Advancements in the Investigation of Vertical Profiles of Thunderstorm Outflows

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ABSTRACT: The dynamic complexity and unpredictability of the occurrence of thunderstorms make it difficult to collect reliable and systematic measurements of this atmospheric phenomenon, which are definitely needed to evaluate its action on structures. The area of the Northern Tyrrhenian Sea is a “hot-spot” for the genesis of severe potentially damaging wind phenomena, such as downbursts, whose occurrence in this geographical region is not well documented. In the context of the two European projects “Wind and Ports” and “Wind, Ports and Sea”, a large and complex wind monitoring network has been installed in this area. Since the years 2014-2015, this network is equipped with three LiDAR profilers which provide vertical scanning of the atmosphere up to 250 m above the ground level. All the wind profiles have been systematically analysed in order to detect the ones that can be referred to thunderstorm events. The aim of this study is to extend a first set of analyses up to mid-2018 to provide a preliminary investigation of the main parameters describing the non-synoptic events and a first classification of thunderstorm events into different subsets.

KEYWORDS: thunderstorm, LiDAR, Mediterranean, vertical profile, nose-shape profile

1 INTRODUCTION

Despite an impressive amount of research, a model for thunderstorm-induced actions on structures is not available yet, mainly because the complexity of thunderstorms makes it difficult to establish physically realistic and simple models as in the case of extra-tropical cyclones [1]. Downbursts present characteristics completely different from extra-tropical cyclones [2]: wind speed time-series are non-stationary and a nose-like vertical profile with its maximum around 50-100 m above the ground level (AGL) often occurs. They are short-living and small-scale phenomena, whose precise spatial and temporal occurrence is unpredictable. This is the reason why a very limited amount of full-scale direct measurements is available and points out the necessity of collecting and analysing as many thunderstorm records as possible [3].

The present paper resumes the previous work by Burlando et al. [4] where a first set of thunderstorms was extracted and analaysed from measurements acquired during the years 2014-2015, enriching and integrating this investigation up to mid-2018. Three LiDAR (Light Detection and Ranging) databases of vertical wind profiles measured from 40 to 250 m AGL, are systematically analysed to extract the ones which relate to thunderstorm events. This is confirmed through cross-checking with meteorological information, such as satellite and lightning data. The nose-like shape of the vertical profiles is analysed in terms of duration, gust factor, directional shift, height of the maximum wind speed. The evolution in time of the velocity vertical profile and the portion of time-history where the nose-like shape can be recognised, are also considered important characteristics. A first separation of thunderstorm records into subclasses is achieved.

2 WIND MONITORING NETWORK IN THE HIGH TYRRHENIAN SEA

In the context of the two European projects “Wind and Ports” (2009-2012) [5] and “Wind, Ports and Sea” (2013-2015) [6], an anemometric network made up of 22 ultrasonic anemometers, 3 meteorological stations and 3 LiDARs has been realised in the main commercial ports of the Northern Tyrrhenian and Liguria Sea. The 3 LiDARs were installed in the years 2014-2015 in the ports of Genoa, Livorno and Savona (codes GE.51, LI.51 and SV.51, respectively). The related databases of measurements cover different periods according to their installation date until 31 August 2018, which is the last date considered in the present analysis. The discontinuities in the data acquisition have to be addressed to malfunctioning, ordinary maintenance and, in the case of LI.51, to vandalism attack.

LiDAR wind profilers provide measurements of the three components of the wind velocity at 12 heights AGL (40, 50, 60, 80, 90, 100, 120, 140, 160, 180, 200, 250 m) with a sampling rate of 1 Hz. The accuracy of LiDAR measurements of mean wind velocity profiles is demonstrated [7,8], whereas the reliability of turbulence measurements is limited and still controversial [9,10].

3 DATA EXTRACTION AND ANALYSIS

All the available data have been systematically analysed in order to detect those events that are believed to be thunderstorms. The first preliminary selection is based on the following analytical criteria: 10-min maximum 1-Hz wind speed, $v_{\max,10}$, greater than 18 m/s; gust factor, defined as the ratio of the above 10-min maximum 1-Hz wind speed over the mean wind speed in the same 10-min interval, $G_{10} = v_{\max,10} / \overline{v}_{10}$, greater than 1.5.

The events obtained according to this automatic selection have been subsequently analysed through the classic wind velocity decomposition process, reported by many authors (e.g. [11,12]), by considering the slowly-varying mean wind velocity, related to the low-frequency content of v. It is largely documented by literature that, after downburst touchdown, the vertical wind profile of the outflow assumes a transient nose-like shape profile [13]. This is noticeable only analysing the vertical profile of the slowly-varying mean wind velocity component and for a maximum duration of few minutes. The usual 10-min average applied to synoptic event time-series completely filters out such peculiarity. However, the quantification and range of variability of some characteristics of these profiles are not well-documented and uniquely recognised, such as their duration, the height of the maximum wind speed and its evolution in time.

4 THE THUNDERSTORM EVENT ON 4 JUNE 2018

In the morning of 4 June 2018, a low-pressure convective system, which had formed over the Tyrrhenian Sea between Corsica Island and the coasts of Liguria and Tuscany, landed in the area of Livorno. At 10:00 UTC, a convective cell with cloud top height at more than 11000 m was exactly over Livorno. The strikes timing clearly shows the northeast-ward movement of the storm.

At the time of the storm, the anemometers and the LiDAR in the port of Livorno recorded a sudden increase of the mean wind speed from about 6 to 19 m/s according to the LiDAR at 120 m AGL, which is the height where the maximum slowly-varying mean wind velocity along the whole profile occurred, and 3.5 to 17.5 m/s according to the closest anemometer (LI.06, placed at 20 m above sea level). Contemporarily, the wind of both LiDAR and LI.06 veered from south to south-west (180° to 230°) during the ramp-up period and maintained this direction when the wind speed returned to the previous low values. This is in contradiction to what is generally assumed by literature, namely the wind back to its original direction after the passage of the storm.

Figure 1 shows the velocity vertical profile at four different representative instants in the time-history. The upper pictures show $v(t)$ at 120 m AGL: the velocity ramp-up lasted for approximately 5 minutes, i.e. from 140 to 460 s, going from a low value of 6 m/s up to the peak, 19 m/s. Afterwards, the descending part of the signal occurred. As shown in the bottom left pictures of Figure 1, representing the vertical wind profile of the slowly-varying mean wind velocity, the nose-like shape appeared only at the beginning of the ramp-up at high altitutes around 180 m AGL, and at the peak, where the maximum velocity occurred at a lower height equals to 120 m AGL and remained constant above this point. During the ramp-up and post-peak periods, the horizontal velocity was almost constant with height. The velocity vertical profile is calculated by means of the averaging period T = 30 s. The nose-like shape disappeared at 475 s, lasting in total only 25 seconds in the peak interval. Finally, the bottom right pictures show the wind direction in terms of wind barbs (in knots), which was from west along the whole profile.

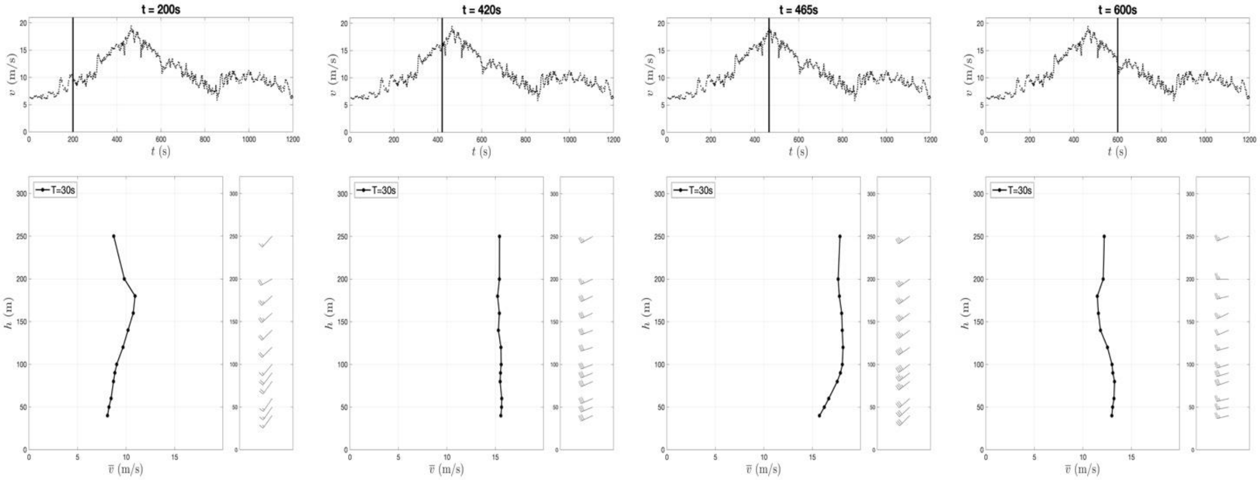
t = 200s
t = 420s
t = 465s
t = 600s

Figure 1. 1-Hz wind speed values at 120 m AGL (upper pictures); vertical profile of slowly-varying mean wind velocity (bottom left pictures); vertical profile of wind barbs (bottom right pictures) after 200 s, 420 s, 465 s and 600 s.

According to the LiDAR measurements, the 10-min maximum gust factor, over the whole profile, was 1.79 at 250 m AGL; at the same height, the 10-min mean wind speed was 10.5 m/s.

5 CONCLUSIONS

This paper provides a preliminary description and interpretation of the wind vertical profiles measured, by means of three LiDARs, during thunderstorms in the period 2015-2018. Such events are selected through an automatic procedure based on fixed thresholds of the 10-min maximum 1-Hz wind speed and gust factor, i.e. $v_{\max,10} \geq 18$ m/s and $G_{10} \geq 1.5$, respectively. A subset of these events is chosen and studied according to subjective analysis of the anemometric signals as well as cross-checking with other meteorological information, e.g. satellite images and lightning occurrence.

The downburst that occurred on 4 June 2018 in Livorno is presented and briefly described. Other thunderstorm signals from the whole LiDAR databases have been selected in the present study and compared each other also in relation to the events sorted by the forerunner study.

Overall, 14 thunderstorms have been compared and a rather high variability of the main describing parameters appeared: gust factor has been found in the range 1.52-2.87; the directional shift during the storm was from 50° to 230°; the height at which the maximum velocity occurred was from 40 to 180 m AGL; the duration of the nose-like shape profile was from a minimum of 15 s to a maximum of 140 s; the vertical component of the velocity was found, in some cases, to be negligible while, in others, a quite strong magnitude up to -10 m/s occurred; after the storm passage, some events showed a velocity back to the values before the ramp-up while, in other cases, the velocity differs quite largely after the dissipation of the downburst. The same consideration can be addressed to the direction shift before and after the occurrence of the storm.

The results and a clear comparison of the parameters describing each investigated event will be shown in detail in the extended version of the paper.

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