB outflows are also addressed and the main statistical and turbulence properties are critically discussed. Finally, Section 4.4 provides the main conclusions of this
study and contextualize it inside the on-going experimental activities performed as part of the project THUNDERR. Prospects for future work are also outlined here.

4.2 Experiment setup

The WindEEE Dome is a large-scale three-dimensional wind simulator capable of producing non-stationary wind systems such as downbursts, tornadoes, gusts, sheared and veered flows and atmospheric boundary layers (Hangan et al., 2017). The facility is composed by a hexagonal chamber of 25 m diameter by 3.8 m height and is surrounded by an outer return circuit of 40 m diameter. One hundred fans are situated on the six peripheral walls of the testing chamber; sixty of them of diameter 0.8 m each are installed in the 60-fan wall, i.e. in a matrix of 4 rows by 15 columns (Figure 4.2). The 60-fan wall is used to reproduce different ABL-like flows while DB-like impinging jets are generated by means of an upper chamber which hosts six fans of larger diameter (i.e. 2.5 times that of the 60-fan wall fans, 2.0 m) and is connected to the testing chamber through a bell mouth of 4.5 m diameter. The dynamic IJ is thus created by firstly launching the six upper fans while keeping the louvers in the bell mouth closed. Once the upper chamber is pressurized to the desired value (approximately 3.4 Pa larger than the pressure in the testing chamber), the louvers are suddenly opened and the air is released downward into the testing chamber (Figure 4.2). The diameter of the bell mouth can vary from a maximum of 4.5 m to a minimum of 1.2 m by mounting a set of different size rings. In this regard, in fact, the WindEEE simulator can produce downburst-like outflows at different geometric scales, from approximately 1:100 to over 1:1000 (Junayed et al., 2019; Romanic et al., 2019), and different $H/D$ ratios where $H = 3.8$ m is the height of the testing chamber. In analogy to the experiments described in Chapter 2 and Chapter 3, the IJ diameter investigated in the present study was constant and set to $D = 3.2$ m; hence $H/D = 1.19$.

Figure 4.2 schematically shows the formation and scenario of inclined-jet downburst embedded in ABL-like flow.
As mentioned above, the WindEEE facility is also capable of simultaneously producing different ABL winds and DB outflows at various Reynolds numbers and momenta ratios of the two flows (Romanic et al., 2019). In this advanced mode, the impinging jet is released into a perpendicular ABL wind. The match of the geometric scale between downburst and ABL flows at the WindEEE Dome is addressed in Chapter 3, Section 3.2.3 and provides rather satisfying remarks that validate the goodness of the outcomes of the present analyses.

For the current study, the IJ-axis was inclined to 30° in respect to the vertical stationary position tested and analyzed in Chapter 2 and Chapter 3; Figure 4.2b shows that the jet axis is inclined towards the same direction of the outgoing ABL flow. In fact, the opening of the louvres at the bell mouth of the WindEEE Dome is limited between fully closed and fully opened following the inclination showed in Figure 4.2 and therefore inclinations of the jet towards the incoming ABL wind is not possible. In analogy to Chapter 2 and Chapter 3, the DB-like impinging jet was released respectively in a calm environment, i.e. no background flow, and in an already developed ABL-like wind, respectively. Hereafter, these new cases will be named respectively inclDB and inclDBABL in order to make a clear distinction from the downburst configurations related to the vertical IJ (Chapter 2 and Chapter 3).

Analogously to the experiments described in Chapter 3, the intensities of ABL and IJ flows were both set to 30% of the nominal power of the respective fans. The corresponding jet velocity at the exit of the bell mouth is 12.4 m s⁻¹ for inclDB and 11.8 m s⁻¹ for inclDBABL. Despite the same power set at the six upper fans creating the DB-like flow, the variation between the jet velocities is due to the closed-circuit nature of the WindEEE Dome which produces a deficit in the momenta of both flows when they are generated simultaneously (Romanic et al., 2019). The inclination of the jet velocity vector to 30° produces
an additional horizontal velocity of 6.2 m s\(^{-1}\) and 5.9 m s\(^{-1}\), respectively for inclDB and inclDBABL, which represents the storm translational velocity and again reflects what observed in nature. The ABL-flow velocities at the outlet section (3 m downstream) of the 60-fan wall are 3.9 m s\(^{-1}\) at \(z = 25\) cm above the floor. The characteristic wind speeds involved in this study are reported in Table 4.1.

Ten Cobra probes were deployed in each experiment and mounted on a heavy and stiff mast that prevented vibrations of the instrumentation during the tests. The mast was moved across the chamber along 10 radial (\(r/D\)) and 7 azimuthal (\(\alpha\)) positions accordingly to Figure 4.3 in order to cover a very large spatial domain of measurements, namely \(r/D\) spanning from 0.2 to 2.0 with a radial increment of 0.2 and \(\alpha\) from 0° to 180° with an azimuthal increment of 30°. \(r/D = 0.8\) is actually measured at \(r/D = 0.75\) due to irregularities of the chamber bare floor in correspondence of the turntable edge, located at the \(r/D = 0.8\), which may distort the flow measurements due to the malposition of the Cobra probe mast. Figure 4.3 shows that \(r/D = 0\) corresponds to the jet touchdown position when the DB is not embedded into the ABL flow, while \(\alpha = 0°\) identifies the direction of the incoming ABL wind. Due to the circular symmetry in respect to the incoming ABL, the results can be mirrored to the other half of the measurement circle, i.e. \(180° < \alpha < 360°\). The ten probes faced the jet impingement position to measure the radial component of the wind speed and were located at heights \(z = 0.04, 0.07, 0.10, 0.125, 0.15, 0.20, 0.30, 0.40, 0.50, 0.70\) m. In the experiments on downburst superimposed to ABL flow, two additional probes facing the incoming ABL were located at \(z = 0.10\) and 0.50 m on the other side of the symmetry plane in respect to the direction of the incoming background ABL wind. In the following of this chapter, the horizontal and vertical distances are normalized by \(D = 3.2\) m and \(z_{\text{max}} = 1.0\), respectively, to be consistent with the analyses reported in Chapter 2 and Chapter 3. For every \(\alpha\) and \(r/D\) position, each experiment with the same initial conditions was repeated 10 times in order to inspect the repeatability of the tests and to draw a statistical investigation of the results. Therefore, 2 experiment setups times 7 azimuthal and 10 radial positions times 10 to 12 measuring probes times 10 repetitions resulted in 15400 velocity records. Figure 4.3 shows the measurement locations while Table 4.1 summarizes the overall experimental setup. As mentioned above, velocity measurements were recorded by Cobra probes (Turbulent Flow Inc.) with a sampling frequency of \(f_s = 2500\) Hz. Cobra probes are designed to acquire the 3 components of the velocity within a cone of ±45° in respect to the incoming flow. The accuracy of velocity and yaw/pitch measurements is ±0.5 m s\(^{-1}\) and ±1°, respectively, up to approximately 30% of turbulence intensity. In order to reproduce the transient features of downburst winds, the louvers at the bell mouth were opened and then closed 4 s later; \(\Delta t = 4\) s corresponds thus to the duration of the jet release into the chamber. A new automated mechanism recently installed at the bell mouth level enabled the recording of both times of opening and closing of the louvers. This allowed the alignment of all repetitions within the same experiment and, furthermore, the overall
synchronization of all signals across the chamber in order to thoroughly inspect the spatial and temporal evolution of the downburst system.

Table 4.1. Experiment setup: Case name; Jet diameter ($D$); Jet velocity ($W_{\text{jet}}$); Straight flow velocity ($V_{\text{ABL}}$) measured at $z = 25$ cm; Azimuthal locations ($\alpha$); Radial locations ($r/D$); Cobra probe heights ($z/z_{\text{max}}$) where IJ identifies probes facing the jet impingement, SF identifies probes facing the direction of incoming ABL; Repetitions per experiment (Reps).

<table>
<thead>
<tr>
<th>Case</th>
<th>$D$ [m]</th>
<th>$W_{\text{jet}}$ [m s$^{-1}$]</th>
<th>$V_{\text{ABL}}$ [m s$^{-1}$]</th>
<th>$\alpha$ [$^\circ$]</th>
<th>$r/D$ [l]</th>
<th>$z/z_{\text{max}}$ [l]</th>
<th>Reps</th>
</tr>
</thead>
<tbody>
<tr>
<td>inclDB</td>
<td>3.2</td>
<td>12.4</td>
<td>\</td>
<td>0:30:180</td>
<td>0.2:0.2:2 *</td>
<td>0.4, 0.7, 1.0, 1.25, 1.5, 2.0, 3.0, 4.0, 5.0, 7.0 (IJ)</td>
<td>10</td>
</tr>
<tr>
<td>inclDBABL</td>
<td>3.2</td>
<td>11.8</td>
<td>3.9</td>
<td>0:30:180</td>
<td>0.2:0.2:2 *</td>
<td>0.4, 0.7, 1.0, 1.25, 1.5, 2.0, 3.0, 4.0, 5.0, 7.0 (IJ) 1.0, 5.0 (SF)</td>
<td>10</td>
</tr>
</tbody>
</table>

* $r/D = 0.8$ is moved to $r/D = 0.75$ due to irregularities of chamber floor.

Figure 4.3. Schematics top-view of inclined downburst supplemented by ABL flow.

4.3 Results

This section shows the important outcomes of the investigation performed on the two sets of downburst experiments here presented. Furthermore, it provides a comprehensive overview and case comparison of the whole experimental campaign carried out at the WindEEE Dome to date in order to weigh the role of each parameter involved in the dynamics of the physically produced DB winds. Section 4.3.1 reconstructs the effect of the IJ-axis inclination on the time and space evolution of the outflows, drawing a clear comparison between the cases of downburst embedded or not in the ABL background flow. The results are also discussed in relation to the vertical IJ-axis cases described in Chapter 2 and Chapter 3. Section 4.3.2 provides important observations on the outflow vertical profiles and shows a clear time development of the height of occurrence of the maximum wind speed. Section 4.3.3 presents spatiotemporal distribution of the turbulent field for the two simulated downbursts cases.
4.3.1 Space and time reconstruction of DB flow fields

Based on the time of opening of the bell mouth louver, all the wind speed records were synchronized and it was thus possible to inspect the time evolution of the generated three-dimensional flow fields. For each grid point the ensemble mean was calculated out of all 10 repetitions. Then, by applying a mobile window of $T = 0.1$ s (Junayed et al., 2019) on this quantity, we obtained the slowly-varying mean wind speed $\bar{V}(t)$; the reader can refer to Solari et al. (2015) for a complete overview of the downburst velocity decomposition process. Chapter 2 shows that the common signature of all downburst measurements is the occurrence of maximum wind speeds in correspondence of the passage of the primary vortex (PV). Within this time lag, denoted as “PV phase”, the highest horizontal velocities are generally experienced below the normalized height $z/z_{max} = 1.0$; Section 4.3.2 will confirm this characteristic. Figure 4.4 shows the DB-like horizontal outflows (plane $r - \alpha$) at $z/z_{max} = 1.0$ for inclined pure downburst (inclDB, panels a-c) and inclined downburst embedded in ABL wind (inclDBABL, panels d-e) cases. The following time steps are plotted: (1) $t = 1.60$ s (panels a,d), time occurrence of the absolute maximum of the slowly-varying mean wind speed $\bar{V}_{max}$ for the case inclDBABL; (2) $t = 1.83$ s (panels b,e), same as (1) but for the case inclDB; (3) $t = 3.00$ s (panels c,f), generic time instant in the middle of the plateau phase, namely the time interval after the PV phase where the wind speed is in steady-state conditions. In this stage the velocity has mean value approximately constant and fluctuations quite symmetric around the mean (Chapter 2). As expected, the radial symmetry appears overall lost and the outflows assume an elliptical shape as first reported by Fujita (1985). Indeed, the downdraft inclination at the ground provokes the flow to intensify in the forward-wind region, i.e. $90^\circ < \alpha \leq 180^\circ$, and to weaken in the back-wind part, i.e. $0^\circ \leq \alpha \leq 90^\circ$.

The absolute maxima of the slowly-varying mean wind speed occur at the locations $\alpha = 150^\circ$, $r/D = 1.4$, $z/z_{max} = 0.4$ and $\alpha = 90^\circ$, $r/D = 1.0$, $z/z_{max} = 0.7$ for the cases inclDB and inclDBABL, respectively. The inclusion of the background wind (panels d-f), in fact, does not strengthen the back wind in terms of velocity magnitudes as noted in the vertDBABL case (Chapter 3) but rather tilts the downdraft to an angle $\theta > 30^\circ$, larger than the set IJ. The touchdown position and, thus, the DB outflow region are shifted towards $\alpha = 180^\circ$ accordingly. On the other hand, in the region $0^\circ \leq \alpha \leq 90^\circ$ the flow is spatially hindered by the counter directed ABL flow which limits the outflow, and thus the PV, expansion. In fact, the PV is observed to remain “locked” at the same approximate radial position throughout the time evolution of the phenomenon; this is clear by observing Figure 4.4e and Figure 4.4f where, despite the large time gap $\Delta t = 1.17$ s between the two scenarios, PV appears approximately at the same location (identified by the higher radial velocities). At the same time, as explained in Chapter 3, the concordant circulation (or horizontal vorticity direction) between DB and ABL flows at their colliding front also leads to the entrainment of ABL air into the primary vortex structure. This in turn causes PV to possibly enlarge in size and to increase its
internal vorticity; it follows that, theoretically, the flow speeds up at the boundary between PV and the ground, namely in the region where the maximum velocities are recorded. As reported above, however, the case inclDBABL does not show the absolute maxima at the front between the two wind systems as it occurred for the vertDBABL case (Chapter 3). The already weaker outflow in the rear side of the outflow, caused by the downdraft tilting at the touchdown towards $\alpha = 180^\circ$ (forward-wind region), may lead to a less symmetric and more chaotic PV structure which, consequently, does not entrain the ABL air as systematically and consistently as in vertDBABL (Figure 4.5). For this reason, the flow speed-up effect in this region appears partially lost and the related wind speeds are of comparable magnitude between the two cases of downburst with and without the inclusion of the ABL-like flow. Nevertheless, despite in the back-wind area $0^\circ \leq \alpha \leq 90^\circ$ the outflow is hindered by the advancing ABL, we notice here slightly higher velocities compared to the case inclDB.

The opposite circulation of the two wind systems in the forward-wind area ($90^\circ \leq \alpha \leq 180^\circ$), namely clockwise for the incoming ABL wind and counter-clockwise for the advancing PV as seen from 270°, may produce, at first sight, the slight velocity reduction in this region for inclDBABL with respect to inclDB. However, this is noticed only starting from approximately $r/D = 1.0$ where the ABL flow, after being deviated externally outwards in the back-wind region, might reattach here to the advancing DB outflow. Nevertheless, this situation is more realistic for full scale downburst events where there are no boundary constraints as in a wind simulator. In fact, despite the very large geometry of the WindEEE chamber, the analyses on our experiments (see Figure 4.4f) show that the ABL flow, once collided against the advancing PV, is deviated outwards to exit the chamber through the peripheral fans at approximately $\alpha = 60^\circ$. In the forward area of the outflow, it is thus reasonable to confirm the assumption made in Chapter 3 according to which the cross ABL flow influences the downburst mainly in its impingement stage where the impact on the descending jet shifts the impingement position further beyond $r/D = 0$ in the direction of $\alpha = 180^\circ$. We therefore believe that the ABL flow would not reach and merge into the downburst outflow in the forward-wind area. The lower velocities of the case inclDBABL in the region $90^\circ < \alpha \leq 180^\circ$ are, instead, to be attributed to the deficit in the momenta of the impinging jet when produced simultaneously with the ABL flow (Romanic et al., 2019).
Figure 4.4. Downburst outflow field at $z/z_{\text{max}} = 1.0$ (horizontal plane $r - \alpha$) and $t = 1.60$ s (a,d); 1.83 s (b,e) and 3.00 s (c,f) for inclDB (a-c) and inclDBABL (d-f) cases. Black spots identify regions where velocity is below 1 m s$^{-1}$ (not considered due to accuracy of probes). Red vectors represent the actual punctual measurements of Cobra probes while the overall flow fields are obtained from their interpolation.

Figure 4.5. Schematics of the DB-ABL interaction (vertical plane as seen from $\alpha = 270^\circ$). +/- indicate the sign of vorticity.

Figure 4.6 shows the envelope of the primary maxima of the slowly-varying horizontal velocity, at the heights $z/z_{\text{max}} = 0.4, 1.0, 2.0$ and 5.0 (panels A-D), in 2D chart (plane $r - \alpha$) of all cases tested at WindEEE and herein compared each other, namely vertDB (panels a) vertDBABL (panels b), inclDB
(panels c) and inclDBABL (panels d). The contribution of the ABL flow (panels b,d) into the counter-directed PV (Figure 4.5 and Chapter 3, Figure 6) to enhance its dynamics and increase the maximum horizontal wind speeds is evident at the height $z/z_{\text{max}} = 0.4$ (panel A). Accordingly, the maximum horizontal velocities are experienced at $\alpha = 30^\circ$ and $r/D = 0.75 - 1.0$. Already starting from $z/z_{\text{max}} = 1.0$ (panel B) the inclDBABL case seems to lose the benefit of the ABL entrainment in the rear side, and the region of highest wind speeds moves to the forward side, i.e. $90^\circ < \alpha < 180^\circ$. Therefore, the effect of the IJ-axis inclination towards $\alpha = 180^\circ$ and the concordant direction of the ABL wind that eventually deflects further the jet in this region, causes an intensification of the forward-side wind, as detailing described above. However, the case vertDBABL shows highest velocities in the rear part, again due to effect of ABL entrainment into the counter directed DB outflow. At $z/z_{\text{max}} = 2.0$ and 5.0 (panels C,D) the cases inclDB and inclDBABL (panels c,d) show a very similar distribution of the maximum wind speeds in the horizontal plane, meaning that the effect of the ABL flow is lost at the higher heights and the IJ-axis inclination becomes the dominant contribute. The intensification of the forward-side wind speeds is clear at any height for the case inclDB. The vertDB case (panels a), which assumes a radial symmetric flow field, shows maximum velocities around $r/D = 1.0$ and at the lower two heights (panels A,B) with very little differences, while lower velocities are gradually experienced with increasing the height AGL.
Figure 4.6. Downburst outflow field (horizontal plane $r - \alpha$) of maximum velocity envelops at $z/z_{\text{max}} = 0.4, 1.0, 2.0$ and 5.0 (panels A-D) for vertDB (a), vertDBABL (b), inclDB (c) and inclDBABL (d) cases. Red vectors represent the actual maximum wind speeds as measured by Cobra probes while the overall flow fields are obtained from their interpolation. The case vertDB was not measured at $z/z_{\text{max}} = 2.0$.

The same concept holds for Figure 4.7, where the horizontal flow fields now represent the envelope of the slowly-varying horizontal wind speeds time-averaged over the plateau segment of each record. Here, the intensification of the back-side wind due to the ABL entrainment is somehow noticed only for vertDBABL and at the lowest height (panel A(b)), whereas it is completely lost at the higher heights where vertDBABL assumes a quasi-symmetric behavior similar to vertDB. In this sense, the contribute of the ABL appears completely lost in the plateau segment for the case inclDBABL. Overall, also here the wind speed magnitude decreases by increasing the height AGL.
Figure 4.7. Same as Figure 4.6 but for envelops of plateau temporal-mean horizontal wind speeds.

Figure 4.8 shows, for the cases inclDB and inclDBABL, the spatial behavior of the outflows in the vertical plane ($r - z$) and at a given instant in time ($t = 1.72$ s) between the occurrences of the absolute maxima of the wind speed in the two cases, i.e. $t = 1.60$ s (inclDBABL) and $t = 1.83$ s (inclDB). The flow field is here shown at three different azimuth angles, i.e. $\alpha = 0^\circ, 90^\circ$ and $180^\circ$, respectively for the cases inclDB (panels a-c) and inclDBABL (panels d-f). What observed above is here validated. In fact, the inclusion of the ABL wind (panels d-f) does not seem to change the velocity magnitudes accordingly but only to shift the instantaneous position of the outflow based on the observation position. At $\alpha = 0^\circ$ (panels a,d) the collision between DB outflow and incoming ABL flow curbs the PV radial expansion which in Figure 4.8d is recorded approximately $\Delta r/D = 0.5$ behind that of inclDB (Figure 4.8a). For the reasons mentioned above, the situation is reversed in the forward-wind side due to the different influence exerted by the cross ABL flow on the downdraft tilting at the ground and consequent shift of the touchdown position. Hence, in this case PV is radially recorded ahead compared to the pure downburst case. This is only little appreciable at $\alpha = 90^\circ$ while it becomes much clearer at $\alpha = 180^\circ$ where the outflow in the case inclDBABL has nearly reached the boundary of the radial domain. Here, the lower wind speeds are due to the reasons mentioned above.
Figure 4.8. Downburst outflow field (vertical plane $r - z$) at $t = 1.72$ s and $\alpha = 0^\circ$ (a,d), $90^\circ$ (b,e) and $180^\circ$ (c,f). Upper (a-c) and bottom (d-f) rows show the case inclDB and inclDBABL, respectively. Black spots identify regions where velocity is below $1 \text{ m s}^{-1}$ (not considered due to accuracy of probes). Red vectors represent the actual punctual measurements of Cobra probes while the overall flow fields are obtained from their interpolation.

Figure 4.9 depicts the flow field in the vertical plane $(r - z)$ at $\alpha = 30^\circ, 90^\circ$ and $150^\circ$ (panels A-C) as envelope of the maximum velocities, for the cases vertDB (panels a), vertDBABL (panels b), inclDB (panels c) and inclDBABL (panels d). It was here decided to show only these three angles for sake of visualization and because the absolute maximum velocities occur indeed at the locations $= 30^\circ, 90^\circ$ and $150^\circ$, respectively for vertDBABL, inclDBABL and inclDB. In the cases where downburst is supplemented with ABL flow and/or subject to the effect of the storm motion (panels b-d), the maximum velocities occur at further in radial distance from the jet touchdown by moving from rear- to forward- side of the flow field. However, the cases with inclined JJ-axis (panels c,d) do not show relevant differences in this regard between $\alpha = 90^\circ$ and $150^\circ$. The effect of the entrainment of ABL wind in the rear side is again very clear for vertDBABL (panel A(b)), whereas the flow field weakens in the forward part for this latter case. Conversely, the case inclDBABL does not benefit of the inclusion of the ABL to intensify the back-side wind but rather is mostly affected by the jet-axis inclination at the forward part.
Figure 4.9. Downburst outflow field (vertical plane $r - z$) of maximum velocity envelopes at $\alpha = 30^\circ, 90^\circ$ and $150^\circ$ (panels A-C) for vertDB (a), vertDBABL (b), inclDB (c) and inclDBABL (d) cases.
The inclusion of the ABL wind clearly affects the downburst field in a very different manner depending on whether the jet axis is vertical or inclined. It is worth reminding here that in case of inclined jet, the bell mouth louvers are opened at $\theta = 30^\circ$ towards the chamber’s side identified by $\alpha = 180^\circ$, concordant to the direction of the background ABL wind. In this configuration, the generated PV in the back-wind area $0^\circ \leq \alpha \leq 90^\circ$ loses its symmetric and consistent structure needed to maintain its local vorticity high and thus to entrain the opposite directed but equally rotating ABL air (Figure 4.5), which eventually leads to the increase of horizontal wind speeds at the boundary with the ground. In addition to this, the inclination of the jet moves the touchdown position beyond $r/D = 0$ in the direction of $\alpha = 180^\circ$ and, hence, the overall outflow in the rear region results weakened. Furthermore, the higher wind speeds appear more confined to the ground in the inclDBABL compared to vertDBABL. This suggests that the tilt of the downdraft, combined with the incoming ABL flow, squashes the primary vortex to the ground for $\alpha \leq 90^\circ$.

As mentioned above, the logarithmic-like shape of the mean ABL profile produces a clockwise vorticity of the flow in respect to an observer located in the region $180^\circ < \alpha < 360^\circ$. We speculate that the ABL wind, being not entrained into the downburst PV structure, may produce a negative lift, or downward momentum, to the ground which may squeeze the primary vortex itself.

### 4.3.2 Space and time transition of outflow vertical profiles

The analysis of full scale downburst events has clearly shown that in the moment of maximum intensity of the horizontal winds, associated with the passage of the gust front, the wind speed vertical profiles assume a transient nose-like shape with maximum wind speeds in the range 50-120 m AGL (Goff, 1976). Chapter 6 analyzes the vertical profiles of a subset of 10 thunderstorm events recorded in the main ports of the Northern Mediterranean by means of LiDAR wind profilers. It shows that the nose-like shape profiles always occur in correspondence of the maxima of the horizontal wind speed signals.

Thanks to the incredibly large number of experiments carried out in the framework of this campaign, the following of this section draws a statistical analysis of the vertical profile transitions along the velocity signals and investigates the differences among the tested DB cases. Important considerations based on the different observation locations along the azimuthal domain of measurements, i.e. in respect to the incoming ABL-like flow, are also reported. To provide a more comprehensive and exhaustive investigation to the reader, the analyses hereafter also include the cases vertDB (Chapter 2) and vertDBABL (Chapter 3).

Figure 4.10 and Figure 4.11 show the vertical profile evolution in space and time of the horizontal slowly-varying mean velocity for inclDB and inclDBABL, respectively. For sake of space, the diagrams are shown only for $\alpha = 0^\circ, 90^\circ, 180^\circ$ and $r/D = 0.6, 1.0, 1.4, 1.8$. At $\alpha = 0^\circ$, the counter ABL-like flow is observed to destroy the DB outflow for $r/D \geq 1.4$ (Figure 4.11c,d). However, for lower radial locations, the entrainment of ABL into the counter-directed PV produces overall higher horizontal wind speeds at $\alpha \leq$
90°. For the reasons explained above, also the vertical extension of the region of maximum velocities seem to increase and the tip of the nose of the vertical profiles to grow in elevation. At $\alpha = 90°$, inclDBABL (Figure 4.11) shows higher velocities than inclDB (Figure 4.10) for $r/D > 1.0$ (panels g,h) possibly due to the favorable effect of the ABL wind which, on the one hand, still entrains into the PV causing an increase of the wind speeds and, on the other hand, pushes the DB downdraft, and consequently the overall outflow, further in the radial distance. No significant differences between inclDB and inclDBABL are observed at $\alpha = 180°$ (panels i-l), despite this latter case shows slightly higher wind speeds. This is again likely due to the effect of the ABL flow that produces a downward momentum on the expanding DB outflow. This, in turn, causes a squeezing of the outflow at the ground and consequent speed-up. In both cases, however, the overall highest wind speeds are observed in the forward-side region due to the inclination of the IJ-axis towards $\alpha = 180°$ which intensifies the forward-side outflow, eventually overcoming any other influence due to the ABL-like wind.

![Figure 4.10](image)

*Figure 4.10. Profiles of $\bar{V}(z, t)$ at $\alpha = 0°, 90°, 180°$ and $r/D = 0.6, 1.0, 1.4, 1.8$ for inclDB.*
Figure 4.11. Same as Figure 4.10 but for inclDBABL

Figure 4.12 and Figure 4.13 show the transition of the vertical profiles in terms of height of maximum wind speed recorded. This analysis considers only the measurement domain $0.6 \leq r/D \leq 1.4$. Here, the lower boundary is intended to exclude from the analysis the radial locations that are potentially inside the projected area of the downdraft current to the ground. On the other hand, the upper boundary is thought to neglect the locations where the downburst is actually overwhelmed by the opposite directed ABL flow, in the forward-wind area, and hence the measurements are partly missing and leading to a false in the assessment of the present analysis. For each of the four downburst cases, i.e. vertical and inclined jet with and without the inclusion of ABL wind, the slowly-varying velocity signals of all azimuthal and radial locations considered were aligned based on the time of occurrence of the absolute maximum of the horizontal slowly-varying velocity along the vertical profile. Hence, the ensemble average of $z(V_{\text{max}})$ was calculated across the experimental repetitions and over all radial and azimuth locations of measurement (Figure 4.12) as well as individually per azimuth location (Figure 4.13). Because of the aligning process of wind speed records, the single ensemble value across all time histories at a given instant in time was assumed valid if at least 80% of all signals contributed to its calculation. Furthermore, the diagrams show the analysis only up to $t = 4$ s, i.e. during the plateau interval, due to the different length of the velocity signals at the different measurement locations. To be noted that the experiments on vertDB (Chapter 2),
produced a radial symmetric outflow and were thus performed along one single azimuth line of measurements that led to a smaller number of overall records to be statistically computed. From here the less deterministic behavior of the related signal.

Figure 4.12 points out a very important aspect of this study. The diagrams, in fact, show analogous trend across the different test cases and bring fundamental understandings on the time evolution of the velocity profiles of downburst winds. The tip of the nose or, in other terms, the height of occurrence of maximum velocity, is observed at high levels \( z/z_{max} > 2.0 \) at the beginning of the velocity signals. In the cases vertDBABL and inclDBABL this behavior is produced by the background ABL wind which is started prior to the release of the IJ and, thus, represents the dominant feature of the first part of the wind speed records. Following the associated logarithmic-like vertical profile, in fact, the maximum wind speeds occur at the top heights. This aspect is very clear at the locations where the Cobra probes are actually oriented against the ABL flow and therefore can measure properly its vertical profile (Figure 4.13c). As explained in Chapter 2, in the pure downburst cases (i.e. vertDB and inclDB) the high elevations of maximum velocities while the DB outflow is still approaching the instrument might be due to viscous effects that arise in the near-surface region and provoke a retardation of the flow at the lower levels and consequent acceleration at the higher heights. The diagrams seem to show a more pronounced behavior of this type in the case of inclined jet. In fact, this aspect is enhanced where the flow is intensified by the IJ inclination (Figure 4.13c), while the height lowers down in the rear-side region where the flow results weakened (Figure 4.13a). By comparing all cases, however, the influence of the ABL-like logarithmic profile seems to be dominant.

Moving forward in time, the height of maximum wind speed is observed to drop drastically concurrently with the start of the ramp-up phase. Here, with the approaching of the downburst primary vortex to the observation position, the decrease of \( z_{V_{max}} \) appears qualitatively inversely proportional to the increase of \( \bar{V}(t) \). In fact, the flow streamlines squeeze to a very short vertical area at the boundary with the ground; consequently, the wind speed increases and the height of the maximum decreases. It lasts until shortly after the occurrence of the absolute maximum \( \bar{V}_{max} \) where the lowest height is reached. This situation marks the passage of the primary vortex over the measuring instruments which, as widely reported in literature (see Section 4.1), produces indeed maximum horizontal velocities at the boundary between the vortex lower end and the ground. In the view of extending this behavior to the full scale occurrence of downbursts, we believe that the implications of this sudden transition of the velocity profiles on the wind loading and response of structures are of great importance and certainly deserves future research. Despite the abrupt decrease of \( z_{V_{max}} \) follows analogous pattern among the different cases, the lowest height reached concurrently with the passage of PV is case-dependent. In the two cases of downburst embedded in background ABL flow, i.e. vertDBABL and inclDBABL, the lowest heights of respectively \( z/z_{max} = 1.12 \) and \( 1.22 \) are rather higher than those for pure downburst cases, both slightly lower than \( z/z_{max} = 1.0 \). This is again the consequence
of the gust front between DB outflow and ABL wind which enables the PV to entrain ABL air and thus to arise while increasing its size and local vorticity. In turn, the maximum horizontal velocities at the boundary between the vortex lower end and the ground are recorded at higher elevations. However, as documented above, this only happens in the area $0^\circ \leq \alpha \leq 90^\circ$ where the two fronts collide against each other. In this regard, Figure 4.13 shows a more remarkable increase of the height of maximum velocity in the rear-side region (panel a). This behavior is more evident in the case inclDBABL where, despite the fact that the velocity does not benefit of the entrainment of the ABL wind into the PV structure, the height of the vortex seems to increase. From here on, $z_{v_{\text{max}}}$ settles to this approximate constant value corresponding to the lowest height which lasts throughout the plateau phase. Little exception is made by the case vertDBABL, where the height of maximum velocity is observed to slowly decrease in the back-wind region (Figure 4.13a). At $\alpha = 90^\circ$ (Figure 4.13b), marking the passage between rear- and forward-wind regions, the height of maximum velocity show very similar values among all cases throughout the duration of the event. Particularly, vertDBABL shows a sudden spike of $z_{v_{\text{max}}}$ concurrently with the occurrence of the absolute maximum wind speed, which may be due to the onset of the SV and interaction with PV. In the forward-wind region (Figure 4.13c), before the passage of the downburst gust, $z_{v_{\text{max}}}$ is higher for the DB cases supplemented with ABL wind, as expected and explained above. This trend holds until the onset of the plateau segment of the velocity where the upward momentum produced by the IJ inclination on the overall flow, provokes an increase of the height of maximum velocity in this stage, which is not observed elsewhere (Figure 4.13b).
Figure 4.12. Time histories of $z_{\max}'$, evaluated as ensemble mean across all repetitions, azimuth locations and radial locations $0.6 \leq r/D \leq 1.4$, for vertDB, vertDBABL, inclDB, inclDBABL. Orange line shows the ensemble average of the 20 mean velocity repetitions at $r/D = 1.0$, $z/z_{\max} = 1.0$ for vertDB; slowly-varying mean wind speed $\bar{V}$ is normalized by its maximum value $\bar{V}_{\max}$ (right-hand secondary y-axis). Vertical gray dotted line shows $t(\bar{V}_{\max})$.

Figure 4.13. Same as for Figure 4.12, but applied separately on the azimuthal locations $\alpha = 0^\circ$ (a), $90^\circ$ (b) and $180^\circ$ (c). Orange dotted lines show the ensemble average of the 20 mean velocity repetitions at $r/D = 1.0$, $z/z_{\max} = 1.0$ for vertDB; slowly-varying mean wind speed $\bar{V}$ is normalized by its maximum value $\bar{V}_{\max}$ (right-hand secondary y-axis). Vertical gray dotted lines show $t(\bar{V}_{\max})$. 
4.3.3 Turbulence intensity and statistical properties of downburst-like outflows

It is proven, by the analysis of large sets of full scale downburst events (Solari et al., 2015; Zhang et al., 2018, 2019; Chapter 6) as well as experimentally produced downburst outflows (Chapter 2 and Chapter 3) that the usual hypothesis adopted in literature of $I_V = \bar{I}_V$ (where $\bar{I}_V$ is the temporal mean of the slowly-varying turbulence intensity $I_V$), namely turbulence intensity constant in time, does not resemble properly the dynamics of the phenomenon. These studies considered the parameter $\mu(t) = I_V(t)/\bar{I}_V$ and found a local maximum and minimum respectively before and after the occurrence of the maximum horizontal velocity, marking the passage of the PV. This aspect is much more enhanced in experimental conditions due to the significantly lower Reynolds numbers $Re$ involved at the WindEEE Dome, as well as in any other laboratory around the world, compared to the full scale environment (Chapter 2). Furthermore, Chapter 3 shows that the embedment of the DB wind into the already developed ABL-like profile contributes to add turbulence to the overall flow field. Figure 4.14 shows the diagrams of the parameter $\mu(t)$ for inclDB at the different $\alpha$ locations and for $r/D \geq 0.6$. The analysis confirms the overall behavior of the turbulence intensity already experienced in the previous experimental campaigns at WindEEE (Chapter 2 and Chapter 3). The highest maxima of $I_V(t)$ are observed for $1.2 < r/D < 1.8$ and at the lowest measurement heights. As expressed in the previous chapters, this might be caused by the onset of a secondary vortex (SV) at these radial locations and consequent interaction with the outer boundary layer governed by the passage of the PV. The azimuth locations of observation of this behavior, which is highlighted for $\alpha > 90^\circ$, seems to corroborate this hypothesis. The counter directed ABL wind in the rear-side region may, in fact, breaks the formation of the SV at the leading front of the DB outflow (Figure 4.5). Furthermore, the intensification of the forward-wind side due to the IJ inclination plays an important role as well. The high values of $\mu(t)$ appear to increase by moving along the radial domain up to the measurement location $r/D = 1.6$. The overall lower wind velocities as well as the three-dimensionality of the flow at the higher radii may, in fact, somehow weaken the coherent structure of the turbulence at these locations. The same is observed at the radial locations $r/D < 1.2$ where the effects of the IJ inclination, i.e. DB outflow shifted to higher radii in the forward-side region, and the absence of the SV do not enable a clear observation of the asymmetry of the turbulence intensity around the maximum velocity. In the rear-side region, where DB outflow and ABL wind are opposite in direction, the fluctuations of the parameter $\mu$ are much more pronounced along the time history, whereas in the forward-side region where the flow structure is more coherent, the fluctuations are reduced and quite symmetric around the mean value, which in the plateau interval is around $\bar{\mu} = 1$. It is worth noting that for $r/D < 1.6$ the highest maxima of $\mu(t)$ that occur at the lowest heights precedes temporally those at the higher heights. The scenario seems to be
somehow reversed for $r/D > 1.6$. This may be linked to the vertical growth of the SV, and thus of the boundary (or inner) layer below the PV, along the radial dimension (Chapter 2).

Figure 4.14. Ensemble averages of 10 time series (experiment repetitions) of $\mu$ at all $\alpha$ locations, $r/D \geq 0.6$ and $z/z_{\text{max}} = 0.7, 1.5, 3.0$ and 7.0 for the inclDB. Vertical gray dotted lines show $t(\bar{V}_{\text{max}})$.

Figure 4.15 and Figure 4.16 show, in analogy to Figure 4.10 and Figure 4.11, the space and time evolution of the slowly-varying standard deviation $\sigma_V(z,t)$ for the cases inclDB and inclDBABL. An absolute maximum is observed shortly prior to the occurrence of the maximum wind speed. The profiles assume a nose-like shape for $r/D \geq 1.0$ and, in analogy to what observed for $\bar{V}(z,t)$, the vertical extension of the region of high $\sigma_V(z,t)$ grows by moving along the radial direction and, overall, seems to be more pronounced for inclDBABL. Furthermore, this latter case shows more spiky profiles, i.e. more fluctuating, due to the inclusion of the ABL wind into the DB outflow. For sake of visualization, the diagrams of the turbulence intensity are here not shown. $I_V(t)$ appears, in fact, much more fluctuating than $\sigma_V(z,t)$ due to the modulation of $\bar{V}(z,t)$. However, the turbulence intensity values appear in the range of those already found in Chapter 2 and Chapter 3 for vertDB and vertDBABL, respectively, with absolute maxima around $I_V = 0.25$. 

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Figure 4.15. Profiles of $\sigma_V(z, t)$ at $\alpha = 0^\circ, 90^\circ, 180^\circ$ and $r/D = 0.6, 1.0, 1.4, 1.8$ for inclDB.
In analogy to all configurations tested in the framework of the experimental campaign at the WindEEE Dome (see Chapter 2 and Chapter 3) and in agreement with literature on full scale downburst events, the reduced turbulent fluctuation component $\tilde{V}(t) = V'(t)/\sigma_V(t)$, being $V'(t)$ the residual fluctuation ($V'(t) = V(t) - \bar{V}(t)$) and $\sigma_V(t)$ its mobile standard deviation, can be treated to a very good extent as a stationary random process with zero mean and unit standard deviation. Furthermore, this study corroborates that the pattern of the power spectral density (PSD) of $\tilde{V}$ (not shown here) follows the law $n^{-\frac{5}{3}}$ (being $n$ the frequency) at the high frequency end, in agreement with the analyses on full scale synoptic-scale ABL winds as well as real downburst occurrences (Holmes et al., 2008; Solari et al., 2015; Burlando et al., 2017).

### 4.4 Conclusions and Prospects

This chapter fits into the context of the large experimental campaign on downburst winds performed at the WindEEE Dome, Western University, Canada, during 2019. Specifically, it draws the conclusions and main findings of the analyses of the dynamic behavior of downburst winds, as reproduced in a large scale laboratory environment. The main focus of the campaign has been on the study of the different physical contributions that take part in the formation of the overall phenomenon, first individually and later in a combined manner. In full scale records the individual components that form the final downburst wind as
recorded by instruments are usually unknown. Furthermore, the very limited spatiotemporal extension of
the phenomenon in nature does not allow to have a thorough view of its behavior and evolution during the
occurrence of the event. However, a clear understanding of the physics and dynamics of downburst winds
is crucial in the view of analyzing the wind-structure interaction. It follows that only experimental and
numerical models can fill this gap. The horizontal outflow that forms upon the downdraft impingement on
the ground is, in fact, the combination of mainly three factors: the downdraft itself, the background low-
level ABL wind, and the storm motion or parent cloud translation. WindEEE Dome is able to reproduce
non-stationary extreme wind events under a superposition of conditions. Here the experimental scale, when
referred to full scale microburst events, can be as large as 1:100. WindEEE can reproduce the three above-
mentioned flow contributes individually: the downdraft is indeed reproduced through an impinging jet (IJ)
that blows through a bell mouth installed on the ceiling of the testing chamber; the background ABL flow
is supplied by means of 60 individually-controlled fans installed on one of the six peripheral walls of the
chamber; the storm motion is accounted herein by setting the inclination of the IJ-axis to non-normal angles.
This latter aspect can indeed faithfully reconstruct the effect of the cloud translation to tilt the downdraft
axis at the ground, as first introduced by Byers and Braham (1948) and later confirmed by several authors
(see, for instance, Fujita (1985)). This produces an asymmetric downburst outflow at the ground, with
intensification of the forward-wind side and weakening of the back-wind side, which is very clear also in
our experiments.

As reported in Chapter 2 in the case of vertical IJ, the entrainment of the ABL flow into the counter-directed
primary vortex (PV) leading the downburst outflow produces an intensification of the horizontal flow
underneath the PV itself. However, this behavior is overall less evident and only partly observed at the
lowest height in the case inclDBABL. The inclination of the impinging jet IJ-axis (concordant with the
direction of ABL) weakens the flow in the back-wind side and, consequently, the PV loses its structure and
the entrainment of ABL wind reduces. At higher heights, the distribution of the horizontal wind speeds is
very similar between inclDB and inclDBABL, meaning that the outflow is not influenced by the ABL-like
flow. At the time of maximum intensity of the DB outflow, i.e. during the passage of the PV, the height of
maximum horizontal velocity drops drastically following the lowering of the boundary layer which is
constrained underneath the vortex itself. However, this height is significantly higher at the front between
DB outflow and ABL wind, due to the raising of PV above the surface after the entrainment of ABL air
because of the concordant vorticity. The IJ-axis inclination in the forward-wind side produces a positive
upward momentum on the downburst outflow which, in turn, elevates the height of maximum horizontal
wind speeds in this region. The azimuth angle defined by $\alpha = 90^\circ$ is the less affected by both the ABL flow
and the IJ-axis inclination and, hence, the height of maximum wind speed at the peak of the phenomenon
appears similar among the different configurations.
In agreement with the findings discussed in Chapter 2 and Chapter 3 and contrary to what was previously assumed in literature, the turbulence intensity is found to be time-dependent and to show a sudden maximum right before the occurrence of the maximum horizontal velocity. This behavior is associated to the formation of the SV ahead of the downburst outflow and to its interaction with the PV in the outer layer. The azimuth and radial locations of evidence of this aspect seem to corroborate this hypothesis. The maxima of the turbulence intensity occur at the lowest heights and apparently slightly before those at the higher elevations. The situation is reversed at further radial locations due to the growth of the SV in the inner layer and consequent interaction with the PV. The values of the turbulence intensity, however, appear in good agreement with the previous experimental findings (Chapter 2, Chapter 3) with maxima of approximately $I_V = 0.3$.

This study closes the investigation of the vast experimental campaign on downburst winds performed at the WindEEE Dome in the context of the project THUNDERR (Solari et al., 2020). The analyses have returned a thorough and comprehensive picture of the physical behavior and dynamics of the downburst phenomenon. The contribution of the individual flow components taking place during the occurrence of a real thunderstorm event has been addressed in qualitatively terms and their weight on the overall generated downburst outflow was properly defined. This lays the foundations for a clear understanding of the structural behavior when subjected to the downburst phenomenon. A crucial step in this sense will come from a comprehensive comparison of the experimentally-produced outflows with a large set of full scale downburst occurrences. The availability of records from state-of-the-art instruments, such as the LiDAR Profiler and Scanner in the wind monitoring network installed recently in the High Tyrrhenian Sea, will allow to draw a refined analysis of the spatiotemporal evolution of flow fields at full scale and in experimental conditions. In turn, this will eventually enable to build an experimental model to include in the design codes to evaluate the response of structures to thunderstorm winds.

References


Chapter V

5 Aerodynamic behavior of two circular cylinders immersed in vertical-jet axis impinging jet with and without inclusion of ABL wind

Abstract
Thunderstorms winds are localized and transient phenomena characterized by three-dimensional non-stationary velocity fields. While numerous studies investigated the wind loading on cantilevered structures under thunderstorm downburst winds, there is a lack of fundamental research on the behavior of simple circular cylinders subjected to downburst-like outflows. This chapter investigates the pressure distribution and aerodynamic coefficients of two cylinders with different diameters immersed in three different types of wind: (1) isolated downburst (DB); (2) downburst embedded in an atmospheric boundary layer (ABL) wind (DBABL); and (3) steady ABL wind. The focus of this study is to provide a comparative analysis between aerodynamic coefficients (drag and lift) and surface pressures that result from these three different wind systems. The ABL winds caused a higher drag on the thinner cylinder than the two DB-like outflows. The lift coefficients during the primary vortex passage in the DB-like outflows were negative at the base of the cylinders and approached zero or to slightly positive values close to the cylinders’ top. The location of the cylinders in DB-like outflows is the dominant factor for their aerodynamics.

Keywords: Downbursts; Circular Cylinders; Aerodynamic Coefficients; Drag; Lift; Surface Pressures; Turbulent Flows, Wind Engineering.

5.1 Introduction
On-going research over the last several decades has demonstrated that the wind loading caused by the atmospheric boundary layer (ABL) winds profoundly differs from the wind loading due to highly three-dimensional and transient winds, such as thunderstorm downbursts (Solari, 2016; Hangan et al., 2019). The main differences in the structural behavior to different wind systems are not only due to potentially higher wind speeds in downburst outflows but predominantly are due to different vertical profiles of the mean wind speed and turbulent characteristics between the two flows, as well as different velocity distributions (De Gaetano et al., 2014; Hangan et al., 2019). By definition, thunderstorm downbursts are cold downdrafts that originate from a cumulonimbus cloud and spread radially upon hitting the surface. The main contributors to the negative buoyancy of descending downdrafts are evaporation and, to a smaller extent, melting of hydrometeors inside and below the cloud, as well as the drag due to the falling hydrometeors.
(e.g., falling raindrops, ice, and graupel). Other contributing factors for descending currents in supercell cumulonimbus clouds have also been identified and discussed in the literature (Markowski, 2002).

In wind engineering applications, circular cylinders are found in construction designs of lighting and luminary poles, chimneys and antenna masts, power transmission lines, silos, wind turbine towers, and bridge supports and cranes, to name few applications. Therefore, the proper understanding of aerodynamic wind coefficients and surface pressures on circular cylinders is needed for the appropriate design of cylindrical structures. While these parameters are well researched and properly reported in many international wind building codes for the case of ABL winds, there is a lack of fundamental research on the behavior of circular cylinders under the transient and non-Gaussian wind actions of downburst-like outflows.

When it comes to cantilevered structures, a lot of wind engineering research has recently been focused on the structural behavior of transmission lines and towers under downburst winds. Savory et al. (2001) performed dynamic structural analysis of a lattice transmission tower to investigate wind loading and failure criteria due to downbursts and tornadoes. Their study concluded that the calculated tornado failures have better agreement with the field damage surveys. However, the study neglected vertical downburst wind components, as well as downburst forces on conductors. Later, Shehata et al. (2005) and Shehata and Damatty (2007) investigated the responses of transmission lines under downburst wind using a computational fluid dynamics (CFD) tool. More recently, Wang et al. (2009), Darwish et al. (2010), Darwish and Damatty (2011), Qu et al. (2013), Elawady et al. (2017) and Elawady et al. (2018) studied transmission line responses under different downburst-like outflows by considering different structural properties of transmission lines. Ibrahim et al. (2017) showed that downbursts could be more hazardous for pre-stressed concrete poles than tornadoes.

In a study on thunderstorm response spectrum technique, Solari (2016) discussed the need for more research on comparative analyses between ABL and thunderstorm winds. One such study was carried out earlier by Kim et al. (2007), in which the authors examined the differences between ABL and downburst wind loads on tall buildings. They showed that the large downdrafts can produce higher shear forces and base moments than the ABL winds. Chen and Letchford (2004) simulated downburst wind actions on a cantilevered structure by assuming deterministic mean wind speed and stochastic fluctuations. They demonstrated that the structure was highly sensitive to wind fluctuations and the properties of coherent function. Later, Chay et al. (2006) concluded that lower turbulence intensities and higher mean wind speeds produced in a downburst outflow than in an ABL wind results in a higher and more correlated loading on a long span structure. In two consecutive papers, Nguyen et al. (2015a; 2015b) investigated aeroelastic responses of complex lighting poles and antenna masts subjected to ABL winds. The obtained aerodynamic coefficients were analyzed in the context of quasi-steady theory. Their analyses based on sectional model tests
demonstrated the existence of certain configurations prone to wind instabilities and strong dynamic responses. Recently, Hangan et al. (2019) discussed the applicability of quasi-steady theory for non-synoptic winds such as downbursts and tornados. However, no study experimentally investigated the influence of downburst-like outflows on slender circular cylinders, which are among the most significant structural shapes in the field of wind engineering.

The main goal of this chapter is to investigate experimentally the pressure distribution and associated aerodynamic force coefficients for two circular cylinders of different diameters with a free end that are immersed in downburst-like outflows. While the model geometry is rather simple, the investigated flows are complex and not investigated thus far in terms of the proposed application. The two circular cylinders were subjected to: (1) An isolated downburst outflow produced without ABL winds; (2) a downburst outflow embedded in ABL winds; and (3) the control case of ABL winds without any downburst outflow.

5.2 Experiments setup and methodology

5.2.1 The WindEEE Dome and experiments setup

All physical experiments in this study were performed in the WindEEE Dome (Hangan et al., 2017), which is a large-scale wind simulator capable of producing downburst-like outflows at different geometric scales varying from approximately 1:100 to over 1:1000 (Junayed et al., 2019; Romanic et al., 2019). The velocity scales are typically between 1:1 and 1:4. This unique wind simulator is capable of simultaneously producing different ABL winds and downburst outflows (Romanic et al., 2019) (Figure 5.1).

![Figure 5.1](image)

Figure 5.1. Downburst released in the background ABL winds inside the WindEEE Dome from (a) top-view and (b) side-view perspectives.

Downburst-like outflows in the WindEEE Dome are created by closing the louvers on the bell mouth and pressurizing the upper plenum (Figure 5.1b). The pressurization is achieved by using six large fans situated
in the upper plenum, each fan with a diameter of 2 m. When the upper chamber is pressurized, the sudden opening of louvers creates an impinging jet that speeds out horizontally upon hitting the surface of the test chamber. The use of impinging jets to replicate downburst-like outflows was proposed by Hjelmfelt (1988) after demonstrating that these two flows have similar radial velocity profiles. The simultaneous downburst and ABL wind mode of the WindEEE Dome are similar to the isolated downburst mode, with the exception that the impinging jet is released into an already developed ABL wind (Figure 5.1). Nine different momentum ratios of ABL winds and downburst impinging jets were recently investigated in Romanic et al. (2019). The ABL winds were generated by using sixty fans installed on one of six peripheral walls in the test chamber (Figure 5.1a). The sixty-fan wall contains four rows of fifteen fans per row. A detailed description of the WindEEE Dome capabilities and a comparison of generated ABL winds against the Engineering Sciences Data Unit (ESDU) wind and turbulence intensity profiles (ESDU, 2002) are presented in Hangan et al. (2017) and Jubayer et al. (2019).

Hereafter, the isolated downburst-like outflow and the downburst simultaneously combined with ABL winds are referred to as DB and DBABL, respectively. The jet centerline velocity at the bell mouth level in the DB and DBABL downdrafts were 12.3 and 11.8 m s⁻¹, respectively, whereas the ABL wind velocity at the height of the cylinder was 3.3 m s⁻¹. The selected configuration of two flows was chosen due to the minimal loss of jet momentum between DB and DBABL cases in this closed-circuit mode of the WindEEE Dome (Romanic et al., 2019). All investigated downbursts had a diameter of \( D = 3.2 \text{ m} \) and the height of the test chamber was \( H = 3.8 \text{ m} \).

The diameters of two rigid Plexiglas circular cylinders considered in this study were \( d_1 = 4 \text{ mm} \) and \( d_2 = 12.5 \text{ mm} \) (Figure 5.2). The cylinders were instrumented with twelve pressure taps, each equally distributed along the cylinders’ circumferences and at a distance of \( 10d \) from the free edge (Figure 5.2). The angle between two adjacent pressure taps was 30°. The rest of the setup is shown in Table 5.1 and Figure 5.2. Since each cylinder was instrumented with only a single row of pressure taps, the different height of cylinders was simulated by increasing the cylinders’ height by raising them from the floor. The installation of multiple rows of pressure taps on these two cylinders (keeping twelve taps per row) is not feasible due to the technical challenge of limited space for pressure tubing inside the cylinders. The base support for the \( d_1 = 4 \text{ mm} \) cylinder was a cylinder of different diameter (Figure 5.2c), but the insertion of the thicker base did not influence the result due to the separation between the taps and the base that was \( >20d_1 \) (Fox and West 1993a; Fox and West 1993b). In both DB and DBABL cases, \( r/D \) was measured from the touchdown position of the DB downdraft. The locations of cylinders in the DB-like outflows are shown in Figure 5.3a.

The pressure measurement system used the Electronically Scanned Pressure (ESP) scanners and Digital Temperature Compensation (DTC) Initiium to record differential pressure at each of twelve pressure taps. The pressure scanners are electronic pressure units that measure differential pressures with an array of
silicon piezoresistive pressure sensors. All twelve pressure taps were connected to a single thirty-two-port scanner that can accommodate tubes with an outer diameter of 1 mm. The pressure range for the scanners was ±4 inches of water (equivalent to ±1 kPa). Proper and periodic on-line calibration of the system maintained static errors, namely the accuracy of static pressure measurements, within ±0.03% of the entire pressure range specified above. The DTC Initium is a pressure data acquisition system that was connected to the scanner via an Ethernet-based connection. The accuracy of the DTC Initium is ±0.05% over the entire operating temperature range (0 °C to 70 °C). The mean air temperature during the tests was 21.2 °C.

The velocity measurements were performed using four-hole Cobra probes. The position of eight Cobra probes on the vertical rack is shown in Figure 5.2d, and their z/L heights are identical to the pressure measurement heights (Table 5.1). It is important to note that the velocity and pressure measurements in the present experiments were not synchronized with each other. Also, the velocity measurements were only conducted during the testing of d_2 (thicker) cylinder (Figure 5.2c,d) because the tested flows around d_1 are the same as in the case of d_2 cylinder. Cobra probes are robust instruments designed to measure turbulent flows by capturing three velocity components from a 45° cone concerning the incoming flow. The measuring accuracy of Cobra probes is within ±0.5 m s^{-1} up to approximately 30% turbulence intensity. Lastly, the velocity measurements were conducted in the same r/D locations that were used in the pressure measurements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Downdraft diameter, D (m)</td>
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</tr>
<tr>
<td>Chamber height, H (m)</td>
<td>3.8</td>
</tr>
<tr>
<td>Diameter of cylinder, d (mm)</td>
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</tr>
<tr>
<td>Distances of cylinders from downdraft center, r (m)</td>
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</tr>
<tr>
<td>Non-dimensional distances of cylinders from downdraft center, r/D</td>
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</tr>
<tr>
<td>Maximum measuring height, L (cm)</td>
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</tr>
<tr>
<td>Measuring heights, z (cm)</td>
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</tr>
<tr>
<td>Non-dimensional measuring heights, z/L</td>
<td>0.056; 0.111; 0.167; 0.222; 0.333; 0.556; 0.778; 1</td>
</tr>
</tbody>
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### Table

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<tr>
<td>Downburst duration, $\Delta T$ (s)</td>
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</tr>
<tr>
<td>Pressure measurements sampling frequency, $f_{sp}$ (Hz)</td>
<td>500</td>
</tr>
<tr>
<td>Velocity measurements sampling frequency, $f_{sv}$ (Hz)</td>
<td>1250</td>
</tr>
</tbody>
</table>

#### Figure 5.2

Two cylinders subjected to DB and DBABL outflows in the WindEEE Dome. Panel (c) shows the cylinder $d_1$ (thinner), while other three panels show the cylinder $d_2$ (thicker). Panel (d) also shows the Cobra probes installed on a rack.

#### Figure 5.3

(a) The locations of cylinders in the outflow (black dots). The directions of ABL winds and DB outflow indicated with black arrows and grey triangles, respectively. (b) Spatial distribution of pressure taps and the direction of positive lift and drag forces to the incoming flow. The tributary length ($b$) and arc angle ($\theta$) demonstrated on the example of tap #4.

### 5.2.2 Methodology

The drag ($c_D$) and lift ($c_L$) coefficients were calculated as:
\[ c_D = \frac{F_D}{0.5 \rho d U_{ref}^2}, \quad (5.1) \]
\[ c_L = \frac{F_L}{0.5 \rho d U_{ref}^2}, \quad (5.2) \]

where \( \rho \) is the air density, \( U_{ref} \) is the reference velocity and \( F_D \) and \( F_L \) are the drag and lift forces, respectively, calculated from the surface pressure measurements as:

\[ F_D = \int_S (p - p_{ref})_D ds, \quad (5.3) \]
\[ F_L = \int_S (p - p_{ref})_L ds. \quad (5.4) \]

Here, \((p - p_{ref})_D\) and \((p - p_{ref})_L\) are the components of differential pressures in the drag and lift directions (Figure 5.2b), respectively, \( p_{ref} \) is the reference static pressure, and \( ds \) is the unit area. Expressing the results per unit length and assigning a tributary width \( b \) for each pressure tap (Figure 5.2b), Eq. (5.3) and (5.4) read:

\[ F_D = \sum_{i=1}^{12} (p_i - p_{ref})_D b_i \cos \theta_i, \quad (5.5) \]
\[ F_L = \sum_{i=1}^{12} (p_i - p_{ref})_L b_i \sin \theta_i, \quad (5.6) \]

where \( i \) is the tap number and \( \theta_i \) is the arc angle of the \( i \)-th tap.

The evaluation of reference pressure, \( p_{ref} \), is crucial to assure the independency of pressure measurements from the daily and hourly variability of atmospheric pressure. Furthermore, it allows for comparison between different experiments and studies. In the current study, \( p_{ref} \) was measured far away from the location of cylinders. To minimize the potential influence of the downburst vortex on the measurements of static pressure, \( p_{ref} \) was chosen at the height of approximately 1.5 m above the floor. This height is above the top height of the leading downburst vortex. This selection of reference pressure is not typical for the classical wind engineering approach where \( p_{ref} \) is obtained at the height of the structure (Solari, 2019). This issue of the proper choice of \( p_{ref} \) in downburst outflows will be further discussed in Section 5.4.

The reference velocities \((U_{ref})\) for the three investigated flows were measured at the height of pressure taps. In the DB and DBABL cases, \( U_{ref} \) is extracted as the peak velocity \((\bar{U})\) from the slowly varying mean velocity record:

\[ \bar{U} = \max_{t \in \Omega} (\bar{U}(t)), \quad (5.7) \]
where t is the time, \( \Delta T \) is the duration of the DB-like outflow, and \( \bar{U}(t) \) is the slowly varying mean velocity. The moving mean averaging window was set at 0.05 s (Junayed et al., 2019; Romanic et al., 2019). In the ABL wind case, \( U_{ref} \) is the mean ABL velocity at the height of the pressure taps (Solari, 2019). The reference velocity at the height of pressure taps is often used in the case of slender structures and elements.

5.3 Results

5.3.1 Flow field

The transient nature of the DB and DBABL outflows at the radial distance \( r/D = 1.2 \) from the undisturbed jet center is depicted in Figure 5.4a–c. Both velocity records show the moving mean extracted from the instantaneous measurements at the height \( z/L = 0.056 \). In contrast to a stationary ABL wind, both DB-like outflows are characterized by a highly transient velocity ramp-up segment that is followed by the peak velocity around 1 s into the records. After reaching the peak, the velocity reduces to the quasi steady-state value that corresponds to the stationary impinging jet established after the passage of the primary vortex. The last portion of the velocity segments corresponds to the outflow dissipation caused by the termination of the DB-like downdraft. The DBABL velocities at the radial distance \( r/D = 1.2 \) are weaker than the DB winds (Figure 5.4a–c). However, the interplay between DB and ABL winds is complex and results in highly three-dimensional wind field in which the relative intensity between DB and DBABL winds highly depends on the position in the outflow. However, this subject will be addressed in detail in the upcoming studies.

The differences between the enveloped peak velocities in DB and DBABL outflows increase with the height (Figure 5.4d–f). The nose-shape curvature in the DBABL outflow is less pronounced than in the DB outflow. This result is in accordance with the numerical simulations in Mason et al. (2010) that demonstrate that the ABL wind tends to amplify the upper regions of the DBABL winds in this part of the outflow. As stated earlier, the flow interaction is highly dependent on the investigated position in the flow field. Both DB-like cases profoundly differ from the logarithmic-like ABL wind profile.

The vertical profiles of radial wind speed extracted at the moment when the velocity peak is observed at the height \( z/L \leq 0.056 \) (Figure 5.4d–f) are significantly different from the enveloped velocity peaks at each height in Figure 5.4d–f. The DB and DBABL outflows are stronger than the ABL winds at the heights below approximately \( z/L = 0.1 \). This result suggests that the DB-like winds are more dangerous to low-rise structures than high-rise buildings. The observed difference between either of the two DB-like profiles and the ABL wind profile also supports the observation discussed in the Introduction that the transmission lines—being a low-rise structure—are more prone to downburst than ABL wind failures.
5.3.2 Drag and lift coefficients

Overall, the ABL winds cause higher drag coefficients \( (c_D) \) than the two DB-like outflows on the C040 cylinder (Figure 5.5a–c). The peak \( c_D \)s in the DBABL outflow are slightly higher than in the ABL wind only close to the top of the cylinder at \( r/D = 0.5 \). However, the results shown in Figure 5.5d-f are more relevant for the wind loading investigations because of the \( c_D \) profiles of the DB-like outflows being extracted at the time of the peak \( c_D \) at \( z/L = 0.056 \). Thus, the profiles are time-dependent and represent the drag values that the structure experienced at that moment. While the mean \( c_D \) along the cylinders’ height in the ABL winds is about 1.0 for both cylinders (slightly higher for C040), the \( c_D \) values in the DB-like outflows are strongly dependent on the height. At \( r/D = 0.5 \), the values close to the base of the cylinders are 5–6 times higher than at the top of the structures. While the height dependency of \( c_D \)s at the other two radial locations in the DB-like outflows is not as pronounced as at \( r/D = 0.5 \), it is still larger than in the
ABL winds. The $c_D$ profiles in the DB-like outflows at $r/D = 1.0$ and 1.2 are similar, as expected. The largest discrepancies between the temporally enveloped peaks in Figure 5.5a–c and the time-dependent profiles of $c_D$s in Figure 5.5d–e are at $r/D = 0.5$. These results indicate that the maximum $c_D$s in the downdraft stagnation region (depicted later in Figure 5.12) are more challenging to analytically represent than they are in the wall region. In the wall region (Figure 5.12), the temporally enveloped peak $c_D$s are similar to the $c_D$ profile at the given moment in time (i.e., the time of the peak $c_D$ close to the cylinders’ base shown in Figure 5.5d–f). This similarity is not warranted in the stagnation region. Therefore, the temporally enveloped peak $c_D$s in the stagnation region might be too conservative for the practical implementation in design standards. These findings agree with the numerical study of Mason et al. (2009) that showed the loading of an isolated structure due to downburst winds never exceeded that from an ABL wind with an equivalent 10 m wind speed. However, our results indicate that the assumption of equal $c_D$s in DB and ABL winds employed in Mason et al. (2010) might not be justifiable in the case of circular cylinders.

![Figure 5.5](image)

Figure 5.5. Drag coefficient ($c_D$) with height in the DB and DBABL outflows. The top row shows the peak $c_D$ at each height (i.e., the enveloped peak of $c_D$), while the bottom row shows the vertical profile of $c_D$ at the instant of peak $c_D$ occurring at $z/L = 0.056$. The vertical profile of mean $c_D$ in the stationary ABL wind is also shown.

The $c_D$ overshot (Figure 5.6) for the two cylinders is defined as the ratio of the temporally enveloped peak $c_D$ in the two DB-like outflows and the mean $c_D$ of the steady ABL wind. This definition is adopted from Takeuchi and Maeda (2013), who analyzed the properties of non-stationary wind forces caused by a rapid
wind gust on an elliptic cylinder. Interestingly, the $c_D$ overshoot is overall below unity for C040, and the steady ABL winds tend to cause higher drag than the DB-like outflows. By comparing DB to DBABL values, the $c_D$ overshoot is usually higher in DB outflow at lower elevations and vice versa (or similar values) close to the top of the cylinders. At $r/D = 1.0$ and 1.2, the $c_D$ overshoot of DB outflow on the C125 cylinder is consistently higher than unity in the height interval $z/L = 0.1$ to 0.4. At the same time, the $c_D$ overshoot of DBABL outflow is below unity. When benchmarked to the steady ABL winds, this result demonstrates that the inclusion of ABL winds in the DB simulations profoundly impacts the aerodynamics behavior of low-rise structures in the wall region of the DB-like outflows. For the C040 cylinder, both DB outflows feature the overshoot below 1. The only exception is the region at the top of the cylinder at $r/D = 0.5$, where both overshoots are higher than 1.

![Figure 5.6. Drag coefficient ($c_D$) overshoot for the two DB-like outflows and C040 (a–c) and C125 (d–f) cylinders. The vertical dotted line is the $c_D$ overshoot equal to 1.](image)

The mean lift coefficient ($c_L$) values in the ABL winds are around zero, as expected (Figure 5.7). The similarity between temporally enveloped peak $c_L$s at $r/D = 0.5$ (Figure 5.7a) and the time-dependent $c_L$ profile (Figure 5.7d) is much higher than in the case of $c_D$s (Figure 5.5a,d). However, the most interesting result might be the sign of $c_L$s in the DB-like winds. Namely, the $c_L$ values at the base of the cylinders are as low as -0.28 and rise to the slightly positive values or close to zero at the top of the structures. This trend is observed at all radial locations in the DB-like outflows, as well as in temporally enveloped peak $c_L$s and time-dependent profiles. The result indicates that the DB winds might cause more complex dynamical
behavior in the crosswind direction than ABL winds. This phenomenon of the change of the sign of $c_L$ along the cylinders’ height was also observed by Omori et al. (2008) in their large eddy simulations of sheared flows past a circular cylinder. The change in $c_L$ sign from negative to positive occurs when the inviscid effects on the $c_L$s become dominant over the wake effects (Omori et al., 2008). The trends of $c_D$ and $c_L$ profiles with height observed in this study corroborate well with the open fluid dynamics literature that demonstrated the $c_L$ increases and the $c_D$ decreases with increasing shear in the flow (Cao et al., 2007).

The $c_D$ records close to the base and the top of the cylinders are markedly different from each other in the DBABL outflow (Figure 5.8 and Figure 5.9). Discrepancies between the time signature of $c_D$s in DB and DBABL outflows are observed close to the surface, while the time series show similar trends at the higher elevations. While the $c_D$s are a non-stationary process in all cases, the absence of the dominant $c_D$ peak in the DBABL outflow is readily observed at $z/L = 0.111$. This peak is associated with the passage of the primary vortex that translates radially outwards. These results demonstrate that the time evolution of the aerodynamics—while being weaker than that in ABL winds—is more challenging to model and more sensitive to the height.

Overall, the $c_D$s around the smaller cylinder (C040) are slightly lower than around the larger cylinder (C125) at $z/L = 0.111$. Besides, we observe that the fluctuations of $c_D$s are higher in the DBABL than in
the DB outflow. The magnitudes of $c_D$ fluctuations around C125 and C040 cylinders are similar. All these differences are attenuated at a higher elevation (Figure 5.9).

Figure 5.8. Time histories of drag coefficient ($c_D$) at the height $z/L = 0.111$ in the DB (top row) and DBABL (bottom row). The black and grey lines correspond to the C125 and C040 cylinders, respectively.
5.3.3 Surface pressures

The strong suction in the leeward side (tap #7) of both cylinders (Figure 5.10 and Figure 5.11) is aerodynamically caused by the wake region behind the cylinders. While the surface pressures for the windward and leeward taps at $r/D = 1.0$ and $r/D = 1.2$ are fairly symmetric around zero value in the DB case; the symmetry line is shifted towards the positive value that corresponds to the ABL wind pressures in the DBABL cases.

We further notice that the surface pressures in the leeward side of the cylinders are slightly positive even during the ABL wind segment of the velocity record. This observation is caused by the “atypical” choice of reference pressure in the downburst outflows (Section 5.2). This issue of proposing the proper location of the reference pressure measurements in DB-like outflows is still under investigation, and more discussion on this topic is included in Section 5.4 (Jubayer et al., 2019). However, the primary significance of the pressure results presented herein is in their relative differences between different cases (DB versus DBABL) and not in the absolute values of the surface pressures obtained in any given experiment. For instance, the surface pressures at tap #7 are always lower than at tap #1 in the ABL portion of the DBABL velocity records (Figure 5.10 and Figure 5.11).

The pressure distribution at $r/D = 0.5$ is profoundly different from that at the other two $r/D$s. The symmetry between positive and negative pressures at tap #1 and tap #7 that is found at larger $r/D$s is
entirely lost at $r/D = 0.5$. Both sides of the cylinders are characterized by positive surface pressures (Figure 5.10 and Figure 5.11). Therefore, the notion of windward and leeward sides of the cylinders is not entirely justified in this situation. Also, the other ten pressure taps on both cylinders are characterized by positive pressures (not shown). The positive sign of surface pressures along the cylinders is due to the predominantly downward orientation of the DB and DBABL flows at $r/D = 0.5$. Here, the cylinders are close to or inside the downdraft region and the dominant component in the outflow is not radial, but rather the vertical (downward) velocity. Geometrically, $r/D = 0.5$ is at downdraft edge but effectively this location is inside the downdraft due to the widening of the downdraft after exiting from the bell mouth. The entrainment of the surrounding air into the impinging jet results in the loss of jet’s momentum (Gauntner et al., 1970). This process is further accompanied by the loss of kinetic energy and the expansion of the velocity profile in the radial direction (Figure 5.12). However, the entire flow field is additionally altered in the DBABL case, which deserves further kinematic investigation in a separate study.

Figure 5.10. Time histories of normalized surface pressures at tap #1 (windward tap on the cylinders) and tap #7 (leeward tap on the cylinders) on the C125 cylinder. The top row is for the DB outflow and the bottom row for DBABL outflow.
Figure 5.12 schematically demonstrates that all sides of the cylinders are similarly impacted by the downdraft at $r/D = 0.5$. Here, we say “similarly” because the windward side is still characterized by higher pressures than the leeward side, but there are no negative pressures in the leeward taps (Figure 5.10 and Figure 5.11). We further notice from these figures that the relative difference between the pressures at different heights and at $r/D = 0.5$ is smaller than that at the other two radial positions. Once again, this difference is due to the underdeveloped radial outflow at $r/D = 0.5$ and the smaller nose-shape curvature at this location (Figure 5.12).
5.4 Discussion of results and prospects for future research

First, we comment on the free end and aspect ratio ($AR$) effects in our experiments. Okamoto and Yagita (1973) showed that the free end of cantilevered circular cylinders produces three-dimensionality of the flow around the cylinder and creates strong longitudinal trailing vortices in the tip region of the body. The same study, as well as Farivar (1981), demonstrated that the free end suppresses the periodic vortex shedding in the tip region. For short cantilevered cylinders with aspect ratio, $AR < 7$, this obstruction of vortex shedding propagates to the root of the cylinder. These experimental findings were later extended by Fox and West (1993a) and Fox and West (1993b), who demonstrated that the free end effects disappear after approximately $20d$ from the tip. Their studies investigated cantilevered circular cylinders with $AR$ in the range 4 to 30. Beyond $20d$, the flow conditions are the same as in the case of an infinitely long circular cylinder. Moreover, their results apply to a low-turbulent uniform flow at a Reynolds number of $4.4 \times 10^4$. As demonstrated later in this section, our experiments are characterized by a similar range of Reynolds numbers. Fox and West (1993b) also reported that the downwash significantly diminishes below $7d$ from the free edge, leading to the increase of $C_p$ with moving away from the tip. With the taps being $10d$ away from the free end in the current experiments, the results from Fox and West (1993b) indicate that the three-dimensionality effects reduce the $C_D$ up to approximately 25% from those found along with an infinitely long circular cylinder. The downwash effects are negligible. However, it is also important to highlight that their results apply to uniform flow, whereas the DB-like flow fields in this study are highly non-uniform. For instance, at $r/D = 1.0$ and $r/D = 1.2$, the DB-like flows have a strong upward component (Figure 5.1b) when impinging on the windward face in the top sections of the cylinders. This outflow does not
promote any downwash regardless of the distance from the free end and \( AR \). On the other hand, at \( r/D = 0.5 \), the DB-like outflows are predominantly downward (Figure 5.1b and Figure 5.12) and, in fact, the entire cylinders are immersed into a downwash-like flow. Therefore, we propose more fundamental and experimental research contributions on bluff body aerodynamics in non-uniform and time-dependent DB-like outflows.

Secondly, the choice of the proper reference pressure and velocity in transient flows, such as downbursts and tornadoes, is still an open question in wind engineering society. The absence of a unified theoretical framework for referencing these flows results in different experimental procedures of replicating transient wind loading from one wind simulator to another, as well as from one type of DB-like outflows to another. Here, we used the peak velocity in the slowly varying velocity record at the height of pressure taps as the proper reference velocity in both DB and DBABL outflows. In principle, the reference velocity height could either be the characteristic height of the structure or the height of the maximum streamwise velocity in the outflow (Figure 5.12). The proper choice of reference pressure is also a nontrivial task. Two-dimensionality of the undisturbed ABL winds and the independence of static pressure in the streamwise direction of developed ABL flow simplifies the choice of reference pressure in the standard engineering practice of testing structures to ABL winds. However, because DB-like outflows are naturally developing in all three spatial dimensions as well as time, this spatiotemporal transiency makes it rather difficult to pinpoint the representative location for reference pressure measurements in the DB-like outflows. This study measured the reference pressure at a location above the vortex height but inside the testing chamber. This choice of reference pressure, however, altered the values of ABL wind pressures from the values expected in the straight ABL winds (Figure 5.10 and Figure 5.11). This discrepancy between the proper referencing for ABL and DB-like winds only demonstrates that more research is needed on relating physical simulations of downbursts to real events. For these reasons, we emphasized in Section 5.3 that the primary significance of the presented pressure results is in the relative comparisons between DB, DBABL, and ABL cases, and not necessarily in the absolute values of pressures.

This research focuses on circular cylinders in which cases the flow features are highly susceptible to the value of Reynolds number (\( Re \)). Here, \( Re \) is calculated using the cylinders’ diameter (\( d \)) and the characteristic flow velocities (\( U_{ref} \), provided in Table 5.2 for DB-like outflows and 3.3 m s\(^{-1}\) for the ABL wind, respectively) as:

\[
Re = \frac{U_{ref}d}{\nu},
\]

(5.8)

where \( \nu = 1.5 \times 10^{-5} \) m\(^2\) s\(^{-1}\) is the kinematic viscosity of air.

The resulting values of \( Re \) in Table 5.3 show that the investigated flows are characterized by different \( Re \) depending on the cylinder and the flow in question. The \( Re \) of ABL winds is lower than that of DB-like
outflows. The C040 cylinder has an order of magnitude lower $Re$ than C125 in the DB-like outflows, and approximately half of an order of magnitude lower $Re$ in the ABL wind. However, $c_D$ is weakly dependent on $Re$ in the range presented in Table 5.3 (Potter et al. 2011). The $Re$ values of $10^4$ are similar to those analyzed by Fox and West (1993a) and Fox and West (1993b) in their study of cantilevered cylinders in a uniform turbulent flow. The range of $Re$ in Table 5.3 is associated with a laminar vortex shedding flow in which the boundary layer around cylinders’ surface is laminar, but alternative vortices are shed off the cylinders resulting in the von Kármán vortices. However, $Re = 10^4$ is also the borderline between the laminar vortex shedding and the subcritical turbulent flow regime in which the von Kármán vortices are becoming turbulent ($10^4 < Re < 2 \times 10^5$). Also, this study is restricted to smooth surfaces of the cylinders as well as the uniform surface roughness of the ground (bare floor). Moreover, the behavior of the DB-like outflows over the surfaces with abrupt changes of roughness, as well as their wind actions on the structures with rough body surfaces with non-uniform roughness are currently unexplored.

### Table 5.2. Peak velocities and their height at three radial locations in the two DB-like outflows.

<table>
<thead>
<tr>
<th></th>
<th>$\bar{U}$ (m s$^{-1}$)</th>
<th>$\bar{z}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r/D$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB</td>
<td>0.5 1.0 1.2</td>
<td>0.5 1.0 1.2</td>
</tr>
<tr>
<td>DBABL</td>
<td>11.93 17.33 18.47</td>
<td>0.05 0.05 0.05</td>
</tr>
</tbody>
</table>

### Table 5.3. $Re$ values associate with three investigated flows and two circular cylinders.

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>DB</th>
<th>DBABL</th>
<th>ABL</th>
</tr>
</thead>
<tbody>
<tr>
<td>C125</td>
<td>$1.5 \times 10^4$</td>
<td>$1.3 \times 10^4$</td>
<td>$0.3 \times 10^4$</td>
</tr>
<tr>
<td>C040</td>
<td>$4.9 \times 10^3$</td>
<td>$4.2 \times 10^3$</td>
<td>$0.9 \times 10^3$</td>
</tr>
</tbody>
</table>

At a ~1:200 mean geometric scale of the WindEEE Dome downbursts (Romanic et al. 2020), the diameters of C040 and C125 cylinders correspond to full-scale structures with the diameter of 0.8 and 2.5 m, respectively. The former diameter is similar to the luminary poles usually installed along the highways, whereas the latter diameter is in the range of wind turbine towers and chimneys. The maximum height of the tested cylinders reached 180 m above ground at the full-scale equivalent.

Lastly, a topic that deserves further research is the coupling between the transient velocity and aerodynamic behavior of structures. Recently, this subject was investigated by Mason and Yuanlung (2019) by analyzing the transient aerodynamics of the CAARC (Commonwealth Advisory Aeronautical Council) building in non-stationary velocity profiles. However, like the present work, the velocity and pressure measurements
in their study were also desynchronized. The proper approach to investigate this aerodynamic dependency is through the convolution ($*$) integral:

$$(U * p)(t) = \int_0^t U(\tau)p(t - \tau)d\tau. \quad (5.9)$$

The blending of velocity ($U$) and pressure ($p$) signatures over the time interval ($t$) is only meaningful if the acquisition of two signals is synchronized. While the current study provided the general relationship between $U$ and $p$ in terms of the governing features of the DB-like outflows (e.g., ramp-up, primary vortex, ramp-down, nose-shape velocity profile), it was impossible to rigorously derive the lag ($\tau$), if any, between $U$ and $p$, and consequently $U$ and $c_D$ or $c_L$ due to the desynchronization of these measurements. Recently, the importance of the $U$–$p$ lag was also demonstrated by Lombardo et al. (2018) in their full-scale measurements of downburst loading on a low-rise building. Their study applied a 2-s lag between the responses of surface pressures on the Texas Tech WERFL building and the velocity measurements on a nearby mast.

### 5.5 Conclusions

This experimental study analyzed the surface pressures and aerodynamic coefficients on two circular cylinders with free end immersed in three different wind fields. The diameters of these two cylinders were 12.5 mm (C125) and 4 mm (C040). The investigated flow fields were (1) a downburst outflow (DB), (2) a downburst outflow supplemented by atmospheric boundary layer (ABL) winds (DBABL), and (3) the steady ABL wind. The motivation to conduct this research came from the continually increasing wind engineering interest to better quantify the wind effects of non-synoptic winds, such as thunderstorm downbursts, on various structures. Circular cylinders—being the classical bluff body that was most studied in the classical fluid mechanics literature—was, therefore, also the starting point of this research. The study provided the first comparisons between surface pressures and aerodynamic coefficients that resulted from these three different wind systems. The flow fields of experimentally produced DB and DBABL outflows were also examined. The main contributions are summarized below.

- The ABL winds caused a higher drag coefficient ($c_D$) than the two DB-like outflows on the C040 cylinder. The results are more height-dependent in the case of the C125 cylinder. The $c_D$ overshoot—defined as the ratio of the peak $c_D$ in the DB-like outflow and the mean $c_D$ in the ABL wind—was higher in DB than in DBABL wind at the lower elevations and vice versa (or similar values) close to the top of the cylinders. At $r/D = 1.0$ and 1.2, the $c_D$ overshoot in the DB outflow around the C125 cylinder was consistently higher than one between $z/L = 0.1$, and 0.4. Also, the $c_D$ overshoot in the DBABL outflow in the same height interval was below unity. Therefore, the
inclusion of ABL winds in the DB simulations significantly influenced the aerodynamics of low-rise structures in the outer regions of the DB-like outflows.

- The lift coefficients ($c_L$s) during the passage of the primary DB-like vortex were negative at the base of the cylinders and approached zero or slightly positive values close to the cylinders’ top. The change in a $c_L$ sign was previously observed in high-shear flows in which there is a strong interplay between the inviscid and the wake effects on a cylinder’s aerodynamics. In the study of ABL winds, the mean $c_L$s are effectively zero.

- The location of the cylinders in the DB-like outflows is aerodynamically more significant than the diameter of a cylinder. This finding is profoundly different from the case of stationary ABL winds.

- While the surface pressures for the windward and leeward taps at $r/D = 1.0$ and $r/D = 1.2$ were symmetric around zero in the DB case; the symmetry line was shifted towards the positive value of the ABL wind pressures in the DBABL outflow. The pressure distribution at $r/D = 0.5$ was profoundly different from that at the other two radial locations. The symmetry between positive and negative pressures at tap #1 (windward tap) and tap #7 (leeward tap in the wake region) that was observed at larger $r/D$s was gone at $r/D = 0.5$. The positive surface pressures everywhere around the cylinders at $r/D = 0.5$ were due to the predominantly downward orientation of the DB and DBABL outflows at this location. The traditional notation of windward and leeward sides of a structure is not meaningful in the regions close to the downburst center.

- Lastly, the study discussed various prospects for future experimental research in this field, such as the proper choices of pressure and velocity references in downburst outflows, and the velocity-pressure coupling that requires the synchronized measurements of these two quantities. Several uncertainties and underlining experimental assumptions were also critically discussed.

References


Chapter VI

6 Vertical profile characteristics of full-scale thunderstorm outflows

Abstract
The dynamic complexity and the limited spatiotemporal structure of thunderstorms make the collection of reliable and systematic measurements of this phenomenon, which are definitely needed to evaluate its action on structures, challenging. The Northern Tyrrhenian is a “hot-spot” for the genesis of severe potentially damaging wind phenomena, such as downbursts. In the context of the European projects “Wind and Ports” and “Wind, Ports and Sea”, a large and complex wind monitoring network has been installed just in this area. Here, three LiDAR profilers provide a vertical scanning of the atmosphere up to 250 m above the ground level. From their continuous recordings, a method to extract thunderstorm events is herein proposed, based on an automated procedure involving systematic quantitative controls and specific qualitative judgments. Starting from it, this chapter provides a comprehensive investigation and comparison of the main parameters ruling the outflow vertical profiles of a selected subset of thunderstorms. The nose shape of the wind profiles appears mainly during the velocity ramp-up and peak stages. During the downburst, the wind direction is systematically invariant with height. The capability of LiDAR to measure the wind speed turbulence component is also discussed and its properties along the vertical profile are shown. Turbulence intensity shows an asymmetric behavior with respect to its temporal mean and question the usual hypothesis of stationarity usually adopted in literature. The findings of this research are then qualitatively discussed in relation to the downburst profiles experimentally produced at the WindEEE Dome, at Western University in Canada. Here, an extensive campaign on downburst winds has recently been performed with the goal of describing the complex physical behavior of the phenomenon and eventually find a proper experimental model to replicate the full scale occurrences of thunderstorm downbursts.

Keywords: Downburst; Field measurements; LiDAR; Mediterranean; Nose shape profile; Thunderstorm; Turbulence; Vertical profile.

6.1 Introduction
Despite an impressive amount of research, a shared model for thunderstorm-induced actions on structures is not available yet, mainly because the complexity of thunderstorms makes it difficult to establish physically realistic and simple models as in the case of extra-tropical cyclones (Solari, 2019); so, the methods currently applied to determine the wind actions on structures are still referred to the synoptic-scale extra-tropical cyclones that strike mid-latitude areas (Davenport, 1967). Unfortunately, thunderstorms
present time-space characteristics completely different from extra-tropical cyclones and in many cases their intensity exceeds that of synoptic events. Thom (1968) first showed that one-third of the yearly peak wind velocities in the United States occur during thunderstorms, which are, in fact, the dominant wind type for structural design in many parts of the world (Gomes and Vickery, 1978; Letchford et al., 2002). Zhang et al. (2018a) also showed that design wind velocities with mean return period greater than 10-20 years are often associated with thunderstorms.

These phenomena are made up of sets of cells that evolve through three stages in about 30 minutes: cumulus, mature and dissipating stages (Byers and Braham, 1948). Fujita (1981, 1985) showed that the downdraft that impinges over the ground produces intense non-stationary radial outflows and ring vortices. The whole of this air movement is called “downburst” and it can be divided into “macro-burst” and “micro-burst” depending on whether its horizontal size is greater or smaller than 4 km, respectively. The research carried out in wind engineering during the last two decades has demonstrated that downbursts, and especially micro-bursts, are extremely damaging not only with regard to flights but, indeed, also for the built environment (e.g. Holmes et al., 2008; Solari et al., 2012, 2015b; Elawady et al., 2017).

According to this finding, many attempts have been carried out to analyse thunderstorm measurements and to obtain the parameters of major interest for evaluating their actions on structures (Goff, 1976; Wakimoto, 1982; Choi, 1999; Choi and Hidayat, 2002; Choi, 2004; Gunter and Schroeder, 2015). Nevertheless, there is still a great number of unknown facets associated with downbursts. The parameters of major interest for wind engineering purposes are difficult to generalize at the global scale and their variability is often very large; downburst properties such as the jet diameter, the spatial and temporal extension of the phenomenon or its intensity at the near-ground levels are event-dependent and vary significantly according to mesoscale and regional climate as well as to the type of thunderstorm cell. In addition, the interaction between the small scale downburst and the large scale synoptic wind as well as the motion of the parent cloud is an open topic, currently under investigation (Romanic et al., 2017; Romanic and Hangan, 2019; Chapter 3; Chapter 4).

Besides this, the lack of information depends mainly on two aspects: firstly, high-sampling-rate anemometric sensors are needed to catch the evolution in time of thunderstorms, but this kind of sensors is not the standard in meteorological stations; secondly, the small size of thunderstorms in respect to met-stations spacing makes these objects most often undetected at the ground. It follows that, in view of providing a complete reconstruction of these phenomena, the available data for thunderstorms are still very limited compared to synoptic events, pointing out the necessity of collecting and analysing as many thunderstorm records as possible (Burlando et al., 2017b). In this perspective, on the one hand, a great contribution has been recently given by the installation of extensive anemometric networks around the globe; probably one of the largest among these has been recently realized for the European projects “Wind
and Ports” (WP, 2009-2012) (Solari et al., 2012) and “Wind, Ports and Sea” (WPS, 2013-2015) (Repetto et al., 2018). On the other hand, a decisive help has been also provided by the recent creation of ad-hoc laboratories able to reproduce extreme wind events. In this sense, the largest geometric scales of about 1:250 or more are achieved at the WindEEE Dome at Western University in Canada, where the physical replicability of downburst winds relies on the impinging-jet technique (Chapter 2). The combination of the two contributions is expected to contribute in reducing the lack of knowledge and the uncertainties on the physical behavior of downbursts, which are the main focus of the recently launched ERC Project THUNDERR – “Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures” (2017 – 2022) (Solari et al., 2020).

The analysis of the field data acquired for the projects WP and WPS represents a unique opportunity to reconstruct the time and spatial evolution of small-scale storms. The three WindCube LiDAR wind vertical profilers which belong to the anemometric network, in particular, can be used to characterise the vertical development of thunderstorm outflows. This analysis is expected to lead, among other benefits, to the definition of the range of heights where the maximum wind speeds are experienced, investigating the transient nose-like shape assumed by the velocity vertical profile (Goff, 1976). In this framework, literature has largely documented that the vigorous horizontal wind speeds, originated upon the jet impingement, present their maxima close to the ground in the interval 50-120 m above ground level (AGL) with related implications for low/mid-rise structures. This is noticeable only by analysing the vertical profile of the slowly-varying mean wind velocity component in the stage of the maximum intensity of the outflow. The usual 10-min average applied to synoptic event time-series completely filters out such features. From LiDAR measurements and their comparison with meteorological information, it can be noted that the long-lasting nose-like shape profiles of the order of 10-min or more, are never associated with thunderstorm events. They occur, for example, when stable atmospheric conditions prevent deep convection, such as in downslope winds (Burlando et al., 2017c). Conversely, short-lasting nose shapes, in the order of 1-min, are observed during thunderstorms (Burlando et al., 2017a).

The present chapter extends on the study by Burlando et al. (2017a), where a first set of thunderstorm measurements was extracted and studied during the period 2014-2015. Such investigation is here enlarged until mid-2018. Three LiDAR (Light Detection and Ranging) databases of continuous wind records are systematically analysed to extract the records which may relate to thunderstorm events. This is confirmed through subjective inspections of the signals and cross-checking interpretations of satellite, radar and lightning data. The wind data are processed through the directional decomposition technique proposed by Zhang et al. (2019), which allows, on the one hand, to address the abrupt change in direction during thunderstorm events with the same approach used for the wind speed component and, on the other hand, to decouple the turbulent fluctuations into longitudinal and lateral components. The downburst signals are
analysed to inspect the time transition of the wind speed and direction vertical profile, the duration of the nose-shaped profile, the gust factor, and the directional shift. The reliability of the LiDAR vertical profilers to detect the turbulence component of the flow is discussed in relation to literature reviews; the related properties are therefore analysed with regard to their time evolution along the height. The results are critically interpreted also in relation to the impinging-jet downburst-like winds produced at the WindEEE Dome to eventually find common characteristics which allow, on the one hand, to obtain a clearer understanding of the dynamic behavior of the phenomenon in nature and thus to build a strong link with the parameters observed from the analyses; on the other hand, the laboratory experiments can be continuously calibrated based on the full scale occurrences of real downburst events in order to formulate a reliable and solid experimental model. In turn, therefore, this research serves as foundation for the extensive comparison with the experimental results presented in Chapter 2, Chapter 3 and Chapter 4 of this thesis.

The rest of this chapter develops through the following sections: Section 6.2 describes the wind monitoring network developed for the projects WP and WPS along with a detailed overview of the LiDAR wind profilers. The definition of the signal decomposition techniques and the extraction criterion here adopted are presented in Section 6.3. Section 6.4 describes, in detail, the thunderstorm event that occurred in Livorno on 13 September 2015, also with an eye to the experimental observations reported in the previous chapters in the context of the extensive campaign carried out at the WindEEE Dome. Section 6.5 discusses the main analogies and differences among the investigated events in terms of vertical profiles of the slowly-varying mean wind speed, direction and turbulence intensity, and draws again a clear comparison with the experimentally produced downburst winds (Chapter 2, Chapter 3 and Chapter 4). Conclusions and future prospects are reported in Section 6.6.

6.2 Wind monitoring network and LiDAR profilers

WP and WPS are two projects financed by the European Territorial Cooperation Objective, Cross-border program “Italy-France Maritime 2007-2013”. An extensive in-situ wind monitoring network made up of 28 ultrasonic anemometers, three meteorological stations and three LiDAR profilers, has been installed in the main commercial ports of the Northern Tyrrhenian and Ligurian Sea: Savona/Vado Ligure, Genoa, La Spezia, Livorno, Bastia and L’Ile Rousse. This has allowed to collect an unprecedented dataset of wind measurements, to develop numerical simulations of wind and wave fields, the statistical analysis of the wind climate, and algorithms for medium term (1-3 days) and short term (0.5-2 h) wind forecasts. The large anemometric network provided by the projects WP and WPS has been regularly enriched with the introduction of new measuring instruments. In this sense, the project THUNDERR has recently
provided a further significant contribution; to be mentioned, among others, the installation of a state-of-the-art pulsed LiDAR scanner, not treated in this study.

The three LiDAR wind profilers, installed in the ports of Genoa, Livorno and Savona, are here investigated. They measure the three components of the wind velocity at 12 heights AGL (40, 50, 60, 80, 90, 100, 120, 140, 160, 180, 200, 250 m) with a sampling rate of 1 Hz, providing a continuous reconstruction of the wind speed vertical profile. A ground ultrasonic anemometer is always supplied in the proximity of the LiDAR system, usually at about 10 m AGL, providing the field reconstruction from the lower levels. The overall system in the three ports where the LiDARs are located is reported in Figure 6.1.

![Figure 6.1. Monitoring network in the Ports of Savona, Genoa and Livorno.](image)

The three LiDARs were installed in the years 2014-2015 (codes GE.51, LI.51 and SV.51). The first of the three was launched in Savona in the second quarter of 2014. The remaining two (Genoa and Livorno) were installed approximately one year later. The related databases of measurements cover different periods according to their installation date until 31 August 2018, which is the last date considered in the present analysis. The discontinuities in the data acquisition have to be addressed to malfunctioning, ordinary maintenance and, in the case of LI.51, to vandalism attack. Other lacks of recorded data are, instead, to be related to heavy precipitations, which prevent the instrument to acquire useful information often reducing the maximum height of measurements because of the scattering due to water raindrops.

Each of the 3 LiDARs investigated here is a ground-based pulsed coherent system manufactured by Leosphere and whose commercial name is “WindCube V2”. It produces regularly spaced emissions of highly collimated light energy for a specified period of time (pulse length). For each azimuth angle, the line-of-sight velocity, i.e. the radial velocity $v_r$, is calculated based on the principle of the Doppler shift in the frequency of the received radiation or, in other words, the time shift of the backscattered light.

At a fixed vertical angle usually equal to $30^\circ$, the instrument measures four sequential radial velocities $v_{r,\theta}$ around the circle formed by a conical scanning, i.e. $\theta = 0^\circ, 90^\circ, 180^\circ$ and $270^\circ$ plus one vertical measurement above the LiDAR itself. The time step between two subsequent pulses is 1-s which leads to
record a complete conical scanning in 5-s. The three components of the velocity are then derived and, assuming the horizontal homogeneity of the wind field over the sensed height, the wind velocity vector can be considered as representative of the central point of the circle (Figure 6.2).

![Figure 6.2. Scheme of the LiDAR and scanning method.](image)

All the wind speed measurements at a certain azimuth angle are acquired simultaneously along the vertical profile due to the pulsed nature of the system. Other commercial LiDAR profilers, such as the ZephIR system, perform continuous conical scannings from the bottom to the top height; however, the non-simultaneity of the recorded profiles make this type of LiDAR less suited for engineering purposes, especially in the light of reconstructing transient events such as downbursts. The LiDARs treated in this study measure with a sensitivity of 0.1 m/s and 2° for the wind speed and direction, respectively. The variance of the recorded velocity is influenced by the volume filtering operated by the system which, however, can be predicted and partly corrected theoretically. LiDAR reconstructs the wind speed at each sensed height by averaging the above-mentioned five 1-Hz measurements; thus, it takes into account the width and depth of the resultant cone of measurements which increases in size with the elevation. LiDAR presents the limit of the non-independency of such measurements which later are brought together to re-compose the resultant radial velocity at the central point of the circle: every second in time the instrument performs a single individual azimuthal measurement and assembles this with the four previous ones. For this reason, none of the radial velocities can be dealt with as independent from both the preceding and following. However, the comparison between anemometric and LiDAR time-series shows a very good agreement at time scales of the order of two seconds.

The accuracy of LiDAR measurements of mean wind velocity profiles is proven (Wilczak et al., 1996; Smith et al., 2006), whereas the reliability of turbulence measurements is still controversial (Sathe et al., 2011; Sathe and Mann, 2013). However, the bias depends strongly on the spatial structure of turbulence,
which changes largely with the atmospheric stability. The unstable condition of the atmosphere during downburst events leads to large eddy structures; they form, in fact, as a consequence of the environmental instability between the denser descending current and the surrounding air. The full scale investigation carried out by Sathe et al. (2011) shows how this turbulence configuration provides a significant decrease of the systematic error, defined as the ratio of the LiDAR second-order moments, $u'u'$ and $u'w'$, to the same “true” second-order moments as measured by sonic anemometers, which assumes values close to 1 above 60 m AGL (Mann et al., 2010). Considering the validity and reliability of the turbulence intensity as acquired by the LiDAR, its properties are here investigated to provide a picture of their behavior along the sensed measurement heights. The results were eventually compared to the same quantities evaluated from sonic and ultrasonic measurements during previous full-scale campaigns (Zhang et al., 2018b, 2019) in order to inspect their mutual similarity. This may somehow and qualitatively confirm the goodness of LiDAR to detect the turbulent part of the wind signal in terms of overall statistical moments whereas it remains highly questionable the possibility of performing time-based analyses and thus synthesizing its harmonic content for instance with reference to a power spectral density or a coherence function.

Leosphere WindCube LiDARs are not designed for measuring at elevations lower than 40 m AGL due to the potential noise in the backscattered signal. This is mainly due to the lens and to the sealing window of the instrument which reflect the emitted radiation and generate noise that cannot be filtered out at the lower heights due to the short time interval elapsing before the signal is received back. Instead, the upper limit of 250 m AGL is related to the power of the laser beam emitted by the instrument. At the higher measurement heights, the density of available aerosol parcels decreases in the atmosphere and, sometimes, the reflected laser beam sent back to the LiDAR is too weak to be measured by the instrument. This is even more noticeable during wet downbursts, which surely represent the vast majority of thunderstorm events in the area of the Northern Tyrrhenian Sea (Burlando et al., 2018). Here, the heavy rain embedded in the downdraft region during the event strongly interferes with the signal emitted by the LiDAR while, after the passage of the storm, the higher atmospheric levels below and behind the cumulonimbus cloud base are densely populated by rain drops not yet evaporated which, therefore, contribute to make the air extremely clean and thus poor of aerosols through atmospheric scavenging.

### 6.3 Data extraction and analysis

The method here adopted to extract thunderstorms involves parameters related to the modulus of the wind speed $U(t)$, defined according to the classical decomposition method for downbursts which is shortly described in Section 6.3.1. Besides it, the obtained signals are processed by means of the novel directional technique (Zhang et al., 2019) with the benefits described in Section 6.3.2. Section 6.3.3 briefly presents the two main families of criteria to extract thunderstorm records from large wind datasets with focus on the
technique used by the authors in the current study. The resulting events are thus shown and the value of the parameters involved in the extraction method is reported for each of them.

6.3.1 Classical decomposition

This approach (Chen and Letchford, 2005; Holmes et al., 2008) consists of decomposing the resultant horizontal wind speed \( U \):

\[
U(t) = \sqrt{V_X^2(t) + V_Y^2(t)}
\]  

(6.1)

into a slowly-varying mean velocity \( \bar{U} \) and a fluctuation \( U' \) that is expressed as the product of the slowly-varying standard deviation \( \sigma_U \) by a reduced turbulent fluctuation \( \bar{U}' \) dealt with as a stationary Gaussian random process with zero mean and unit standard deviation. In Eq. (6.1) \( t \) is the time, while \( V_X \) and \( V_Y \) are the horizontal components of the wind speed. So, the resultant velocity may be expressed as:

\[
U(t) = \bar{U}(t) + U'(t) = \bar{U}(t) + \sigma_U(t)\bar{U}'(t) = \bar{U}(t) \left[ 1 + I_U(t)\bar{U}'(t) \right]
\]  

(6.2)

\( I_U(t) = \sigma_U(t)/\bar{U}(t) = \bar{I}_U\mu_U(t) \) being the slowly-varying turbulence intensity, \( \bar{I}_U \) is the mean value of \( I_U \) whereas \( \mu_U \) is a non-dimensional function of \( t \) that describes the slow variation of \( I_U \) with \( \bar{\mu}_U = 1 \). In this study, all the slowly-varying quantities are determined through a moving average filter with a moving average period \( T = 30 \text{ s} \) (Solari et al., 2015a).

6.3.2 Directional decomposition

This approach (Zhang et al., 2019) consists of decomposing the wind speed components \( (V_X, V_Y) \) into the slowly-varying mean \( (\bar{V}_X, \bar{V}_Y) \) and the residual fluctuation \( (V'_X, V'_Y) \) components. The resultant slowly-varying mean wind speed is given by:

\[
\bar{u}(t) = \sqrt{\bar{V}_X^2(t) + \bar{V}_Y^2(t)}
\]  

(6.3)

The slowly-varying direction of \( \bar{u} \), according to the geographical notation, is identified by the angle \( \bar{\alpha} \in [0,360] \) defined as:

\[
\bar{\alpha}(t) = 270 - \arctan\left( \frac{\bar{V}_Y(t)}{\bar{V}_X(t)} \right)
\]  

(6.4)

The residual fluctuation is projected onto a new Cartesian reference system \((x, y)\) where the \( x \)-axis is aligned with \( \bar{u} \) and is rotated \( \bar{\beta} = \bar{\alpha}(t) = 270 - \bar{\alpha}(t) \) with respect to the fixed \( X \)-axis. Thus:

\[
u'(t) = V_Y'(t)\cos\bar{\beta}(t) + V_X'(t)\sin\bar{\beta}(t) ; \quad \nu'(t) = -V_X'(t)\sin\bar{\beta}(t) + V_Y'(t)\cos\bar{\beta}(t)
\]  

(6.5)

where \( u' \) and \( v' \) are the longitudinal and lateral turbulence components, respectively. They are expressed as the product of their slowly-varying standard deviations \( (\sigma_u, \sigma_v) \) by a couple of longitudinal and lateral reduced turbulent fluctuations \( (\bar{u}', \bar{v}') \) dealt with as stationary Gaussian non-correlated random processes with zero mean and unit standard deviation:
Accordingly, the longitudinal and lateral components of the wind velocity may be expressed as:

\[ u'(t) = \sigma_u(t) \bar{u}'(t) \]

\[ v'(t) = \sigma_v(t) \bar{v}'(t) \]

(6.6)

Accordingly, the longitudinal and lateral components of the wind velocity may be expressed as:

\[ u(t) = \bar{u}(t) + u'(t) = \bar{u}(t) [1 + I_u(t) \bar{u}'(t)] \]

\[ v(t) = v'(t) = \bar{u}(t) I_v(t) \bar{v}'(t) \]

(6.7)

where \( I_u(t) = \sigma_u(t)/\bar{u}(t) = \bar{I}_u \mu_u(t) \) and \( I_v(t) = \sigma_v(t)/\bar{u}(t) = \bar{I}_v \mu_v(t) \) are respectively, in analogy with Section 6.3.1, the longitudinal and lateral slowly-varying turbulence intensities.

This approach contains the classical decomposition as a particular case, establishes a perfect parallelism with the classical decomposition of synoptic wind speed records, provides substantial advantages for the reconstruction of detected moving downbursts as well as for evaluating the dynamic response of structures in terms of alongwind and crosswind vibrations, as this is classical for synoptic winds.

### 6.3.3 Wind data separation and classification method

The methods to separate thunderstorm from non-thunderstorm events may be subdivided into two families mainly associated with the meteorological and wind engineering fields: the first family identifies thunderstorm events by detailed inspections and reconstructions of the meteorological conditions, relying on surface measurements of the main meteorological parameters, radar and satellite images, soundings and other suitable data (Geerts, 2001; Gast and Schroeder, 2003); the second family is based on the signal analysis and the resultant systematic separation and classification of measurements belonging to large datasets, with the purpose of performing statistical analyses of the extreme wind velocities and their effects on structures. Since the continuous acquisition of measurements leads to the formation and constant growth of very large wind signal databases, the latter methods avoid to provide a detailed meteorological investigation and representation of all wind events, in favor of an automated, systematic and fast procedure to separate and classify the recorded events into sub-datasets (Kasperski, 2002; Durañona et al., 2007; De Gaetano et al., 2014).

The extremely large amount of data examined in the present study led to adopt a separation method belonging to this latter class of criteria rather than a purely meteorological one. All the available data were systematically analysed in order to detect those events that were believed to be thunderstorms. The first preliminary selection is based on the following analytical criteria:

- 10-min maximum 1-Hz (1-s) wind speed, \( U_{max,10} \), greater than 18 m/s;
- Gust factor, defined here as the ratio of the above 10-min maximum 1-Hz (1-s) wind speed over the 10-min mean wind speed in the same interval, \( G_{10} = U_{max,10}/\bar{U}_{10} \), greater than 1.5.

It is to be noted that the wind speed \( U \) here involved derives from the classical downburst decomposition technique (Section 6.3.1). According to the above procedure, the event is classified as a potential thunderstorm when at least one elevation AGL satisfies both the above conditions. Specifically, the fulfilment of the first condition links to the severity of the event recorded, while the latter implies that a
short-time interval of high and off-mean wind speed has occurred during the 10-min observation which, therefore, might indicate the onset of thunderstorm winds.

Following this automated control, visual and qualitative inspections of the signals were carried out in order to verify whether they resembled the typical pattern of downburst time histories, where a sudden ramp-up of the velocity is followed by the related peak and dissipation stage. Finally, interpretations and cross-checking analyses with satellite and radar images, suitable to identify the height, shape and time evolution of the potential parent cloud, as well as with lightning occurrences were performed. Both the lightnings and the presence of high and spatially localized clouds, typical of cumulonimbus, may indeed confirm the thunderstorm nature of the event. This allowed to select and examine a subset of 10 downbursts over the whole dataset of events extracted with the automated procedure. The related parameters, shown in Table 6.1, are based on a time period $\Delta t = 10$ min, containing the development of the storm, in agreement to the analytic criterion of extraction.

Table 6.1. 10 downburst events extracted: port, date and time of occurrence; maximum gust factor and its height, $G_{10,\text{max}}$ and $z(G_{10,\text{max}})$; maximum 1-Hz wind speed $U_{\text{max,10}}$ at the height $z(G_{10,\text{max}})$; absolute maximum 1-Hz wind speed $U_{\text{max,10}}$ and its height $z(U_{\text{max,10}})$; gust factor $G_{10}$ at the height $z(U_{\text{max,10}})$.

<table>
<thead>
<tr>
<th>Port</th>
<th>Date (YYYYMMDD)</th>
<th>Time (hh:mm) UTC</th>
<th>$G_{10,\text{max}}$</th>
<th>$z(G_{10,\text{max}})$ [m]</th>
<th>$U_{\text{max,10}}$ at $z(G_{10,\text{max}})$ [m/s]</th>
<th>$U_{\text{max,10}}$ [m/s]</th>
<th>$z(U_{\text{max,10}})$ [m]</th>
<th>$G_{10}$ at $z(U_{\text{max,10}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE</td>
<td>20150814</td>
<td>22:15</td>
<td>2.46</td>
<td>100</td>
<td>21.2</td>
<td>21.4</td>
<td>90</td>
<td>2.37</td>
</tr>
<tr>
<td>GE</td>
<td>20150815</td>
<td>19:55</td>
<td>2.53</td>
<td>200</td>
<td>24.9</td>
<td>31.8</td>
<td>60</td>
<td>1.84</td>
</tr>
<tr>
<td>GE</td>
<td>20160305</td>
<td>08:15</td>
<td>1.53</td>
<td>80</td>
<td>22.9</td>
<td>23.1</td>
<td>200</td>
<td>1.33</td>
</tr>
<tr>
<td>GE</td>
<td>20160503</td>
<td>18:15</td>
<td>2.87</td>
<td>80</td>
<td>21.3</td>
<td>24.3</td>
<td>140</td>
<td>2.82</td>
</tr>
<tr>
<td>GE</td>
<td>20180412</td>
<td>16:20</td>
<td>1.64</td>
<td>80</td>
<td>18.3</td>
<td>19.4</td>
<td>200</td>
<td>1.56</td>
</tr>
<tr>
<td>GE</td>
<td>20180513</td>
<td>18:40</td>
<td>1.59</td>
<td>180</td>
<td>19.0</td>
<td>19.0</td>
<td>180</td>
<td>1.59</td>
</tr>
<tr>
<td>LI</td>
<td>20150725</td>
<td>09:50</td>
<td>2.00</td>
<td>40</td>
<td>21.6</td>
<td>21.6</td>
<td>40</td>
<td>2.00</td>
</tr>
<tr>
<td>LI</td>
<td>20150913</td>
<td>11:10</td>
<td>1.82</td>
<td>120</td>
<td>26.3</td>
<td>26.3</td>
<td>120</td>
<td>1.82</td>
</tr>
<tr>
<td>LI</td>
<td>20151028</td>
<td>19:30</td>
<td>1.67</td>
<td>40</td>
<td>20.3</td>
<td>22.4</td>
<td>250</td>
<td>1.44</td>
</tr>
<tr>
<td>LI</td>
<td>20180604</td>
<td>10:10</td>
<td>1.65</td>
<td>250</td>
<td>18.8</td>
<td>19.4</td>
<td>100</td>
<td>1.53</td>
</tr>
</tbody>
</table>

Figure 6.3 depicts, at the height of $G_{10,\text{max}}$ defined in Table 6.1, the 20-min time histories of the slowly-varying mean wind speed $\bar{U}(t)$ (Eq. (6.2)) and direction $\bar{\alpha}(t)$ (Eq. (6.4)) for the 10 events extracted and classified as thunderstorms.
Figure 6.3. 10 downburst events extracted: slowly-varying mean wind speed (black line) and direction (gray line) time histories. Event names are given in terms of station, SS, year, YYYY, month, MM, and day, DD.

Table 6.2 reports, in a more quantitative form, the main meteorological information extracted from the related diagrams leading to the final definition of the subset of events. Based on the 1-h cumulative precipitation and on the definition given by Fujita and Wakimoto (1983), a downburst event is classified as wet when the cumulative precipitation is greater than 0.01 inch/h = 0.254 mm/h. The information on the cumulative precipitations were collected in the stations of Madonna delle Grazie (Genoa) and Stagno (Livorno), located approximately 3.15 km north-west and 7.10 km north-east in respect to the LiDARs in the port of Genoa and Livorno, respectively.

Table 6.2. Main meteorological characteristics of the 10 downburst events according to radar (reflectivity [dBZ]), satellite (cloud top height [m]), lightning (strikes [Y/N]), and rain rate (ground cumulated precipitation [mm/h]) measurements, and corresponding downburst classification between wet and dry. Radar measurements were not available (NA) in 2015 in Livorno.

<table>
<thead>
<tr>
<th>Port</th>
<th>Date (YYYYMMDD)</th>
<th>Time UTC</th>
<th>Reflectivity [dBZ]</th>
<th>$h_{\text{cloud}}$ [km]</th>
<th>Lightnings (yes [Y], no [N])</th>
<th>1-h precipitation [mm/h]</th>
<th>Downburst type</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE</td>
<td>20150814</td>
<td>22:15</td>
<td>50</td>
<td>12</td>
<td>Y</td>
<td>13.4</td>
<td>Wet</td>
</tr>
<tr>
<td>GE</td>
<td>20150815</td>
<td>19:55</td>
<td>48</td>
<td>11</td>
<td>Y</td>
<td>5.4</td>
<td>Wet</td>
</tr>
<tr>
<td>GE</td>
<td>20160305</td>
<td>08:15</td>
<td>27</td>
<td>11.5</td>
<td>N</td>
<td>9.5</td>
<td>Wet</td>
</tr>
<tr>
<td>GE</td>
<td>20160503</td>
<td>18:15</td>
<td>22</td>
<td>7.5</td>
<td>N</td>
<td>0</td>
<td>Dry</td>
</tr>
<tr>
<td>GE</td>
<td>20180412</td>
<td>16:20</td>
<td>31</td>
<td>9</td>
<td>N</td>
<td>4.4</td>
<td>Wet</td>
</tr>
<tr>
<td>GE</td>
<td>20180513</td>
<td>18:40</td>
<td>24</td>
<td>9.5</td>
<td>N</td>
<td>3</td>
<td>Wet</td>
</tr>
<tr>
<td>LI</td>
<td>20150725</td>
<td>09:50</td>
<td>NA</td>
<td>15</td>
<td>Y</td>
<td>6.4</td>
<td>Wet</td>
</tr>
<tr>
<td>LI</td>
<td>20150913</td>
<td>11:10</td>
<td>NA</td>
<td>12.5</td>
<td>Y</td>
<td>14</td>
<td>Wet</td>
</tr>
</tbody>
</table>
Hereafter, each downburst signal and the related statistical parameters will be evaluated over the time interval $\Delta t = 20$ min, centered on the occurrence of the peak wind speed at the height of occurrence of $G_{10\text{max}}$. This assumption, which is usually disregarded in literature, where the investigation of the signal is performed over the period $\Delta t = 10$ min, was herein adopted with the aim of including the whole downburst-related part of the signal in the analysis. According with the different characteristics and durations of the downbursts here investigated, the 20-min time interval was found suitable to statistically address all of them.

6.4 The thunderstorm event on 13 September 2015

This section describes in detail the thunderstorm that occurred in Livorno on 13 September 2015 at about 11:00 UTC. Section 6.4.1 provides the meteorological scenario that triggered the formation of the downburst. Section 6.4.2 gives a first feedback on the wind speed and direction measurements during the event as acquired by the LiDAR and the anemometers. Section 6.4.3 applies the two decomposition techniques (Sections 6.3.1 and 6.3.2) to the signals recorded along the measurement heights. The wind speed and direction vertical profiles are critically interpreted in Section 6.4.4, whereas those related to the turbulence intensity are described in Section 6.4.5.

6.4.1 Meteorological scenario

On 13 September 2015, a deep Atlantic surface low pressure system moved to the south-west of Ireland. Meanwhile, a pronounced trough aloft extended its axis southward to Spain. During the day, the low-pressure system deepened and the movement of the narrow sector of warm and humid air of subtropical origin, which extended southward along the Mediterranean, induced south-westerly winds that triggered instability over northern and central Italy.

In the morning of 13 September, a deep convective system, which had formed over the Tyrrhenian Sea between Corsica Island and Tuscany, landed in the area of Livorno.
Panel (a) of Figure 6.4 shows the distribution of cloud top heights obtained from the cloud analysis performed by Eumetsat, based on infrared measurements collected by SEVIRI on board the Meteosat Second Generation satellites. At 11:00 UTC, two different convective cells with cloud top height at more than 12000 m approached the Italian coast, the northern one was exactly over Livorno (see red circle). The occurrence of these convective storms is confirmed by the intense lightning activity, which can be observed in Panel (b). From 10:45 to 11:15 UTC, the Blitzortung network recorded more than 7000 strikes overall. The strikes occurrence in time, defined by colors red to white, shows the northeast-ward movement of the storm.

6.4.2 LiDAR and anemometer measurements in the port of Livorno

At the time of the storm, the anemometers and the LiDAR in the port of Livorno recorded a sudden increase of the instantaneous horizontal wind speed \( U(t) \) from about 6 to 26 m/s according to the LiDAR at 120 m AGL, which is the height where the maximum gust factor \( G_{10} \) along the whole profile occurred, and from 5 to 24 m/s according to the closest anemometer (LI.04, placed at 20 m above sea level). Contemporarily, the wind of both LiDAR and LI.04 veered about 100° from south-southeast to west-northwest during the ramp-up period and backed to the original direction after the wind speed returned to the previous low values. After the passage of the storm, in fact, the mobile mean wind speed and direction stabilised approximately to \( \bar{U}(t) = 8 \text{ m/s} \) and \( \bar{\alpha}(t) = 160^\circ \). This is captured in Figure 6.5, showing the 1-hour instantaneous horizontal wind speed and direction, as recorded by the LiDAR and anemometer LI.04, as well as their slowly-varying mean evaluated through a mobile time window \( T = 30 \text{ s} \). The classical decomposition method was invoked for the resultant mean wind speed \( \bar{U}(t) \) (Eq. (6.2)), while the directional strategy was adopted for the mean wind direction \( \bar{\alpha}(t) \) (Eq. (6.4)).
According to the LiDAR measurements, the 10-min maximum gust factor, over the whole profile, was 2.26 at 120 m AGL; at the same height, the 10-min mean wind speed was 11.7 m/s. However, the storm development lasted globally more than 10 minutes; the gust factor defined over 1 hour at 120 m AGL was 3.29 as the 1-h mean wind speed was 8.0 m/s.

It is worth noting that the acquiring frequency of LiDAR and anemometers are different, i.e. 1 Hz and 10 Hz, respectively. As illustrated in Section 6.2, the LiDAR also measures the vertical component \( w \) of the velocity (Figure 6.5a), which may provide an information about the intensity of the downdraft stage of the storm when located within the measurement cone of the instrument. Non-zero values of this quantity, particularly closer to the ground, may also relate to the magnitude of the vertical component of the primary vortex embedded into the outflow.
6.4.3 Application of the classical and directional decomposition techniques

Figure 6.6 shows the application of the classical downburst decomposition technique, described in Section 6.3.1, to four of the 12 measurement heights, i.e. \( z = 50, 100, 160 \) and 200 m; the rest of the heights are here not shown for sake of visualization. According to Zhang et al. (2019), high turbulence intensities (greater than 0.2) related to low slowly-varying mean wind velocities (below 5 m/s) were disregarded.

![Figure 6.6. Application of the classical decomposition (Section 6.3.1) to the downburst signal at \( z = 50, 100, 160 \) and 200 m.](image)

The maximum value of the slowly-varying mean wind velocity is \( \overline{U}_{\text{max}} = 24.6 \text{ m/s} \), recorded at the height \( z = 180 \text{ m AGL} \). The slowly-varying turbulence intensity has its maximum and minimum 20-min mean values respectively equal to \( \overline{I}_{U_{\text{max}}} = 0.097 \) at \( z = 200 \text{ m} \) and \( \overline{I}_{U_{\text{min}}} = 0.074 \) at \( z = 180 \text{ m} \), while at the reference height of 120 m, \( \overline{I}_{U} = 0.077 \). The reduced turbulent fluctuation is characterised by near-zero mean and unit standard deviation throughout the elevation; the maximum and minimum values of its skewness are \( \gamma_{U_{\text{max}}} = 0.126 \) at \( z = 100 \text{ m} \) and \( \gamma_{U_{\text{min}}} = -0.246 \) at \( z = 180 \text{ m} \), while those of kurtosis are \( \kappa_{U_{\text{max}}} = 2.586 \) at \( z = 120 \text{ m} \) and \( \kappa_{U_{\text{min}}} = 2.287 \) at \( z = 140 \text{ m} \). At 120 m AGL, these parameters assume values \( \gamma_{U} = 0.023 \) and \( \kappa_{U} = 2.586 \). The average skewness and partly the kurtosis values are indeed in the neighborhood of the reference values associated to the Gaussian distribution, i.e. \( \gamma = 0 \) and \( \kappa = 3 \). However, the lower values of \( \kappa \) indicate a more flattened distribution with values more dispersed around the mean.

Figure 6.7 shows part of the directional decomposition (Section 6.3.2) applied to the downburst outflow. The results are here shown only for \( z = 120 \text{ m} \), which is the height where the maximum value of \( G_{10} \) is observed.
The maximum value of the slowly-varying mean wind speed is $\bar{u}_{max} = 24.6 \text{ m/s}$, recorded at $z = 180 \text{ m}$, which exactly corresponds to the observed $\bar{U}_{max}$. Turbulence intensities show similar values in terms of longitudinal and lateral components which, in turn, are very close to the quantity referred to $I_U$ (Section 6.3.1). At $z = 120 \text{ m}$, where the maximum gust factor $G_{10}$ is observed, $I_u = 0.076$ and $I_v = 0.082$, respectively, which are almost identical to the $I_U = 0.077$ value evaluated for the resultant wind speed $U$ by means of the classical decomposition technique; their ratio $I_v/I_u = 1.079$ is however greater than the reference value commonly adopted for synoptic winds in neutral conditions, $I_v/I_u = 0.75$ (Solari and Piccardo, 2001). The reduced turbulence components have again both fairly zero mean value and unit standard deviation along the height. At the reference height $z = 120 \text{ m}$ the skewness and kurtosis values are, respectively, $\gamma_u = 0.027$, $\gamma_v = -0.083$ and $\kappa_u = 2.559$, $\kappa_v = 2.219$. The longitudinal values of the skewness and kurtosis are found to closely match those obtained from the classic downburst decomposition at the same heights, with analogous considerations concerning their Gaussian properties also to extend to the lateral components.

### 6.4.4 Wind speed and direction vertical profiles

Figure 6.8 shows the slowly-varying mean wind velocity (Eq. (6.2)) and direction (Eq. (6.4)) vertical profiles at 12 significant instants in the period from 11:00 to 11:20 UTC (1200 seconds). The related time histories of $\bar{U}(t)$ and $\bar{\alpha}(t)$ at 120 m AGL are shown in the upper-left box. Here, the velocity ramp-up lasts for
approximately 75 s, i.e. from 215 to 290 s, with magnitudes from about $\bar{U} = 6$ m/s to the first peak, $\bar{U} = 18.3$ m/s. Meanwhile, the mean wind direction oscillates around $\bar{\alpha}(t) = 180^\circ$ shortly before the storm occurrence and, concurrently with the wind speed ramp-up, it starts to veer clockwise from south to west. At $t = 290$ s, the direction settles to approximately 270° and remains fairly constant throughout the occurrence of the downburst. Similarly, the wind speed shows a plateau of roughly constant high wind speed in the range 15-18 m/s. The absolute peak mean wind speed $\bar{U}_{\text{max}} = 21.6$ m/s is reached at $t = 480$ s. At this moment, however, the absolute value is observed at the measurement height $z = 180$ m, where $\bar{U}_{\text{max}} = 24.6$ m/s (Figure 6.8, Box 9). The wind speed likely continues to increase above this height forming a nose-shaped profile with tip higher in elevation, but the lack of records in the period of maximum intensity of the storm prevents to confirm such assumption.

Figure 6.9 depicts the 10-min magnitude diagrams of the horizontal $\bar{U}(t)$ and vertical $\bar{w}(t)$ mean wind speed along with the mean wind direction $\bar{\alpha}(t)$, centered at the time of $\bar{U}_{\text{max}}$, as a function of time and height AGL.

![Figure 6.8](image-url)

*Figure 6.8. Slowly-varying mean wind speed (black line) and direction (gray line); 20-min time-history at 120 m AGL (upper left-hand picture); vertical profiles at: 200, 240, 270, 290, 320, 400, 420, 440, 480, 540, 660 and 800 s (sub-boxes).*
Panel (a) of Figure 6.9 shows the occurrence of the two observed velocity maxima in the time-space domain: the first appears very localized in time around $t = 290$ s with highest velocities in the range $z = 80$ m to $z = 120$ m; the second covers a wider time interval, starting 20 s before the time of the absolute peak, and spreads into a larger elevation range from $z = 60$ m.

Figure 6.9b shows important aspects related to the vertical mean wind speed. At the time $t = 290$ s of the first peak of $\bar{U}(t)$, the little positive value of $\bar{w}(t)$ might be related to the upward vertical component of the primary vortex which has just impinged on the ground and is now leading the outflow. In agreement with the dynamics of the vortex itself, the maximum positive values are observed higher in elevation and few seconds before those related to the horizontal component of the wind speed. This scenario is confirmed by the subsequent zero and little negative $\bar{w}$ values, respectively concurrent with the maximum $\bar{U}$ and with the back-downward component of the vortex. At the time of the absolute peak of $\bar{U}$, the negative-sign intensification of $\bar{w}$ for high elevations suggests that the storm is passing over the instrument. This seems to be confirmed by the missing measurements above 160-180 m AGL, likely due to the heavy rain which characterizes the spatial region defined by the downdraft. Large negative vertical velocities of about 6-8 m/s are found for heights $z \geq 160$ m while, going down in elevation, the magnitudes are reasonably lower as streamlines have to spread horizontally at the ground.
To comprehend better what we are referring to in relation to the dynamics of the phenomenon, Figure 6.10 depicts the flow visualization of a generic physical reproduction of a downburst at the WindEEE Dome in the vertical impinging-jet mode (Chapter 2). Based on the location of the measuring instrument, five main different situations can be identified in the outflow dynamics, as schematically shown by white arrows. With reference to the figure and to the downburst event herein analysed, the LiDAR’s location allows, firstly, the recording of (1), (2) and (3) defining the first peak of the horizontal wind speed and, secondly, the passage of the downdraft over the instrument which is captured in the scenarios (4) and (5).

After the occurrence of the absolute peak, the horizontal velocity $\bar{U}$ in Figure 6.9a shows a second plateau of magnitude approximately 18.5 m/s, higher in respect to the previous stage of roughly constant velocity between the two peaks. After about 80 s, at $t = 560$ s, the descending part of the signal takes place. At $t = 750$ s, eventually, the velocity returns to low values of approximately $\bar{U} = 8$ m/s. Nevertheless, the vertical wind speed $\bar{W}(t)$ is observed to be still negative. The mean wind direction $\bar{\alpha}(t)$, instead, maintains the direction west-to-east for approximately 10 minutes and only at $t = 920$ s starts to veer anticlockwise towards the original south-southwest direction.

According to the boxes of Figure 6.8, the velocity nose-like profile appears only in discrete portions before and eventually during the peaks. The colormap of Figure 6.9 allows the analysis of the real duration of the nose shape profiles: it is clear in the final part of the ramp-up period, where the maximum velocity is experienced in the elevation range between 80 and 120 m AGL and lasts from 260 to 325 s; it appears, less clearly, in the plateau interval before the second peak from 375 to 460 s in a somewhat spread range of
altitudes (90 to 180 m AGL). In this latter interval, in fact, the maximum of the nose occurs at the highest elevations at \( t = 380 \) s, while it decreases to \( z = 60 \) m at \( t = 425 \) s. The velocity remains approximately constant above this height and up to the occurrence of the absolute peak. In the other parts of the ramp-up and in the post-peak period, the horizontal mean wind speed can be considered as almost constant or increasing with height. The nose-like shape, in the region of major evidence, disappears at 330 s lasting in total 65 seconds. The maximum velocity occurs at 480 s when the nose has already disappeared.

The wind direction \( \alpha(t) \) is observed to maintain a constant trend along the height throughout the downburst occurrence in Figure 6.9c. The full scale investigation by Hjelmfelt (1988) and Wakimoto (1982) reported an average depth of the outflow leading front of about 1.4 km, or even larger, with the vortex center located in the range 700-800 m AGL. It follows that the LiDAR’s vertical range of measurements only covers the lower portion of the gust front outflow and below it, where the dominant flow component is the radial (scenario (2) of Figure 6.10) and the maximum horizontal wind speed is experienced; for this reason, the direction is here observed to remain constant throughout the inspected heights. Since the same situation occurs for all the thunderstorms analysed here (Section 6.5.2), it represents a crucial finding and signature of the outflow vertical profile of thunderstorm winds, with highly relevant implications to the wind loading on structures: the wind direction can be assumed as invariant with height. By examining Figure 6.8 and Panel (c) of Figure 6.9, however, slight exceptions are here observed during the ramp-up stage of the velocity and simultaneous rotation of the direction where the wind seems to veer to west sooner at the lower heights. At the beginning of the ramp-up stage, \( t = 200 \) s, the approaching primary vortex pushes the ambient air outwards according to the outflow direction, likely forming a secondary and smaller vortex ahead of it. Consequently, the change in wind direction is sensed earlier at the lower heights: at 40 m and 250 m AGL \( \alpha \) is, respectively, 230° and 211°. With the occurrence of the first velocity peak 90 s later, at \( t = 290 \) s, the wind direction assumes a strong west component and the direction gap between the two heights is sharply reduced, \( \alpha = 272° \) and \( \alpha = 266° \), respectively.

### 6.4.5 Turbulence intensity vertical profile

Figure 6.11 shows the vertical profile of the slowly-varying turbulence intensity (Section 6.3.1) at the same time frames considered in Figure 6.8. Firstly, it is to be noted that the turbulence intensity magnitudes are all confined within \( I_U = 0.23 \), at least for the height \( z = 120 \) m shown in the upper panel. The mean turbulence intensity values extracted over the duration of the experimentally produced downbursts for the case DB1.0 at the WindEEE Dome (Chapter 2) show good agreement with the results here, while overall greater magnitudes, of about 3-4% higher in respect to the values here observed, are experienced in the experiments on downburst embedded in ABL flow (Chapter 3). The height of maximum turbulence intensity seems to increase during the velocity ramp-up stage up to the top of the profile at the first peak, \( t \)
During the plateau part of the wind speed, instead, a clear nose-shaped profile appears at elevations 40-50 m AGL. A sudden change of the height of maximum turbulence intensity concurrently with the passage of the primary vortex is thus observed and partly corroborates the experimental observations made in Chapter 2. Furthermore, Chapter 2 reports that the vertical profile of turbulence intensity is of nose-shaped type at the time of maximum intensity of the phenomenon, which is also clearly pointed out in Figure 6.11 (Box 5-8). At the time of the absolute peak velocity, \( t = 480 \) s (Box 9), the maximum value of \( I_U = 0.149 \) is found at \( z = 120 \) m. Later, its vertical trend does not appear to assume a recognizable behavior.

Figure 6.11. Slowly-varying turbulence intensity: 20-min time-history at 120 m AGL (upper picture); vertical profile at: 200, 240, 270, 290, 320, 400, 420, 440, 480, 540, 660 and 800 s (sub-boxes).
Figure 6.12. 10-min slowly-varying mean standard deviation (a) and turbulence intensity (b): time histories at 120 m AGL (upper pictures); interpolated magnitude-maps as function of time and height (bottom pictures). Vertical dashed red lines indicate the time of the first and second peak of the horizontal mean wind speed. Horizontal dotted gray lines (bottom pictures) indicate the height at which the time histories are depicted (upper pictures).

In analogy to Figure 6.9, Figure 6.12 shows the evolution of the slowly-varying standard deviation (a) and turbulence intensity (b) (Section 6.3.1) along the time and height AGL. The two parameters differ by a normalization factor $\bar{U}(t)$ in the evaluation of the non-dimensional quantity $I_U(t)$. Contrary to what assumed before, it is here decided to plot the entirety of values of $I_U$ in order to obtain a more complete map, being aware that non-realistic high values might arise in correspondence of low $\bar{U}(t)$; the qualitative comparison with the graph of $\sigma_U$ (Panel (b)) can overcome this issue. The two parameters assume an analogous general trend which, in the following, is discussed in relation to the behavior of $\bar{U}(t)$ (Figure 6.9a). The first peak in the velocity domain does not link with a simultaneous increase of $I_U$. In fact, a region of higher turbulence magnitude is observed approximately 25 s prior to the first velocity peak. Furthermore, such area is shifted at higher elevations in respect to the maximum $\bar{U}(t)$ in this stage. Analogous time-shift with the wind speed is observed in correspondence of the second maximum where, however, the turbulence intensity seems to occur at about the same height. In addition to that, about 60 s before the absolute peak of the mean wind velocity, $I_U$ shows a localized region of rather high values at the lowest heights. Overall, the turbulence intensity maxima appear to precede the related wind speed peaks. This time-dependent behavior along the profile is observed in most events here analysed and will be discussed further in Section 6.5.3. The same concept is already found in Zhang et al. (2018b, 2019): by considering, respectively, 277 and 141 thunderstorm recordings, the ensemble mean of the parameter $\mu_U(t)$...
shows a pronounced and off-mean spike few tens of seconds before the occurrence of the peak velocity. Furthermore, this aspect is strongly corroborated during the large experimental campaign at the WindEEE Dome (Chapter 2, Chapter 3 and Chapter 4), where the three orders or so lower Reynolds numbers involved in the laboratory simulations at the WindEEE Dome enhance this aspect much more. Our findings thoroughly mirror this situation. Its engineering implications in terms of wind loading and response of structures are not yet clear and out of the domain of this study, but surely represent an open topic which deserves future research.

6.5 Characteristics of the vertical wind profiles

This section provides a comprehensive discussion and comparison of the 10 downburst events extracted, in terms of vertical profiles of the slowly-varying mean wind speed (Section 6.5.1) and direction (Section 6.5.2) as well as the turbulence intensity (Section 6.5.3).

6.5.1 Slowly-varying mean wind speed

It is widely discussed by literature that, in the phase of maximum energy of the downburst, the outflow vertical profile assumes a typical nose-shaped form. In the mature stage of the phenomenon, the descending cold and dense column provokes high shear with the surrounding environment that triggers the formation of a vortex ring which, after its impingement on the ground, mightily spreads horizontally within a few hundred meters vertical layer. In this time frame, the maximum horizontal velocities are experienced at the boundary between the ground and the center of the vortex filament, usually in the range from 50 to 120 m AGL (e.g. Goff, 1976; Hjelmfelt, 1988; Lombardo et al., 2014).

In terms of mean wind speed signals $\bar{U}(t)$ (Eq. (6.2), four of 10 downburst events are depicted in Figure 6.13-6.16. Each of them shows the 10-min horizontal and vertical velocity time histories at the height of the maximum $G_{10}$ (upper pictures) as well as the related magnitude maps (bottom pictures). Conventionally, the related diagrams are centered on the time of occurrence of the horizontal peak mean wind speed in the upper time histories ($t = 300$ s). Few investigated events show rather similar characteristics in respect to the downburst that struck Livorno on 13 September 2015 (Section 6.4.4). Two distinguished velocity maxima, of about the same magnitude, are observed in the event recorded in Genoa on 14 August 2015 (Figure 6.13). Both the upper and bottom pictures of Panel (a) show that the horizontal mean wind speed, after a 130-s ramp-up stage, reaches the first peak $\bar{U} = 15.1$ m/s at $t = 246$ s and elevations above 140 m. The lack of data, however, does not allow to confirm whether the velocity above 160 m decreases, as it may appear in the black line in Box (1) of Figure 6.13, which represents the vertical profile of the horizontal mean wind speed. Around 300 s, which is about 1 minute after the first peak, a second peak occurs, but the height of the maximum wind speed is now shifted down to the range 40 to 120 m AGL. As highlighted in
Box (2), the velocity profile here settles to a maximum value of $\bar{U} = 15.2 \text{ m/s}$ in the range 60-100 m AGL and then decreases quite rapidly until $z = 160$ m. A third, less intense, local maximum occurs around 400 s again in the range between 60 and 100 m AGL (Figure 6.13a, bottom picture). All these maxima correspond to vertical profiles of the horizontal mean wind speed with a clear nose-like shape, which comes and goes three times during the whole thunderstorm record. A quite strong downward flow component (Panel (b)) is observed during the time frames affected by high values of the horizontal wind speed. Both boxes (1) and (2) show values of the vertical component around -3 and -2 m/s at the first and second peak occurrence, respectively. Two aspects of these profiles are worth noting: first, the vertical profile in Box (1) shows a significant reduction of the vertical intensity at $z = 200$ m; second, in both profiles, $\bar{w}$ decreases from 200 to 40 m AGL, as expected because of the constraint $\bar{w} = 0$ at the ground. Also interestingly, the horizontal and vertical components of the wind speed seem to assume a quite correlated behavior, as it can be clearly noticed that the maximum negative vertical mean component occurs immediately after both the first and second maximum horizontal mean wind speed (see the red dashed lines (1) and (2) in Figure 6.13 for reference). In an attempt to speculate about the physical meaning of the measurements described so far, we suggest that the first peak of $\bar{U}$, followed by the first minimum of $\bar{w}$, is related to the passage of the vortex ring above the LiDAR, which is always the first signature of a thunderstorm outflow. The earlier positive values of $\bar{w}$ above 180 m, cut off by the lack of data at the top of the profile, seem to confirm the situation depicted in the scenarios (1) to (3) of Figure 6.10 where a snapshot of a flow visualization at the WindEEE Dome (Chapter 2) clearly shows the main dynamic pattern of the downburst outflow. Then, the second peak of $\bar{U}$, followed by the second minimum of $\bar{w}$, might be the footprint of the downdraft ((4) and (5), Figure 6.10). This description seems to be consistent with the profile of the vertical velocity in Box (1) which sharply reduces to almost zero at 200 m AGL and therefore can be hardly associated to the downdraft. Conversely, in the profile in Box (2) the vertical component remains always negative as expected in case of the downdraft.

Similar considerations in terms of horizontal wind speed can be expressed for the thunderstorm event recorded on 13 May 2018 still in the port of Genoa (Figure 6.14). Here, however, the time gap between the two peaks is about 100 s and the magnitude of the first appears approximately 3 m/s lower in respect to the absolute maximum. Both peaks occur at elevations above 120 m: at $t = 196$ s, depicted in Box (1), the velocity maintains a constant value of approximately $\bar{U} = 13.0 \text{ m/s}$ from $z = 120$ m to $z = 200$ m; at the time of the absolute peak (Box (2)), the horizontal wind speed increases up to 160 m AGL and, after a 40-m high plateau, decreases significantly to the top measurement height. Therefore, once again, it is confirmed that nose-like shape profiles occur concurrently with the maxima of the horizontal mean wind speed. Contrary to the event previously analysed, no relevant negative vertical velocity is measured during the whole thunderstorm, likely because the downdraft does not really pass over the LiDAR. Even more
noteworthy, the vertical velocity increases between the occurrences of the two peaks and assumes positive values up to 3.0 m/s at the top of the profile (Figure 6.14b, bottom picture). Following the same considerations addressed to the downburst LI29150913 (Section 6.4.4), this may be related to the passage of a vortex, which is supposed to be the primary vortex ring produced by the downdraft. Indeed, the LiDAR measures firstly the upward positive component in the leading part of the vortex and, secondly, the maximum horizontal wind speed which occurs closer to the ground at the bottom of the swirling structure; the subsequent slightly negative values of $\bar{w}$ at the top heights confirm this hypothesis (situation (1) to (3), Figure 6.10). If this is the case, the first peak would be related to the secondary vortex which, as mentioned above, is sometimes produced ahead of the primary vortex ring when air is pushed outwards by the vortex expansion at the ground. This flow pattern clearly recalls what observed in controlled conditions during the experiments at the WindEEE Dome (see Figure 2.5 in Chapter 2). Here, in fact, the onset of a secondary vortex, and eventually the boundary layer detachment from the surface, is observed at further radial positions from the jet touchdown. The same situation seems to occur in the full scale event here analyzed where, for the reasons mentioned above, the downdraft stage of the storm is indeed rather far from the measuring station.

Figure 6.13. Downburst in Genoa on 14 August 2015. 10-min horizontal (a) and vertical (b) slowly-varying mean wind speed: time histories (upper pictures); interpolated magnitude-maps as function of time and height (bottom pictures). Vertical dashed red lines indicate the time of the horizontal peak mean wind speeds, at which the vertical profiles of the horizontal and vertical slowly-varying mean wind speed are depicted (right-hand boxes). Horizontal dotted gray lines (bottom pictures) indicate the height at which the time histories are plotted (upper pictures).
Figure 6.14. Same as Figure 6.13, but for the downburst in Genoa on 13 May 2018.

The other analysed events show more regular features, in the sense that the wind speed ramp-up and the ramp-down stages are of comparable duration and defined by the occurrence of a unique and clear peak. The storm recorded in Genoa on 3 May 2016 (Figure 6.15) is characterized by an area of maximum intensities above 140 m which lasts for about 30 s. At the time of occurrence of the maximum velocity at $z = z(G_{10_{\text{max}}})$, a nose-shaped profile with tip at 160 m AGL is observed. Likewise most cases here investigated, a strong downdraft stream, clear above 200 m AGL, is observed slightly later than the occurrence of the maximum horizontal wind speed. This is believed to link with the passage of the storm over the measuring instrument when the downdraft touchdown is not far from the instrument itself, so that the primary vortex ring and the impinging jet-like phase cannot be clearly distinguished in the measurements (scenario (4) and (5), Figure 6.10). Quite the same scenario can be observed for the radial locations in proximity of the touchdown position in the WindEEE Dome where the measuring instrument records both the negative vertical component related to this and, partly, the horizontal component proper of the primary vortex.

The downburst that occurred in Livorno on 4 June 2018 (Figure 6.16) shows, again, a unique velocity peak. This is, however, contoured by smooth and slow-time stages of increasing and reduction of the wind speed. The highest magnitudes of about 18.2 m/s are experienced in the range of heights from 100 to 160 m AGL. The roughly uniform trend above the height of maximum wind speed has been observed also in other two events here not reported and is recorded in quite many studies in literature (Orwig and Schroeder, 2007;
Ponte and Riera, 2007; Durañona et al., 2007; Holmes et al., 2008), even if a widely accepted explanation for that is not available. However, we may hypothesize that this situation happens when the vortex travels higher on the ground and thus the maximum horizontal velocities, occurring underneath the vortex itself, develop over a larger vertical extension. In the latter event shown, the vertical velocity does not record very negative values, but a rapid change of sign occurs exactly at the time of the peak, when the vertical velocity switches from positive to negative values. This seems related to the passage of a primary vortex ring when its shape is still quite symmetric, which means that the touchdown position is not very far from the instrument (scenario (1) to (3), Figure 6.10). Moreover, as the upward and downward velocities $\bar{w}$ are in the order of 1 m/s, which is a rather low value, the core of the vortex was probably pretty much higher than 250 m AGL, which would confirm the assumption above. Finally, after 2-3 minutes from the peak $\bar{w}$ is zero again, so that it seems likely that the instrument was not affected by the impinging jet-like flow of the thunderstorm downdraft.

Figure 6.15. Same as Figure 6.13, but for the downburst in Genoa on 3 May 2016.
Figure 6.16. Same as Figure 6.13, but for the downburst in Livorno on 4 June 2018.

Table 6.3 shows the main parameters describing the slowly-varying mean part of each outflow signal here investigated, with particular regard to their vertical profiles.

Table 6.3. Main characteristics of the nose-shaped profiles: maximum horizontal mean wind speed along the profile and its height, $U_{\text{max}}$ and $h_{U_{\text{max}}}$; vertical mean wind speed $\bar{w}$ at the time and height of $U_{\text{max}}$; range of heights of the nose and its duration, $h_{\text{nose}}$ and $T_{\text{nose}}$; maximum negative vertical mean wind speed and its height, $w_{\text{max}(-)}$ and $h_{w_{\text{max}(-)}}$; maximum positive vertical mean wind speed and its height, $w_{\text{max}(+)}$ and $h_{w_{\text{max}(+)}}$. Event names are given in terms of station, SS, year, YYYY, month, MM, and day, DD.

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The spatial evolution of the experimental downburst-like outflow, portrayed by means of flow visualization in the WindEEE Dome (Figure 6.10), allows a qualitative interpretation of the dynamic behavior of the events described above, clarifying the nature of the observed positive and negative vertical velocities. The strongest negative values of the vertical mean wind speed \( \overline{w} \) are likely to be related to the downdraft component of the storm (see (4) and (5), Figure 6.10). In this situation, the instrument is located within the idealized cone defined by the descending and vigorous flow towards the ground. Indeed, Table 6.3 shows that the maximum negative values of \( \overline{w} \) are often acquired at the top of the profile measured by the LiDAR, around 200-250 m AGL. On the other hand, low or even positive values of this quantity imply that the touchdown position of the storm is further away from the location of the instrument. Lower negative and positive values can, however, be due respectively to the back-downward and front-upward components of the vortex ring during its passage over the instrument (see (1) and (3), Figure 6.10).

6.5.2 Slowly-varying mean wind direction

One of the main advantages of the new decomposition strategy is the ability to extract the time-dependent slowly-varying wind direction \( \alpha \) or \( \beta \) (Section 6.3.2), which is thus dealt within the wind velocity model itself. This allows to overcome the drawbacks of the classical rule, where the wind direction is considered only qualitatively but, eventually, disregarded in quantitative terms.

During the occurrence of thunderstorm outflows, the wind direction is usually observed to veer significantly with respect to the direction of the background wind – namely the synoptic wind in which the downburst embeds into. In agreement with literature, Figure 6.3 (Section 6.3.3) has pointed out the following relevant aspect: the sudden change in the slowly-varying mean wind direction often occurs in correspondence of the simultaneous increase of the wind speed prior to the occurrence of the peak. The wind direction recorded by the measuring instrument corresponds, at first, with that of the background wind in the boundary layer; subsequently, the embedded outflow provokes the direction to change accordingly to the position of the instrument in respect to the touchdown position. The translation of the thunderstorm cell plays, then, a significant role in the rate of this change.

Therefore, the main focus of this paragraph is to investigate the vertical variation of the mean wind direction along the profile recorded by the LiDAR. Figure 6.17 shows, for the 10 downbursts examined, the maximum variation of the mean wind direction \( \alpha(t) \) among the sensed heights (black dotted line). This is computed for the 20-min time interval containing the peak wind velocity. The overlap with the wind speed time history (gray solid line) allows to draw some conclusions on the along-height change of the wind direction during the development of the storm.
Section 6.4 has described in detail the downburst event LI20150913. By considering the time instants highlighted by the vertical red lines of Figure 6.8 and, even more intuitively, Panel (c) of Figure 6.9, the maximum vertical variation of the mean wind direction is about 20° at the beginning of the velocity ramp-up stage (Box (1) of Figure 6.8). However, Figure 6.17 now points out that the direction varies up to $\Delta \alpha \approx 40°$ prior to the embedment of the outflow into the background wind. Almost the entirety of the events studied here show a very similar behavior in this sense. Indeed, the direction along the profile is observed to largely vary prior to or at the very first stage of the velocity ramp-up. While increasing the wind speed, the vertical variation of the direction becomes smaller and smaller until the occurrence of the peak, where $\Delta \alpha$ is at the minimum value, usually in the range 5-10°. Here the wind direction can be dealt with, to a very good extent, as constant along the vertical profile. This behavior is maintained throughout the peak interval while, during the velocity decreasing phase, the vertical variation widens again visibly; in the very last part of the velocity ramp-down and later, $\Delta \alpha$ is sometimes found to reach values of 80°.

Two events show slightly different behavior of this parameter. GE20180513 and LI2015028 respectively exhibit the maximum values $\Delta \alpha = 24°$ and 41° only 15 s and 35 s prior to the peak velocity. In general, however, the wide vertical changes in direction are in correspondence of the background wind, in both pre- and post-outflow intervals. Upon the downdraft impingement on the ground, the vigorousness of the generated outflow overcomes the influence of the boundary layer flow and the wind direction measured by the instrument is actually the non-linear superposition of both flows.
6.5.3 Turbulence intensity

Figure 6.18 shows the time-dependent variation along the height of the turbulence intensity $I_U$, evaluated by means of the classical method (Section 6.3.1), for the four events depicted in Section 6.5.1. It aims at providing a clear framework of the turbulence characteristics corresponding to the related slowly-varying mean wind speeds. The dimensional standard deviation $\sigma_U$ (not shown here) has again provided an interpretation and double-check on the values assumed by the turbulence intensity.

![Figure 6.18. Downburst events: Genoa on 14 August 2015 (a), 13 May 2018 (b) and 3 May 2016 (c); Livorno on 4 June 2018 (d). 10-min time histories of the horizontal slowly-varying mean wind speed at $z = z(G_{10_{\text{max}}})$ (upper pictures); interpolated magnitude-maps of the turbulence intensity $I_U$ as function of time and height (bottom pictures). Vertical dashed red lines indicate the time of occurrence of the horizontal peak mean wind speeds. Horizontal dotted gray lines (bottom pictures) indicate the height at which the time histories are depicted (upper pictures).](image)

At the beginning of the ramp-up phase of $\bar{U}$, the downburst recorded in Genoa on 14 August 2015 (Panel (a)) exhibits turbulence intensities in the order of $I_U = 0.25$ at $z = 160$ m. The same values of $I_U$ are found in the middle of the velocity ramp throughout the whole vertical profile while about 40 s prior to the first velocity peak $I_U$ assumes very low values tending to zero. Two localized maxima of the turbulence intensity are observed in between the two wind speed peaks. The first is observed at $t = 275$ s and $z = 160$ m; it appears with a time delay of approximately 25 s in respect to the first maximum in terms of horizontal velocity, and its height of occurrence suggests the correlation with this latter. About 5 s later, the second area of high off-mean values of $I_U = 0.38$ is observed at the location $z = 50$ m and few seconds earlier in
respect to the high values of $\overline{U}$ defining the earlier boundary of the absolute peak velocity time interval. The maximum values of $\overline{U}$ at the second peak interval are, in fact, observed starting from a near-ground elevation up to about 120 m AGL. The elevation of both regions of local maxima of $I_U$ seems to lie at the lower boundary of those related to the local maxima of $\overline{U}$.

Two confined areas of higher turbulence intensity ($I_U \approx 0.23$) are observed also in the event shown in Panel (b). In this case, they are both slightly prior compared to the occurrences of the velocity peaks: the first is observed about 8 s earlier and few tens of meters higher, while the second, located at $z = 200$ m, occurs 15 s prior to that related to $\overline{U}$. The two areas seem now to seat at the top of those related to the high values of $\overline{U}$. The low magnitude of this latter parameter clearly causes the high values of $I_U$ at the bottom of the profile at $t = 250$ s. It is again confirmed the non-stationarity of the turbulence intensity, which shows a spike few instants before the occurrence of the maximum wind speed that has to be related to the passage of the primary vortex over the instrument. The same findings are reported in previous investigations by Zhang et al. (2018b, 2019) on a large set of downburst records extracted from anemometric recordings, and are corroborated by the experimental observations made in Chapter 2 and Chapter 3 on large-scale physically produced downburst winds. The event occurred in Genoa on 3 May 2016 (Panel (c)) shows, at the beginning of the ramp-up stage of $\overline{U}$ ($t = 195$ s), an area of high localized $I_U \approx 0.7$ at $z = 60$ m. The thunderstorm in Livorno on 4 June 2018 presents very low values of the turbulence intensity throughout the time history. During the velocity ramp-up, the area defined by the iso-contour of $I_U \approx 0.12$ seems to shift to higher elevations by increasing $\overline{U}$. A peak of $I_U \approx 0.2$, confirmed by the analysis of $\sigma_U$, is surprisingly observed at the top elevation $z = 250$ m during the ramp-down of the mean wind speed.

Figure 6.19 shows, for each of the 10 downburst events, the vertical profiles of the 20-min mean slowly-varying turbulence intensities evaluated through the classical method, $I_U$, and directional method, $I_u$ and $I_v$. 
Most events here analyzed show the maximum 20-min mean value of the turbulence intensity at the bottom of the profile, \( z = 40 \text{ m} \), which decreases above following, however, different behaviors. At the top of the profile the turbulence intensity is usually observed to increase again. The occurrence of the maximum is observed in the mid-level profile, i.e. in the range 120-180 m AGL, only in the case of GE20160503. As discussed in relation to the event LI20150913 (Section 6.4), the turbulence intensity profiles assume here a nose-like shape with maximum values experienced in the near-ground region. This confirms again the experimental observations reported in Chapter 2 and, moreover, find a good match with the mean turbulence intensity profiles reported in the case of downburst supplemented with ABL-like wind (Chapter 3), where a clear spike of \( I_U \) was noted at the lower measuring heights. In Chapter 3, we speculate that the higher turbulence level near the ground is caused by the interaction between inner and outer surface layer, respectively dominated by the secondary and primary vortices.

As envisaged in Section 6.4, the longitudinal component of the turbulence intensity \( I_u \) assumes very similar, almost overlapping, values in respect to \( I_U \) referred to the resultant wind speed \( U \). Little variations in this sense are observed only in the events GE20160305 and GE20160503, where \( I_u \) is slightly lower than \( I_U \) at elevations above 100 m, approximately. \( I_u \) appears lower throughout most of the profile in the event LI20150725. It is again highlighted the little detachment of \( I_v \) from both the previous profiles. In general terms, it appears shifted to slightly lower values in all events.
Table 6.4 reports, for each event, the average value over the measurement heights of the 20-min mean slowly-varying turbulence intensity \( \bar{I}_u \) (Section 6.3.1) and \( \bar{I}_v \) (Section 6.3.2) as well as of the skewness \( \gamma_u \) and \( \gamma_v \), and kurtosis \( \kappa_u \) and \( \kappa_v \) of the reduced turbulent fluctuations along with their cross-correlation coefficient \( \rho_{uv} \). It is worth reminding that the statistical parameters are obtained upon the use of a mobile averaging period \( T = 30 \) s to filter the signal.

Table 6.4. Along-height average value of: 20-min mean slowly-varying turbulence intensities \( \bar{I}_u \), \( \bar{I}_u \) and \( \bar{I}_v \); skewness \( \gamma_u \) and \( \gamma_v \); kurtosis \( \kappa_u \), \( \kappa_u \) and \( \kappa_v \); cross-correlation coefficient \( \rho_{uv} \). Event names are given in terms of station, SS, year, YYYY, month, MM, and day, DD.

<table>
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<th>port_date</th>
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<th>( \bar{I}_u )</th>
<th>( \bar{I}_v )</th>
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<th>( \gamma_u )</th>
<th>( \gamma_v )</th>
<th>( \kappa_u )</th>
<th>( \kappa_u )</th>
<th>( \kappa_v )</th>
<th>( \rho_{uv} )</th>
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The last two rows of the table show the ensemble values of the investigated parameters performed separately over the records in the ports of Genoa and Livorno. \( \bar{I}_u \), \( \bar{I}_u \) and \( \bar{I}_v \) present very similar values: \( \bar{I}_u \) is almost coincident or slightly greater than \( \bar{I}_u \) which, in turn, results few thousandths greater than \( \bar{I}_v \). Overall, these values result slightly lower but in general good agreement with the findings of Zhang et al. (2018b, 2019).

The values of \( \bar{I}_u \) reported in Table 6.4 match rather closely those evaluated from physically produced isolated vertical-jet downbursts at the WindEEE Dome (Chapter 2), especially in the range of experimental measurement positions \( 0.4 \leq r/D \leq 1.2 \), where \( r \) is the radial distance from the jet touchdown and \( D \) is the jet diameter. The inclusion of the ABL wind in the experimental runs contributes to add turbulence to the environment (Chapter 3). The same is somehow observed in the rear-wind side of travelling downburst (Chapter 4), reproduced at WindEEE by means of a non-vertical inclination of the jet axis, where the loss of symmetry and coherency of the vortex structures makes the outflow more spatially dispersed and, consequently, more turbulent.

While the skewness values are all found to be very close to zero, with \( \gamma_u = 0.083 \) being the most detached value, \( \kappa \) is observed to be around 2.4 for all events. This result confirms the theoretical considerations
provided by Tubino and Solari (2020); in this specific case they are strengthened by the capability of LiDAR to properly measure turbulence despite the Gaussian properties of $\bar{U}'(t)$ are not entirely complied. Moreover, as remarked by Zhang et al. (2019) and in analogy to synoptic winds, the cross-correlation coefficient $\rho_{uv}$ shows that the longitudinal and lateral reduced turbulence components can be dealt as uncorrelated.

6.6 Conclusions and prospects

This chapter provides a description and interpretation of the wind vertical profiles measured, by means of LiDAR wind profilers located in the Northern Mediterranean, during 10 thunderstorm events in the period 2015-2018. The events are selected through an automated procedure involving systematic quantitative controls of fixed thresholds of the 10-min maximum 1-Hz wind speed and gust factor. The actual nature of these events is checked with information such as satellite and radar images as well as lightning occurrences. Overall, important aspects related to the mean (i.e. deterministic) part of the signal are found. Part of the events examined show a single maximum of the horizontal wind speed, whereas other events show two localized maxima. This characteristic can be referred to two different scenarios: in the case of LI20150913 (Section 6.4) and GE20150814 (Section 6.5), the LiDAR records first the travelling radial vortex and, afterwards, the passage of the downdraft over the instrument itself, producing two distinct peaks; in the event GE20180513 (Section 6.5), the first peak is likely to be related to the secondary vortex which is, few seconds later, followed by the primary one. This scenario is also corroborated by numerous experimental observations (Chapter 2) where, at further distances from the jet touchdown as in the full scale event here mentioned, the onset of the secondary vortex takes places and the boundary layer eventually detaches from the ground. The nose shape of the wind speed vertical profile is somewhat clear in all the downburst events here investigated; this is limited to quite short time intervals during the ramp-up and peak stages. The velocity is often found to assume a roughly constant value above the height of occurrence of the maximum, but the lack of data above 250 m AGL prevents to confirm such characteristic.

The analysis of the wind direction along the profile delivers a very important outcome: during the occurrence of the downburst, the direction is observed to be invariant with the height for all the events investigated. The strength of the outflow, generated by the impingement of the downdraft, suppresses the effects of the background wind.

The accuracy of LiDAR to measure turbulence components is discussed and the resulting values of each signal, cleaned from abnormal large values in correspondence of very low $\bar{U}$, are found to be in good agreement with those evaluated for large datasets of downburst outflows both from ultrasonic measurements (Zhang et al., 2018b, 2019) and from wind tunnel simulations using a vertical isolated impinging jet (Chapter 2). When the latter is supplemented with ABL-like flow (Chapter 3) and/or the jet-
axis is inclined to a non-vertical angle to reproduce the effect of the thunderstorm cloud translation (Chapter 4), the turbulence level increases due to the higher flow mixing and to the loss of symmetric structure of the travelling vortices. It is proven that the quantities classically evaluated with reference to the resultant wind speed closely match those obtained through the directional decomposition rule, especially with regard to the longitudinal component of the wind speed. However, also the lateral turbulence component is found to assume very similar values and only slightly lower.

The temporal analysis of the along-height behavior of the turbulence intensity $I_U$ shows another relevant aspect: its highest values are usually found few tens of seconds prior to the occurrence of the horizontal peak wind speed. This reflects the findings of Zhang et al. (2018b, 2019) where a sharp increase of $I_U$ was observed prior to the occurrence of the velocity peak on a large set of downbursts. This point is significantly highlighted in experimental observations where the much lower Reynolds numbers involved make the environment smoother and thus more susceptible to turbulence variations. This makes questionable the usual hypothesis adopted in literature, where $I_U = \bar{I}_U$, i.e. $\mu_U = 1$. Research is still on-going to identify its implications in terms of structural loading and response. Besides this, in the present research we could not find a defined vertical behavior of the maximum values of $I_U$ in respect to those of the horizontal wind speed. However, the vertical profiles of the turbulence intensity, time-averaged over the duration of the downburst events, show that the highest values occur close to the ground, in agreement with the experimental results at the WindEEE Dome (Chapter 2 and Chapter 3).

A clear understanding of the evolution in time of the wind direction, as shown in Sections 6.4 and 6.5, is of crucial importance to fully comprehend the travelling nature of downbursts and the related impact on structures by analysing their behavior in terms of alongwind and crosswind response. Indeed, the systematic analysis of downburst vertical profiles is one of the main targets of the THUNDERR Project in order to clarify the time and height evolution of the mean and turbulent components of the signals. In this sense, a great and additional contribution to the WPS monitoring network has recently been given by the introduction of the new “Scanning WindCube” LiDAR, installed in the port of Genoa. It provides the reconstruction of the wind field on both the vertical and horizontal planes by taking advantage of a wide and deep scanning resolution. The complementary use of the “Scanning” and “Vertical Profiler” LiDARs will offer a full picture of the storm physical behavior, starting from tracking its propagation and core dimension at the near-ground region and, also, shedding new lights on the interplay of the outflow embedded in the background ABL wind and influenced by the thunderstorm cell translation. In this panorama and by looking at the project THUNDERR from a wider and general perspective, the physical investigation of such interactions in ad-hoc laboratories, such as the WindEEE Dome, provides a further and necessary step towards the detailed reconstruction and interpretation of the phenomenon, as remarked.
across this thesis. The implications for future research related to the design of safer and cost-efficient structures are considerable.

References


Chapter VII

7 Conclusions

Thunderstorm winds, namely downbursts, present characteristics completely different from the “usual” synoptic-scale extra-tropical cyclones that strike the mid latitudes of our regions, developing over few thousands of kilometers on the horizontal with a duration of 1-3 days. Here the velocity records can be considered as stationary in time. Downbursts are meso-scale phenomena lasting few tens of minutes and developing over few kilometers in space. This makes their recording very challenging in nature and leads to approach the study of the phenomenon with experimental and numerical tools. Furthermore, the velocity records present highly non-stationary characteristics.

The understanding of the dynamics of the phenomenon is indeed the key to assess, both from the quantitative and qualitative point of view, its potential danger in wind and structural engineering terms. As a result a large experimental campaign has been developed in the WindEEE Dome at Western University, Canada, which is the subject of this thesis.

7.1 Summary of the results

The experimental investigation at the WindEEE Dome has aimed at drawing a clear picture of the physics and dynamics of the downburst phenomenon, and of its evolution in space and time. The complexity of the study of thunderstorm winds, from a physical point of view, in fact, comes from the highly three-dimensional nature of the phenomenon. The overall outflow field near the ground level is indeed the superposition of several contributions that take place from the cloud level down to the ground. Among these, the most influent contributors can be identified as follows: (i) the downdraft, i.e. the descending column of air originate from the cumulonimbus (parent) thunderstorm cloud; (ii) the background, or low-level, horizontal atmospheric boundary layer (ABL) wind; (iii) the translation of the parent cloud releasing the downdraft. Most of the experimental, numerical and analytical models on downbursts in literature neglect these interactions or treat them in an oversimplistic way through a vector superposition. WindEEE Dome has the unique capability of reproducing these three components independently and simultaneously. The downdraft is created through an impinging jet that runs through a bell mouth installed on the ceiling of the main chamber; the background ABL wind is launched through the so-called 60-fan wall, i.e. a matrix of 4x15 fans installed on one of the six peripheral walls of the hexagonal testing chamber; the translation of the thunderstorm cloud can be simulated by inclining the louvres at the bell mouth level, or in other terms the jet-axis itself, to a non-vertical angle. This creates an asymmetric (elliptical) outflow at the ground as observed in full scale occurrences when the storm is actually moving while releasing the downdraft (Byers and Braham, 1948; Fujita, 1985).
In agreement with a vast literature (e.g., Chay and Letchford, 2002; Kim and Hangan, 2007; McConville et al., 2009), it is found that the maximum horizontal velocities occur around the location $r/D = 1.0$, where $r$ is the radial distance from the jet touchdown and $D$ is the jet diameter. The downward-directed flow that exits from the outlet section, i.e. bell mouth at the ceiling level, is subject to a strong flow instability with the surrounding calm environment (i.e., Kelvin-Helmoltz instability). This causes the formation of ring vortices that travel downwards and, after the impingement on the ground, change the flow momentum from vertical to horizontal, and expand symmetrically in the radial direction. The first of these vortices is called “primary vortex” (PV) and is the one responsible for the maximum velocities in the radial-expanding outflow occurring between the vortex lower end and the ground (Goff, 1976; Hjelmfelt, 1988; Lombardo et al., 2014). This gives rise to the well-known and established nose-like shape vertical profile of the horizontal velocity. The subsequent vortices, so-called “trailing vortices” detach from the outlet section with a quasi-constant frequency. At the outflow stage of the phenomenon in the near-ground region, the PV is often preceded by the formation of the secondary vortex SV. This latter is, in fact, generated by the air pushed outwards by the approaching PV and by the viscous effects that arise at the ground. The formation of the SV in our experiments is observed from $r/D = 1.2 - 1.4$ outwards and is responsible for the increase of the height of the surface layer above the ground. The surface layer so formed is thus divided into two portions, inner and outer layers, respectively dominated by the SV and PV. In this first stage of the recording of the horizontal outflow, the maximum wind speeds occur at the boundary between the two vortices and the shape of the interface between the layers produce also a rather strong upward component, indeed recorded by the measuring instruments.

The height of maximum velocity is observed to decrease drastically in correspondence of the passage of the PV, which constrains the horizontal flow underneath its structure. The turbulence intensity profiles show a significant peak right before that of the horizontal velocity. The same observations are found in full scale investigations (Zhang et al., 2019; Chapter 6) and question the usual hypothesis made in literature of time-stationarity of the turbulence component. This non-stationarity appears even more evident in our experiments compared to the real case due to the different Reynolds Numbers $Re$ involved, which are in the order of $10^6$ at the WindEEE Dome and $10^9$ in full scale. The experimental environment is therefore much less turbulent, and the non-stationarity of the turbulence component appears thus very much enhanced. In analogy to the velocity profiles, the height of maximum turbulence intensity is observed to change drastically in correspondence of the passage of the PV, or in other terms of the occurrence of the maximum velocity. Contrary to the velocity profile evolution, however, the height of maximum turbulence switches from the lower to the higher heights due to the increase of the surface layer due to the formation of the SV ahead of the PV.
When the downburst is released into the already developed ABL-like flow (Chapter 3), the interaction at the boundary between the opposite-directed flows creates an augmentation of the horizontal velocities in the outflow. At the rear-wind side of the outflow the ABL flow and the radially advancing PV have the same vorticity sign (i.e., circulation). This causes the ABL flow to entrain into the primary vortex structure and, consequently, the internal rotational speed of PV to increase which, in turn, increases the horizontal velocities at the boundary between its structure and the ground. At these locations, it is found that the height of maximum wind speed increases compared to the case of isolated vertical downburst. Because of the impact of the ABL on to the PV structure, this latter rises above the surface. At the higher heights, however, the downburst outflow does not seem to sense the influence of the ABL and behaves similar to what observed in the isolated case. On the other hand, however, the counter directed ABL wind hinders the radial advancement of the overall outflow structure. On the other side of the domain of measurements, i.e. forward downburst region, the ABL and downburst outflow are now directed towards the same end while the circulation of the two is opposite. The ABL here acts more as a horizontal force to the descending column of air, i.e. downdraft, and somehow tilts the jet at the ground. The jet touchdown is thus located downwind beyond the position $r/D = 0$, namely the geometric touchdown position of the isolated vertical-jet case, and the outflow structure itself results speeded-up at the forward-wind side. The opposite circulation of the two systems in this region may cause the ABL to act as a downward force on the developing outflow and, therefore, the height of maximum velocity is not observed to rise over the ground. The drastic change in the vertical profile appears here much more pronounced. The ABL logarithmic-like profile, indeed, is replaced by a nose-like shape profile with tip close to the ground in correspondence of the passage of the PV.

The inclination of the jet at the ground (Chapter 4) produces, as hypothesized, an asymmetric horizontal outflow with elliptical shape. The forward side of the downburst intensifies while the back side weakens. The incoming ABL-like flow at the rear of the downburst and its inherent circulation, does not provoke the same effect of flow intensification observed in the case of vertical jet. In fact, in this situation, the PV at the rear side loses its symmetric and coherent structure needed for the ABL entrainment. The maximum horizontal velocities develop at the forward side following the inclination of the jet axis. Furthermore, in this region the height of maximum horizontal wind speed increases above the ground due to the upward flow momentum generated by the jet inclination.

Overall the turbulence intensity shows values in good agreement with the full scale investigations on large sets of downburst records (Solari et al., 2015; Zhang et al., 2018, 2019) and also in relation to the downburst vertical profile (Chapter 6). The same pattern of the height of maximum turbulence is found among all cases. In analogy to real downburst occurrences, the reduced turbulent fluctuation is found to be stationary, with approximately zero mean and unit standard deviation. Concordantly to the analyses on synoptic ABL
winds, as well as to previous investigations on downburst winds both in full scale (Holmes et al., 2008; Solari et al., 2015; Burlando et al., 2017) and at the WindEEE Dome (Junayed et al., 2019), the power spectral density (PSD) of the reduced turbulence is found to follow the law $n^{-5/3}$, where $n$ is the frequency, at the high frequency end of the spectra.

7.2 Conclusions

For the first time, the downburst phenomenon has been experimentally characterized in its complete and complex dynamic behavior in the spatiotemporal domain. The limited spatial dislocation of measuring instruments in nature does not allow to fully comprehend the dynamics of the phenomenon. This thesis serves as a basis to understand the physical behavior of downburst winds that hides behind the full scale anemometric measurements. The behavior of the slowly-varying wind speed is outlined in detail and can be considered as a reference for wind engineering applications and for the dynamic response of structures to this extreme wind system. The qualitative comparison with full scale occurrences of downbursts from anemometric records (Solari et al., 2015; Zhang et al., 2018, 2019) and from LiDAR Wind Profilers installed in the Northern Tyrrhenian Sea (Chapter 6) corroborates the analyses done in the course of the present thesis. The nose-like shape of the vertical profiles appears evident during the most intense phases of the phenomenon in both scenarios, full scale and experimental. The wind vertical profiles acquired from LiDAR recordings show that the PV can be sometime preceded by the SV. Also, the turbulence intensity shows analogous and non-stationary trends between the real and modeled occurrences.

On the other hand, there are surely factors that, at first sight, partly limit the applicability to the full scale scenario. Downburst-like winds at the WindEEE Dome are created through the impinging-jet technique, which does not consider the thermal effects that cause the actual development of the storm in nature and the vertical downward motion of the cold air from the parent cloud to the ground due to buoyancy effects. However, from a wind engineering perspective, the outflow field generated by the jet impingement on the ground reproduces faithfully what observed in full scale.

The ABL-like flow at the WindEEE Dome is not naturally developed, as in classic boundary layer (BL) wind tunnels, but rather mechanically produced by imposing different intensities of the fans at the 60-fan wall. The generated ABL wind profile is not perfectly adherent to the standard logarithmic ESDU profiles. However, Romanic and Hangan (2020) proved that the unstable atmospheric conditions in which the thunderstorm downburst develop in nature produce a different shape of the ABL profile, which detaches from the logarithmic shape, and closely matches that recreated at the WindEEE Dome.

Despite the large geometric scales achieved at the WindEEE Dome, the Reynolds Numbers $Re$ involved in the experiments are still far from those experienced in nature (see above). However, we can say that WindEEE Dome is likely the laboratory that approximates at the closest the geometric, kinematic and
dynamic parameters observed in the full scale scenario. Chapter 2 discusses the open question of the downburst geometric scaling, which is largely dependent on the parameters chosen to downscale the phenomenon to the laboratory environment and, in turn, to the availability of these parameters from full scale measurements. However, as seen in Chapter 3, the possible scales of downburst and ABL flows at WindEEE Dome are rather coherent. In the vertical two-dimensional plane, in fact, the height of the atmospheric boundary layer (ABL) and primary vortex (PV) core can be hypothetically assumed to have the same order of magnitude in both full scale and WindEEE experimental scenarios.

7.3 Future prospects

The present thesis is part of the project THUNDERR (Figure 1.11), “Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures” (PI Prof. Giovanni Solari), awarded with an ERC Advanced Grant 2016. The project provides two other complementary approaches to the problem in respect to the experimental investigation presented in this thesis. Namely, the downburst phenomenon is studied through Computational Fluid Dynamics (CFD) tools (Zuzul et al., 2019) and analytical modelling. Currently, the former is assessing the validity of the URANS (Unsteady-Reynolds-Averaged-Navier-Stokes) and LES (Large-eddy-simulation) simulations by reproducing the experimental scenario investigated at the WindEEE Dome. In a second stage, CFD simulations will be used to assess the full scale occurrences of the downburst phenomenon and set themselves as a powerful tool to understand, from another point of view, the dynamics and evolving characteristics of the storm. On the other hand, analytical investigations are on-going to determine solutions able to describe the behavior of the thunderstorm wind in terms of geometric, kinematic and dynamic parameters (Xhelai et al., 2020). Indeed, the combination of these three high-performant tools will lead to build a unique and state-of-the-art model to evaluate the downburst characteristics of interest for wind engineering purposes, such as the space and time evolution and intensity of the horizontal wind speed vertical profiles and of the turbulence features. In this framework, the experimental analyses are still on-going. In the last months a new set of experiments have been carried out at the WindEEE Dome, taking advantage of the use of Particle Image Velocimetry (PIV) technique to obtain a comprehensive understanding of the interaction between downburst outflow and ABL wind. Several horizontal planes of measurement have been investigated on the chamber with a wide spatial and adequate time resolutions to study the behavior and evolution of the interface between the opposite directed downburst and ABL winds. This will certainly provide further insight on the transient physical behavior of the flow in the area subject to the interplay and mix between the two wind systems. Furthermore, experimental testing at the WindEEE Dome has also regarded the investigation of the effects of the roughness length on the development of the downburst outflow. In particular, three different surfaces were tested in the chamber to observe the degree of dependence of the transient wind profiles from the
roughness of the surface. The results of these on-going analyses fall inevitably outside the content of this thesis and will be released soon with future publications. A future decisive step will be the applicability of the outcomes of all these heterogeneous analyses described above, and eventual downburst model, to study the dynamic response of structures to the phenomenon. In this regard, a branch of the THUNDERR Project is already currently devoted to the analysis of the dynamic behavior of structures through empirical formulations, such as the Evolutionary Power Spectral Density model (Roncallo and Solari, 2020), and mixed empirical-experimental approaches that consider the susceptibility of structures and aeroelastic phenomena that arise due to the strong accelerations inherent in the downburst wind speed records (Brusco and Solari, 2021) and to the rapid change of the wind direction (Brusco et al., 2019) in correspondence of the passage of the front. On the other hand, once the phenomenon is fully understood in its complexity and dynamics, the same experimental and numerical simulations described above may also involve structural scaled models to study the actions and effects due to the non-stationarity and highly transiency of the storm. In this sense, a key role will be played by the quantitative, and not only qualitative, comparisons of our experimental results with the full scale outcomes from large set of real downburst events. The last ten years have seen the emergence of new and innovative measuring instruments, which do not provide a single unique measurement in the space but investigate a wider field. Especially, the recent installation of three LiDAR Wind Profilers (Chapter 6) in the ports of Genoa, Savona and Livorno and a LiDAR Scanner in the port of Genoa, as part of the large anemometric network deployed in the main ports of the Northern Tyrrhenian Sea within the European projects “Wind and Ports” (WP, Solari et al., 2012) and “Wind, Ports and Sea” (WPS, Repetto et al., 2018), has provided a fundamental contribution towards this direction. The LiDAR Wind Profiler is, in fact, capable of measuring simultaneously at 12 heights above the ground level, from 40 to 250 m, and thus to reconstruct the wind vertical profile. On the other hand, and in addition to this, the LiDAR Scanner can perform horizontal scanning of the atmosphere at four elevation angles, from 2.5° to 10°, and with a very wide spatial resolution. It will be possible therefore to detect several parameters of absolute importance in the real downburst occurrence, such as the downburst diameter and the horizontal extent of the outflow, as well as the track of the space and time evolution of the phenomenon. The comparison with the outflow fields obtained from experimental campaigns will allow to find a match in the view of building an experimental model capable of characterizing the complete occurrence of the downburst event, as mentioned above, and to validate the goodness of the experimental simulations to be eventually refined with the input of new full scale data from these innovative measuring systems. The idea behind the whole project is that different wind phenomena cannot be treated under a unique wind loading combination rule when applying the structural codes at the design stage. In fact, as mentioned in Chapter 1, the methods currently applied to determine the wind actions on structures are still referred to the
synoptic-scale extra-tropical cyclones that strike mid-latitude areas (Davenport, 1967). There are several
decisive inputs that, only recently, have been changing the classical view of the wind engineering
community on this matter (Solari et al., 2020): (i) different wind events are indeed endowed with different
velocity profiles; (ii) different phenomena are characterized by different parametrization rules for roughness
length, topography and thermal stratification that lead to different transferring tools from one site to another;
(iii) The different stationary/non-stationary and Gaussian/non-Gaussian character of the wind speed leads
to different structural responses; (iv) the application of directional coefficients calibrated for depressions to
thunderstorms distorts reality and forces the application of related concepts and rules outside their correct
domain; (v) different wind events have different distributions, extensions and durations.

The Independent Wind Loading Technique (IWLT), proposed by Prof. Solari, overcomes all the above
remarks without modifying the spirit of the engineering models and regulatory schemes currently in use.
Furthermore, it can be easily generalized to any wind loading mechanism (tornadoes, tropical cyclones,
downslope winds, intermediate events, …), simply adding each of these as a new independent wind loading
condition.

Therefore, the ultimate goal of the THUNDERR Project is indeed to combine the outcomes of the vast set
of heterogeneous analyses mentioned above on downburst winds to define a separate, independent wind
loading technique for thunderstorms to implement the design codes for the wind loading and response of
structures.

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