# THE NEW PARADIGM OF THUNDERSTORM DOWNBURSTS FOR SAFE AND SUSTAINABLE DEVELOPMENT

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## ABSTRACT

The wind climate of many parts of the world is dominated by synoptic extra-tropical cyclones and mesoscale thunderstorm downbursts. Thunderstorms are frequent phenomena that cause wind speeds and damage often greater than those due to synoptic cyclones. This new paradigm of wind engineering gave rise to a recent burst of research despite which there is not yet a model of thunderstorms and their loading of structures like the one developed for cyclones in the early 1960s and still in use in engineering practice. THUNDERR is an ERC project that pursues three objectives: 1) to formulate an interdisciplinary and unitary model of the thunderstorm outflows; 2) to assess a wind loading model of structures due to thunderstorm outflows and to encapsulate it and the classic method for cyclones into a unitary wind loading format; 3) to spread the results to international community. This paper provides the general framework of the THUNDERR project, illustrates the results at present obtained, describes the perspectives of the studies undertaken, discusses their potential impact on society and on building safety and sustainability.

## INTRODUCTION

The safety and sustainability of built environment are primary goals for engineering and society [1]. The wind is the most destructive natural phenomenon [2]: 70% of the damage and death caused by nature every year in the world comes from the wind. The European wind climate and that of many parts of the world are dominated by extra-tropical cyclones and thunderstorms. The genesis and evolution of cyclones is known from the 1920s. Their actions on structures were framed in the 1960s and civil engineers still use these models [3]. Thunderstorms are complex, frequent and devastating phenomena that cause actions often more intense and damaging than those of cyclones [4, 5].

Despite this awareness and the huge amount of research carried out in in the last 30 years on this topic, there is no model of thunderstorm winds and their actions similar to that established over half a century ago for cyclones. Likewise, there is no unified framework for thunderstorm and cyclone wind actions. This occurs because the complexity of thunderstorms makes it difficult to establish realistic and simple models; their short duration and small extension limit the available data; there is a clear gap between research in atmospheric sciences and wind engineering.

This is a serious shortcoming in structural and civil engineering, as it gives rise to unsafe and/or overly expensive works. The unsafety of small and medium-height light structures is pointed out by their frequent damage and collapse in thunderstorm days. The excessive cost of tall buildings in areas dominated by thunderstorms is testified by the apparent absence of collapses, probably due to the fact that the wind speed due to thunderstorms is maximum close to the ground.

THUNDERR is the acronym (THUNDERstorm Roar) of a research project leaded by author and funded by the European Research Council (ERC) through an Advanced Grant 2016. It aims to detect thunderstorms, to create a database of meteorological records and scenarios, to conduct unprecedented laboratory tests and numerical simulations, to formulate a thunderstorm model appropriate for both atmospheric sciences and structural design, to change the format of wind actions, of engineering practice and of codes, to make building safer and more sustainable, to bring about a profound impact on society and its economy [6].

This paper provides the general framework of the THUNDERR project, illustrates the results obtained in this phase of the research, describes the perspectives of the studies currently undertaken, discusses their potential impact on civil and structural engineering, as well as their consequences on building safety and sustainability.

## THUNDERSTORM DOWNBURSTS

The thunderstorm is a violent and impressive form of convection. It appears like a wild cloud, accompanied by lightning and thunders, gusty winds, heavy rain and, every now and then, hail. It consists of cells arranged either randomly or in squall-lines. In each cell, a process lasting nearly 30 minutes and evolving over three stages takes place: 1) the cumulus stage, in which an updraft of hot air takes place, originating a large size cumulus; 2) the mature stage, in which the cumulus becomes a cumulonimbus, intense precipitations occur and a downdraft of cold air appears that diffuses at ground level, causing sudden wind changes, a temperature drop and an increase in pressure; and, 3) the dissipative stage, in which the thunderstorm exhausts itself.

During the mature stage (Figure 1), the downdraft that impinges over the terrain produces radial outflows and vortex rings. Fujita called the whole of these air movements downburst and divided them into macro-bursts and micro-bursts depending on whether their size is greater or smaller than 4 km [7]. The radial outflows of a downburst are characterized by non-stationary velocity fields with a nose-shaped profile that increases up to 50-100 m height, then decreases above [8, 9].

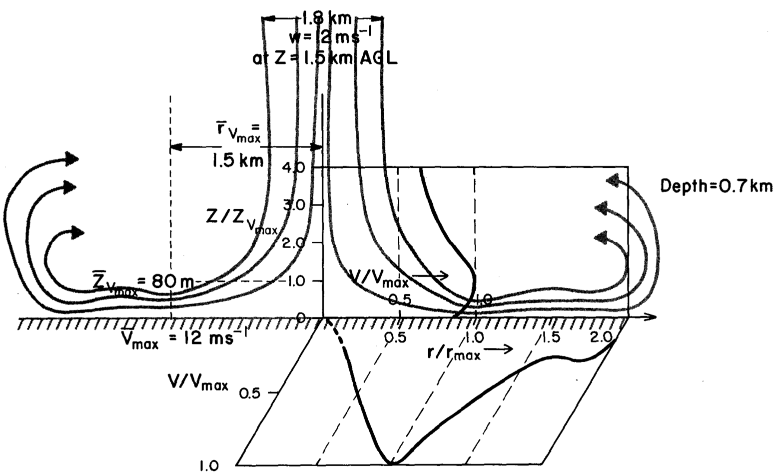

Figure 1 - Structure of the outflow at maximum intensity and typical average values

The first objective of the THUNDER project aims at formulating a novel, interdisciplinary and unitary model of the thunderstorm outflow, with the dual prospect of being itself a challenging scientific result and a robust basis to carry out engineering analyses of the structural loading and response. This objective includes 3 work packages, namely, thunderstorm detection, analysis and modelling.

## Thunderstorm Detection

The THUNDERR project originates from two European projects, Wind and Ports (WP, 2009-2012) [10] and Wind, Ports and Sea (WPS, 2013-2015) [11], financed by the European cross-border program Italy–France Maritime 2007-2013. They handled the wind safe management and risk assessment of the High Tyrrhenian seaport areas through an integrated set of tools including an extensive wind monitoring network, multi-scale numerical models, medium- and short-term forecast algorithms, and statistical analyses. Results are made available to port operators through an innovative Web GIS platform [12].

The wind monitoring network created by the WP and WPS projects currently includes nearly 40 ultrasonic anemometers, 3 meteo-stations and 3 LiDAR profilers (Figure 2). The THUNDERR project has enhanced the unique potential of the WP and WPS network through a Windcube 400S pulsed LiDAR scanning system, installed in the Port of Genova in April 2018 (Figure 3). It detects the wind speed up to a nominal distance of 14 km, with a space step up to 100 m and a sampling frequency up to 1 Hz. It involves a specific software to record and to display the data in real time. It is used with the perspective of detecting the touch-down position and the diameter of the downdrafts, their direction and translational speed, and the background wind speed in which the downbursts are embedded.

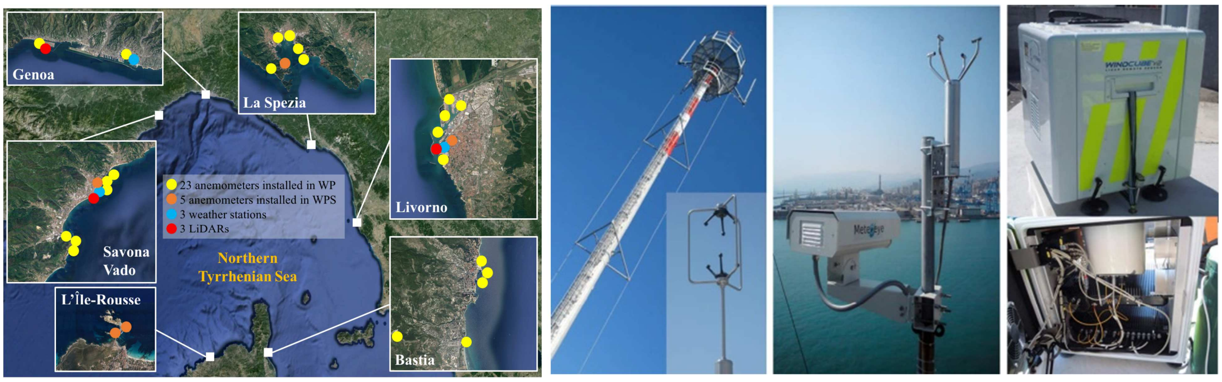

Figure 2 - WP and WPS wind monitoring network, three-axial and bi-axial ultrasonic anemometers, LiDAR profiler

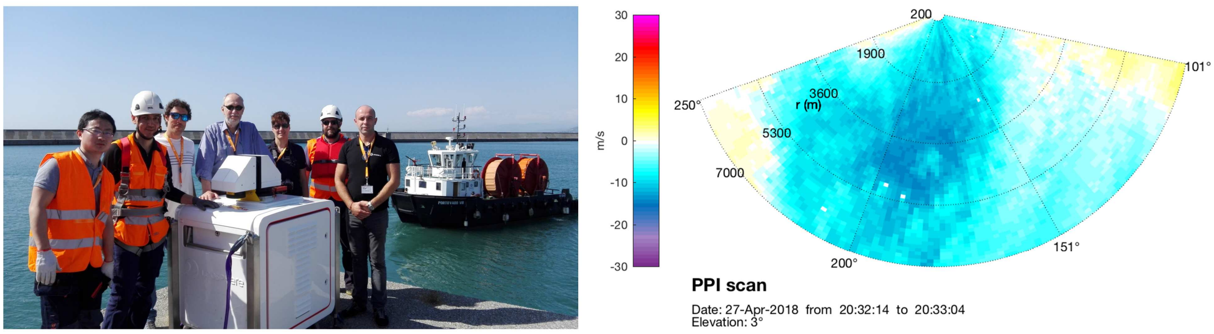

Figure 3 - Windcube 400S pulsed LiDAR scanning system: picture and measurements

The data recorded by the ultra-sonic anemometers have been analyzed through a semi-automatic computational procedure that separates different wind events - synoptic extra-tropical cyclones, thunderstorm outflows and intermediate events (Figure 4) - into so-called selective datasets [13]. Studies are in progress to extend this procedure to the data detected by LiDAR Profilers and by the new LiDAR scanner.

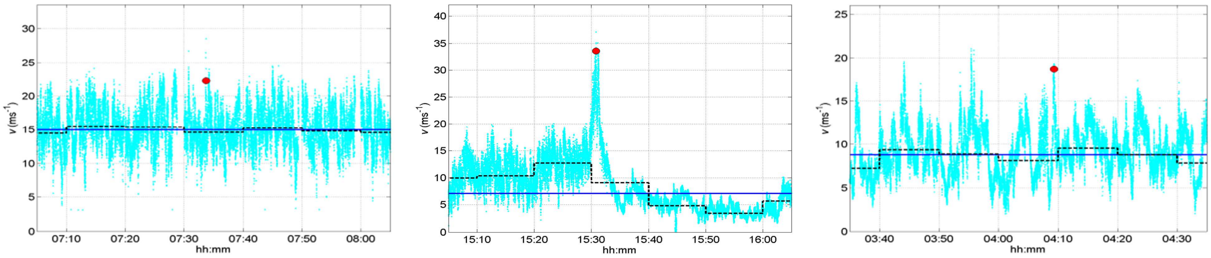

Figure 4 - Time-histories of the wind speed during a cyclone, a thunderstorm and an intermediate event

## Thunderstorm Analysis

One of the aim of the THUNDERR project is to develop an unprecedented comparative analysis of thunderstorm outflow measurements, laboratory and CFD simulations, weather scenarios and damage survey, aiming to formulate a comprehensive representation of downburst wind field.

Initially, thunderstorm outflow signals have been decomposed into component sample functions and their statistical properties have been analyzed based upon a large number of events [14, 15]. Currently, three lines of research are pursued: 1) a novel directional decomposition method has been formulated to take into account the directional shifts of thunderstorm outflows (Figure 5) due to their translational motion [16]. This opens the doors to advanced thunderstorm models in terms of wind speed, wind loading and wind-induced response; 2) systematic analyses about the time evolution of the vertical profile of the wind speed have been carried out based on the measurements performed by LiDAR profilers (Figure 6) [17]; 3) international co-operations have been opened in order to repeat the analyses carried out in the Northern Mediterranean area in other parts of the world, to understand whether downbursts have similar properties everywhere, or whether such properties depend on the local climate [18].

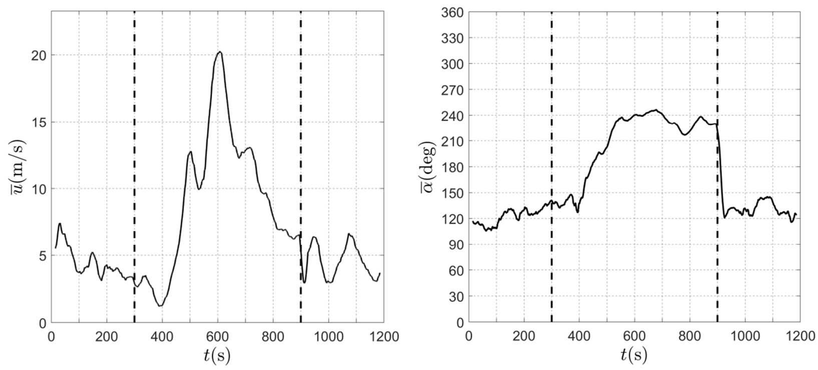

Figure 5 - Directional decomposition: slowly-varying mean wind speed and direction

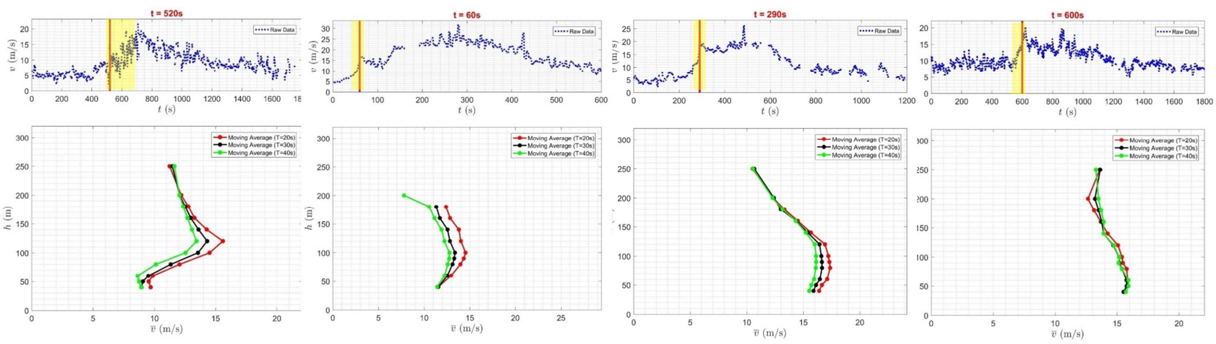

Figure 6 - Wind speed profiles detected by LiDAR profilers during the ramp-up stage of some thunderstorm outflows

Exploiting the unique potential of the WindEEE Dome (Figure 7) at the University of Western Ontario [19], in this stage of the project four pathways are pursued: 1) a preliminary campaign of wind tunnel tests have been carried out [20] to check the replicability of field measurements in a large-scale laboratory; 2) an extensive campaign of tests has been carried out to investigate the role of terrain roughness; 3) another extensive campaign of tests has been carried out to inspect the reliability of combining the wind speed components associated with the stationary downdraft, cell translation and background flow through the vector composition rule traditionally used in literature; 4) a novel scaling rule between laboratory tests and full-scale measurements [21] has been formulated.

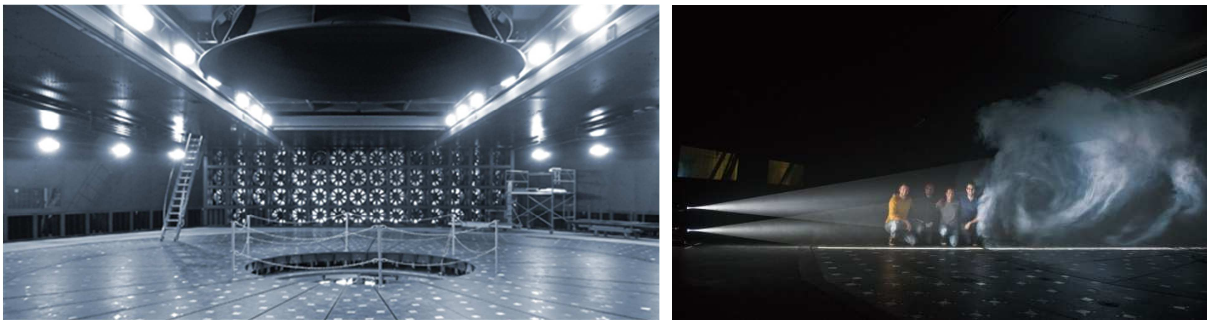

Figure 7 - Inner chamber of the WindEEE Dome and simulated downburst

In parallel with physical simulations, a collaboration has been established with the Technical University Eindhoven in order to develop innovative CFD simulations of thunderstorm outflows and calibrate them using both the results of full-scale measurements and laboratory experiments [22]. Preliminary results based on the impinging wall jet technique elucidate the limited validity range of RANS models and the potential of URANS simulations to reproduce laboratory tests (Figure 8) [23]. Sub-cloud models and LES simulations will be carried out soon.

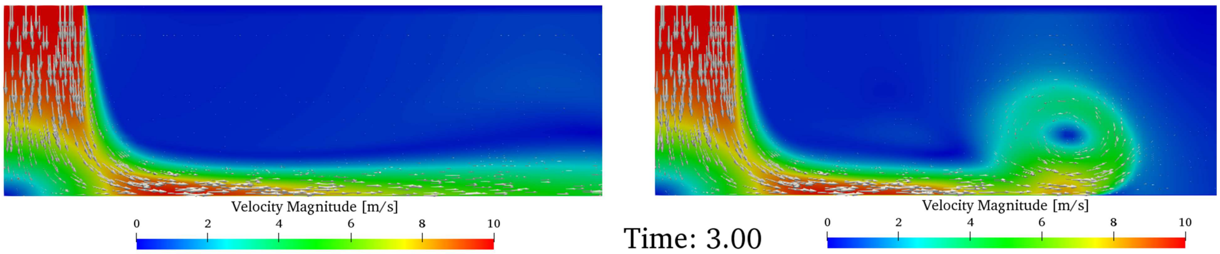


Figure 8 - RANS and URANS simulations

A collaboration has been recently established also with the Freie University, Berlin, in order to create a robust link between wind engineering and atmospheric sciences, and possibly to inspect the role of climate changes with regard to local wind storms [24]. In the meanwhile, systematic investigations about the weather scenarios in which thunderstorms occur have been carried out taking, as a reference model, the downburst that struck Livorno on 1 October 2012 (Figure 9) [25]. Since this study involved a huge amount of work to inspect a single event, fully unsuitable to analyze a long series of thunderstorms, a procedure has been formulated carry out preliminary rapid evaluations of these phenomena [26].

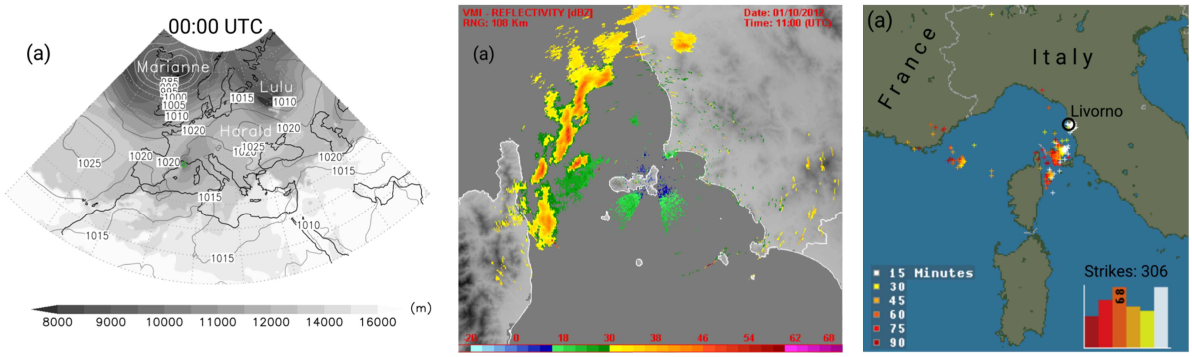


Figure 9 - Satellite images, radar Doppler images and strike recording

It is also worth noting that the THUNDERR project foresees the study of damage and losses due to windstorms in the monitored area, in order to support the separation and classification of the different impacts due to cyclones and thunderstorms. Some preliminary evaluations confirm the severe consequences of thunderstorms (Figure 10).

Figure 10 - Consequences of the thunderstorm downburst occurred in the Port of Genoa on 31 August 1994

## Thunderstorm Representation

A crucial aim of the THUNDERR project is combining turbulence modelling, the fundamental equations of fluid dynamics, random field theory, full-scale measurements, laboratory tests, and CFD simulations in order to establish a novel model of the wind velocity field of thunderstorm outflows, duly considering weather scenarios. Accordingly, in addition to the specific researchers described with reference to the individual topics, a great effort has been devoted to formulate a robust though preliminary thunderstorm model that takes into account the stationary downdraft, its translational speed and the background flow into which it is embedded [27]. The studies in progress show the capacity of this model not only to replicate actual events, but also to extract their main parameters (Figure 11).

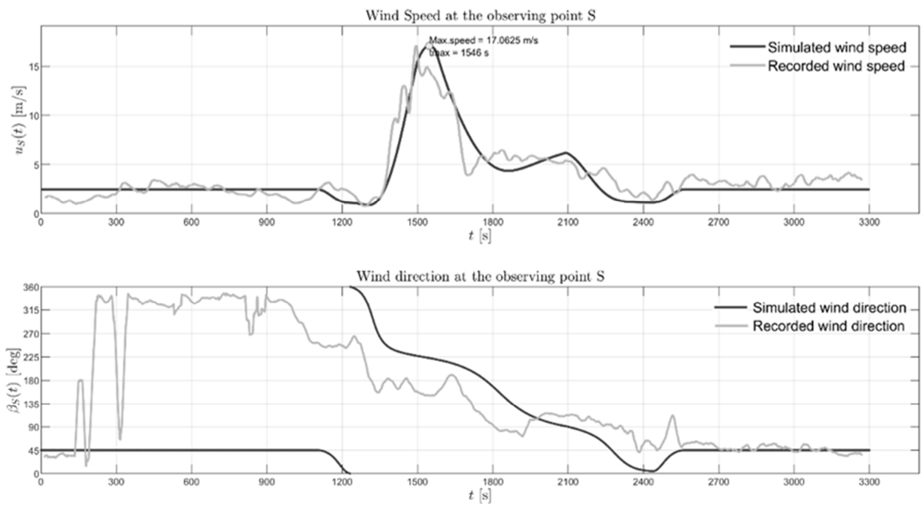


Figure 11 - Comparison between measured and simulated mean wind speeds and directions

In parallel with these studies, relying on almost 10 years of measurements (from the beginning of previous European projects) and on the procedures established to separate different wind events, the distribution functions of the extreme wind speed of thunderstorm outflows, synoptic cyclones and intermediate events have been assessed and then combined through ensemble and mixed statistics. The results prove that in the Northern Mediterranean area, likewise in many other parts of the world, thunderstorms are the main events as far as concerns mean return periods above 5-20 years, namely the ones that determine the safety of structures (Figure 12) [28].

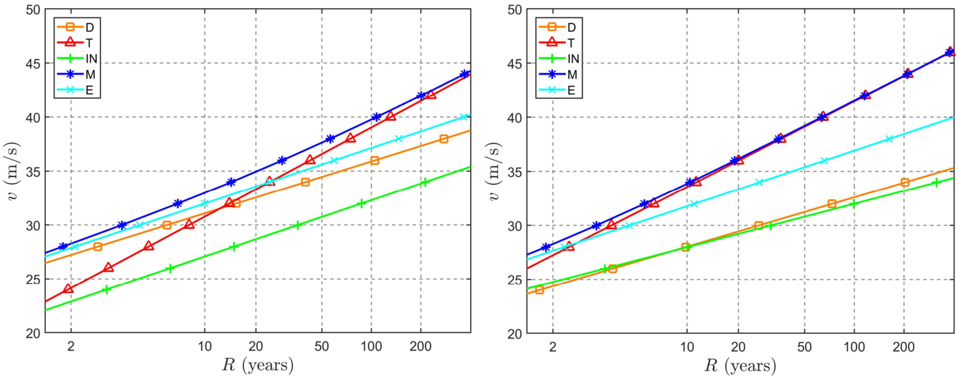

Figure 12 - Extreme wind speed distributions in the ports of Livorno and La Spezia

Finally, according to project plans, a pair of Monte Carlo simulators will be developed: the outer one will generate long-term series of thunderstorm parameters, namely the touch-down position, the diameter of the down-draft, the translational speed and direction of the thunderstorm cell, and the background win speed [29]; the inner one will simulate, for each set of the above parameters, non-stationary and non-Gaussian outflow velocity fields. At present the work is focused on the inner simulator and a novel hybrid technique has been implemented by which the component signals of the outflow fields are generated separately and then recombined (Figure 13) [30]. A major step forward of this procedure is represented by the application of the equivalent wind spectrum technique to the stationary Gaussian part of the wind field [31]. Thanks to it, applying a mono-variate simulation of a stationary Gaussian process, it is possible to re-construct a multi-variate non-stationary non-Gaussian random field with unbelievable precision.

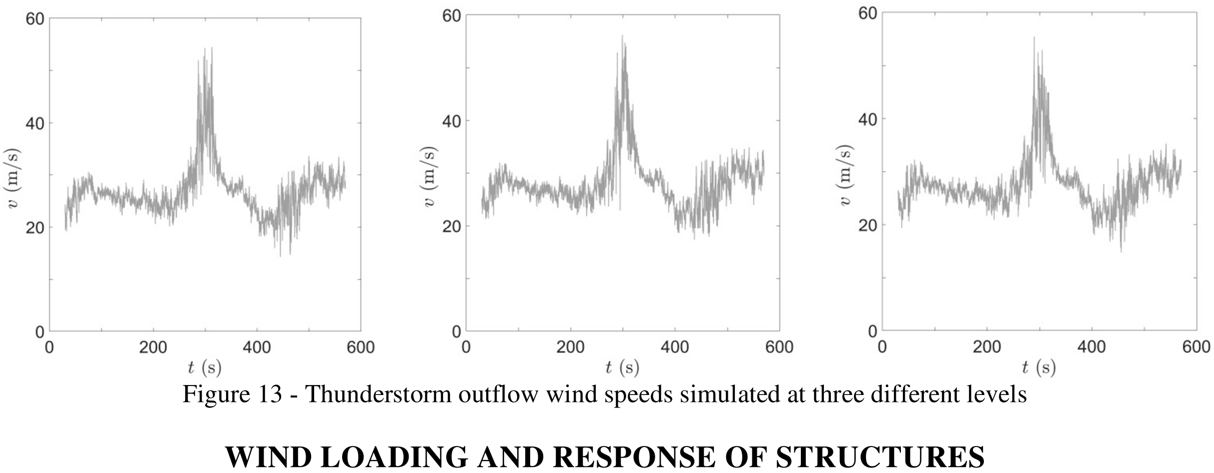

Figure 13 - Thunderstorm outflow wind speeds simulated at three different levels

## WIND LOADING AND RESPONSE OF STRUCTURES

Despite a lot of research worldwide [32, 33], literature is still lacking in simple and physically realistic methods for determining the wind loading and response of structures to thunderstorm outflows. Based on the results provided by the first objective of the THUNDERR project – thunderstorm detection, analysis and representation – the second objective of this project is to overcome this limitation by developing a challenging method to evaluate thunderstorm actions on structures and to encapsulate the classical method for synoptic cyclones and the new method for thunderstorm outflows into a novel wind loading format, easily and rapidly transferable to design practice and codification.

**Structural Analysis**

In the course of previous projects a wind turbine in the Port of Savona was monitored in order to study its wind-induced behavior [34]. A lighting tower in the Port of La Spezia has been also monitored for the THUNDERR project, by making recourse to anemometers, accelerometers, and strain-gauges; in addition, wind tunnel tests have been conducted to estimate its aerodynamic parameters (Figure 14). Other activities aiming to create a long-term full-scale monitoring of mono-tubular towers, cranes and lattice masts are in progress. The final objective of this activity is to gather simultaneous data of the outflow velocity and structural response in order to check and calibrate the methods developed to determine the wind loading and response of structures to thunderstorm outflows.

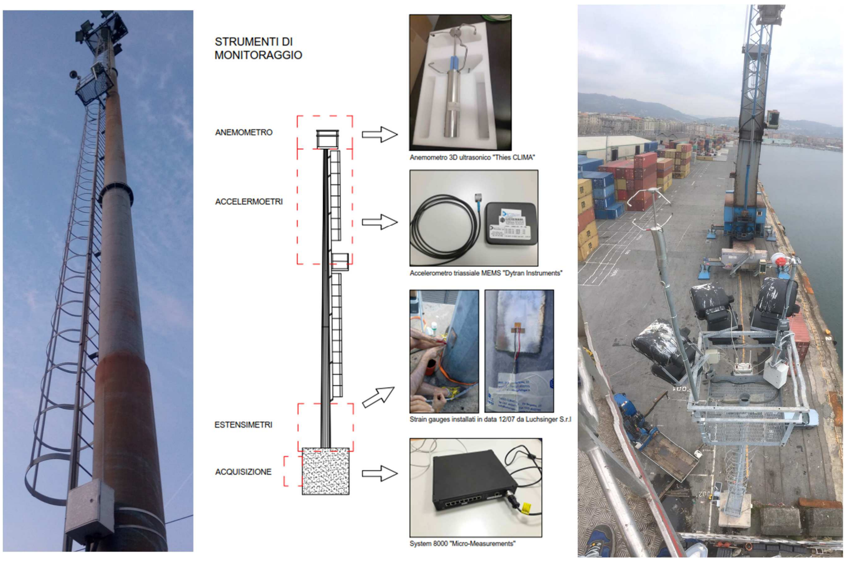

Figure 14 - Full-scale monitoring of a steel tower in the Port of La Spezia

Another main aim of this project is to determine the wind loading and response of structures to thunderstorm outflows by means of three fully revised methods – response spectrum technique, time-domain integration and evolutionary spectral density – strictly linked with each other and based upon reliable measurements.

The response spectrum technique applied in this research was born from the idea of generalizing to thunderstorm outflows the method currently applied in seismic engineering [35, 36]. Initially, an ideal point-like SDOF system was studied [37]. Later, the formulation was generalized to a real 3D MDOF system subjected to a partially coherent wind field [38]. Analyses were carried out making recourse to the equivalent wind spectrum technique. In parallel with this approach, time domain analyses were carried out based upon the novel hybrid strategy described above [31]. The comparison between the results provided by these two methods led to improve both of them up to obtain results very close to each other [39]. This is impressive considering the burden of time-domain solutions and the simplicity of the response spectrum technique (Figure 15). New results have been also obtained (Figure 16) with reference to the directional analysis [40], never used before, of the structural response to downbursts. An evolutionary power spectral density model of the thunderstorm outflow is also in progress with the aim of conducting non-stationary analyses of the stochastic response [41].

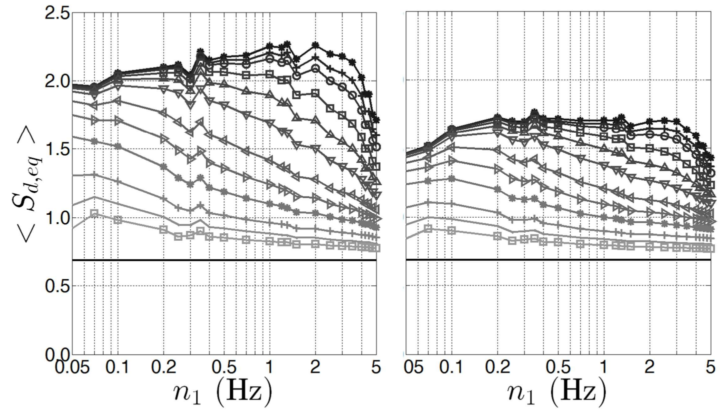


Figure 15 - Equivalent response spectra for different damping ratios (0.002 and 0.01)

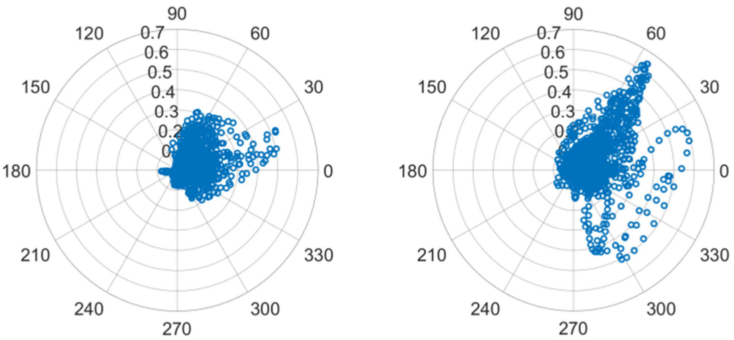

Figure 16 - Directional response of a tower structure to a synoptic and to a thunderstorm event.

The final aim of the structural analysis to thunderstorm outflows is to change the classical unique wind loading framework and separate it into two wind loading conditions, one for cyclones and the other for thunderstorms [42]. This choice is supported by the different profiles and time-histories of cyclones and thunderstorms and by their different size, duration and frequency that makes the use of one set of wind partial coefficients and combination factors non-sense. This implies the calibration of novel sets of partial coefficients and combination factors. It is worth noticing that this framework may accommodate any method to evaluate cyclone and thunderstorm loading. Moreover, tropical cyclones, tornadoes, downslope winds and other wind types may be easily included, each one dealt with as another wind loading condition.

**Impact on Construction**

The lack of engineering methods to calculate the wind loading of structures under thunderstorm outflows and the indiscriminate use of design techniques inspired to cyclones are responsible of the realization of unsafe and/or costly structures. The insufficient safety of light structures with small to medium height is proved by the frequent damage and by the widespread collapse they exhibit in thunderstorm days. The excessive cost of tall buildings is pointed out by the extremely reduced rate of their damage and collapse; in areas in which the design wind speed is due to thunderstorms, this may be a consequence of using wind speed profiles that grow with height, while the maximum power of downbursts is developed close to ground.

The final aim of the THUNDERR project is to create a new wind loading framework that may re-center the safety and sustainability of construction. For this reason an extensive dataset of structure test-cases has been gathered and will be analyzed at the end of the project to classify situations where classic analysis leads to unsafe design or excessive caution. Safety and economic evaluations will be conducted to estimate the global impact of the new wind loading format.

## CONCLUSIONS

The study of thunderstorm downbursts is a dominant issue of the research carried out in the last decades in wind engineering and atmospheric sciences. Despite this huge effort, the modelling of these phenomena and their impact on built environment is still dominated by many uncertainties, by the lack of a shared model, and by the need of a rational framework. This represents a major shortcoming in civil engineering since the wind is the most destructive natural phenomenon and thunderstorm downbursts produce wind speeds and damage often more intense than those due to the synoptic events for which structural engineering is usual to evaluate the design wind loading.

The THUNDERR project may represent a great opportunity to provide innovative answers to the questions still opened and to fill several gaps. A key requirement for its success is realising an interdisciplinary viewpoint on this matter, such as to dissolve the many boundaries that limit the development of knowledge. In particular, an interdisciplinary vision of wind engineering and atmospheric sciences is necessary to develop a thunderstorm model that may represent a physically correct and simple starting point to evaluate the actions of thunderstorm outflows on structures. At same time, this research should pursue the widest possible vision to embrace analytical methods, numeric simulations, laboratory tests and full-scale measurements.

Finally, it is essential to quantify the actual effects of thunderstorm outflows on single structures and on the whole built environment, embedding this knowledge into a joint vision of the societal safety and economical sustainability. This analysis cannot preclude from a deeper knowledge of the physics of downbursts, exactly in the spirit pursued by the THUNDERR project.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] Solari G. Wind science and engineering: origins, developments, fundamentals and advancements. Switzerland: Springer; 2019. p. 1-944.

[2] Tamura Y, Cao S. International Group for Wind-Related Disaster Risk Reduction (IG-WRDRR). In: Proceedings of the 13th International Conference on Wind Engineering. Amsterdam (The Netherlands); 2011.

[3] Davenport AG. 1961. The application of statistical concepts to the wind loading of structures. In: Proceedings of the Institution of Civil Engineers. Volume 19. p. 449-472.

[4] Letchford CW, Mans C, Chay MT. 2002. Thunderstorms – their importance in wind engineering (a case for the next generation wind tunnel). In: Journal of Wind Engineering and Industrial Aerodynamics. Volume 90. p. 1415-1433.

[5] Solari G. 2014. Emerging issues and new frameworks for wind loading on structures in mixed climates. In: Wind and Structures. Volume 19. p. 295-320.

[6] Solari G. Mixed climatology, non-synoptic phenomena and downburst wind loading of structures. In: Proceedings of the 15th International Conference of the Italian National Association for Wind Engineering. Naples (Italy). IN-VENTO 2018; 2018.

[7] Fujita TT. Downburst: microburst and macroburst. University of Chicago Press; 1985.
[8] Goff RG. 1976. Vertical structure of thunderstorm outflows. In: Monthly Weather Review. Volume 104. p. 1429-1440.
[9] Hjelmfelt MR. 1988. Structure and life cycle of microburst outflows observed in Colorado. In: Journal of Applied Meteorology. Volume 27. p. 900-927.
[10] Solari G, Repetto MP, Burlando M, De Gaetano P, Pizzo M, Tizzi M, Parodi M. 2012. The wind forecast for safety and management of port areas. In: Journal of Wind Engineering and Industrial Aerodynamics. Volume 104-106. p. 266-277.
[11] Repetto MP, Burlando M, Solari G, De Gaetano P, Pizzo M. 2017. Integrated tools for improving the resilience of seaports under extreme wind events. In: Sustainable Cities and Society. Volume 32. p. 277-294.
[12] Repetto MP, Burlando M, Solari G, De Gaetano P, Pizzo M, Tizzi M. 2018. A web-based GIS platform for the safe management and risk assessment of complex structural and infra-structural systems exposed to wind. In: Advances in Engineering Software. Volume 117. p. 29-45.
[13] De Gaetano P, Repetto MP, Repetto T, Solari G. 2014. Separation and classification of extreme wind events from anemometric records. In: Journal of Wind Engineering and Industrial Aerodynamics. Volume 126. p. 132-143.
[14] Solari G, Burlando M, De Gaetano P, Repetto MP. 2015. Characteristics of thunderstorms relevant to the wind loading of structures. In: Wind and Structures. Volume 20. p. 763-791.
[15] Zhang S, Solari G, De Gaetano P, Burlando M, Repetto MP. 2018. A refined analysis of thunderstorm outflow characteristics relevant to the wind loading of structures. In: Probabilistic Engineering Mechanics. Volume 54. p. 9-24.
[16] Zhang S, Solari G, Burlando M, Yang Q. 2019. Directional decomposition and analysis of thunderstorm outflows. In: Journal of Wind Engineering and Industrial Aerodynamics. Volume 189. p. 71-90.
[17] Canepa F, Burlando M, Solari G. Advancements in the investigation of vertical profiles of thunderstorm outflows. In: Proceedings of the 15th International Conference on Wind Engineering. Beijing (China). ICWE 15; 2019.
[18] Huang G, Jiang Y, Peng L, Solari G, Liao H, Li M. 2019. Characteristics of intense wind in mountain area based on field measurement. In: Journal of Wind Engineering and Industrial Aerodynamics. Volume 190. p. 166–182.
[19] Hangan H, Refan M, Jubayer C, Romanic D, Parvu D, Lo Tufo J, Costache A. 2017. Novel techniques in wind engineering. In: Journal of Wind Engineering and Industrial Aerodynamics. Volume 171. p. 12-33.
[20] Burlando M, Romanic D, Hangan H, Solari G. Wind tunnel experimentation on stationary downbursts at WindEEE Dome. In: Proceedings of the 15th International Conference of the Italian National Association for Wind Engineering. Naples (Italy). IN-VENTO 2018; 2018.
[21] Xu Z, Hangan H. 2008. Scale, boundary and inlet condition effects on impinging jets. In: Journal of Wind Engineering and Industrial Aerodynamics. Volume 96. p. 2383-2402.
[22] Blocken B. 2014. 50 years of Computational Wind Engineering: past, present and future. In: Journal of Wind Engineering and Industrial Aerodynamics. Volume 129. p. 69-102.
[23] Zuzul J, Burlando M, Solari G, Blocken B, Ricci A. 2019. Comparison between the impinging jet model and experimental stationary downbursts. In: Proceedings of the 15th International Conference on Wind Engineering. Beijing (China). ICWE 15; 2019.
[24] Nissen KM, Leckebusch GC, Pinto JG, Ulbrich U. 2014. Mediterranean cyclones and windstorms in a changing climate. In: Regional Environmental Change. Volume 14. p. 1873-1890.

[25] Burlando M, Romanic D, Solari G, Hangan H, Zhang S. 2017. Field data analysis and weather scenario of a downburst event in Livorno, Italy on 1 October 2012. In: Monthly Weather Review. Volume 145. p. 3507-3527.

[26] Burlando M, Zhang S, Solari G. 2018. Monitoring, cataloguing and weather scenarios of thunderstorm-induced intense wind events. In: Natuaral Hazard and Earth Systems. Volume 18. p. 2309–2330.

[27] Xhelaj A, Burlando M, Solari G. An advanced analytical model for simulating thunderstorm outflows. In: Proceedings of the 15th International Conference on Wind Engineering. Beijing (China). ICWE 15; 2019.

[28] Zhang S, Solari G, Yang Q, Repetto MP. 2018. Extreme wind speed distribution in a mixed wind climate. In: Journal of Wind Engineering and Industrial Aerodynamics. Volume 176. p. 239-253.

[29] Aboshosha H, Mara T, Case P. New framework for estimating thunderstorm design speed. In: Proceedings of the 13th Americas Conference on Wind Engineering, Gainesville (Florida); 2017.

[30] Solari G, Rainisio D, De Gaetano P. 2017. Hybrid simulation of thunderstorm outflows and wind-excited response of structures. In: Meccanica. Volume 52. p. 3197–3220.

[31] Piccardo G, Solari G. 1998. Generalized equivalent spectrum technique. In: Wind and Structures. Volume 1. p. 161-174.

[32] Chen X. 2008. Analysis of alongwind tall building response to transient nonstationary winds. In: Journal of Structural Engineering ASCE. Volume 134. p. 782-791.

[33] Kwon DK, Kareem A. 2009. Gust-front factor: new framework for wind load effects on structures. In: Journal of Structural Engineering ASCE. Volume 135. p. 717-732.

[34] Pagnini LC, Piccardo G, Repetto MP. 2018. Full scale behavior of a small size vertical axis wind turbine. In: Renewable Energy. Volume 127. p. 41-55.

[35] Housner GW, Martel RR, Alford JL. 1953. Spectrum analysis of strong-motion earthquakes. In: Bulletin of the Seismological Society of America. Volume 43. p. 97-119.

[36] Solari G. 1989. Wind response spectrum. In: Journal of Engineering Mechanics ASCE. Volume 115. p. 2057-2073.

[37] Solari G, De Gaetano P, Repetto MP. 2015. Thunderstorm response spectrum: fundamentals and case study. In: Journal of Wind Engineering and Industrial Aerodynamics. Volume 143. p. 62-77.

[38] Solari G. 2016. Thunderstorm response spectrum technique: theory and applications. In: Engineering Structures. Volume 108. p. 28-46.

[39] Solari G, De Gaetano P. 2018. Dynamic response of structures to thunderstorm outflows: response spectrum technique vs time-domain analysis. In: Engineering Structures. Volume 176. p. 188-207.

[40] Brusco S, Lerzo V, Solari G. 2019. Directional response of structures to thunderstorm outflows. In: Meccanica. Volume 54. p. 1281–1306.

[41] Roncallo L, Solari G. Modelling of thunderstorm outflows by means of the evolutionary power spectral density. In: Proceedings of the 15th International Conference on Wind Engineering. Beijing (China). ICWE 15; 2019.

[42] Solari G, De Gaetano P, Repetto MP. Wind loading and response of structures in mixed climates. In: Proceedings of the 8th Asia-Pacific Conference on Wind Engineering. Chennai (India); 2013.