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Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures

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A B S T R A C T

Wind actions are crucial for the safety and sustainability 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 that cause wind speeds and damage often greater than those of cyclones. This paper describes a wide research activity including an extensive monitoring network, an unprecedented database of transient wind speed recordings, a broad spectrum of numerical tools for elaborating data and extracting their statistical properties relevant to the wind loading of structures, the development of wind tunnel tests and CFD simulations, investigations on weather scenarios and damage surveys aiming to complete the information provided by field measurements. Based on these resources, a new generation of wind loading models is being developed – response spectrum technique, time-domain integration, evolutionary spectral density - robustly coherent with measured data and intrinsically coherent with each other. These studies are being carried out in the framework of the project THUNDERR, funded by the European Research Council (ERC) with an Advanced Grant 2016 in order to produce outcomes physically correct, transferable to design and standards, suitable to modify the current wind loading format and make constructions wind-safer and cost-efficient.

1. Introduction

A primary aim of engineering is to pursue the safety and sustainability of the built environment under natural and anthropogenic actions. The wind is the most destructive natural phenomenon - over 70% of damage and casualties due to natural hazards are due to the wind (Tamura and Cao, 2012; Ulbrich et al., 2013) - so that knowledge of wind actions on structures is crucial to make them more reliable and less costly. Their proper evaluation is thus a societal need for safety and economy.

The wind climate of Europe and many other parts of the world at the mid-latitudes is dominated by extra-tropical cyclones at the synoptic scale and by mesoscale thunderstorm outflows. The genesis and evolution of extra-tropical cyclones have been known since the 1920s (Bjerknes and Solberg, 1922). A rationale framework of their actions and effects on structures was provided by Davenport (1961) and wind engineering still uses his model (Solari, 2019). Thunderstorms are complex, devastating and still mostly mysterious natural phenomena.

The modern study of thunderstorms started when Byers and Braham (1949) showed that these phenomena consist of cells that develop in a few kilometres and evolve in about 30 min through three stages in which an updraft of warm air is followed by a downdraft of cold air. In the 1970s and 1980s, Fujita (1985, 1990) proved that the downdraft that impacts over Earth's surface produces intense radial outflows and ring vortices. The whole of these air movements was called downburst and was classified as a macro-burst or a micro-burst depending on whether its size is greater or less than 4 km (Fig. 1). Differently from synoptic winds, the radial outflows exhibit a non-stationary speed with a "nose profile" that increases up to 50–100 m height, then decreases above (Goff, 1976; Hjelmfelt, 1988).

Despite an impressive amount of research carried out in atmospheric sciences and wind engineering over the last 30 years (Letchford et al., 2002; Solari, 2014), this matter is still dominated by many uncertainties, and there is not yet a shared model of the thunderstorm outflows and their actions on structures like the one for cyclones (Davenport, 1961). Yet, a rational scheme that joins the wind loading due to cyclones and thunderstorms into a homogeneous framework is still missing. 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 persistent gap between wind engineering and atmospheric sciences.

This is a serious shortcoming in structural and civil engineering, as it may give rise to unsafe and/or overly expensive works. The insufficient

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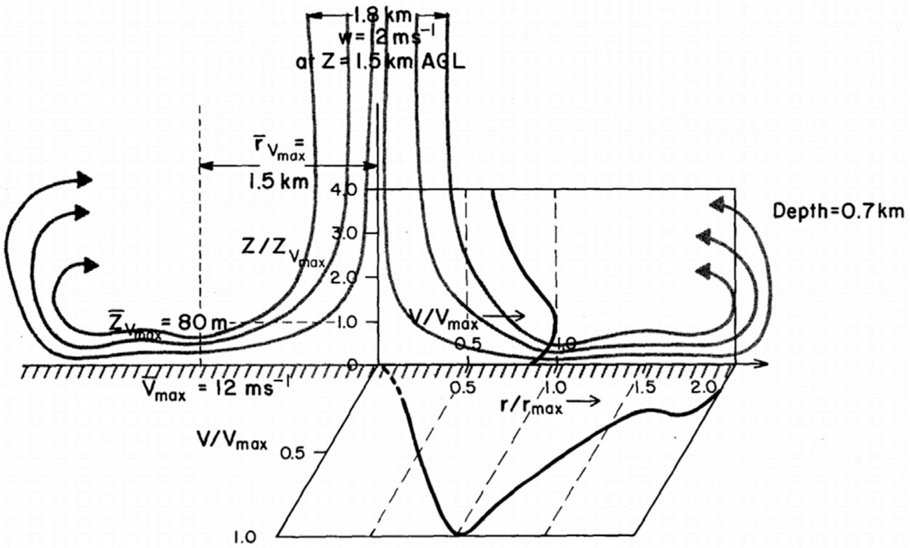

Fig. 1. Thunderstorm downburst and nose velocity profile in the radial outflow (Hjelmfelt, 1988).

safety of small and medium height structures is proved by the frequent damage and widespread collapse they exhibit in thunderstorm days (Fig. 2). The excessive cost of tall buildings is pointed out by the extremely reduced rate of their collapse; in areas in which the design wind speed is due to thunderstorms, this may be a consequence of using boundary layer wind speed profiles that grow with height, while the maximum power of downbursts is developed close to the ground.

The research carried out at the University of Genoa on thunderstorms originated quite occasionally from two European projects, "Wind and Ports" (WP, 2009–2012) (Solari et al., 2012) and "Wind, Ports and Sea" (WPS, 2013–2015) (Repetto et al., 2017), funded by European cross-border program "Italy–France Maritime 2007–2013". They handled the wind safe management and risk assessment of High Tyrrhenian seaports by an integrated set of tools including an extensive wind monitoring network, multi-scale wind numerical models (Burlando et al., 2007, 2013), medium- and short-term wind forecast algorithms (Burlando et al., 2014) and wind climate statistical analyses (Castino et al., 2003; Burlando et al., 2013). Results were made available to port operators through an innovative Web GIS platform (Repetto et al., 2018).

Realized in a geographic area well-known for the intense convective activity and its often dramatic consequences, the WP and WPS monitoring network produced an unprecedented amount of non-stationary wind speed recordings due to gust fronts potentially associated to thunderstorm outflows. This inspired two Italian projects, one supported by "Compagnia di San Paolo" ("Wind monitoring, simulation and forecasting for the smart management and safety of port, urban and territorial systems", 2016–2018), and the other by the Italian Ministry for Instruction, University and Research (MIUR) ("Identification and diagnostic of complex structural systems", 2016–2019), during which extensive research was carried out on downburst wind fields and the associated wind loading and response of structures.

Hence it originated and drove forward the project THUNDERR – "Detection, simulation, modelling and loading of thunderstorm outflows to design wind-safer and cost-efficient structures", from which the title of this paper derives – awarded with an Advanced Grant 2016 from the European Research Council (ERC) under Horizon 2020 (2017–2022). 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 by pursuing three general 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 model for cyclones into a unitary wind loading format; 3) to spread these results to international community.

After these introductory notes, this paper provides a unitary framework and the main results of the research carried out about thunderstorm outflows by the Windyn research group (www.windyn.org). Despite these results cover the full pathway of the studies that originated from the "Wind and Ports" and "Wind, Ports and Sea" projects, their presentation is structured according to the five technical work packages into which the project THUNDERR is organised: thunderstorm detection (Section 2), thunderstorm analysis (Section 3), thunderstorm representation (Section 4), structural analysis (Section 5), and impact on construction (Section 6). Section 7 summarizes the main conclusions and depicts the many prospects that this research is opening.

Fig. 2. Consequences of the downburst occurred in the Port of Genoa on 31 August 1994.

2. Thunderstorm detection

The WP and WPS projects involved a joint co-operation between the main commercial seaports authorities in the High Tyrrhenian Sea - namely the Ports of Genoa, Livorno, Savona and Vado, La Spezia, Bastia and L'Île-Rousse – and the University of Genova. In this framework, an extensive wind monitoring network was created.

The WP project originated a network made up of 23 ultrasonic anemometers (yellow circles in Fig. 3) 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. The WPS project 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) (yellow circles in Fig. 3), LiDAR (Light Detection And Ranging) wind profilers WINCUBEv2 by Leosphere in the Ports of Genoa (1), Savona (1), and Livorno (1) (red circles in Fig. 3), and 3 weather stations - each one including another ultrasonic anemometer, a barometer, a thermometer and a hygrometer - in the Ports of Genoa (1), Savona (1), and Livorno (1) (blue circles in Fig. 3). Other 10 ultrasonic anemometers have been installed at the end of 2019 by the Port Authority of Genoa (yellow circles in the box of Genoa Fig. 3).

The ultrasonic anemometers, in part tri-axial (Fig. 4a) and part bi-axial (Fig. 4b), detect the wind speed and direction with a precision of 0.01 m/s and 1°, respectively. Their sampling rate is 10 Hz except for one sensor in the Port of Savona, with sampling frequency 1 Hz, and the sensors 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 were homogeneously distributed in open port areas and mounted on high-rise towers (Fig. 4c) and 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 the ultrasonic anemometers in their 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 through the Internet to the central server at the Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genova. Here, a preliminary check is carried out and data are stored in a database. The prosecution of this activity after the end of the WP and WPS projects is regulated by contracts between Port Authorities and the University of Genoa.

The LiDAR wind profilers (Fig. 5a) detect the three components of the wind speed at 12 heights between 40 and 250 m above ground, with sampling frequency 1 Hz. They are intended to detect the wind speed profile of the thunderstorm outflows that pass over their position and measure their characteristics like the height of maximum wind speed, the vertical variability of wind direction and possibly some turbulence properties.

In the framework of the THUNDERR project, a Windcube 400S pulsed LiDAR scanning system by Leosphere is operational in the Port of Genoa from 18th April 2018 (Fig. 5b and green circle in Fig. 3). It detects the wind speed up to a nominal distance of 14 km, with a maximum spatial resolution of approximately 100 m, but different settings with higher resolutions can be adopted at the expense of the maximum distance. It is fully programmable to scan in PPI (Plan Position Indicator) or RHI (Range Height Indicator) mode, or a combination of both. It involves specific software to record and display data in real-time. It is used with the key perspective of detecting the touch-down position and the diameter of downdrafts, their direction and translational speed, and the background wind speed field in which they are embedded.

Several structures are being monitored with the aim of detecting simultaneously the wind velocity and their dynamic response to thunderstorm downbursts (Section 5).

3. Thunderstorm analysis

Thunderstorm analysis is the link between their measurement (Section 2) and their representation (Section 4). The studies carried out on this topic can be traced back to three research lines dealing with the analysis of registered signals (Section 3.1), velocity profile (Section 3.2), meteorological events (Section 3.3) and their physical and numerical simulation (Section 3.4).

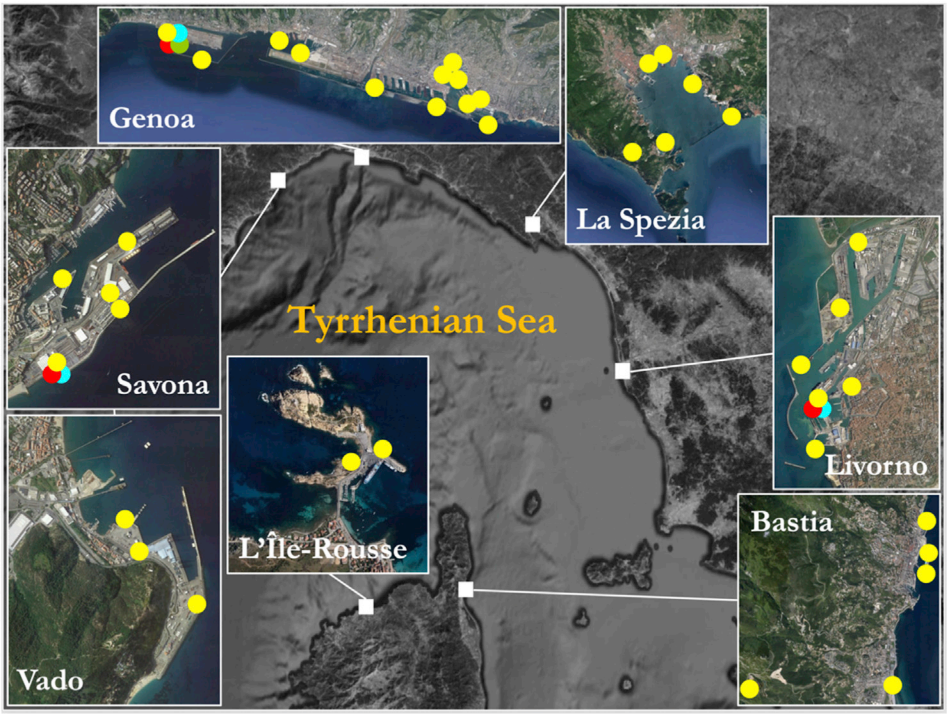

Fig. 3. Overall WP and WPS wind monitoring network: ultrasonic anemometers (yellow circles), met stations (blue circles), pulsed LiDAR profilers (red circles), and pulsed LiDAR scanner (green circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

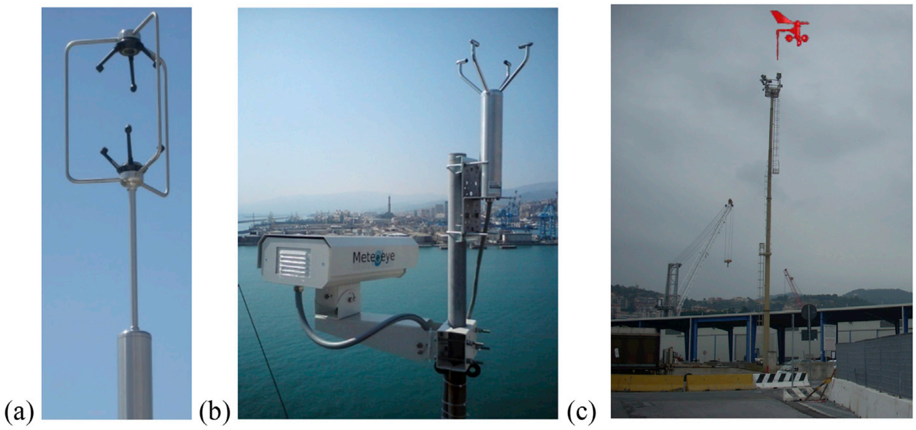

Fig. 4. (a) tri-axial ultrasonic anemometer; (b) bi-axial ultrasonic anemometer; (c) anemometric tower.

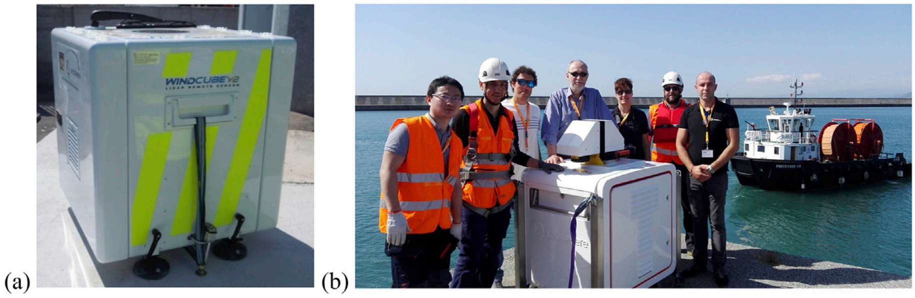

Fig. 5. (a) pulsed LiDAR profiler WINDCUBEv2; (b) pulsed LiDAR scanner WINDCUBE 400S.

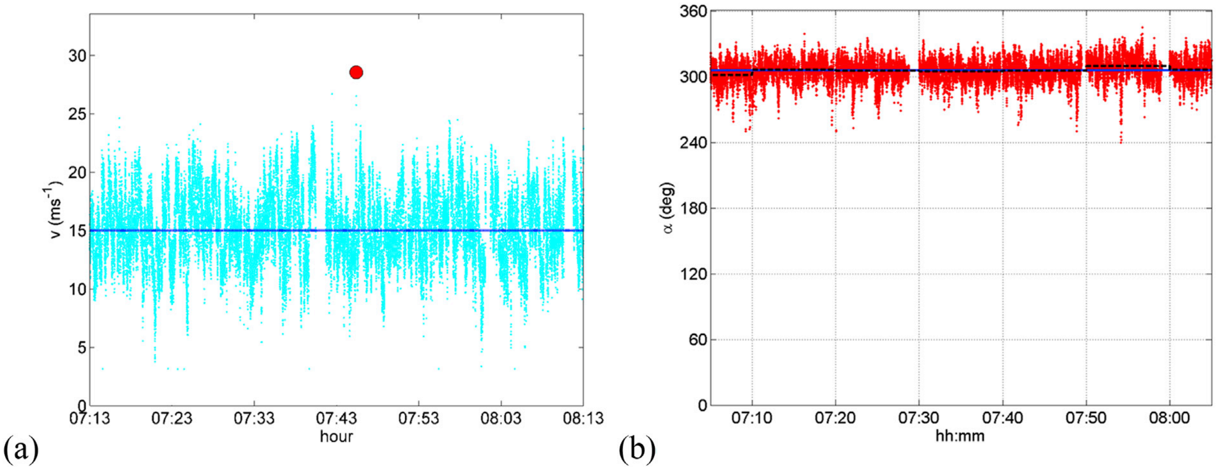

Fig. 6. Recording of a synoptic extra-tropical cyclone detected in the Port of Savona on 22th November 2011 (De Gaetano et al., 2014): (a) velocity; (b) direction.

3.1. *Signal analysis*

Considering that the first anemometric sensors belonging to the monitoring network described above were installed in 2010 and most of them detect the wind speed in continuous mode with a sampling frequency of 10 Hz, a huge dataset is now available for research purposes. At present, it consists of about 0.4 TB of raw data, including indexing and metadata, and it increases every day of more than 20 million new measurements when all instruments are operational.

The data detected by the wind monitoring network points out a typical mixed climatic condition (Gomes and Vickery, 1977/1978) testified by recordings associated with different wind phenomena, namely extra-tropical synoptic cyclones, thunderstorm outflows and intermediate events. For each of them, Figs. 6–8 show typical wind speed and direction recordings. An interpretation of these different signals is given for instance by De Gaetano et al. (2014).

In order to focus on intense thunderstorm outflows, a semi-automatic procedure was implemented that extracts these events (De Gaetano et al., 2014; Burlando et al., 2018b). This method generalizes some previous criteria (Kasperski, 2002; Lombardo et al., 2009; Duranona, 2015) developed and calibrated to process a huge amount of data based on few synthetic parameters, derived from sole anemometric records, without carrying out systematic and prohibitive meteorological surveys of the weather scenarios out of which they took place (Vallis et al., 2019). Initially, 93 transient records labelled as thunderstorms outflows were extracted (Solari et al., 2015a). Later, on increasing the number of the

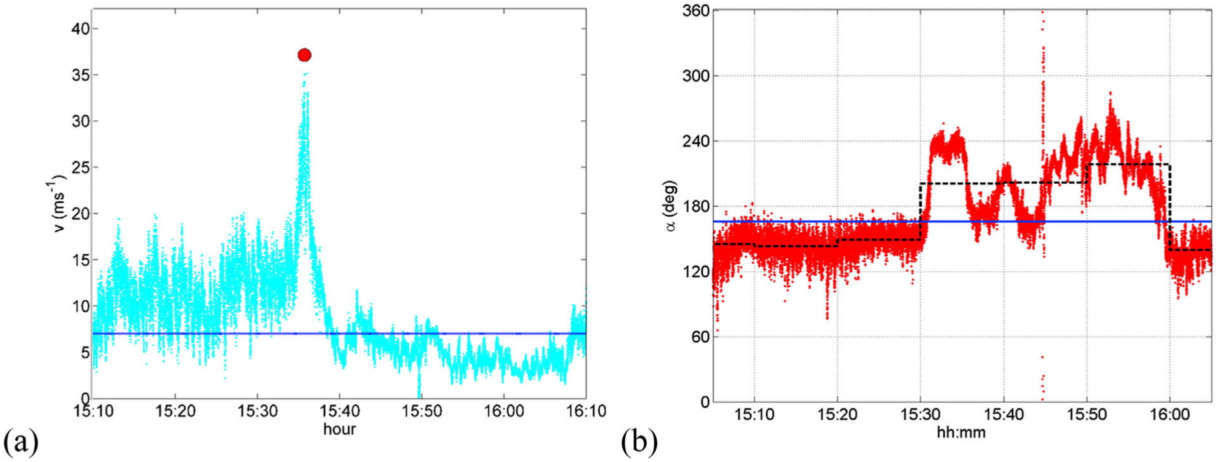

Fig. 7. Recording of a thunderstorm outflow detected in the Port of La Spezia on 25th October 2011 (De Gaetano et al., 2014): (a) velocity; (b) direction.

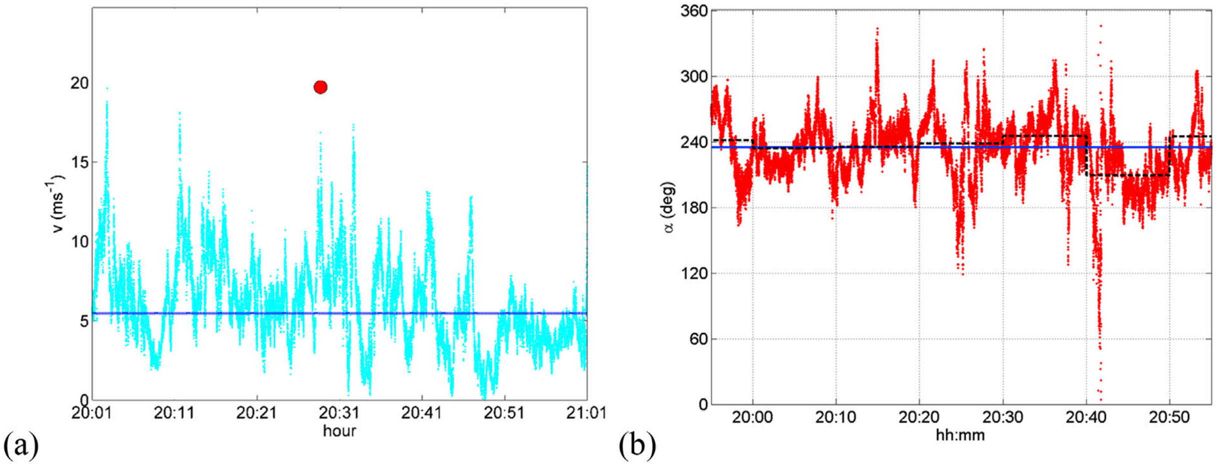

Fig. 8. Recording of an intermediate event detected in the Port of La Spezia on 16th December 2011 (De Gaetano et al., 2014): (a) velocity; (b) direction.

available data, nearly 250 transient recordings were gathered (Zhang et al., 2018a).

All these records were decomposed (Solari et al., 2015a; Zhang et al., 2018a) by the classical method proposed by Chen and Letchford (2004) and Holmes et al. (2008). In this framework (Fig. 9), the wind velocity $v(t)$ in the time interval T was expressed as the sum of a slowly-varying mean wind velocity $\overline{v}(t)$ plus a residual rapidly-varying random fluctuation $v^{'}(t)$, where t is time. This latter quantity was expressed in turn by the product of its slowly-varying standard deviation $\sigma_v(t)$ by a so-called reduced turbulent fluctuation $\tilde{v}^{'}(t)$, dealt with as a stationary Gaussian process with zero mean and unit standard deviation. The ratio between $\sigma_v(t)$ and $\overline{v}(t)$ was referred to as the slowly-varying turbulence intensity $I_v(t)$. The ratio between the peak wind velocity $\widehat{v}$, averaged over a short time interval $\tau \ll T$, and the maximum value of the slowly-varying mean wind velocity $\overline{v}_{\max}$ was referred to as the gust factor G_v. The analyses developed by Solari et al. (2015a) and Zhang et al. (2018a) were based on $\tau = 1$ s and $T = 10$ minutes; the slowly-varying time-functions $\overline{v}(t)$ and $\sigma_v(t)$ were extracted through a mobile mean operator with moving average $\Delta T = 30$ s.

Based on these analyses, thunderstorm records were classified in two families depending on whether the peak associated with the gust front passage is apparent in a 10-min period (Fig. 10) or a 1-h period (Fig. 11). Some criteria to define the duration of the gust front passage were proposed and the different shapes of thunderstorm outflows were classified by Zhang et al. (2018a). The average value of the turbulence intensity $\overline{I}_v$ and integral length scale L_v are weakly dependent of roughness length. The occurrence of higher values of $\overline{I}_v$ and L_v for synoptic winds rather than for thunderstorm outflows (Solari et al., 2015a) is fictitiously linked to the averaging time, i.e. the 10-min mean for synoptic winds and a moving average filter (much smaller than 10 min) for thunderstorms; using the latter approach for both of them, $\overline{I}_v$ and L_v have been shown to assume similar values (Zhang et al., 2018a). The power spectral density of the reduced turbulence closely matches the synoptic trend in the inertial sub-range whereas the low-frequency range is deeply influenced by the extraction procedure of the slowly-varying mean speed. Its parameterization calls for expressing this quantity as a function of a reduced frequency in which the classical height above ground (Solari et al., 2015a) has to be replaced by the integral length scale of the reduced turbulent fluctuation evaluated through its auto-correlation function (Zhang et al., 2018a).

A novel decomposition rule of the velocity recordings of thunderstorm outflows has been recently formulated (Zhang et al., 2019a). It is based on the remark that the classical decomposition is applied to the modulus of the wind speed disregarding the shift of the wind direction that represents the key issue of a translating downburst; in addition, it is incoherent with the traditional decomposition of synoptic wind speeds, where the mean wind velocity $\overline{u}$ and the mean wind direction $\overline{\beta}$, dealt with as constant over time intervals in the spectral gap, are firstly determined; the residual fluctuation is then decomposed into its longitudinal $u^{'}(t)$ and lateral $v^{'}(t)$ stationary Gaussian turbulence components.

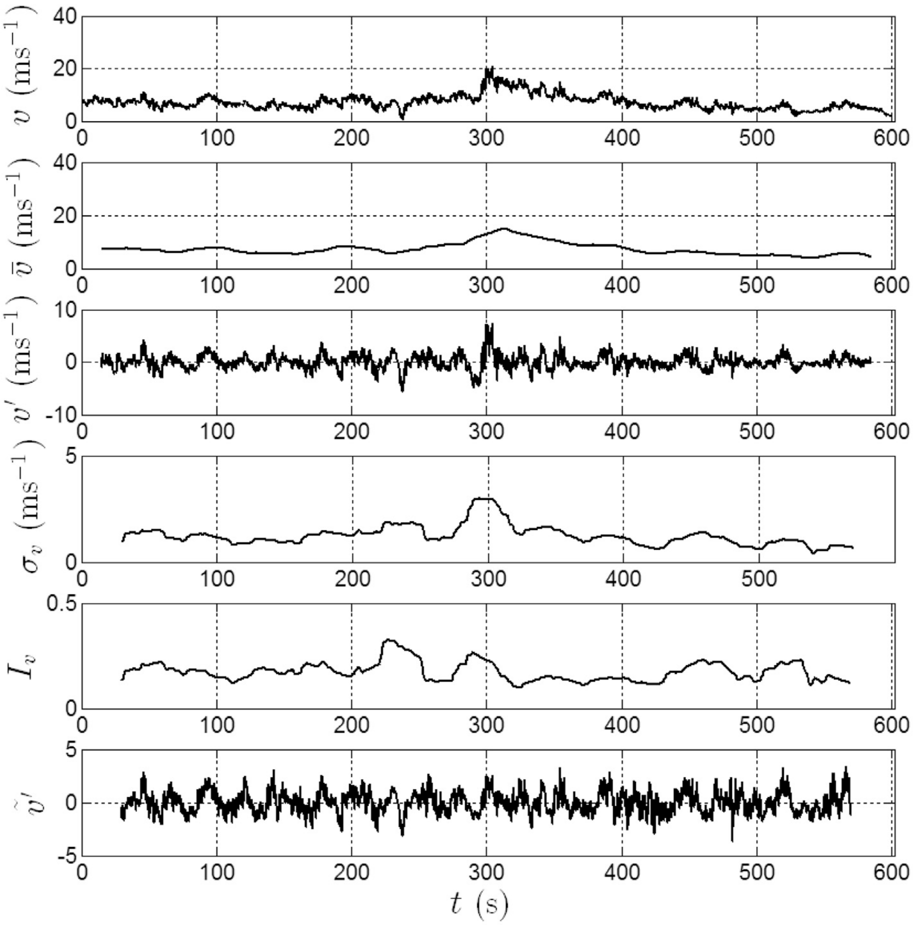

Fig. 9. Decomposition of a thunderstorm outflow velocity record (Solari et al., 2015a).

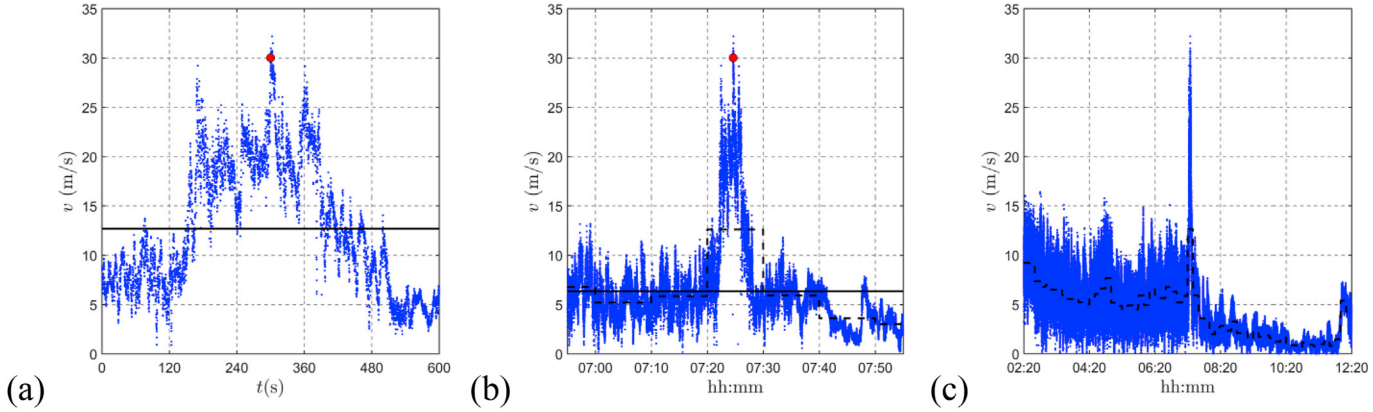

Fig. 10. Thunderstorm outflow recorded in the Port of La Spezia on 11 April 2012 (Zhang et al., 2018a): velocity in a 10-min period (a), in a 1-h period (b) and in a 10-h period (c).

The novel directional decomposition rule makes the analysis of thunderstorm outflows and synoptic winds coherent jointly introducing the slowly-varying mean wind velocity $\overline{u}(t)$ and direction $\overline{\beta}(t)$; accordingly, the residual fluctuation is decomposed into its longitudinal $u^{'}(t)$ and lateral $v^{'}(t)$ non-stationary turbulence components. These quantities are expressed in turn by the product of their slowly-varying standard deviation, $\sigma_u(t)$ and $\sigma_v(t)$, by so-called reduced turbulent longitudinal and lateral fluctuations, $\tilde{u}^{'}(t)$ and $\tilde{v}^{'}(t)$, dealt with as un-correlated stationary Gaussian processes with zero mean and unit standard deviation. The ratios between such standard deviations and the slowly-varying mean wind velocity are referred to as the slowly-varying longitudinal and lateral turbulence intensities, $I_u(t)$ and $I_v(t)$.

Figs. 12 and 13 show the directional decomposition of the wind velocity of two thunderstorm outflows with similar slowly-varying mean speed and different directional features. The statistical analysis of the measured signals shows that, once the velocity has been purged of the low-frequency harmonic content associated with the slowly-varying mean component, the longitudinal and lateral turbulence components have similar properties (Zhang et al., 2019a).

Huang et al. (2019) and Zhang et al. (2019b) provide a comparison of

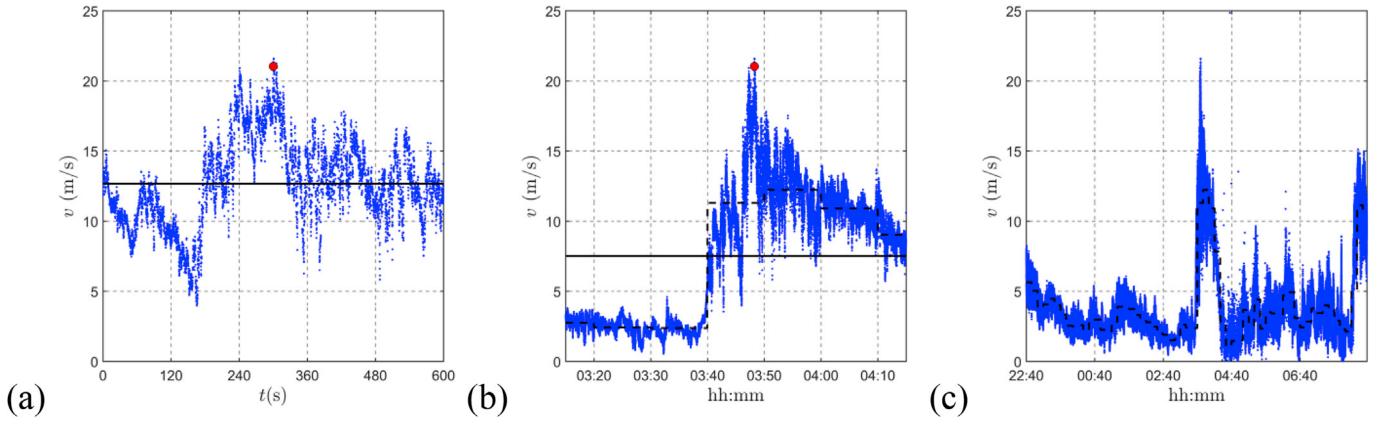

Fig. 11. Thunderstorm outflow recorded in the Port of Livorno on 21 July 2014 (Zhang et al., 2018a): velocity in a 10-min period (a), in a 1-h period (b) and in a 10-h period (c).

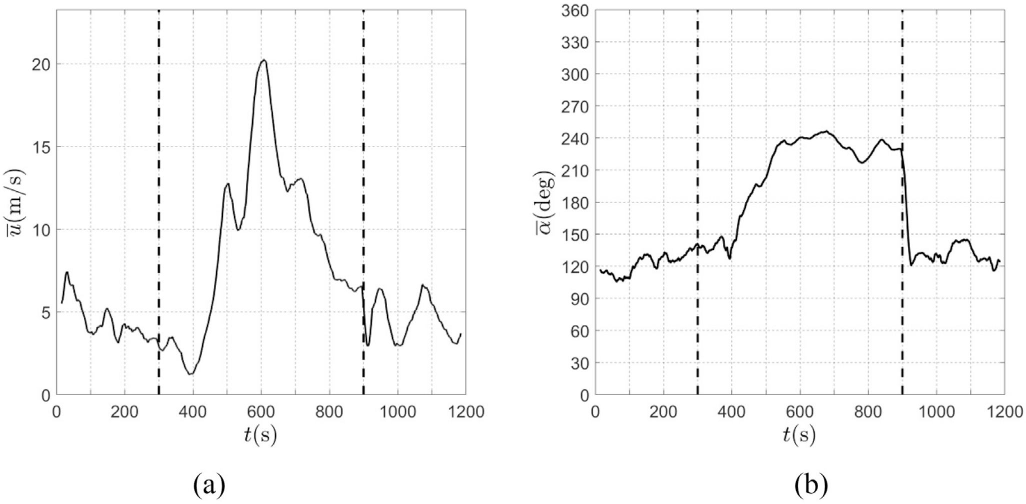

Fig. 12. Slowly-varying mean wind velocity (a) and direction (b) during a thunderstorm outflow occurred on October 15, 2012 in the Port of La Spezia (Zhang et al., 2019a).

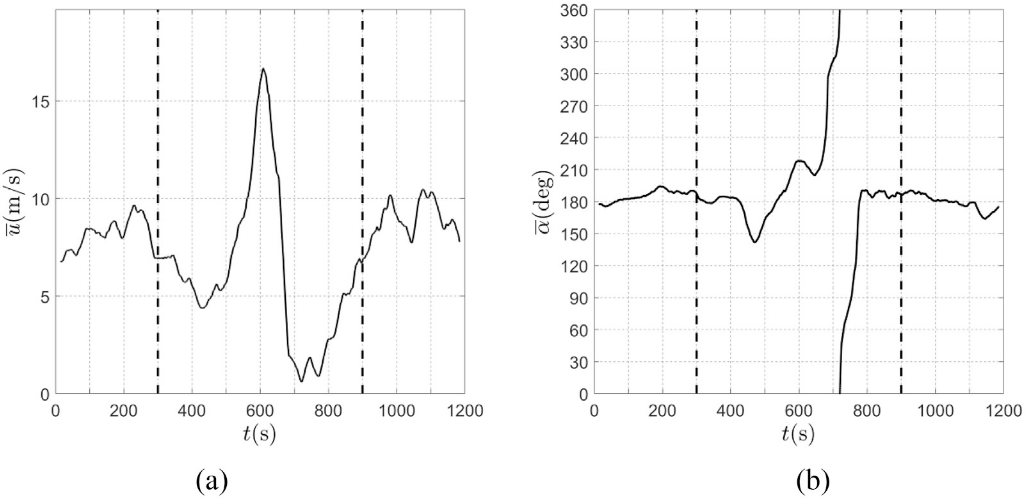

Fig. 13. Slowly-varying mean wind velocity (a) and direction (b) during a thunderstorm outflow occurred on January 18, 2014 in the Port of Livorno (Zhang et al., 2019a).

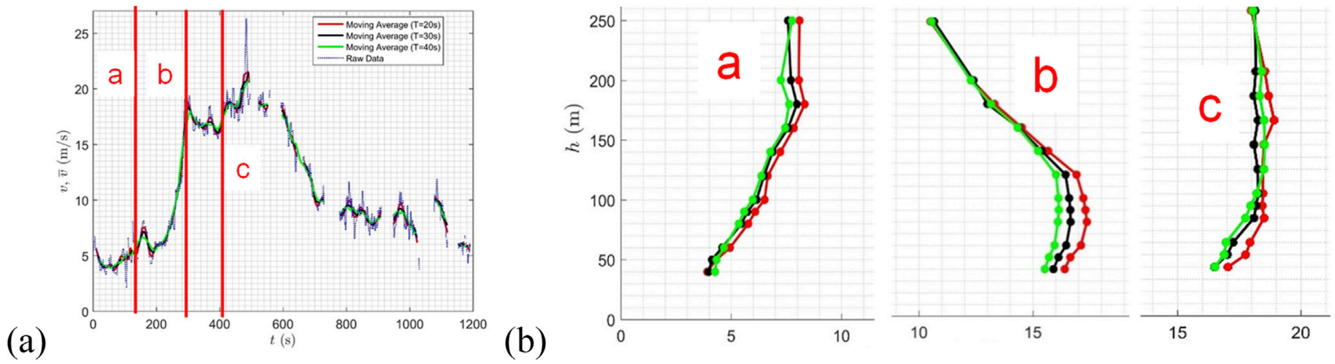

Fig. 14. LiDAR profiler measurements in the Port of Livorno, 13 September 2015: (a) velocity at 120 m above ground; (b) evolutionary vertical wind velocity profile (Burlando et al., 2017b).

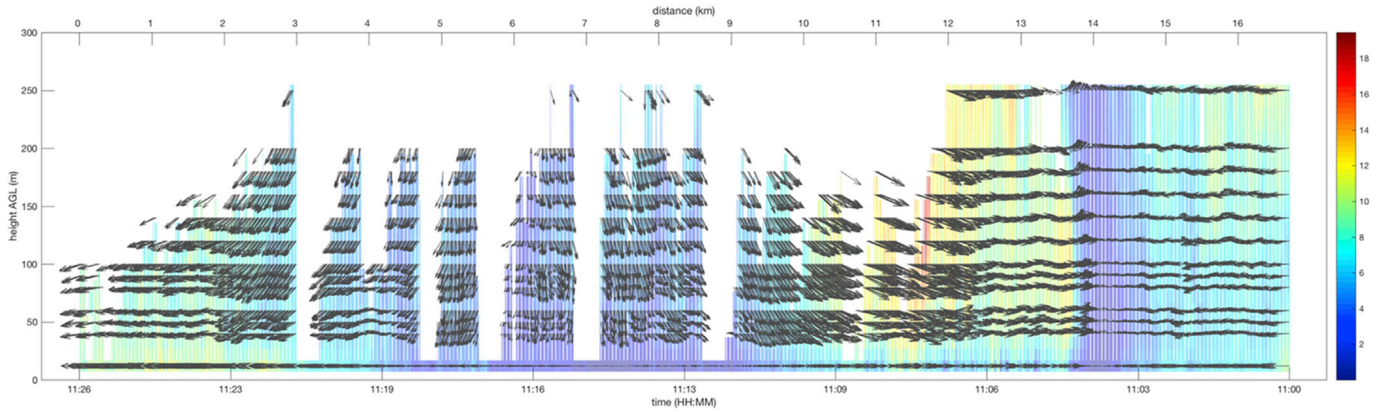

Fig. 15. Reconstruction of the downburst occurred in the Port of Livorno on 13 September 2015, based on measurements carried out through a LiDAR profiler (Burlando, 2019).

the wind speed in thunderstorm outflows detected respectively in the areas of Chengdu and Beijing, China, with those recorded in the northern Mediterranean, providing a preliminary answer to the crucial question whether thunderstorms have similar properties in different areas, or, better, what of their properties are similar and what depend on the area itself.

3.2. *Velocity profile*

Studies are in progress on the evolutionary properties of the vertical profile of the wind speed and direction as recorded by LiDAR profilers (Burlando et al., 2017b; Canepa et al., 2019). They show (Fig. 14) that the wind speed profile is initially growing with height, as expected in the atmospheric boundary layer (ABL) (position a). Then, it takes a classic nose shape at the base of the ramp-up part of the record and retains it for no more than 30–40 s (position b). After the peak wind speed, the profile becomes at first almost flat and then returns to growing with height (position c). It is very worth noting that during this evolution the wind direction exhibits a rapid shift over time but, diversely from the wind speed, keeps the same value over the height.

Fig. 15 provides a reconstruction of the downburst detected by the LiDAR profiler in the Port of Livorno on 13 September 2015 (Burlando, 2019). The ordinate refers to the height above ground, the abscissa corresponds to the time; the contributions of storm motion (also called translational component) and boundary layer (or background) flow have been removed in Fig. 15 so that vertical wind profiles represent the thunderstorm outflow while passing over the LiDAR. Their evolution denotes the transient character of the phenomenon and depicts the diverging flow that spreads out of the downdraft when it gets to the ground.

3.3. *Weather scenarios*

The extraction procedure described in Section 3.1 has the capability of detecting the presence and characteristics of transient events, labelled as thunderstorm outflows, based on sole anemometric measurements. However, the knowledge of the weather scenarios concurrent with these phenomena is very useful to identify their meteorological nature, to improve their knowledge, and to link their properties with the measured records.

In order to make a first step in this direction, the transient event occurred on 1 October 2012 over the city of Livorno was selected as a test case (Burlando et al., 2017a). In this circumstance, detailed analyses were made of the wind speed and direction detected simultaneously by three anemometers of the monitoring network (Fig. 16a). 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), proxy data (lightning, Fig. 16b), remote sensing (radar and satellite images) and visual observations (from European Severe Weather Database). This information led to reconstruct the weather scenario, to classify this event as a wet downburst, to determine its time-space evolution, and to embed signal analysis in this framework to extract the key parameters for evaluating the wind loading of structures.

Unfortunately, this study required a great deal of work and time and repeating the same analysis for each thunderstorm event of a historical series of measurements represents a utopian prospect. In order to find a reasonable balance between expeditionary evaluations based on sole wind recordings and studies that encapsulate the above information within an extensive meteorological survey, a synthetic procedure was formulated for expressing a judgement, with limited burden, on the events related to

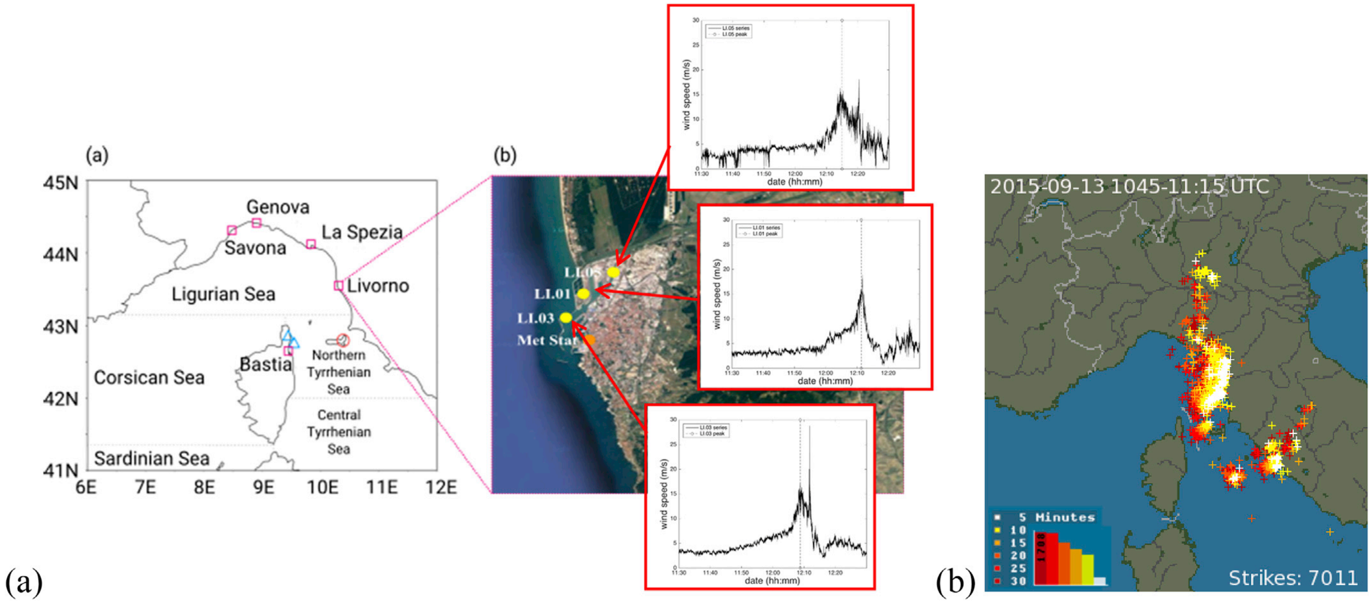

Fig. 16. Livorno downburst, 1 October 2012 (Burlando et al., 2017a): (a) map and velocity measurements; (b) lightning.

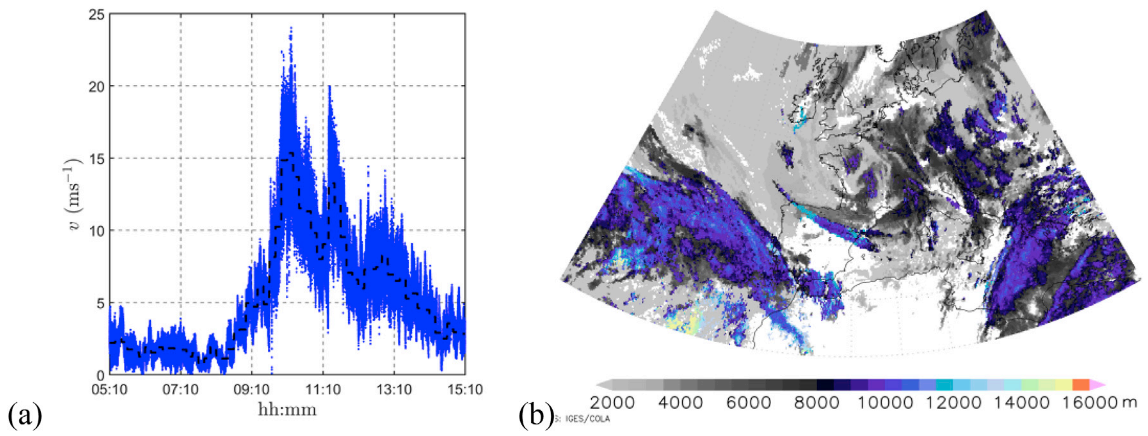

Fig. 17. (a) 10-h wind velocity record detected on 21 November 2013 by the anemometer 2 of the Port of Genoa; (b) cloud top height from MSG (Burlando et al., 2018b).

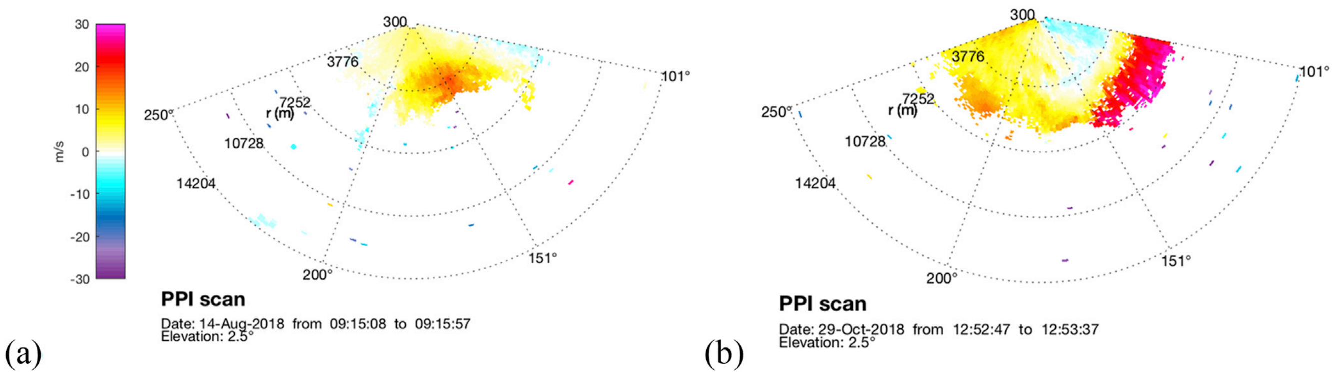

Fig. 18. Radial wind speed detected by the Windcube 400S pulsed LiDAR scanning system in the Port of Genova: (a) 14 August 2018; (b) 29 October 2018.

transient velocity measurements (Burlando et al., 2018b). Based on this procedure some phenomena, initially misclassified as thunderstorm outflows, were later defined as synoptic events with a rapid evolution (Fig. 17). The prosecution of this research involves a co-operation with the Institut für Meteorologie of the Freie Universität Berlin, Germany, aiming to fill the gap between wind engineering and atmospheric sciences, as well as to investigate the role of climate changes on the evolution of thunderstorms (Nissen et al., 2014; Púcik et al., 2017).

Meanwhile, a new research line has been opened aiming to process the data detected by the LiDAR scanner (Section 2, Fig. 18), integrating

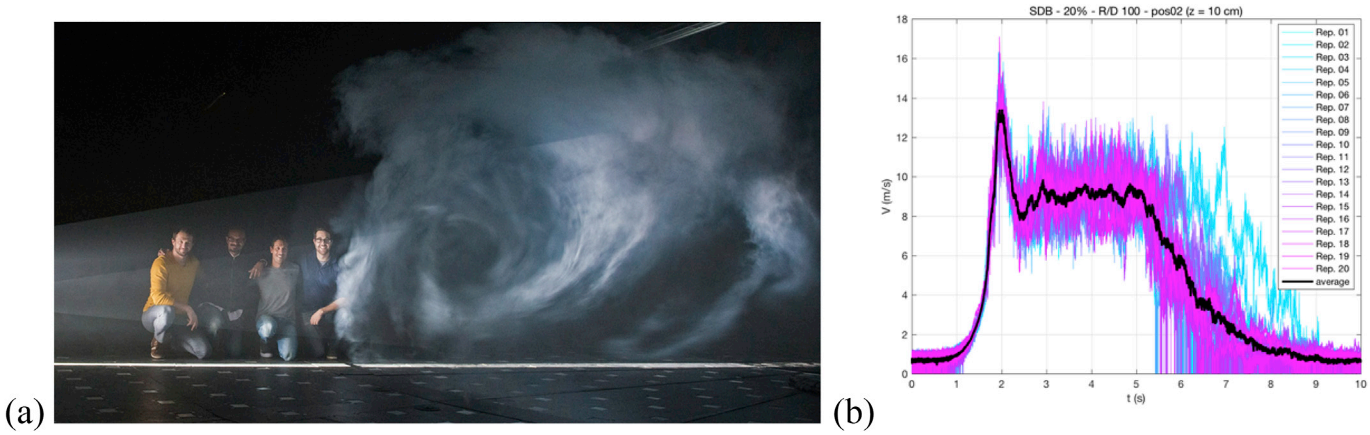

Fig. 19. Wind tunnel simulations at the WindEEE Dome: (a) outflow and vortex ring; (b) time series of the wind speed and their ensemble mean (Burlando et al., 2018a).

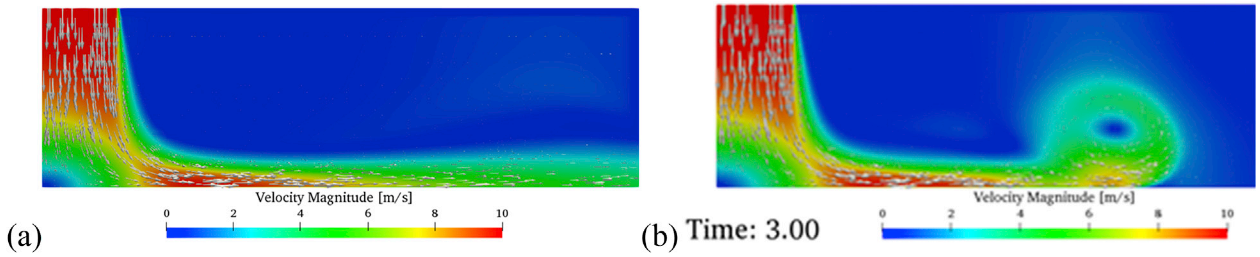

Fig. 20. RANS and URANS simulations of an impinging wall jet.

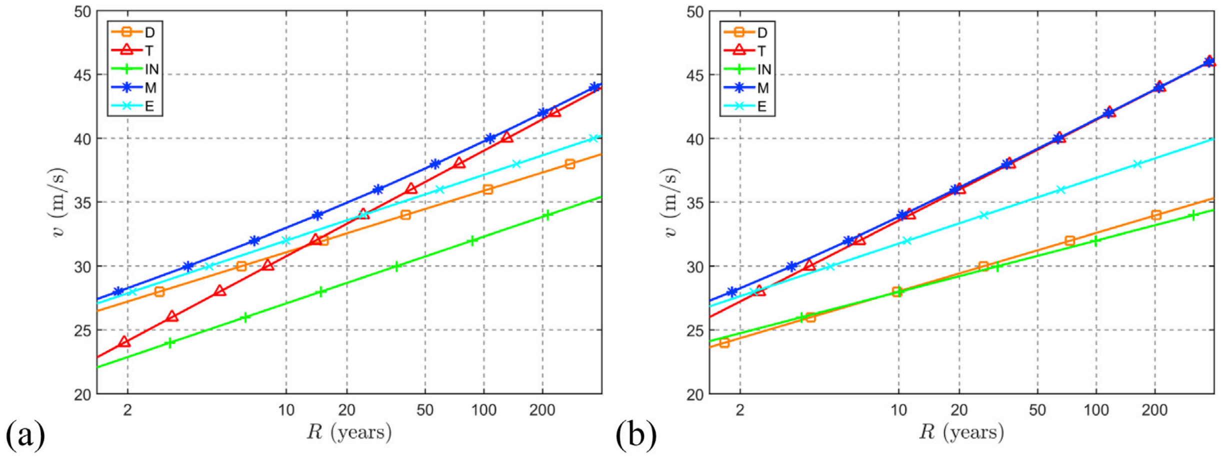

Fig. 21. Peak wind velocity as a function of the return period: (a) anemometer 02 of the Port of Livorno; (b) anemometer 03 of the Port of La Spezia (Zhang et al., 2018b).

this information with that provided by the meteorological radar Doppler of the Italian Meteo-radar Network which is installed over the Alps in the western part of Liguria at 1395 m above sea level. The analysis of measurements collected by both instruments is finalised to detect downdrafts inside clouds and study their evolution into gust fronts or downbursts at the surface.

3.4. Physical and numerical simulation

Thanks to several distributed sensors, the actual monitoring network provides a fine description of the local time structure of downbursts. However, this is not enough to derive a detailed model of the spatial structure of a phenomenon that runs out in a few kilometres on Earth's surface and in a few hundred metres along the vertical direction. Wind tunnel tests and CFD simulations are fundamental tools to fill this gap.

Wind tunnel simulations are conducted in co-operation with the University of Western Ontario in London, Canada, at the WindEEE Dome (Fig. 19), where a large-scale translating downburst can be embedded into a background boundary layer flow field (Hangan et al., 2017; Romanic et al., 2019a; Junayed et al., 2019). Initially, preliminary tests have been carried out to evaluate the feasibility of this laboratory to reproduce the flow fields of the downbursts as detected in the High Tyrrhenian area (Burlando et al., 2018a). Later, attention was focused on scaling criteria between model experiments and full-scale conditions (Xu

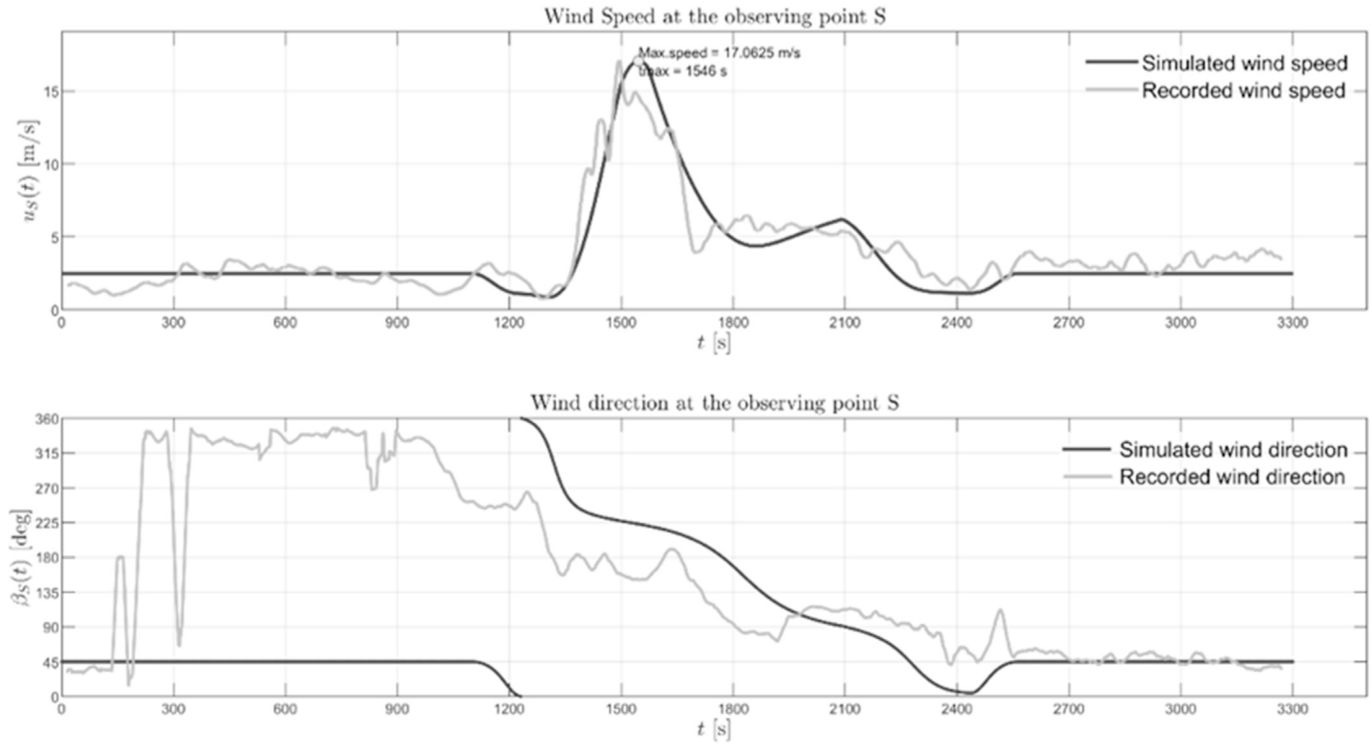

Fig. 22. Comparison between measured and simulated slowly-varying mean wind speeds and directions (Xhelaj et al., 2019).

and Hangan, 2008; McConville et al., 2009; Sterling et al., 2011), up to derive a novel procedure fitting this aim (Romanic et al., 2019b). Finally, a systematic campaign of experiments has been carried out to inspect the role of the roughness length, the efficacy of reproducing the wind field of a translating downburst through an inclined jet and the effectiveness of the vector re-composition (Holmes and Oliver, 2000) of outflow wind velocity, translational velocity and background velocity.

In parallel with physical simulations, CFD simulations have been exploited in co-operation with the Urban Physics and Environmental Wind Engineering Research Centre at the Technical University of Eindhoven, The Netherlands (Blocken, 2014). In this framework, systematic simulations have been carried to reproduce by RANS and URANS the experimental conditions created at the WindEEE Dome by an impinging wall jet (Fig. 20) (Zuzul et al., 2019). According to plans of the THUNDERR project, new analyses will be soon performed using LES and implementing a sub-cloud model with the aim of reproducing laboratory and full-scale measurements.

4. Thunderstorm representation

The representation of the thunderstorm outflows is the core of the THUNDERR project since it is the output of the first objective, thunderstorms, and the input to the second objective, structures. It involves the formulation of a mathematical model that synthesizes the data gathered through field measurements, laboratory tests and CFD simulations in the framework of the fundamental equations of fluid dynamics, random fields and turbulence. This model should be enough detailed to capture the main physical features of thunderstorm outflows and enough simple to be transformed into wind loading from an engineering point of view. In addition, it is essential that this model is embedded into a robust probabilistic framework to create a link between thunderstorm outflow parameters and their probability of occurrence. The studies currently in progress to pursue this aim can be traced back to three research lines dealing with the extreme wind speed statistics (Section 4.1), downburst modelling (Section 4.2) and Monte Carlo simulations (Section 4.3).

4.1. *Extreme wind speed statistics*

Relying on almost 10 years of continuous measurements at some anemometers of the monitoring network and on the procedures established to separate different wind events preliminary estimates of the extreme peak wind speed distribution have been carried out (Zhang et al., 2018b). In Fig. 21, D denotes depressions or extra-tropical cyclones, T thunderstorm outflows, and IN intermediate events; M corresponds to a mixed statistics analysis (Gomes and Vickery, 1977/1978), whereas E denotes the statistical analysis of the ensemble of the data gathered in a unique dataset as a term of reference (Lombardo et al., 2009).

As for many other parts of the world, the most intense wind events in the High Tyrrhenian Sea area are mainly due to thunderstorms. Also, gathering the ensemble of the extreme wind speed values in a unique dataset leads to underestimating the mixed distribution especially for high return periods (Lagomarsino et al., 1992), those that determine structural safety, where the actual mixed distribution tends to coincide with the thunderstorm outflow distribution.

4.2. *Thunderstorm outflow modelling*

An effort is being devoted to formulate a thunderstorm model of the slowly-varying mean wind velocity in which the horizontal wind speed is expressed as the vector summation of the stationary radial velocity generated by an impinging jet, the downdraft translating velocity and the background wind field velocity into which the downburst is embedded (Xhelaj et al., 2019). All parameters employed by this model – the touch-down position, the downdraft diameter, the translating velocity and direction of the thunderstorm cell, the background wind velocity, the maximum wind velocity and the periods that rule the ramp-up and decay phases-are related to meteorological variables that are susceptible of statistical assessment.

Despite a parallel laboratory research is investigating the feasibility of combining different velocity components by a vector summation, all the analyses carried out until now show the capacity of this model not only to replicate actual events (Fig. 22) but also to extract their main parameters.

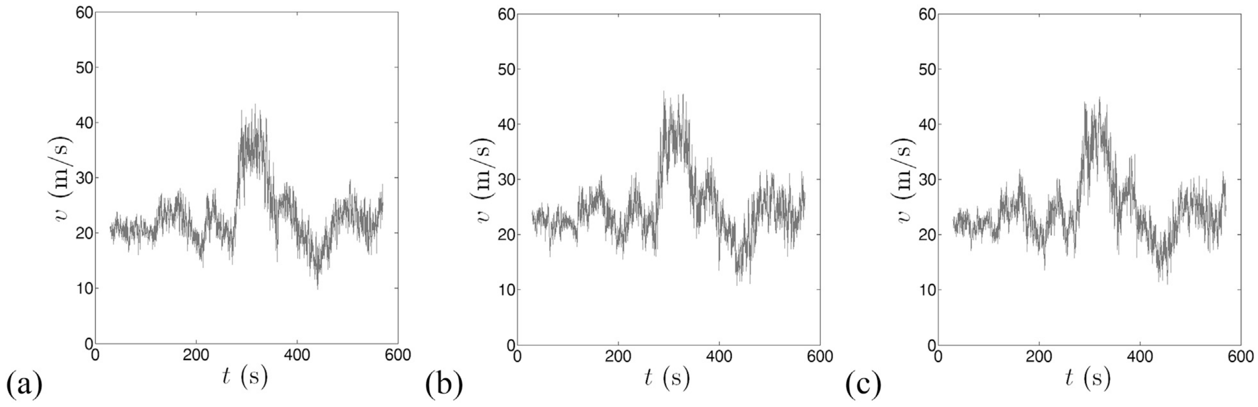

Fig. 23. Simulated velocity histories of a thunderstorm outflow at three heights: (a) $z = 18$ m; (b) $z = 54$ m; (c) $z = 80$ m (Solari et al., 2017).

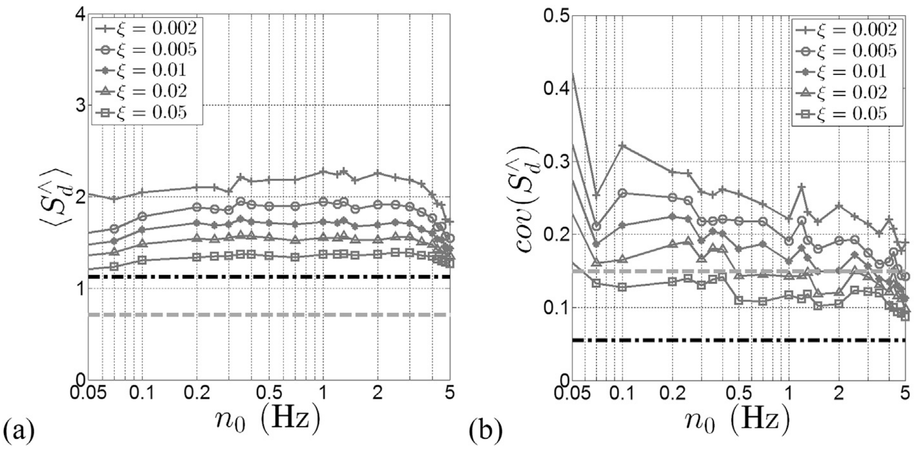

Fig. 24. Mean value (a) and coefficient of variation (b) of the thunderstorm response spectrum (Solari et al., 2015b).

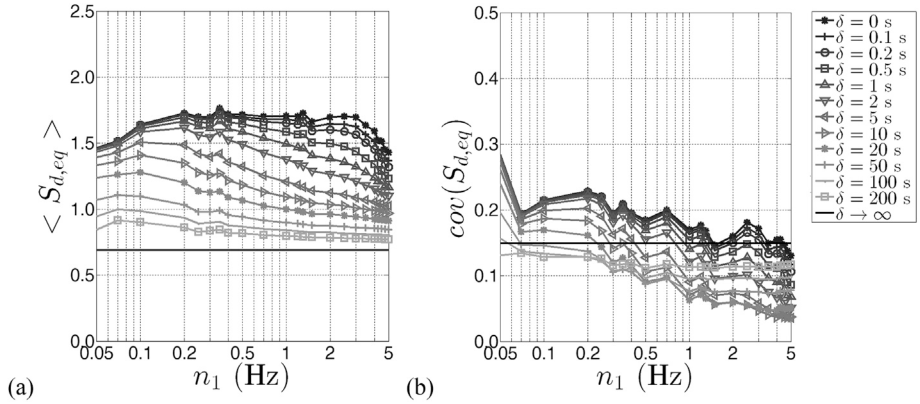

Fig. 25. Mean value (a) and coefficient of variation (b) of the equivalent response spectrum ($\xi = 0.01$) (Solari and De Gaetano, 2018).

Under this point of view, research is in progress aiming to create an automatic procedure to gather the sequence of the parameters associated with the thunderstorm outflows detected by the monitoring network. The final aim of this research is to characterize these parameters by a joint distribution function to be used in the framework of the Monte Carlo simulation strategy described in the next section.

4.3. Monte Carlo simulations

According to the THUNDERR project, a pair of serially connected Monte Carlo simulators should be developed.

The outer simulator should generate long-term series of thunderstorm parameters - the touch-down position, the downdraft diameter, the translating velocity and direction of the thunderstorm cell, the background wind velocity, the maximum wind velocity and the periods that rule the ramp-up and decay phases - based on their joint distribution, in a spirit close to the one used by Georgiou et al. (1983), Vickery et al. (2009) and many other authors for the statistical analysis of tropical cyclones. Similar studies concerning thunderstorm outflows have been carried out by Ponte and Riera (2010) and Aboshosha et al. (2017).

The inner simulator should generate, for each set of above parameters, a non-stationary velocity field. Diversely from the classical Monte

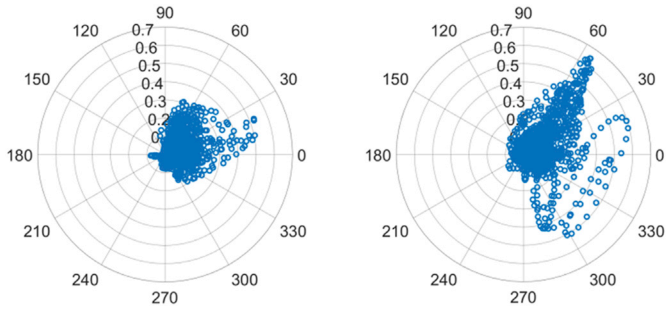

Fig. 26. Directional response of the Brancusi Endless Column (Solari, 2013) to a synoptic and to a thunderstorm event (Brusco et al., 2019).

Carlo simulations of non-stationary random vectors (Li and Kareem, 1991; Sakamoto and Ghanem, 2002) and some simulation techniques recently proposed with regard to downbursts (Wang et al., 2013; Peng et al., 2017), a novel strategy was formulated that captures the inherent properties of thunderstorm outflows making recourse to simple physical concepts and measured velocity records (Solari et al., 2017). It consists in generating the different components that make up the wind field (Section 3.1) by taking into account their own different sources of randomness, then recomposing the overall wind field (Fig. 23).

A major step forward of this procedure is the application of the equivalent wind spectrum technique (Piccardo and Solari, 1998) to the stationary Gaussian reduced turbulent fluctuation $\tilde{v}'$ (Solari and De Gaetano, 2018). Thanks to it, a multi-variate non-stationary non-Gaussian random field may be reconstructed by simulating a mono-variate stationary Gaussian process. The high precision of this algorithm was verified by comparing its results with the target wind field and the measured data.

5. Structural analysis

Despite a lot of research mostly carried out in the last two decades (Chen, 2008; Kwon and Kareem, 2009), the literature is still lacking in simple and physically realistic methods, shared by scientific community, applied in engineering practice, supported by robust field data, suitable to evaluate the loading and response of structures due to thunderstorm outflows. The second objective of the THUNDERR project just aims at overcoming this major shortcoming by formulating a unitary model of the thunderstorm outflow loading of structures, embedding it into a robust and general format of the wind loading of structures in mixed climatological conditions. The studies currently in progress to pursue this aim can be traced back to three research lines dealing with the dynamic response of structures (Section 5.1), full-scale measurements (Section 5.2) and wind loading format (Section 5.3).

5.1. Dynamic response

Despite numerous studies on the wind-excited response of structures to thunderstorm outflows, the first complete model proposed on this topic is quite recent (Kwon and Kareem, 2009). It determined the dynamic response in the mixed time-frequency domain by the evolutionary power spectral density method and expressed the equivalent static force as the product of the mean force by a non-dimensional coefficient, called

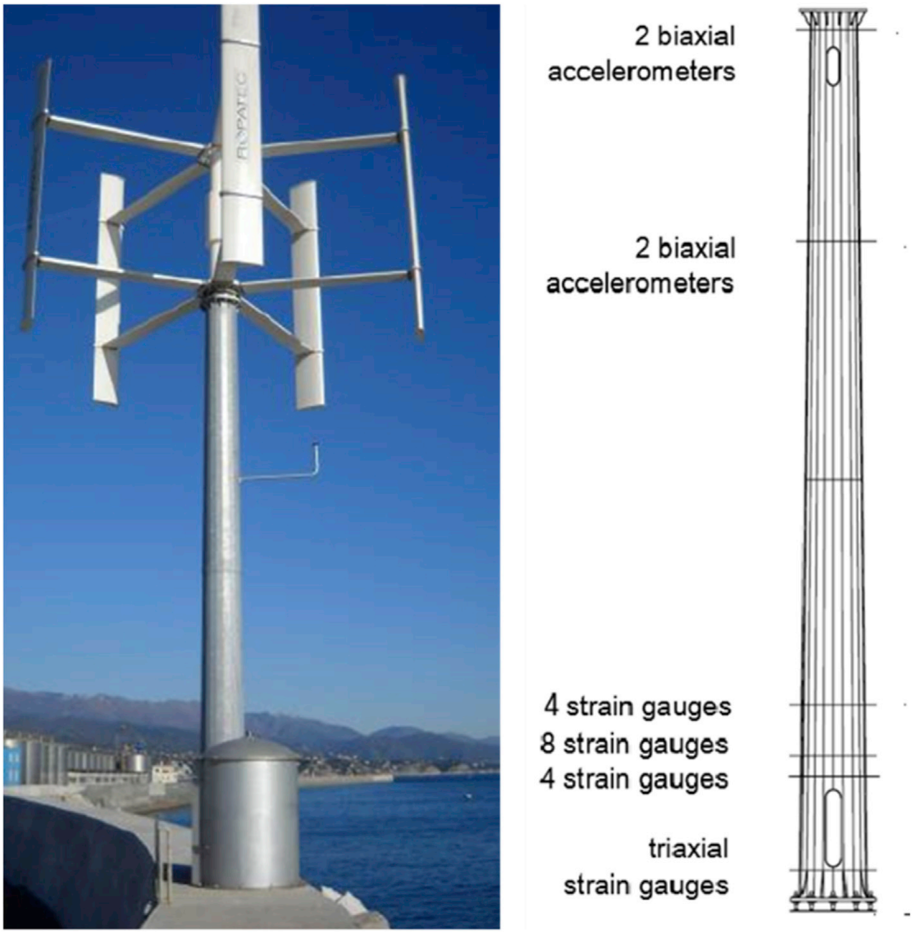

Fig. 27. Full-scale monitoring of a wind turbine in the Port of Savona.

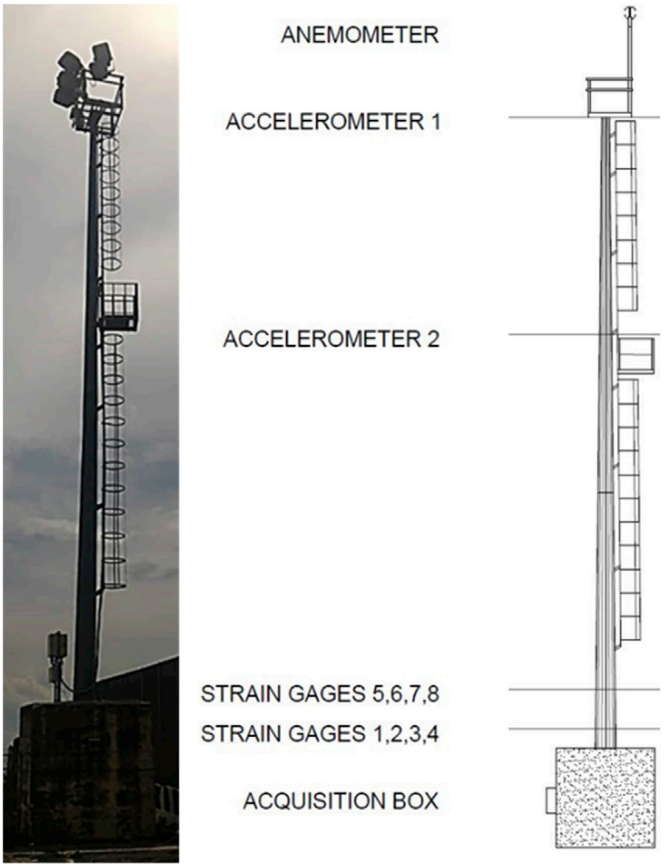

Fig. 28. Full-scale monitoring of a light tower in the Port of La Spezia.

gust front factor, through which it generalizes the method developed by Davenport (1961) for synoptic winds to transient phenomena.

The study of the thunderstorm loading and response of structures carried out at the University of Genoa was inspired by the consideration that thunderstorm outflows are transient phenomena with short duration and that the structural response to these phenomena, most notably to earthquakes, is usually evaluated by the response spectrum technique (Housner, 1959). Based on this remark and some previous studies carried out by the first author (Solari, 1989), a "new" method was formulated that generalised the "old" response spectrum technique from earthquakes to thunderstorm outflows.

Initially, this problem was formulated for a Single-Degree-Of-Freedom (SDOF) system (Solari et al., 2015b) subjected to a perfectly coherent wind field. This led to express the equivalent static force as the product of the peak wind force by a non-dimensional quantity, the thunderstorm response spectrum, depending on the fundamental frequency n_0 and damping ratio ξ of the structure (Fig. 24).

Later, this formulation was generalised to Multi-Degree-Of-Freedom (MDOF) systems (Solari, 2016) subjected to a partially coherent wind field; the structure was modelled as a slender vertical cantilever beam whose dynamic response was dependent on the sole first vibration mode. Analyses were carried out making recourse to the equivalent wind spectrum technique (Piccardo and Solari, 1998), which makes the use of the response spectrum straightforward. The equivalent static force is expressed as the product of the peak wind force by a non-dimensional quantity, the equivalent response spectrum, depending on the first natural frequency n_1, the damping ratio ξ and the reference structural size δ; this latter quantity synthesizes the role of aerodynamic admittance.

In parallel with the thunderstorm response spectrum technique, time-domain analyses were carried out based on the hybrid simulation strategy described in Section 4.3 (Solari et al., 2017), taking into account all vibration modes. This study showed that the probability density function of the maximum value of the structural response due to thunderstorm outflows is more spread than that related to synoptic extra-tropical cyclones. Thus, diversely from synoptic winds (Davenport, 1964), it is not appropriate to identify the maximum response with its mean value. On the other hand, many other aspects of the wind loading and response of structures to thunderstorm outflows are qualitatively similar to those exhibited for synoptic winds. The structural displacement is almost unaffected by the contribution of higher vibration modes. The aerodynamic admittance gives rise to analogous effects for thunderstorms and cyclones. The resonant part of the response to thunderstorms is apparent despite their short duration.

Solari and De Gaetano (2018) carried out a joint calibration and advancement of the two methods described above, proving that the results provided by the response spectrum technique (Fig. 25) and the time-domain solutions closely agree. This confirms the potential of the response spectrum to be a suitable tool for evaluating the thunderstorm loading and response of structures and the efficiency of hybrid simulation and time-domain integrations to study, with a limited computational burden, advanced structural issues. Kwon and Kareem (2019) showed that the response spectrum technique and the gust front factor method lead to similar results.

Taking advantage of the wealth of information gathered by the monitoring network, an evolutionary spectral density model of thunderstorm outflows coherent with measurements is currently studied to evaluate the transient response of structures through non-stationary random dynamics (Roncallo and Solari, 2019). This aims at generating a triad of methods – response spectrum technique, time-domain analysis, evolutionary power spectrum – to be jointly or alternatively used according to the properties of the problem dealt with and the aims of the solution inspected.

Finally, it is worth mentioning the first research (Brusco et al., 2019) aiming to study the dynamic response of structures taking into account the directional shift of the outflow due to the translation of the thunderstorm cell (Fig. 26). It proves that this shift often involves a relevant increase in the response.

5.2. *Full-scale measurements*

A key issue of the THUNDERR project is to detect simultaneously the wind velocity field due to thunderstorms and the structural response to these phenomena to calibrate and improve the methods described in Section 5.1. In this stage of the project, two structures have been equipped by ultrasonic anemometers, servo-accelerometers and strain-gauges. The first monitored structure is a 20 kW vertical axis wind turbine (VAWT) (Fig. 27) in the Port of Savona (Pagnini et al., 2015, 2018). The second one is an 18 m high light tower in the Port of La Spezia (Fig. 28). High-resolution wind velocities, recording the three components of the wind with a frequency rate of 10 Hz, and structural response, recording acceleration and deformation components with a frequency rate of 200 Hz, are registered simultaneously and continuously, using synchronized accelerometers and strain-gauges. Some selected measured records, coupled with a refined 3D finite element model of the structures, have been used to identify carefully the dynamic properties of the structures.

Wind tunnel tests have been also conducted to determine aerodynamic parameters in the steady-flow laboratory of the University of Genova. Other aerodynamics and aeroelastic tests are planned at the end of the project at the WindEEE Dome in non-steady flow.

Applying the semi-automatic procedure already described in Section 3.1 (De Gaetano et al., 2014; Burlando et al., 2018b), records related to intense thunderstorm outflows are being selected and will constitute benchmark cases for structural response models.

The effects of a non-stationary wind event on the VAWT response have been analysed in (Orlando et al., 2020), showing that the rapid increase and decrease of the wind velocity caused a sudden stop and restart of the rotor, giving rise to few large cycles, very dangerous for the

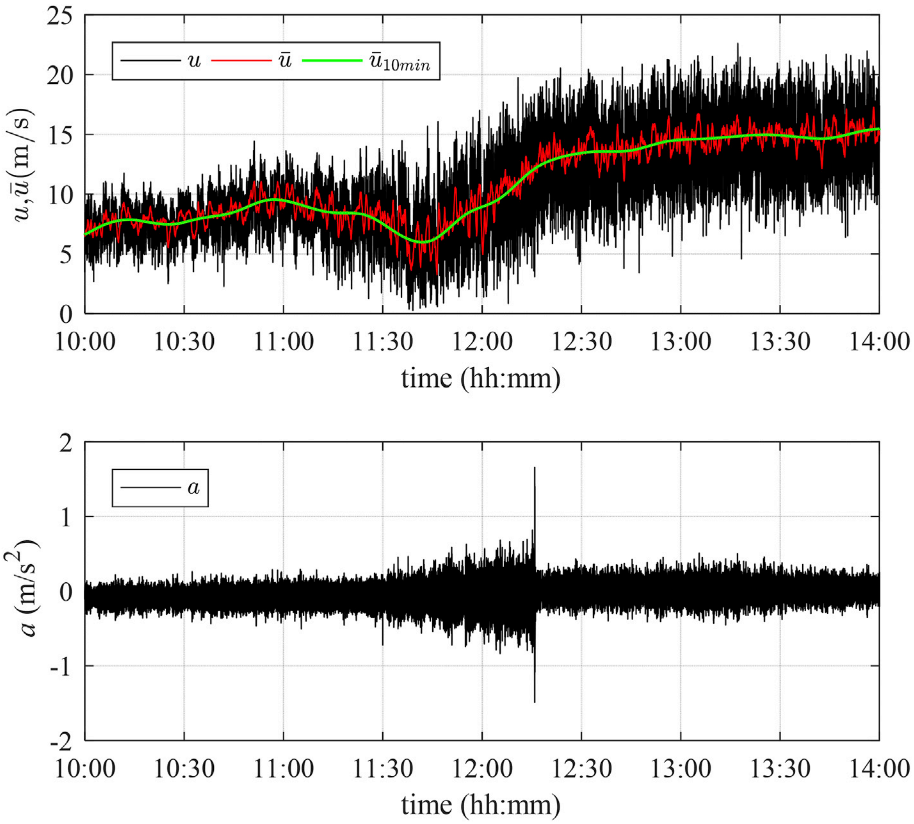

Fig. 29. Full-scale monitoring of the VAWT during a non-stationary event of 30th April 2018: (a) wind speed; (b) top acceleration.

fatigue damage of the structure. Fig. 29 shows the non-stationary wind event registered on 30th April 2018 on the VAWT. In correspondence of the wind velocity rump-up, the acceleration of the shaft grows rapidly, reaching a large peak when the rotor suddenly stops. After that, the wind velocity still increases, while the structural acceleration reduces, due to the vanishing of the rotating mass contribution. It is worth noticing that the registered non-stationary event was not a thunderstorm. In case of a downburst, the rapid ramp-up of the wind velocity could give rise to even more relevant effects.

Fig. 30 shows the thunderstorm wind event detected on 4th April 2019 on the light tower in the Port of La Spezia. The large acceleration cycles generated by the wind gust are apparent, especially in correspondence of the rapid increase of the instantaneous wind velocity in the time interval 8:40–8:50.

New monitoring activities are currently in progress in the Ports of Genova and La Spezia, on a hill close to Genova and in Romania, in order to detect different structural types, orography and climate conditions.

5.3. *Wind loading format*

Wind loading on structures is usually evaluated neglecting the presence of thunderstorm outflows. In the rare cases in which data on thunderstorm outflows are available, a 5-step procedure is used: 1) synoptic extra-tropical cyclone and thunderstorm outflow recordings are separated; 2) the disjoint extreme distribution of each phenomenon is determined; 3) such distributions are joined in a mixed distribution (Gomes and Vickery, 1977/1978); 4) the design wind speed is determined with regard to an assigned design return period; 5) without suitable models for thunderstorm outflows, wind loading is evaluated by the classical method for synoptic winds (Davenport, 1961). This is at odds with the awareness that the design wind speed is often due to thunderstorm outflows and they have different properties from synoptic cyclones.

The THUNDERR project aims at overcoming this shortcoming by implementing a renewed 4-step approach (Solari, 2014). The first two steps are the classical ones. The following steps are innovatory: 3) the design wind speed is determined, separately for cyclones and thunderstorms, in correspondence of an assigned design return period; 4) the wind loading is evaluated by distinct methods for cyclones and thunderstorms, so separating the classical unique wind loading into two distinct wind loading conditions. This choice is supported by the different profiles and time-histories of these events and by their different size, duration and frequency that makes the use of one set of wind partial and combination factors non-sense. This necessarily implies the calibration of a novel set of partial and combination factors for thunderstorms.

It is worth noting that this new 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.

6. 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 for the building of unsafe and/or too expensive structures. The insufficient safety of structures with small to medium height – namely cranes, small turbines, light poles, canopies, etc. - 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 reduced rate of their damage and collapse; in areas in which the design wind speed is due to thunderstorms, this may be due to using boundary layer wind speed growing with height, while the maximum power of downbursts occurs close to ground.

The final aim of the THUNDERR project is to create a new wind loading framework that may re-centre the safety and sustainability of

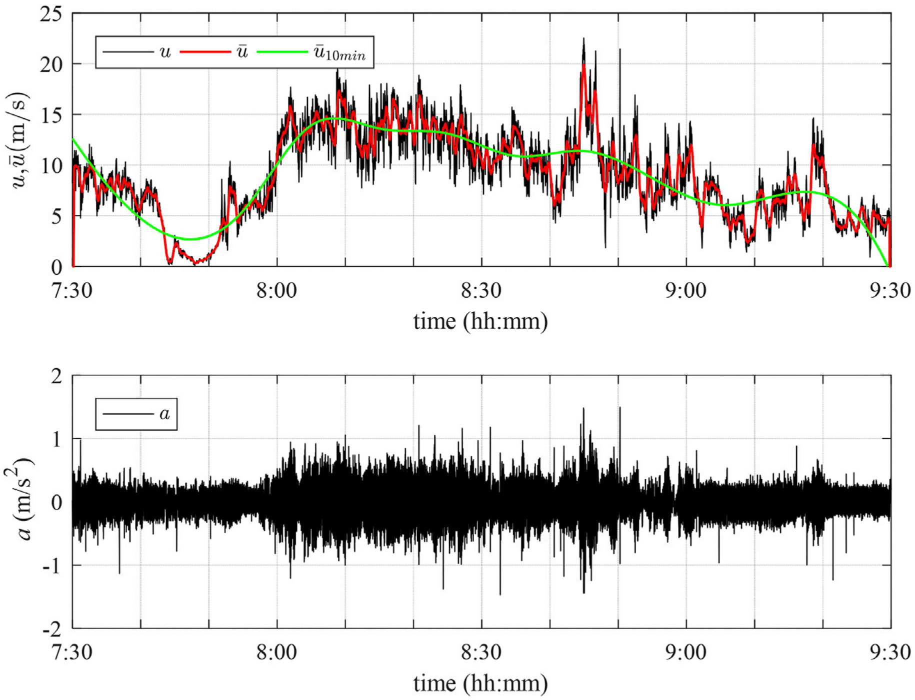

Fig. 30. Full-scale monitoring of the lighting pole during the thunderstorm event of 4th April 2019: (a) wind speed; (b) top acceleration.

construction. For this reason, an extensive dataset of structure test-cases has been gathered and will be analysed 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.

7. Conclusions and prospects

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 the built environment is still dominated by many uncertainties, by the lack of a shared model, and by the need of a rational framework in which wind actions due to synoptic events and thunderstorm outflows are embedded. The many shady areas that weigh on these topics represent a major shortcoming in civil engineering since wind is the most destructive natural phenomenon and thunderstorm outflows produce wind speeds and damage often more intense than those caused by the synoptic events in relation to which structural engineering is usual to determine design wind loading.

The THUNDERR project may represent a great opportunity to provide some answers to the many questions still opened and to fill several gaps. A key requirement for the success of this project is pursuing and realising an interdisciplinary viewpoint on this matter, such as to dissolve the many borders that still contribute to limit the development of knowledge in this field. In particular, an interdisciplinary vision of wind engineering and atmospheric sciences is indispensable to develop a thunderstorm model that in itself constitutes an innovative result and represents, at the same time, a physically correct and simple enough starting point to build around it a robust method to evaluate the wind actions and effects of thunderstorm outflows on structures. At the same time, the development of research in this field should pursue the widest possible vision that embraces analytical methods, numerical simulations, laboratory tests and full-scale measurements in a unified way. It is also essential that this vision is articulated on different time and space scales that are closely linked with each other.

In parallel and to support this vision, the awareness that wind measurements as they are performed now according to international standards are implicitly linked and calibrated for the phenomena at the synoptic scale must grow. This situation deprives such measurements and wind databases of the information necessary to recognize the occurrence of events on a local scale, such as downbursts, and does not provide the information required to depict their space-temporal properties. Only the recognition of this limitation may favour a generational change in the format of weather data and may allow a renewed knowledge of non-synoptic phenomena such as downbursts.

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

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Giovanni Solari: Conceptualization, Methodology, Supervision, Project administration, Funding acquisition, Writing - original draft. **Massimiliano Burlando:** Methodology, Formal analysis, Investigation, Validation, Writing - review & editing. **Maria Pia Repetto:** Methodology, Formal analysis, Investigation, Validation, Writing - review & editing.

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References

Aboshosha, H., Mara, T., Case, P., 2017. New framework for estimating thunderstorm design speed. In: Proc., 13th Amer. Conf. On Wind Engineering, Gainesville, Florida.

Bjerknes, J., Solberg, H., 1922. Life cycle of cyclones and the polar front theory of atmospheric circulation. Geofys. Publ. 3, 3–18.

Blocken, B., 2014. 50 years of Computational Wind Engineering: past, present and future. J. Wind Eng. Ind. Aerod. 129, 69–102.

Brusco, S., Lerzo, V., Solari, G., 2019. Directional response of structures to thunderstorm outflows. Meccanica 54, 1281–1306.

Burlando, M., 2019. Downburst outflow reconstruction by wind profile measurements. In: Proc., 15th Int. Conf. On Wind Engineering, Beijing, China.

Burlando, M., Carassale, L., Georgieva, E., Ratto, C.F., Solari, G., 2007. A simple and efficient procedure for the numerical simulation of wind fields in complex terrain. Bound. Lay. Meteorol. 125, 417–439.

Burlando, M., De Gaetano, P., Pizzo, M., Repetto, M.P., Solari, G., Tizzi, M., 2013. Wind climate analysis in complex terrain. J. Wind Eng. Ind. Aerod. 123, 349–362.

Burlando, M., Pizzo, M., Repetto, M.P., Solari, G., De Gaetano, P., Tizzi, M., 2014. Short-term wind forecasting for the safety management of complex areas during hazardous wind events. J. Wind Eng. Ind. Aerod. 135, 170–181.

Burlando, M., De Cio, A., Pizzo, M., Solari, G., 2017b. Analysis of wind vertical profiles of thunderstorm events in the Mediterranean. In: Proc., 9th Asia-Pacific Conf. On Wind Engineering, Auckland, New Zealand.

Burlando, M., Romanic, D., Hangan, H., Solari, G., 2018a. Wind tunnel experimentation on stationary downbursts at WindEEE Dome. In: Proc., 15th Int. Conf. Of the Italian National Association for Wind Engineering (IN-VENTO 2018), Naples, Italy.

Burlando, M., Romanic, D., Solari, G., Hangan, H., Zhang, S., 2017a. Field data analysis and weather scenario of a downburst event in Livorno, Italy on 1 October 2012. Mon. Weather Rev. 145, 3507–3527.

Burlando, M., Zhang, S., Solari, G., 2018b. Monitoring, cataloguing and weather scenarios of thunderstorm-induced intense wind events. Nat. Hazards Earth Syst. Sci. 18, 2309–2330.

Byers, H.R., Braham, R.R., 1949. The Thunderstorm: Final Report of the Thunderstorm Project. US Government Printing Office, Washington, DC.

Canepa, F., Burlando, M., Solari, G., 2019. Advancements in the investigation of vertical profiles of thunderstorm outflows. In: Proc., 15th Int. Conf. On Wind Engineering, Beijing, China.

Castino, F., Rusca, L., Solari, G., 2003. Wind climate micro-zoning: a pilot application to Liguria Region (North-Western Italy). J. Wind Eng. Ind. Aerod. 91, 1353–1375.

Chen, L., Letchford, C.W., 2004. A deterministic-stochastic hybrid model of downbursts and its impact on a cantilevered structure. Eng. Struct. 26, 619–629.

Chen, X., 2008. Analysis of alongwind tall building response to transient nonstationary winds. J. Struct. Eng. ASCE 134, 782–791.

Davenport, A.G., 1961. The application of statistical concepts to the wind loading of structures. Proc. Inst. Civ. Eng. 19, 449–472.

Davenport, A.G., 1964. Note on the distribution of the largest value of a random function with application to gust loading. Proc. Inst. Civ. Eng. London U.K. 24, 187–196.

De Gaetano, P., Repetto, M.P., Repetto, T., Solari, G., 2014. Separation and classification of extreme wind events from anemometric records. J. Wind Eng. Ind. Aerod. 126, 132–143.

Duranona, V., 2015. The significance of non-synoptic winds in extreme wind climate of Uruguay. In: Proc., 14th Int. Conf. On Wind Engineering Porto Alegre, Brasil.

Fujita, T.T., 1985. Downburst: Microburst and Macroburst. University of Chicago Press, Chicago, IL.

Fujita, T.T., 1990. Downburst: meteorological features and wind field characteristics. J. Wind Eng. Ind. Aerod. 36, 75–86.

Georgiou, P.N., Davenport, A.G., Vickery, B.J., 1983. Design wind speeds in regions dominated by tropical cyclones. J. Wind Eng. Ind. Aerod. 13, 139–152.

Goff, R.G., 1976. Vertical structure of thunderstorm outflows. Mon. Weather Rev. 104, 1429–1440.

Gomes, L., Vickery, B.J., 1977/1978. Extreme wind speeds in mixed climates. J. Ind. Aerod. 2, 331–344.

Hangan, H., Refan, M., Jubayer, C., Romanic, D., Parvu, D., Lo Tufo, J., Costache, A., 2017. Novel techniques in wind engineering. J. Wind Eng. Ind. Aerod. 171, 12–33.

Hjelmfelt, M.R., 1988. Structure and life cycle of microburst outflows observed in Colorado. J. Appl. Meteorol. 27, 900–927.

Holmes, J.D., Hangan, H.M., Schroeder, J.L., Letchford, C.W., Orwig, K.D., 2008. A forensic study of the Lubbock-Reese downdraft of 2002. Wind Struct. 11, 19–39.

Holmes, J.D., Oliver, S.E., 2000. An empirical model of a downburst. J. Ind. Aerod. 22, 1167–1172.

Housner, G.W., 1959. Behavior of structures during earthquakes. J. Mech. Div. ASCE 85, 109–129.

Huang, G., Jiang, Y., Peng, L., Solari, G., Liao, H., Li, M., 2019. Characteristics of intense wind in mountain area based on field measurement. J. Wind Eng. Ind. Aerod. 190, 166–182.

Junayed, C., Jubayer, C., Parvu, D., Romanic, D., Hangan, H., 2019. Flow field dynamics of large-scale experimentally produced downburst flows. J. Wind Eng. Ind. Aerod. 188, 61–79.

Kasperski, M., 2002. A new wind zone map of Germany. J. Wind Eng. Ind. Aerod. 90, 1271–1287.

Kwon, D.K., Kareem, A., 2009. Gust-front factor: new framework for wind load effects on structures. J. Struct. Eng. ASCE 135, 717–732.

Kwon, D.K., Kareem, A., 2019. Towards codification of thunderstorm/downburst using gust front factor: model-based and data-driven perspectives. Eng. Struct. 199, 109608.

Lagomarsino, S., Piccardo, G., Solari, G., 1992. Statistical analysis of high return period wind speeds. J. Wind Eng. Ind. Aerod. 41, 485–496.

Letchford, C.W., Mans, C., Chay, M.T., 2002. Thunderstorms – their importance in wind engineering (a case for the next generation wind tunnel). J. Wind Eng. Ind. Aerod. 90, 1415–1433.

Li, Y., Kareem, A., 1991. Simulation of multivariate nonstationary random processes by FFT. J. Eng. Mech. ASCE 117, 1037–1058.

Lombardo, F.T., Main, J.A., Simiu, E., 2009. Automated extraction and classification of thunderstorm and non-thunderstorm wind data for extreme-value analysis. J. Wind Eng. Ind. Aerod. 97, 120–131.

McConville, A.C., Sterling, M., Baker, C.J., 2009. The physical simulation of thunderstorm downbursts using an impinging jet. Wind Struct. 12, 133–149.

Nissen, K.M., Leckebusch, G.C., Pinto, J.G., Ulbrich, U., 2014. Mediterranean cyclones and windstorms in a changing climate. Reg. Environ. Change 14, 1873–1890.

Orlando, A., Pagnini, L.C., Repetto, M.P., 2020. Structural response and fatigue assessment of a small vertical axis under stationary and non-stationary wind events. Appl. Energy (submitted for publication).

Pagnini, L.C., Burlando, M., Repetto, M.P., 2015. Experimental power curve of small-size wind turbines in turbulent urban environment. Appl. Energy 154, 112–121.

Pagnini, L.C., Piccardo, G., Repetto, M.P., 2018. Full scale behavior of a small size vertical axis wind turbine. Renew. Energy 127, 41–55.

Peng, L., Huang, G., Chen, X., Kareem, A., 2017. Simulation of multivariate nonstationary random processes: hybrid stochastic wave and proper orthogonal decomposition approach. J. Eng. Mech. ASCE 143, 04017064.

Piccardo, G., Solari, G., 1998. Generalized equivalent spectrum technique. Wind Struct. 1, 161–174.

Ponte Jr., J., Riera, J.D., 2010. Simulation of extreme wind series caused by thunderstorms in temperate latitudes. Struct. Saf. 32, 131–137.

Púcik, T., Groenemeijer, P., Rädler, A.T., Tijssen, L., Nikulin, G., Prein, A.F., Van Meijgaard, E., Fealy, R., Jacob, D., Teichmanni, C., 2017. Future changes in European severe convection environments in a regional climate model ensemble. J. Clim. 30, 6771–6794.

Repetto, M.P., Burlando, M., Solari, G., De Gaetano, P., Pizzo, M., 2017. Integrated tools for improving the resilience of seaports under extreme wind events. Sustain Cities Soc 32, 277–294.

Repetto, M.P., 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. Adv. Eng. Software 117, 29–45.

Romanic, D., LoTufo, J., Hangan, H., 2019a. Transient behavior in impinging jets in crossflow with application to downburst flows. J. Wind Eng. Ind. Aerod. 184, 209–227.

Romanic, D., Nicolini, E., Hangan, H., Burlando, M., Solari, G., 2019b. A novel approach to scaling experimentally produced downburst like impinging jet outflows. J. Wind Eng. Ind. Aerod. (in press).

Roncallo, L., Solari, G., 2019. Modelling of thunderstorm outflows by means of the evolutionary power spectral density. In: Proc., 15th Int. Conf. On Wind Engineering, Beijing, China.

Sakamoto, S., Ghanem, R., 2002. Simulation of multi-dimensional non-Gaussian non-stationary random fields. Probabilist. Eng. Mech. 17, 167–176.

Solari, G., 1989. Wind response spectrum. J. Eng. Mech. ASCE 115, 2057–2073.

Solari, G., 2013. Brâncuşi Endless Column: a masterpiece of art and engineering. Int. J. High-Rise Buildings 2, 193–212.

Solari, G., 2014. Emerging issues and new frameworks for wind loading on structures in mixed climates. Wind Struct. 19, 295–320.

Solari, G., 2016. Thunderstorm response spectrum technique: theory and applications. Eng. Struct. 108, 28–46.

Solari, G., 2019. Wind Science and Engineering: Origins, Developments, Fundamentals and Advancements. Springer, Switzerland.

Solari, G., Burlando, M., De Gaetano, P., Repetto, M.P., 2015a. Characteristics of thunderstorms relevant to the wind loading of structures. Wind Struct. 20, 763–791.

Solari, G., De Gaetano, P., 2018. Dynamic response of structures to thunderstorm outflows: response spectrum technique vs time-domain analysis. Eng. Struct. 176, 188–207.

Solari, G., De Gaetano, P., Repetto, M.P., 2015b. Thunderstorm response spectrum: fundamentals and case study. J. Wind Eng. Ind. Aerod. 143, 62–77.

Solari, G., Rainisio, D., De Gaetano, P., 2017. Hybrid simulation of thunderstorm outflows and wind-excited response of structures. Meccanica 52, 3197–3220.

Solari, G., Repetto, M.P., Burlando, M., De Gaetano, P., Pizzo, M., Tizzi, M., Parodi, M., 2012. The wind forecast for safety and management of port areas. J. Wind Eng. Ind. Aerod. 104–106, 266–277.

Sterling, M., Baker, C., Haines, M., Quinn, A., 2011. Scaling a thunderstorm downburst simulator. In: Proc., 13th Int. Conf. On Wind Engineering Amsterdam, The Netherlands.

Tamura, Y., Cao, S., 2012. International group for wind-related disaster risk reduction (IG-WRDRR). J. Wind Eng. Ind. Aerod. 104–106, 3–11.

Ulbrich, U., Leckebusch, G.C., Donat, M.G., 2013. Windstorms, the most costly natural hazard in Europe. In: Boulter, S., Palutikof, J., Karoly, D., Guitart, D. (Eds.), Natural Disasters and Adaptation to Climate Change. Cambridge University Press, pp. 109–120.

Vallis, M.B., Loredo-Souza, A.M., Ferreira, V., De Lima Nascimento, E., 2019. Classification and identification of synoptic and non-synoptic extreme wind events from surface observations in South America. J. Wind Eng. Ind. Aerod. 193, 103963.

Vickery, P.J., Masters, F.J., Powell, M.D., Wadhera, D., 2009. Hurricane hazard modeling: the past, present and future. J. Wind Eng. Ind. Aerod. 97, 392–405.

Wang, L., McCullough, M., Kareem, A., 2013. A data-driven approach for simulation of full-scale downburst wind speeds. J. Wind Eng. Ind. Aerod. 123, 171–190.

Xhelaj, A., Burlando, M., Solari, G., 2019. An advanced analytical model for simulating thunderstorm outflows. In: Proc., 15th Int. Conf. On Wind Engineering, Beijing, China.

Xu, Z., Hangan, H., 2008. Scale, boundary and inlet condition effects on impinging jets. J. Wind Eng. Ind. Aerod. 96, 2383–2402.

Zhang, S., Solari, G., De Gaetano, P., Burlando, M., Repetto, M.P., 2018a. A refined analysis of thunderstorm outflow characteristics relevant to the wind loading of structures. Probabilist. Eng. Mech. 54, 9–24.

Zhang, S., Solari, G., Yang, Q., Repetto, M.P., 2018b. Extreme wind speed distribution in a mixed wind climate. J. Wind Eng. Ind. Aerod. 176, 239–253.

Zhang, S., Solari, G., Burlando, M., Yang, Q., 2019a. Directional decomposition and analysis of thunderstorm outflows. J. Wind Eng. Ind. Aerod. 189, 71–90.

Zhang, S., Yang, Q., Solari, G., Li, B., Huang, G., 2019b. Characteristics of thunderstorm outflows in Beijing urban area. J. Wind Eng. Ind. Aerod. 195, 104011.

Zuzul, J., Burlando, M., Solari, G., Blocken, B., Ricci, A., 2019. Comparison between the impinging jet model and experimental stationary downbursts. In: Proc., 15th Int. Conf. On Wind Engineering, Beijing, China.