# Mixed Climatology, Non-synoptic Phenomena and Downburst Wind Loading of Structures

G. Solari(✉)

Department of Civil, Chemical and Environmental Engineering (DICCA),
Polytechnic School, University of Genova,
Via Montallegro, 1, 16145 Genoa, Italy
giovanni.solari@unige.it

**Abstract.** Modern wind engineering was born in 1961, when Davenport published a paper in which meteorology, micrometeorology, climatology, bluff-body aerodynamics and structural dynamics were embedded within a homogeneous framework of the wind loading of structures called today "Davenport chain". Idealizing the wind with a synoptic extra-tropical cyclone, this model was so simple and elegant as to become a sort of axiom. Between 1976 and 1977 Gomes and Vickery separated thunderstorm from non-thunderstorm winds, determined their disjoint extreme distributions and derived a mixed model later extended to other Aeolian phenomena; this study, which represents a milestone in mixed climatology, proved the impossibility of labelling a heterogeneous range of events by the generic term "wind". This paper provides an overview of this matter, with particular regard to the studies conducted at the University of Genova on thunderstorm downbursts.

**Keywords:** Downburst · Extra-tropical cyclones · Mixed climatology · Non-synoptic phenomena · Thunderstorm outflows · Wind loading of structures

## 1 Introduction

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". The International Association for wind engineering (IAWE) promotes international co-operation among scientists, engineers and professionals for advancement of knowledge in the broad field of wind engineering (Solari 2007).

The process that transformed a set of distinct topics related to wind into a homogeneous discipline originated in the first half of the 20th century from a series of studies on the wind loading of structures. Pagon (1934, 1935) published eight papers on Engineering News Records that transferred a synthesis of the knowledge in meteorology and aerodynamics to civil engineering. Karman (1948) delivered a lecture at the Société des Ingenieurs Civils de France in which he described many applications and perspectives of aerodynamics in the engineering and industrial fields. Davenport (1961) published a paper that represented a constitutive deed for wind engineering, where meteorology, micrometeorology, climatology, aerodynamics and structural dynamics were embedded into a homogeneous framework of the wind loading of structures.


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This scheme, known as "Davenport chain", opened unlimited prospects to the comprehension and calculation of the dynamic response of structures creating, since then, a growing interest of structural engineering towards this matter.

In the meanwhile this paper was a sort of straitjacket in which wind engineering was trapped. The wind model conceived by Davenport referred to an extra-tropical cyclone at synoptic scale. In such framework the mean wind velocity, dealt with as horizontal, was characterized by a vertical profile in equilibrium with an atmospheric boundary layer whose depth is about 1–3 km; here, within time intervals between 10 min and 1 h, the turbulent field was considered as stationary and Gaussian. This model was so simple and elegant as to become, in the course of the years, an axiomatic base to which wind engineering was often inspired in an uncritical way.

Curiously, Davenport (1968) himself published another fundamental paper in which a prophetic viewpoint on intense local storms was provided: "In certain parts of the world it appears that a significant proportion of maximum gusts arise from thunderstorms. (…) These storms may last 5–10 min and subside rapidly during which time severe convective turbulence may induce strong gusts. From the design point of view, the question is probably best treated by adopting an approach in which the mean velocities are obtained for intervals short enough to reflect the higher winds prevalent in the thunderstorm (…). Eventually, it may be possible to treat thunderstorms separately and (…) prove important design accordingly."

These concepts were taken up by Gomes and Vickery between 1976 and 1978. They carried out a study of the extreme wind speed in Australia (Gomes and Vickery 1976), in which they separated thunderstorm from non-thunderstorm winds, determined their disjoint extreme distributions and derived a mixed statistical model later extended to other Aeolian phenomena (Gomes and Vickery 1977/1978). Far beyond their separation for statistical purposes, it stated the impossibility of labelling their whole with the generic term "wind". Many of them - tropical cyclones, tornadoes, monsoons and down-slope winds - occur in relatively small and well-known areas. Extra-tropical cyclones and thunderstorms affect all countries at the mid-latitudes.

This paper provides a short introduction to thunderstorms and downbursts in the framework of mixed climatology and non-synoptic phenomena (Sect. 2), an overview of the studies developed world-wide (Sects. 3–7), and a brief illustration of the research projects carried out at the University of Genova (Sect. 8). In the light of the huge amount of papers in this field, the references furnish a limited and non-exhaustive panorama.

## 2 Thunderstorms and Downbursts

The attention of mankind for thunderstorms dates back to antiquity. Anassimandro of Mileto (610–546 B.C.) argued in *Della Natura* that "thunders in thunderstorms are due to the shear among clouds". Similar concepts were exposed by Lucius Anneus Seneca in *Les Quaestiones Naturales* (41 A.D.), where he wrote that "both wind storms and thunderstorms have their origin in clouds that burst or explode".

After writing *Discourse concerning the origins and properties of wind* (1671) Ralph Bohun discussed the formation of storm clouds and their ability to produce "violent air explosions that are almost perpendicular to earth". James Pollard Espy published *The Philosophy of Storms* (1840), claiming that "as soon as clouds begin to form, the latent heat liberated from condensation originating from a violent expansion of the air, that is, a wind storm". William Ferrell first illustrated the occurrence of an ascending current, its rising energy and condensation, the copious precipitations, and the appearance of a descending current in *A popular treatise on the winds* (1889).

In 1925, public opinion was troubled by the crash in U.S. of the Shenandoah Airship during a thunderstorm, which caused the death of many passengers. This disaster favoured the development of a vast literature, also stimulated by the awareness that a better knowledge of thunderstorms would have had a strategic importance for the growth of civil aviation and for the evolution of war strategies.

This led to several projects among which Thunderstorm Project (1946–1949) that gave rise to the first modern model of a thunderstorm (Byers and Braham 1949). It is a mesoscale phenomenon that develops in a few kilometres on the horizontal and consists of a set of cells that evolve through three stages in about 30 min: the cumulus stage, due to convective unstable phenomena, originates an updraft of warm air that gives rise to a large size cumulus; the mature stage, in which the cumulus becomes a cumulonimbus and, while the updraft is still present, a downdraft of cold air occurs; and the dissipating stage, in which the thunderstorm is first dominated by the downdraft, then it losses force and disappears.

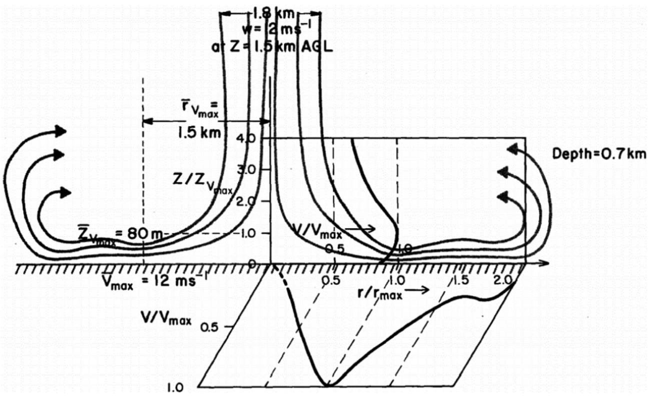


**Fig. 1.** Thunderstorm downburst and nose velocity profile in the radial outflow (Goff 1976)

Fujita (1985, 1990) contributed to the knowledge of thunderstorms showing that the downdraft that impinges over the ground produces radial outflows and ring vortices. The whole of these air movements was called downburst and was divided into macro- and micro-burst depending on size. Their knowledge was supported by three projects - NIMROD (1978), JAWS (1982) and MIST (1986) - which provided an unprecedented amount of data. On the one hand, they showed that the radial outflows of a downburst are non-stationary velocity fields with a "nose profile" that increased up to 50–100 m height, then decreased above (Fig. 1). On the other hand, they generated an extraordinary fervour of research in atmospheric sciences, focusing on the causes, morphology and life-cycle of thunderstorms (Goff 1976; Hjelmfelt 1988).

In the same period, wind engineering realized that the design wind speed is often due to thunderstorm outflows and they therefore have a focal role in structural safety (Letchford et al. 2002). Hence, a striking research arose in five main themes (Solari 2014): (1) wind statistics, precursors and climate change; (2) wind detection and measurements; (3) wind modelling and simulation; (4) wind loading of structures; (5) wind-excited response.

Despite this reality this matter is still dominated by huge uncertainties and there is not yet a shared model for thunderstorm outflows and their actions on structures like the one formulated by Davenport (1961) for synoptic cyclones. Yet, there is no rational framework in which the wind actions due to cyclones and thunderstorms are embedded. This happens because the complexity of thunderstorms makes it difficult to establish physically realistic and simple models. Their short duration and small size make a limited data available. The gap between wind engineering and atmospheric sciences exacerbates this reality.

## 3 Wind Statistics, Precursors and Climate Change

Taking a leaf from the papers by Gomes and Vickery (1976, 1977/1978) the study of the extreme wind speed in thunderstorm outflows and mixed climates was prosecuted by Riera et al. (1977), Riera and Nanni (1989), Twisdale and Vickery (1992), Lombardo (2014), and Mohr et al. (2017).

The role of the downdraft size and of the touch-down position in the probability of occurrence of a downburst at a point or along a line, in particular a transmission one, was examined first by Oliver et al. (2000) and by Li (2000).

The extraction and classification criteria for separating thunderstorm from non-thunderstorm winds without making recourse to a systematic survey of the weather scenarios in which storms occur was elucidated by Kasperski (2002) and Lombardo et al. (2009), who implemented semi-automated procedures to carry out this delicate but essential operation.

A lot of research has been also devoted to precursors or indexes (Lifted Index, Showalter Index, Total Totals, K Index, SWEAT, Bulk Richardson number, CAPE, WINDEX) that may provide elements to identify the weather conditions in which the probability of occurrence of thunderstorms increase (McCann 1994; Haklander and Van Delden 2003).

Of course, climate changes play a crucial role in all the above topics. In a field still dominated by many uncertainties and diversity of viewpoints (Marsh et al. 2009; Nissen et al. 2014; Púcik et al. 2017), the opinion that thunderstorms and downbursts are increasing in frequency and intensity seems to be quite shared.

## 4 Wind Detection and Measurements

The study of the phenomenology of thunderstorms and of their wind fields received great impulse from the evolution of the detection and measurement systems - mainly anemometers installed on antenna masts, radar Doppler, LiDAR, and aircrafts instrumented for meteorological surveys. After the pioneering monitoring campaigns carried out for the projects NIMROD, JAWS, and MIST (Fujita 1990), the literature on this topic exhibited two complementary pathways.

On the one hand, a research line was developed, of meteorological imprint, which studies the causes, morphology and life-cycle of thunderstorms also with regard to their classification (Goff 1976; Fujita and Wakimoto 1981; Hjelmfelt 1988; Gunter and Schroeder 2015).

On the other hand, in a typical wind engineering spirit, there was a proliferation of measurements and interpretations of downburst according to signal analysis and models providing key elements for the wind loading of structures (Choi and Hidayat 2002a; Choi 2004; Chen and Letchford 2007; Duranona et al. 2006; Holmes et al. 2008; Lombardo et al. 2014).

## 5 Wind Modelling and Simulation

The modelling and simulation of downbursts is carried out by laboratory tests, CFD simulations, analytical methods and Monte Carlo techniques.

### 5.1 Laboratory Tests

Laboratory tests may be classified in three main families involving fluid release method, impinging wall jet technique, and the use of modified or new facilities.

The first family, pioneered by Lundgren et al. (1992) and Alahyari and Longmire (1995), involves the release of a liquid mass into a body of less dense liquid; this simulates the effects of buoyancy and produces a ring vortex, favouring the study of the morphology and of the physics of downbursts. It is limited to small geometric and velocity scales, not suitable to determine the wind loading of structures.

The second family involves a jet that impinging on a flat surface creates a wall radial outflow. The first impinging wall jet tests were carried out by Bakke (1957) to investigate experimentally the theory formulated by Glauert (1956). Advances in this technique were reported by Poreh et al. (1967), Didden and Ho (1985) and Wood et al. (2001). Chay and Letchford (2002) first studied the downburst by a stationary wall jet simulation, then realized an equipment to reproduce the effects of the downburst translation (Letchford and Chay 2002). Richter et al. (2018) simulated the downburst by embedding the impinging wall jet into a boundary layer flow. Scaling criteria for model experiments and full-scale conditions are discussed by Xu and Hangan (2008) and by McConville et al. (2009).

The third family involves the techniques that modify the traditional axial flow of a wind tunnel in order to simulate the outflow of a downburst. This family includes the pulsed wall jet method (Mason et al. 2005), the stationary and non-stationary slot jet technique (Lin and Savory 2006; Lin et al. 2007), the generation of gust fronts by a multiple fan wind tunnel with individually controlled fans (Cao et al. 2002), and the use of shutter mechanisms (Matsumoto et al. 2007). Hangan et al. (2017) describe some large-scale laboratories recently developed in the wind engineering field, focusing on the simulation of tornadoes and downbursts at the WindEEE Dome.

### 5.2 CFD Simulations

CFD simulations may be classified into three main groups referred to as the full-cloud models, the sub-cloud models, and the impinging wall jet technique.

Full-cloud models simulate the whole region, the life cycle and the microphysical processes involved by thunderstorms. The first ones, appeared in 2-D version in the 1960s (Ogura 1963) and in 3-D version in the 1970s (Steiner 1973), were conditioned by the computational limits and by the scarcity of observed data. The situation improved in the mid '80s, thanks to the evolution of computing power and to first experimental campaigns. Among others, the 3-D model named Terminal Area Simulation System (TASS) (Proctor 1987a, 1987b) and the studies carried out by Hjelmfelt et al. (1989), Knupp (1989) and Straka and Anderson (1993) deserve mention. Nicholls et al. (1993) simulated the actions induced by a downburst on a building by a multi-scale LES 3-D model.

Sub-cloud models waive to simulate the whole thunderstorm to focus on near-ground flow dynamics, i.e. on the domain of major interest for engineering. They are driven by a sort of thermal forcing, imposed under the cloud at an elevated region of the domain, which simulates the microphysical cooling processes. This method, introduced by Mitchell and Hovermale (1977), was developed by Proctor (1988, 1989), Straka and Anderson (1993), Orf and Anderson (1999), Mason et al. (2009), and Vermeire et al. (2011). Orf et al. (2012) pointed out that computational advances will allow the use of full-cloud models also for wind engineering applications.

The impinging wall jet technique replicates the corresponding laboratory tests by CFD simulations. They have similar properties to sub-cloud models because waive to simulate the whole thunderstorm to focus on the near-ground flow field; diversely from sub-cloud models, however, the forcing source is not thermal but mechanical. This method, introduced by Selvam and Holmes (1992), was developed by Wood et al. (2001), Kim and Hangan (2007), and Vermeire et al. (2011). Zhang et al. (2013a, 2013b) carried out systematic comparisons between the results provided by the impinging jet model, the cooling source model and full-scale measurements. Aboshosha et al. (2015) used LES to improve the simulation of turbulence.

### 5.3 Analytical Models

Analytical models get leverage from measurements, experiments and simulations.

They initially applied basic fluid dynamic laws to stationary flows, in order to obtain simplified analytical expressions, independent of time, of the vertical and radial components of the wind velocity. This led to the impinging wall jet (Oseguera and Bowles 1988) and to the vortex ring (Zhu and Etkin 1985; Vicroy 1992) models. Holmes and Oliver (2000) developed the impinging jet model providing a simplified expression of the radial component of the wind speed as a function of the distance from the jet axis and of the time; they also expressed the horizontal velocity as the vector sum of the stationary radial velocity and of the translational or background velocity of the downburst. Abd-Elaal et al. (2013) used a coupled parametric-CFD model to reconstruct downburst age and evolution based on measures.

The turning point in this topic is represented by a paper in which Choi and Hidayat (2002b) expressed the instantaneous wind velocity as the sum of its time-varying mean part, averaged over a suitable moving period, plus a zero mean fluctuation dealt with as a stationary random process. This approach was developed later by Chen and Letchford (2004a, 2007), who expressed the time-varying mean part of the wind velocity as the product of a function depending on space, provided by the previous time-independent analytical models, by a function slowly varying on time; regarding the fluctuation, dealt with as non-stationary, this was given by the product of its time-varying standard deviation by a random stationary Gaussian process with zero mean and unit standard deviation, whose spectral properties were expressed by the classical models adopted for synoptic wind speeds. Huang and Chen (2009) represented the fluctuation by wavelet transforms and evolutionary spectra. Ponte and Riera (2010) merged these models into a Monte Carlo algorithm aiming to provide the distribution of the maximum velocity in mixed climates.

### 5.4 Monte Carlo Techniques

Based on the above analytical models, many papers have been developed to represent or simulate transient wind fields. Wang et al. (2013) conceived a data-driven approach to simulate downburst wind speeds by Hilbert transform, stationary wavelet transform, and Proper Orthogonal Decomposition (POD). Huang et al. (2015) used discrete wavelet transform and kernel regression to infer the time-varying mean and variance of non-stationary wind speeds, respectively. Peng et al. (2017) simulated multi-variate non-stationary wind fields along lines with uniformly distributed nodes, by hybrid stochastic waves and POD factorization.

## 6 Wind Loading of Structures

The study of the wind loading of structures aiming to take into account the transient nature of the oncoming flow field may be framed into two families of methods.

The first one, not strictly related to downbursts and mainly focused on the fundamentals of transient aerodynamics, involves almost exclusively laboratory tests on slender reference elements (Sarpkaya 1963; Katsura 1997; Matsumoto et al. 2007).

The second group, concerning 3-D bluff-bodies, avails itself of laboratory tests, CFD simulations and full-scale measurements. Starting from the pioneering papers by Chay and Letchford (2002) and Letchford and Chay (2002), Sengupta and Sarkar (2008) simulated the wall jet both in wind tunnel and through CFD to determine the wind loading on a cubic building. Zhang et al. (2013a, 2013b, 2014) carried out wind tunnel tests on low- and high-rise buildings, respectively, by the impinging wall jet technique.

## 7 Wind-Excited Response of Structures

The research activity on the wind-excited response of structures to thunderstorm outflows concerns two main topics: idealized reference systems and real structures.

Idealized reference systems are studied, as it is typical of structural dynamics, to formulate general models and to inspect the role of model parameters. Choi and Hidayat (2002a, b) studied for the first the wind-induced response of a Single-Degree-Of-Freedom (SDOF) system to thunderstorm outflows identically coherent in space, in order to generalize the classical gust response factor technique for synoptic events. This approach was developed by Chen and Letchford (2004b), who analyzed a SDOF system through a so-called Maximum Dynamic Magnification Factor, given by the ratio between the maximum value of the dynamic response and the static response to the peak loading, and by Chay et al. (2006), who applied a time-domain approach based on ARMA simulations. Chen (2008) studied the dynamic response of a building to a transient wind field modelled by an evolutionary power spectral density (EPSD). Kwon and Kareem (2009) proposed a gust front factor framework where the original gust response factor technique was generalized from stationary to non-stationary wind actions by an EPSD approach. Le and Caracoglia (2015) adopted the Wavelet-Galerkin method to evaluate the non-linear and/or non-stationary response of SDOF and NDOF systems. Chen (2015) investigated the multimode coupled buffeting response of long-span bridges by EPSD. Wang et al. (2017) studied the buffeting response of a hinged overhead transmission conductor.

The analysis of real structures is mainly addressed to transmission lines and towers, the structural types that suffer the largest damage and collapse due to thunderstorms. In this framework, thunderstorms are often simulated by CFD codes whose output is transformed into aerodynamic loads applied to finite element structural models (Shehata et al. 2005; Darwish et al. 2010). Aeroelastic wind tunnel tests on a transmission line model at the WindEEE Dome are described by Elawadi et al. (2017).

## 8 Thunderstorm Research at the University of Genova

### 8.1 WP and WPS Projects

The research on thunderstorms at the University of Genoa originated from two European Projects - "Wind and Ports" (WP) (Solari et al. 2012) and "Wind, Ports and Sea" (WPS) (Repetto et al. 2017, 2018) - financed by the European Cross-border program "Italy–France Maritime 2007–2013", which handled the wind safe management and risk assessment of the main commercial ports in the High Tyrrhenian Sea. This aim was pursued through an integrated set of tools including an extensive monitoring network made up of 28 ultrasonic anemometers, distributed in the Ports of Genoa (2), La Spezia (6), Livorno (1), Savona (7), Bastia (5) and L'Île Rousse (2), 3 LiDAR wind profilers, and 3 weather stations, each one including another ultrasonic anemometer, a barometer, a thermometer and a hygrometer.

The ultrasonic anemometers detect the wind speed and direction with a sampling rate of 10 Hz with few exceptions. Sensors are mounted on towers and at the top of buildings, at least at 10 m height above ground level (AGL). The LiDAR profilers detect the wind speed at 12 heights between 40 and 250 m AGL, with a sampling rate of 1 Hz. A set of local servers receives the data from its own port area and sends it to the central server in DICCA, where they are checked and stored in a database.

### 8.2 Wind Speed Analysis

The data detected by the monitoring network shows the occurrence of extra-tropical cyclones, thunderstorm outflows and intermediate events. Thus, in order to focus on intense thunderstorm outflows, a semi-automatic procedure was implemented to extract these events (De Gaetano et al. 2014) without carrying prohibitive meteorological surveys. First, 93 transient records were extracted (Solari et al. 2015a). Then, on increasing available data, 247 records labelled as thunderstorm outflows were gathered (Zhang et al. 2018a) and subjected to probabilistic analyses aiming at evaluating their properties relevant to the wind loading of structures.

Later on, in order to inspect and interpret the weather scenarios concurrent with these events, the event occurred in Livorno on 1st October 2012 was chosen as a test case (Burlando et al. 2017) and studies were carried out of its atmospheric conditions by gathering model analyses, standard in-situ data, remote sensing, proxy data and visual observations. This information lead to classify this event as a wet downburst, and to determine its space-time evolution.

Moreover, thanks to the acquisition of over 6-years measurements at some anemometers, estimates of the extreme peak wind speed distribution were carried out (Zhang et al. 2018b). As in many other parts of the world, they show that the most intense wind events in the High Tyrrhenian Sea are due to thunderstorms.

### 8.3 Wind Loading and Response of Structures

Thunderstorms are transient phenomena with short duration and the response to these phenomena, most notably to earthquakes, is usually evaluated by the response spectrum technique. Accordingly, a "new" method was proposed that generalises the "old" response spectrum technique from earthquakes to thunderstorms.

Firstly, this problem was formulated for a point-like SDOF system (Solari et al. 2015b), proving that the equivalent static force is the product of the peak wind force by a non-dimensional quantity, the thunderstorm response spectrum, depending on the fundamental frequency and on the damping ratio.

Then, this method was generalized to a space MDOF system (Solari 2016). The structure was modelled as a slender vertical beam whose response depends on the first mode and the generalised equivalent wind spectrum technique (Piccardo and Solari 1998) was applied to replace the multi-variate wind field by an equivalent mono-variate one. The equivalent static force is the product of the peak wind force by a non-dimensional quantity, the equivalent response spectrum, depending on the first frequency, on the damping ratio and on a size factor.

To check and refine the response spectrum technique, time domain analyses were carried out based on a novel hybrid simulation strategy (Solari et al. 2017), which consists in assembling the various components that make up the wind speed model.

The time-domain integration of the equations of motion shows that the density function of the maximum value of the response to thunderstorm outflows is more spread than that due to synoptic cyclones. Thus, differently from classic wind excitation, it is not appropriate to identify the maximum response with its mean value.

## 8.4 The ERC THUNDERR Project

Realized in an area well-known for its intense convective activity and its dramatic outcomes, the WP and WPS network produced an unprecedented dataset of transient records. This inspired the THUNDERR project - Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures – awarded by an Advanced Grant 2016 of the European Research Council (ERC) under Horizon 2020. It pursues three aims.

The first one is addressed to formulate a unitary model of thunderstorm outflows that may represent a novel result for atmospheric sciences and a sound basis for assessing realistic wind loading of structures. Accordingly, the WP and WPS network will be strengthened through other instruments at the frontier of current technology, large-scale tests will be conducted in the WindEEE Dome at the Western, Ontario (Hangan et al. 2017), CFD simulations will be performed with the Technical University Eindhoven, Netherlands (Blocken 2014), weather scenarios in which thunderstorms occur and their damage will be studied with the Freie Universität Berlin, Germany (Nissen et al. 2014) and with the European Severe Storm Laboratory (Púcik et al. 2017).

The second objective concerns the thunderstorm loading and response of structures. Two anemometer towers and a wind turbine will be equipped by accelerometers and strain-gauges to detect simultaneously wind velocity and response. Time-domain analysis, response spectrum technique and EPSD models will be jointly developed. Wind loading will be separated into two loading conditions, one for cyclones and the other for downbursts. An archive of structure test-cases will be gathered and wind loading will be evaluated by the classical method and by the new loading format in order to inspect the safety and economic impact of this new approach.

The third objective, dissemination, aims to create a vast involvement of the international community and its direct support to the project. An open-website catalogue of thunderstorm outflows will be opened (2018); an International Advanced School (2020) and an International Workshop (2022) on "Thunderstorm outflows and their impact on structures" will be held in Genoa, Italy.

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