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A refined analysis of thunderstorm outflow characteristics relevant to the wind loading of structures

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ABSTRACT

The study of thunderstorm outflows and their loading and response of structures is a key topic in modern wind engineering. This paper provides a new contribution to this research by analyzing a wide dataset of 277 wind velocity records characterized by strong transient properties and labeled by thunderstorm outflow. These records have been detected for up to 6 years by 14 anemometers belonging to an extensive in-site monitoring network distributed in the Northern Mediterranean ports. Analyses are carried out in order to extract the parameters of major interest for evaluating the wind loading effects of structures and furnishing a comprehensive statistical characterization of the huge amount of data recorded. Results lead to a novel classification of thunderstorm outflows with reference to the time scale of the gust front passage and their intensity; a refined interpretation of the differences involved by the turbulence intensity, the integral length scale and the gust factor of mesoscale downbursts and synoptic low-pressure systems; a confirmation of the substantial independence of these quantities with respect to the ratio between the height above ground of the sensor and the roughness length of the terrain, together with their correlation with the wind velocity; a new parameterization of the harmonic content of the turbulent fluctuations.

1. Introduction

The study of thunderstorm outflows and their loading of structures is a key topic of modern wind engineering [1,2]. This depends mainly on the fact that the methods currently used to determine the wind actions on structures are still mostly based on the synoptic extra-tropical cyclone model introduced by Davenport in 1961 [3]; this model assumes neutral atmospheric conditions, statistical stationarity features and wind velocity profiles in equilibrium with the atmospheric boundary layer (ABL). Thunderstorm outflows are transient phenomena at the mesoscale [4,5] that occur in convective conditions with "nose" velocity profiles [6] totally different from those that are typical of the ABL. Several studies show that the design wind velocity is often linked with thunderstorm events [7–11].

The literature is rich in contributions that illustrate measurements of thunderstorm outflows whose analysis is carried out in order to extract their parameters of major interest for evaluating the wind loading of structures. Refs. [12–14] describe the results of a monitoring program in Singapore, which gave particular remark to the definition and values of the gust factor. Ref. [15] analyzes the time evolution of the vertical profile of the mean wind velocity and the turbulence properties of transient events registered in the north-European coastal areas. Ref. [16] investigates the space–time properties of the rear-flank downdraft of a super-cell and of a derecho detected in a thunderstorm outflow experiment conducted in 2002 in Lubbock, Texas. Inspecting the same rear-flank downdraft, Ref. [17] develops the decomposition of its velocity in a moving average mean and a residual turbulent component whose characteristics are examined in detail. Similar evaluations are reported in [18] with reference to a downburst occurred in 2004 at the SMEAR II Station in Finland. Ref. [19] investigates some thunderstorms that occurred in Lubbock in order to elucidate their properties relevant to wind engineering. Ref. [20] depicts high-resolution field measurements of thunderstorm outflows carried out at Texas Tech University by means of surface instruments and mobile Doppler radars.

Despite these and many other analyses, the understanding, the representation and the modeling of thunderstorm outflows are still full of uncertainties and problems to be clarified. On the one hand, the

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complexity of these atmospheric phenomena makes very difficult to formulate models that are physically realistic and simply applicable as in the case of synoptic depressions. On the other hand, their short duration and small size make very limited the available data, precluding the possibility of carrying out, as in the case of synoptic events, robust statistical evaluations and interpretations of the signals detected [21,22].

The projects "Wind and Ports" (WP) [23] and "Wind, Ports and Sea" (WPS) [24] represent a unique opportunity to contribute to the growth and the advance in the knowledge of thunderstorm outflows and their parameters relevant to the wind loading of structures. Started in 2009 and finished in 2015, these projects were financed by the European Territorial Cooperation Objective, Cross-border program "Italy-France Maritime 2007–2013". They involved the Port Authorities of the five main commercial ports in the Northern Tyrrhenian area, namely Genoa, La Spezia, Livorno, Savona– Vado Ligure (Italy) and Bastia–L'Île Rousse (France). The Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genoa was the only scientific partner. These projects focused on the wind forecast and developed an integrated system made up of an extensive in-site monitoring network, an unprecedented dataset of wind measurements, the numerical simulation of wind and wave fields, the statistical analysis of the wind climate, an algorithm for the medium term (1–3 days) wind and wave forecast, and an algorithm for the short-term (0.5–2 h) wind forecast. Results are available to port operators by an integrated web-based GIS system for the safe management of port areas. The prosecution of this activity after 2015 is regulated by a Memorandum of Understanding between the University of Genoa and the Port Authorities involved in the above projects.

Thanks to the WP and WPS wind monitoring network and working on the wind dataset that it generated, a semi-automatic procedure was implemented to recognize and extract thunderstorm outflow records [25]. By means of this procedure a preliminary set of 93 records, labeled as thunderstorm outflows, was gathered from measurements carried out for 2 years by 9 anemometers. These records were decomposed into the sum of a slowly-varying mean wind velocity plus a residual fluctuation. In turn, the fluctuation was expressed as the product of its slowly-varying standard deviation by a reduced turbulent fluctuation dealt with as a rapidly-varying random stationary process with zero mean value and unit standard deviation. The extraction of the mean value and of the standard deviation were carried out by a moving average filter with period 30 s. Special attention was dedicated to the duration of the gust front passage, turbulence intensity, power spectral density, integral length scale and gust factor [26]; all these analyses were carried out comparing the statistical parameters of the selected thunderstorm outflows with those of 229 synoptic wind records. These properties formed the base to formulate two novel methods for determining the structural response to thunderstorm outflows: the first represents a generalization of the response spectrum technique widely used in the seismic field [27,28]; the second involves time-domain integrations based upon a so-called hybrid simulation technique of the thunderstorm outflow wind field [29].

In the meanwhile, the monitoring network has been enhanced with other instruments and new analyses have been performed on the records gradually acquired. This led to gathering a broader and more controlled dataset, including 277 records of thunderstorm outflows and other events with highly transient properties as extracted from measurements carried out for up to 6 years by 14 anemometers. This paper describes the analyses of this data repeating, improving, extending and often changing the methods applied in the previous study [26] on the basis of the new experience and knowledge acquired.

In particular, Section 2 illustrates the main properties of the wind monitoring network and of the measured wind dataset. Section 3 describes the criterion by means of which intense wind events are separated and thunderstorm outflows are extracted and cataloged. Section 4 depicts the method used to decompose thunderstorm outflow signals into component parts whose statistical properties are later on evaluated. Accordingly, Sections 5–7 examine the slowly-varying mean wind velocity, the turbulence intensity and the reduced turbulent fluctuations, respectively. Sections 8 and 9 discuss the turbulence intensity modulation and some noteworthy wind velocity ratios. Section 10 summarizes the main conclusions and provides some prospects for future research.

2. Monitoring network and wind dataset

Fig. 1 shows an outline of the in-site wind monitoring network created by the WP [23] and WPS [24] European Projects. The yellow circles correspond to the first 23 ultrasonic bi- or tri-axial anemometers, distributed in the Ports of Genoa (2), La Spezia (5), Livorno (5), Savona–Vado Ligure (6) and Bastia (5) in the course of the WP Project. The orange circles refer to 5 new ultra-sonic anemometers mounted in the Ports of Savona (1), La Spezia (1), Livorno (1) and L'Île Rousse (2) during the WPS Project. Still in the frame of the WPS Project, the monitoring network has been enlarged by adding 3 weather stations (blue circles), each one including another ultra-sonic anemometer, one barometer, one thermometer and one hygrometer, and 3 LiDAR (Light Detection And Ranging) (red circles), which detect the wind velocity profile from 40 to 250 m above ground level (AGL). Other sensors autonomously installed by single Port Authorities are in the stage of becoming integral parts of the WP and WPS network.

The instruments are distributed in order to homogeneously cover the port areas involved in these projects. To avoid local effects and to register undisturbed wind velocities, they are mounted at least at 10 m height AGL, mainly on high-rise towers or, in few cases, on antenna masts at the top of buildings. Wind measurements are recorded with a precision of 0.01 m/s and 1° for the intensity and direction, respectively. The sampling rate is 10 Hz with the exception of the anemometers in the port area of Bastia–L'Île Rousse, whose sampling rate is 2 Hz. Table 1 shows the main properties of the 31 ultra-sonic anemometers at present available; h is the height of the sensors AGL. A description of the LiDAR properties is given in [24].

A set of local servers placed in each Port Authority headquarter receives the data acquired by the anemometers in their own port area and elaborates their basic statistics on 10-min periods, namely the mean and peak wind velocities and the mean wind direction. Each server automatically sends this information to the central server at DICCA that carries out a preliminary check of the quality of the data, then stores it into a central dataset.

Table 1 shows periods of measurements varying from anemometer to anemometer. This depends, first of all, on the successive installation of the instruments. In addition, there are several periods in which measurements have been not carried out due to accidents or malfunctions of the instruments, these including some cases in which sensors have not been restored yet. Of course, there are also periods in which measurements have been not enough reliable to be examined [30,31]. Finally, taking into account the burden of the analyses described in this paper, the data provided by several sensors has not been studied yet; more precisely, at present analyses have been carried out for 14 sensors out of 31 available. The last column of Table 1 provides the percentage of the examined data for each examined instrument. Obviously, the correctness and reliability of the dataset is fundamental to carry out correct and reliable signal analyses.

Some preliminary evaluations on the data detected by the LiDAR profilers are illustrated in [32].

3. Extraction and classification of thunderstorm outflows

Coherently with modern trends in mixed wind climate conditions [2,11,33,34], the separation and classification of intense wind events into homogeneous categories is a fundamental preliminary step to carry out refined analyses of different phenomena and of their loading and response of structures. In principle, this separation calls for the joint

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