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THUNDERR: an ERC Project for the “detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures”

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Abstract

Wind actions are crucial for the safety and cost of structures. The wind climate of Europe and many other parts of the world is dominated by synoptic extra-tropical cyclones and mesoscale thunderstorms. Thunderstorms are frequent events causing wind speeds often higher than cyclones. Despite extensive research, a model for thunderstorm outflows and their actions on structures like that for cyclones is still missing. Thus, thunderstorm actions on structures are mainly determined by the cyclone model developed half a century ago. THUNDERR is a research project funded by European Research Council to detect thunderstorm measures, create a dataset of field data, interpret weather scenarios, conduct wind tunnel and numerical simulations, set a thunderstorm model physically correct and transferable to engineering and standards, modify the existing wind loading format, design safer and cost-efficient structures.

Keywords: Thunderstorms, Detection, Simulation, Modelling, Loading

1 INTRODUCTION

A primary aim of engineering is to pursue the safety and cost-efficiency of structures under natural and anthropogenic actions. Wind is the most destructive natural phenomenon - over 70% of damage and deaths caused by nature is due to the wind - so its actions are crucial for the safety and cost of construction. Their evaluation is thus a societal need for safety and economy.

Figure 1. Synoptic extra-tropical cyclone and mesoscale thunderstorm

The wind climatology of Italy, Europe and many other countries is dominated by extra-tropical cyclones at synoptic scale and by mesoscale thunderstorm outflows (Figure 1). The genesis and evolution of the extra-tropical cyclone have been known since the 1920s. Its actions on construction were framed in the 1960s and engineering still uses such models. The thunderstorm is instead one of the most complex, mysterious and devastating natural phenomena.

The modern study of thunderstorms started in 1946, when Byers and Braham showed that they consist of cells that develop in a few kilometers and evolve in about 30 minutes through 3 stages in which an updraft of warm air is followed by a downdraft of cold air. In the ‘70s and ‘80s Fujita proved that the downdraft that impinges on the ground produces intense radial outflows. The whole of these air motions is called downburst (Figure 2). Differently from synoptic winds, the radial outflows exhibit a non-stationary and non-Gaussian speed with a “nose profile” that increases up to 50-100 m height, then decreases above.

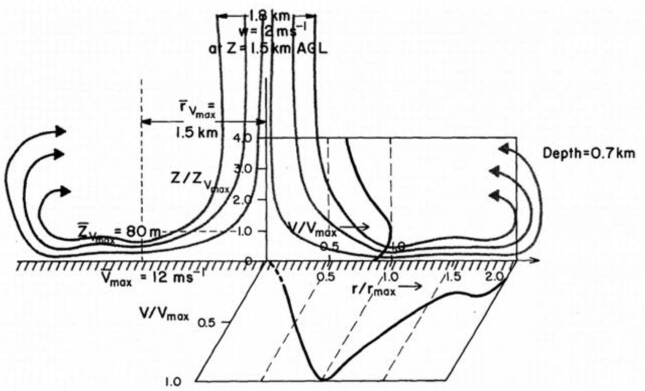

Figure 2. Thunderstorm downburst and nose velocity profile in the radial outflow [1]

In spite of an impressive amount of research carried out in atmospheric sciences and wind engineering in the last 30 years, this matter is still dominated by huge uncertainties, and there is not yet a shared model of the thunderstorm outflows and their actions on structures like that for cyclones. Yet, there is no rational scheme that joins the wind loading due to cyclones and thunderstorms. This happens because the complexity of thunderstorms makes it difficult to establish physically realistic and simple models. Their short duration and small size make few data available. There is a large gap between wind engineering and atmospheric sciences [2].

This shortcoming leads to unsafe and expensive structures. The insufficient safety of light structures with small to medium height is proved by the frequent damage and collapse in thunderstorm days (Figure 3). The excessive cost of tall buildings in areas whose design wind speed is due to thunderstorms comes from using wind speed profiles that grow with the height, while downburst outflows are close to the ground.

Figure 3. Consequences of the downburst occurred in the Port of Genoa on 31 August 1994

2 THE “WIND AND PORTS” AND “WIND, PORTS AND SEA” PROJECTS

“Wind and Ports” (WP) [3] and “Wind, Ports and Sea” (WPS) [4] are two projects financed by the European Cross-border program “Italy–France Maritime 2007-2013”, which handled the wind safe management and risk assessment of the Ports of Genoa, Livorno, Savona and Vado, La Spezia, Bastia and L’Île-Rousse. This aim was pursued by creating an integrated set of tools including an extensive monitoring network (Figure 4), multi-scale simulation models, medium- and short-term forecasting algorithms, statistical analyses and climatological maps. The results are made available to port operators through an innovative Web GIS platform [5].

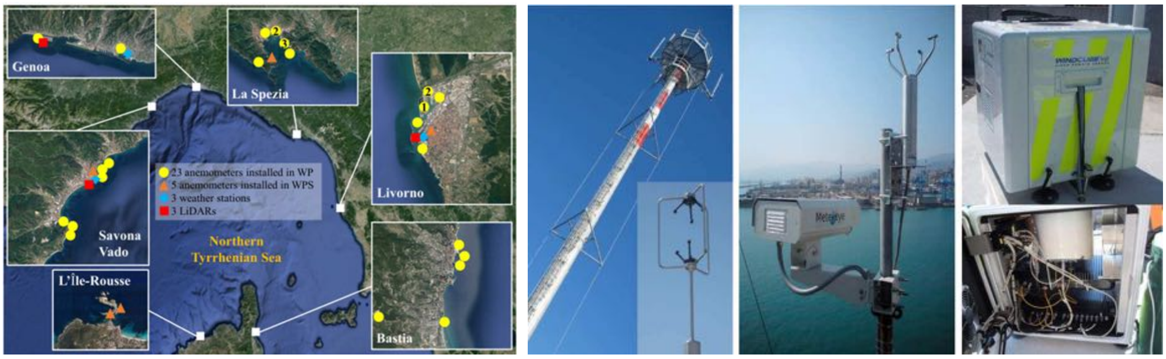

Figure 4. WP and WPS wind monitoring network and sensors

WP created a network made up of 23 ultrasonic anemometers, some of which tri-axial and the other bi-axial, distributed in the Ports of Genoa (2), La Spezia (5), Livorno (5), Savona (Italy) (6), and Bastia (France) (5); the port area of Vado is part of the Port of Savona. WPS enhanced this network by means of 5 new ultrasonic anemometers in the Ports of Savona (1), La Spezia (1), Livorno (1) and L’Île Rousse (2), 3 LiDAR (Light Detection And Ranging) scanners, and 3 weather stations, each including another ultrasonic anemometer, a barometer, a thermometer and a hygrometer. Other sensors installed by single Port Authorities are in the stage of becoming parts of the WP and WPS network.

The ultrasonic anemometers detect the wind speed and the wind direction with a precision of 0.01 m/s and 1 degree, respectively. Their sampling rate is 10 Hz with the exception of one sensor in the Port of Savona, with sampling frequency 1 Hz, and of those in the Ports of Bastia and L’Île Rousse, with sampling frequency 2 Hz. To avoid local effects contaminating the measurements and to register undisturbed wind speeds, the sensors are homogeneously distributed in port areas and mounted on high-rise towers (Figure 4) and on some antenna masts at the top of buildings, at least at 10 m height above ground level. A set of local servers, placed in each port authority headquarter, receives the records acquired by sensors in their own port area, and elaborates basic statistics on 10-min periods, namely the mean and peak wind speed and the mean wind direction. Each server automatically sends this information and the whole raw data recordings to the central server in the Department of Civil, Chemical and Environmental Engineering of the University of Genoa. It performs a preliminary check of the data received and stores it into a database.

3 THUNDERSTORM OUTFLOW WIND FIELD ANALYSIS

The analysis of the data detected by the WP and WPS monitoring network shows the presence of recordings due to wind phenomena of different nature, namely extra-tropical cyclones, thunderstorms outflows and intermediate events (Figure 5). Thus, in order to focus on the study of intense thunderstorm outflows, a semi-automatic procedure has been implemented in order to extract these phenomena [6]. This method generalizes some previous procedures developed and calibrated in order to process a huge amount of data based on few synthetic elements derived from the sole anemometric recordings, without carrying out systematic and prohibitive meteorological surveys of the weather scenarios out of which they take place.

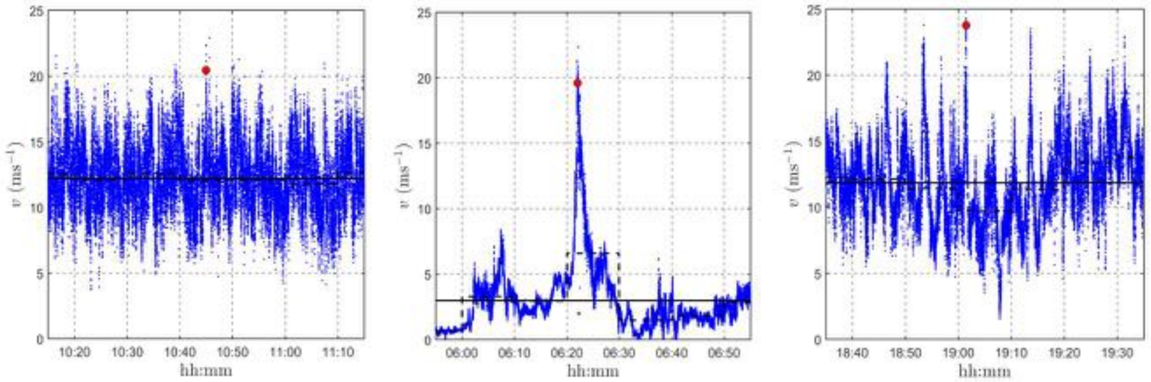

Figure 5. Records of an extra-tropical cyclone, a thunderstorm outflow and an intermediate event

According to this criterion, an extensive set of records labeled as thunderstorm outflows has been gathered and decomposed by means of the following approach (Figure 6). The wind velocity is expressed as the sum of a slowly-varying mean wind velocity with a low frequency content, and a residual fluctuation with a high frequency content. This second quantity is given in turn by the product of its slowly-varying standard deviation by a so-called reduced turbulent fluctuation dealt with as a stationary Gaussian random field with zero mean and unit standard deviation. The ratio between the slowly-varying standard deviation and the mean wind velocity is referred to as the slowly-varying turbulence intensity. The ratio between the peak wind velocity and the maximum value of the slowly-varying mean wind velocity is referred to as the gust factor. All these quantities have been subjected to extensive probabilistic analyses aiming at evaluating their main properties relevant to the wind loading of structures [7, 8].

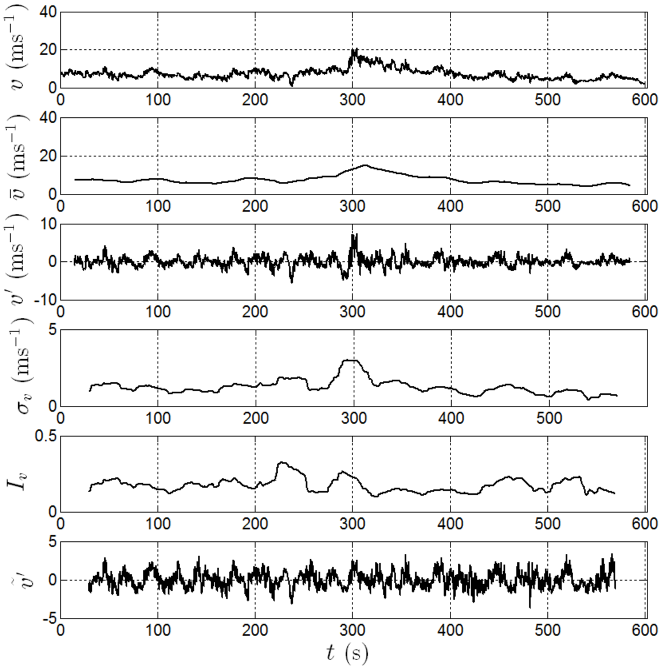

Figure 6. Thunderstorm outflow velocity, mean wind velocity, residual fluctuation, standard deviation, turbulence intensity, reduced turbulence fluctuations

This approach has capability of detecting the presence and the characteristics of thunderstorm outflows based on the sole anemometric measures However, the knowledge of the weather scenarios that occur during these events would be very useful to confirm the meteorological nature of the outflows classified as thunderstorms. In order to make a first step in this direction, the thunderstorm downburst occurred on 1 October 2012 over the City of Livorno, Italy was selected as a reference test case [9]. Detailed analyses were carried out of the wind speed and direction records detected by the WP and WPS network. In parallel, the atmospheric conditions concurrent with this event were studied by gathering all the meteorological data available in this area, namely model analyses, standard in-situ data (stations and radio-soundings), remote sensing (radar and satellite, Figure 7), proxy data (lightning), and visual observations (from European Severe Weather Database). This information lead to reconstruct the weather scenario, to classify this event as a wet downburst, to determine its space-time evolution, and to embed in this framework signal analyses aiming to extract the key parameters for determining the wind loading of structures.

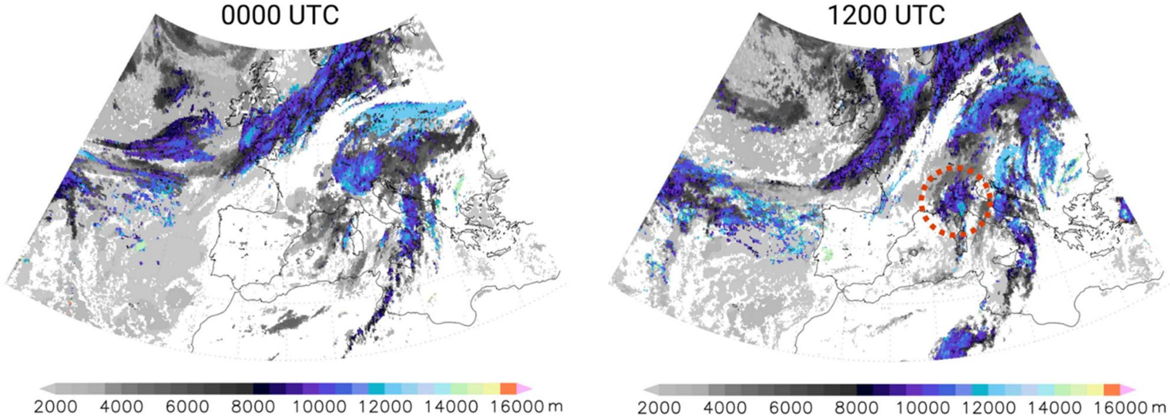

Figure 7. Livorno, 1 October 2012: cloud top height from Meteosat data

Recently, preliminary studies on the vertical profile of the wind speed and direction recorded by the LiDAR wind profilers have been performed [10]. At least for the first thunderstorms examined, they highlight the appearance of the nose-shaped profile of the wind speed for a very short period linked to the ramp-up phase of the wind speed recording (Figure 8).

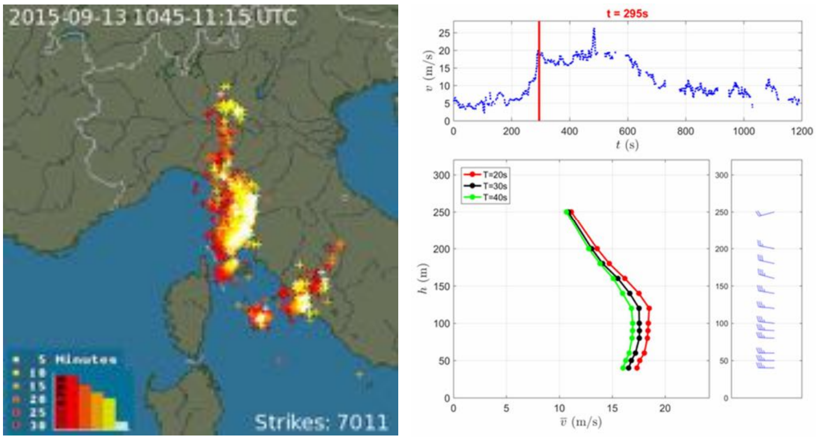

Figure 8. Port of Livorno, 13 September 2015: strikes from 10:45 to 11:15 (courtesy Blitzortung.org); wind speed and direction vertical profiles as detected by the LiDAR

Moreover, relying on the acquisition of over 6-years of measurements at several anemometers of the monitoring network, the first estimates of the extreme peak wind speed distribution have been carried out [11]. In Figure 10, D denotes depressions, T thunderstorms, IN intermediate events, M mixed climate, E ensemble. All the examined data show, for high return periods, a clear prevalence of thunderstorm winds (Figure 9).

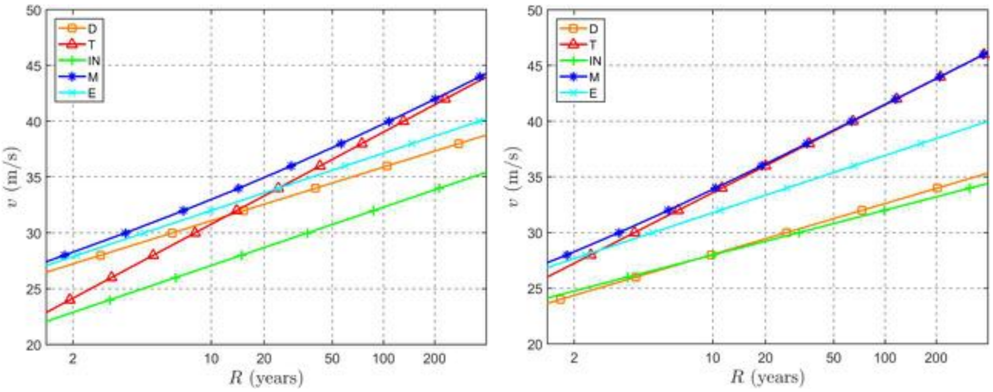

Figure 9. Peak wind speed as a function of the return period for the anemometer 02 of the Port of Livorno and for the anemometer 03 of the Port of La Spezia

4 THUNDERSTORM LOADING AND RESPONSE OF STRUCTURES

The study of the thunderstorm loading and response of structures started from the consideration that thunderstorms are transient phenomena with short duration and the structural response to transient phenomena, most notably to earthquakes, is traditionally evaluated by the response spectrum technique. Based on this remark, a “new” method was formulated to generalise the “old” response spectrum technique from earthquakes to thunderstorms.

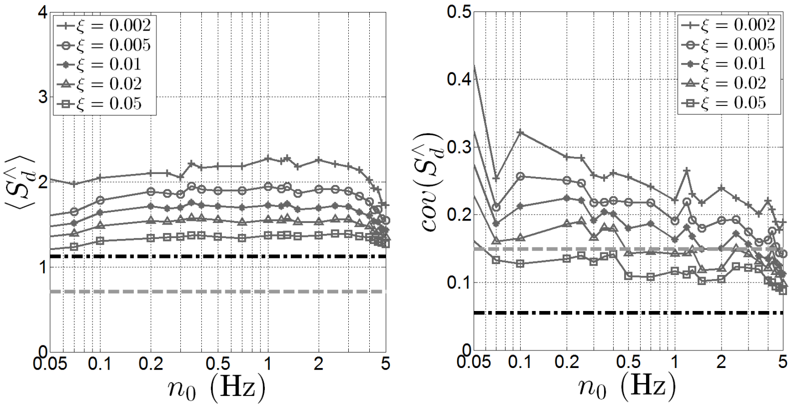

Figure 10. Mean value and coefficient of variation of the thunderstorm response spectrum on varying parametrically the damping ratio

Initially, this problem was formulated with regard to an ideal point-like Single-Degree-Of-Freedom system [12] subjected to perfectly coherent wind actions over the exposed structural surface. It was demonstrated that for such a system the equivalent static wind loading is the product of the peak wind force by a non-dimensional quantity, referred to as the thunderstorm response spectrum, depending on the structural fundamental frequency and damping ratio (Figure 10).

Later on, a paper was published that generalizes this formulation to a real space Multi-Degree-Of-Freedom system [13] subjected to partially coherent wind fields with assigned speed profile and turbulence properties; for sake of simplicity, in this stage of the research, the structure was modelled as a continuous slender vertical cantilever beam whose dynamic response depends on the sole first mode of vibration. Analyses were carried out by making recourse to the equivalent wind spectrum technique [14], a method by which a multi-variate stochastic stationary wind velocity field is replaced by an equivalent mono-variate one. In spite of a rather complex treatment, the use of the thunderstorm response spectrum technique is straightforward: the equivalent static force is the product of the peak wind loading by a non-dimensional quantity, the equivalent response spectrum, depending on the structural fundamental frequency, damping ratio and reference size (Figure 11).

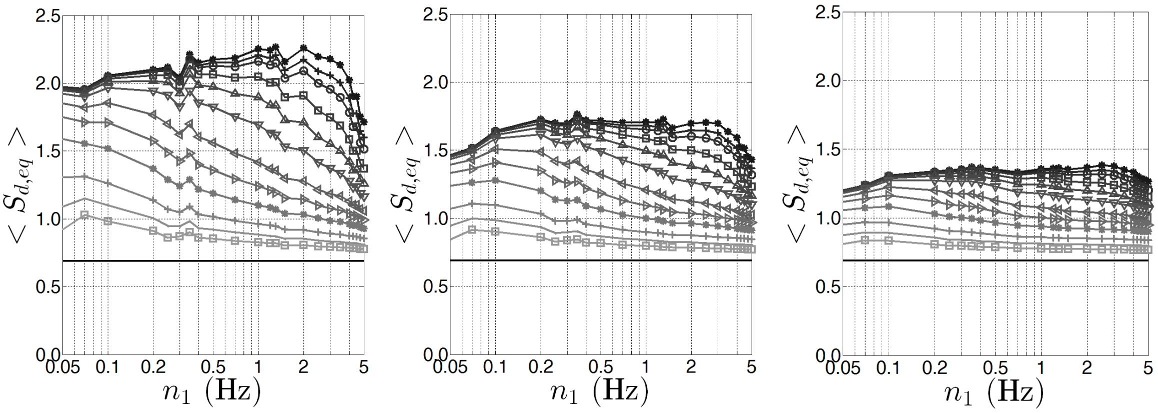

Figure 11. Mean value of the thunderstorm equivalent response spectrum for three decreasing damping ratio and on varying parametrically the reference size of the structure

In order to check and refine the thunderstorm response spectrum technique, time domain analyses have been carried out based upon a novel hybrid strategy aiming to simulate the wind field of thunderstorm outflows [15]. Diversely from the classical Monte Carlo simulations of non-stationary random vectors and from the simulation techniques recently developed with regard to downbursts, the present strategy captures the inherent properties of the thunderstorm outflows by making recourse to simple physical concepts and real velocity records. It consists in assembling the different component signals that make up the wind velocity model, taking into account their inherent sources of randomness (Figure 12).

The time-domain integration of the equations of motion based upon the simulation strategy outlined above shows that the pdf of the maximum value of the structural response induced by thunderstorm outflows is much more spread than that corresponding to synoptic extra-tropical cyclones. Thus, differently from the classic wind excitation it is not appropriate, or at least this results much more approximated, to identify the maximum value of the response with its mean value. On the other hand, the wind loading and the structural response to thunderstorms are qualitatively similar to those experienced with regard to synoptic events. The displacement is almost unaffected by the contribution of the higher modes of vibration. The aerodynamic admittance plays a similar for thunderstorms and cyclones. The resonant part of the response to thunderstorms is slightly lower than that related to synoptic winds but clearly perceivable: in fact, despite thunderstorms are transient events, they do not seem rapid enough as to avoid that structures may achieve relevant resonant oscillations.

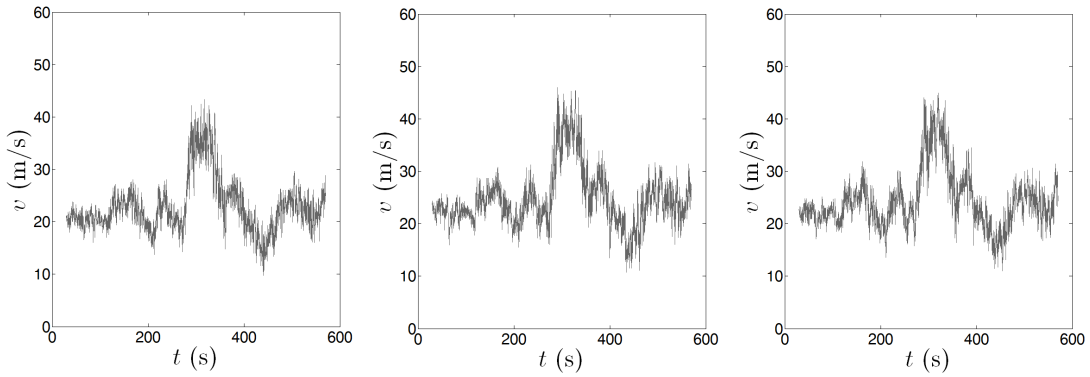

Figure 12. Simulated velocity histories of a thunderstorm outflow at three different heights

5 THE ERC THUNDERR PROJECT

THUNDERR is an acronym of THUNDERstorm that expresses the Roar with which this project aims at creating innovation at the frontier of the state-of-the-art. It pursues 3 objectives.

The first objective concerns the thunderstorm as a physical phenomenon. It aims to formulate a unitary and interdisciplinary model of downburst, with the dual prospect of constituting an innovative result for atmospheric sciences and a basis for realistic wind engineering assessments of thunderstorm outflow actions on structures. This aim will be pursued by strengthening the WP and WPS monitoring network by new instruments at the frontier of current technology, creating a database of measurements open to international scientific community, conducting large-scale experiences in the WindEEE Dome at the University of Western Ontario, Canada (UWO) (eee.windeee.ca) (Figure 13) and smaller scale ones in other laboratories, performing numerical CFD simulations (Figure 14) in collaboration with the Technical University Eindhoven, The Netherland (TU/e) (www.urbanphysics.net), calibrating the results obtained by means of field measurements (Figure 15), studying the weather scenarios in which thunderstorms occur and their damage in collaboration with Freie Universität Berlin (www.geo.fu-berlin.de/met/ag/clidia), Germany and the European Severe Storm Laboratory (www.eswd.eu). Research will also be carried out to identify the precursors of thunderstorms and the effects of climate changes.

Figure 13. Wind tunnel simulations at WindEEE, UWO (courtesy Prof. Horia Hangan)

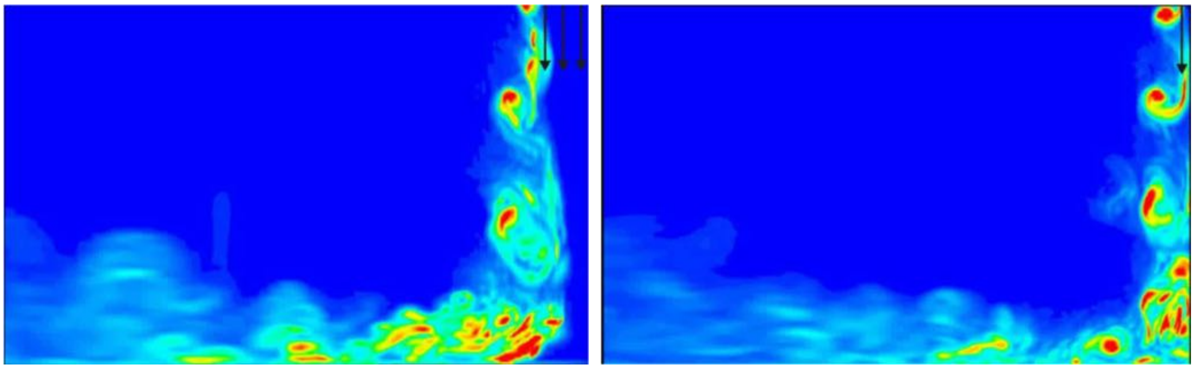

Figure 14. LES simulations at TU/e (courtesy Prof. Bert Blocken)

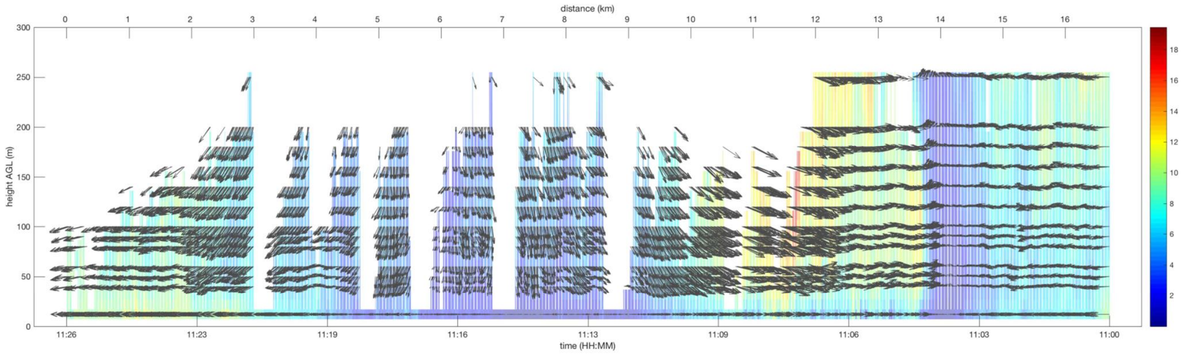

Figure 15. Full-scale wind field as detected by a LiDAR profiler, WS and WPS network

The second objective concerns the thunderstorm loading and response of structures. Two towers will be equipped by anemometers, accelerometers and strain-gauges. This monitoring activity will provide simultaneous measures of the outflow velocity and structural response. Three complementary methods will be set to evaluate equivalent static loading: time-domain analysis, response spectrum technique and evolutionary spectral method. Closed form solutions will be pursued. The classical unique wind loading will be separated into two loading conditions for cyclones and thunderstorms, producing a novel set of partial and combination factors for thunderstorms. Research will be carried out to merge this new philosophy into performance-based design. An archive of structure test-cases in different wind climates will be gathered. Equivalent static wind loading will be evaluated by the classic method and the new loading format. Additional costs and savings due to changes involved by the new method will be estimated. Structures and climates for which classic analyses lead to unsafe design or excessive caution will be identified. Conditions where damage and collapse occurred will be investigated to ascertain the presence of thunderstorms. Global economic analyses will be conducted per classes of structures and climates in order to evaluate the global impact of new loading format.

The third objective concerns dissemination and will be conducted by classical tools such as publications, conference presentations, and a dedicated project website. In addition, some new ideas will be implemented aiming to create a vast involvement of the international scientific community and, even more, a direct support of this same community to the project itself; these activities will be carried according to three pathways: An open-website catalogue of thunderstorm outflows will be created (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; International Awards for research activities and master theses linked to this project will be awarded (2022). It is also planned the launch of three international co-operation projects: a comparative study of the thunderstorm outflows as measured in various parts of the world; a comparison of physical and numerical simulations of thunderstorms and their calibration by means of field measurements; the evaluation of thunderstorm loading and response on two benchmark structures, e.g. transmission lines, communication towers and container cranes.

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