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Analysis of Wind Vertical Profiles of Thunderstorm Events in the Mediterranean

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Abstract

The research on thunderstorms and their actions on structures has been a dominant subject in wind engineering since the last 30 years. Despite an impressive amount of work, a model for thunderstorm outflow is not available yet, and the evaluation of thunderstorm actions on structures is still based on the cyclone model developed half a century ago. This is because the dynamic complexity and unpredictability of occurrence of thunderstorms make it difficult to collect reliable and systematic measurements of this atmospheric phenomenon, which are definitely needed in an attempt to develop realistic and simple models.

In the context of the two European projects “Wind and Ports” and “Wind, Ports, and Sea”, a complex anemometric monitoring network has been realised in the area of the Northern Tyrrhenian and Liguria Sea (North-western Italy) during the period 2009-2015. Since the years 2014-2015, this network is equipped by three LiDAR wind profilers that provide wind velocity measurements up to 250 m above the ground level. All the wind profiles measured until the end of 2015 have been analysed systematically in order to detect the ones that can be referred to thunderstorm events. Preliminary results of the analyses are reported in the present paper.

Introduction

The methods currently applied to determine the wind actions on structures [1] are still based on the synoptic-scale extra-tropical cyclone model developed by Davenport in the 60’s [2]. However, nowadays it is clearly recognised in the wind engineering community the importance of thunderstorms in determining the design wind speed [3].

Despite an impressive amount of research that occurred in the last 30 years, a model for thunderstorm-induced downburst outflow is not available yet, mainly because the complexity of thunderstorms makes it difficult to establish physically realistic and simple models. Thunderstorms present characteristics completely different from extra-tropical cyclones: wind speed time-series are non-stationary and non-Gaussian, 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, however, whose precise spatial and temporal occurrence is totally unpredictable. This is the reason why still a very limited amount of direct measurements is available and points out the necessity of collecting and analyse as many thunderstorm records as possible.

In the present paper, three databases of vertical wind profiles measured from 40 to 250 m AGL by means of LiDAR (Light Detection And Ranging) systems are systematically analysed in order to detect the ones which relate to thunderstorm events. This is confirmed through cross-checking with satellite and lightning data. In particular, the nose-like shapes of the profiles have been analysed in terms of duration, gust factor, directional shift and height of the maximum wind speed.

Monitoring network and LiDAR databases

In the context of the two European projects “Wind and Ports” (2009-2012) [4] and “Wind, Ports, and Sea” (2013-2015) [5], 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, namely Savona/Vado Ligure, Genoa, La Spezia, Livorno, Bastia, and L’Ile Rousse. The overall system installed in the three ports where the LiDARs are installed, i.e. Savona, Genoa, and Livorno, is reported in figure 1.

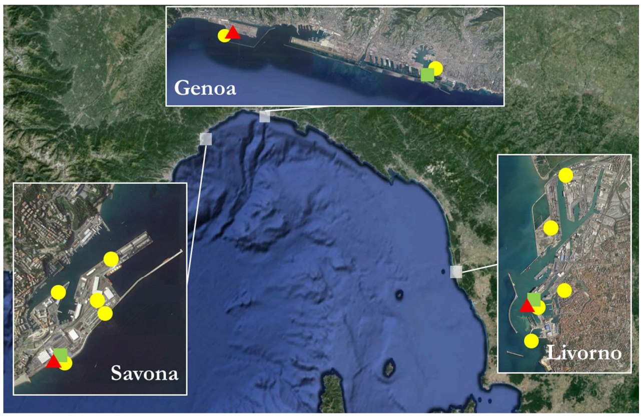

Figure 1. Monitoring network in the Ports of Savona, Genoa, and Livorno: anemometers (yellow circles); met stations (green squares); LiDARs (red triangles).

Some details about the LiDARs and their installation are reported in table 1. These 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) with a sampling rate 1 Hz. Many papers demonstrate the accuracy of LiDAR measurements concerning mean wind velocity profiles [6,7], whereas the reliability of its turbulence measurements is still controversial [8,9] and deserve further research. For this reason, results about turbulence intensity are not reported in the present paper.

Port	Code	Position	Height AGL (m)	Installation date
Savona	SV.51	Square	0	2014-Q2
Genoa	GE.51	Pier	5	2015-Q2
Livorno	LI.51	Quay	0	2015-Q2

Table 1. Main characteristics of the LiDARs belonging to the “Wind, Ports, and Sea” anemometric monitoring network. Install dates are in terms of quarters (Q1, Q2, Q3, Q4) of the year (YYYY).

Data analysis

Events selection

The databases of LiDAR measurements cover different periods according to their installation date (see table 1) until 31 December 2015, which is the last date considered in the present analysis. Figure 2 shows the data availability for the three LiDARs: SV.51 was installed about 1 year before LI.51 and GE.51 and worked continuously apart during September and October 2015, when it stopped for ordinary maintenance; LI.51 worked discontinuously for about 6 months, then it stopped recording because of a vandalism attack; GE.51 worked properly for the whole period from installation until 22 December 2015.

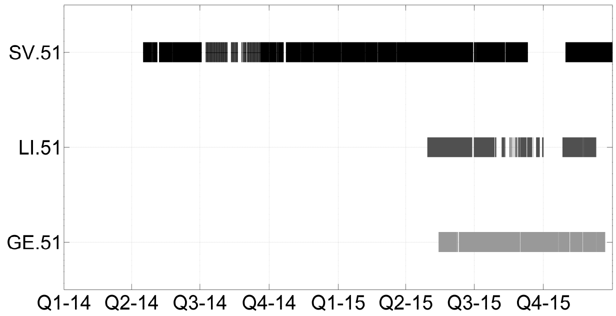

Figure 2. Database extension and data availability of the three LiDARs installed in the Port of Savona (SV.51), Genoa (GE.51), and Livorno (LI.51).

All the available wind profiles have been systematically analysed in order to identify those anemological events that are believed to be thunderstorms. A preliminary selection was based on the following analytic criteria:

- 10-min mean wind speed, $\bar{v}_{10}$, greater than 18 m/s.
- Gust factor, defined as the ratio of the maximum 1-Hz wind speed over the 10-min mean wind speed, G_{10}, greater than 1.5.

Note that G_{10} values evaluated from LiDAR measurements could be underestimated to some extent. This can happen because turbulence acquired by means of remote sensing techniques is expected to be partially filtered out as these measurements are evaluated through a volume averaging process. Nevertheless, a lower threshold 1.5, which is commonly considered an upper limit for synoptic disturbances, has been adopted for G_{10} as the intrinsic volume averaging bias is not known a priori.

The subset of events obtained according to this automatic selection has been subsequently analysed through the wind velocity decomposition method reported by [10], briefly described in the next section. By means of such decomposition, a few events that present a nose-like shape of the wind profile have been identified. It is worth noting that the nose-like shape associated to downbursts is discernible only analysing the profiles of the slowly-varying mean wind velocity component and for the duration of a few minutes maximum. The usual 10-min average applied to wind velocity time-series filters out such profiles completely. These events have been further compared to other meteorological data to be sure that they are actually thunderstorm events.

Wind velocity decomposition

The wind velocity in thunderstorm outflows can be represented through the decomposition

$$v(t) = \bar{v}(t) + v'(t) \tag{1}$$

where t is time, $\bar{v}$ is the slowly-varying mean wind velocity, related to the low-frequency content of v, and v' is the residual fluctuation, related to the high-frequency content of v. According to [10], the calculation of $\bar{v}(t)$ has been performed here applying a moving average filter of period $T = 30$ s.

The residual velocity, v', which is thought to be induced by the small-scale turbulence, can be dealt with as a non-stationary random process given by

$$v'(t) = \sigma_v(t)\tilde{v}'(t) \tag{2}$$

where σ_v is the slowly-varying standard deviation of v', and $\tilde{v}'$ is referred to the reduced turbulent fluctuation and is dealt with as a rapidly-varying stationary Gaussian random process with zero mean and unit standard deviation. As already said, turbulence obtained from LiDAR measurements will not be analysed in the present paper.

The decomposition reported in equation (1) has been applied to each one of the 12 time-series of 1-Hz measurements available at the heights where the LiDARs profiles are sampled.

Thunderstorms recognition from LiDAR profiles

It is commonly expected that, during strong thunderstorm events after downburst touchdown, the wind profiles assume a transient nose-like shape at the passage of the gust front [11]. This is not, however, really well-documented in the literature and the range of variability of some characteristics of these profiles are not uniquely recognised, such as their duration, the height of the maximum wind speed and maximum gust factor, as well as the profiles shape evolution in time.

From the analysis of the LiDARs' wind velocity profiles, $v(t)$, and their comparison with satellite images and lightning occurrence, the long-lasting, i.e. of the order of 10-min or more, nose-like shapes are never associated to thunderstorm events. They occur, for example, during downslope winds, when stable atmospheric conditions prevent deep convection. Conversely, short-lasting, i.e. of the order of 1-min, nose-like shapes of the slowly-varying mean wind velocity profiles, $\bar{v}(t)$, have been observed during thunderstorms. The real nature of these thunderstorms has been confirmed by cross-checking anemometric signals with satellite images and lightning occurrence.

The next section presents one of the thunderstorms recorded at Livorno, which occurred on 13 September 2015. The variability of the parameters of the nose-like profiles during about 10 thunderstorms measured at Genoa, and Livorno is then presented and discussed in the conclusions.

The thunderstorm on 13 September 2015

The 13 September 2015 a deep Atlantic surface low pressure system had moved eastward to the south-west of Ireland. Contemporary, a pronounced trough aloft extended its axis southward to Spain. During the day, the low pressure deepened and the movement of the narrow warm air sector extending southward into the Mediterranean, which was a maritime warm and humid air mass of subtropical origin, induced south-westerly winds that triggered instability over northern and central Italy.

In the morning of 13 September, a deep convective system, which had formed over the Tyrrhenian Sea between Corsica Island and Tuscany, landed on the Italian coast in the area around Livorno City. Figure 3 shows the distribution of cloud top heights obtained from the cloud analysis performed by Eumetsat, based on infrared measurements collected by SEVIRI on board the Meteosat Second Generation satellites. At 11:00 UTC, two different convective cells with cloud top heights of more than

12000 m were approaching the Italian coast, the northward one was exactly over Livorno (see the red circle in figure 3).

The existence of strong convective motions associated to these storms is proven by the intense lightning activity, which is shown in figure 4. From 10:45 to 11:15 UTC, more than 7000 strikes overall were recorded by the Blitzortung network in the two areas where the aforementioned convective cells occurred. Note that the strikes timing clearly show the storm movement from southwest to northeast.

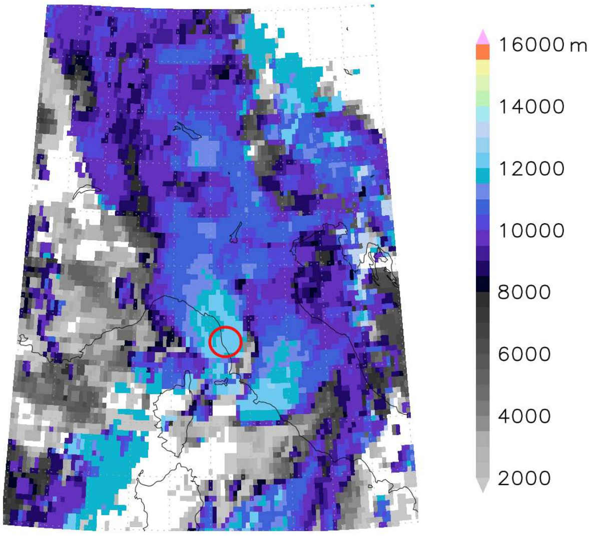

Figure 3. Cloud top height distribution from MSG data, valid for 13 September 2015 at 11:00 UTC. The red circle shows to the position of Livorno City.

At the same time of the storm, the anemometers and the LiDAR in the Port of Livorno recorded a sudden increase of the wind speed from about 6 to 20 m/s according to the LiDAR (maximum value in the whole profile, at 120 m AGL), and 6.5 to 20 m/s according to the southernmost anemometer (LI.04, placed at 20 m above sea level). Contemporarily, the wind of both LiDAR and LI.04 veered about 90° from south-southwest to west-northwest during the ramp-up period and backed to the original direction when the wind speed returned to the previous low values.

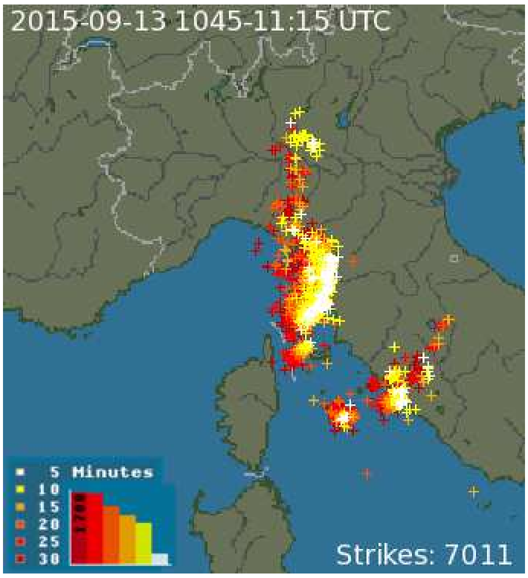

Figure 4. Strikes recorded from 10:45 to 11:15 UTC on the 13 September 2015 by means of the Blitzortung network for lightning and thunderstorms, retrieved from the online archive. Courtesy Blitzortung.org.

Figure 5 shows the wind speed and direction values measured by the LiDAR in the period from 11:00 to 11:20 UTC (1200 seconds) on 13 September. The upper picture shows $v(t)$ at 120 m AGL, which is also the height where the maximum slowly-varying mean wind speed occurs: the ramp-up lasted slightly more than 1 minute, i.e. from 225 to 300 s, then a roughly constant high wind speed period till 600 s followed, and finally the descending part of the signal occurred. The nose-like shape profile appeared clearly only during the ramp-up period, as shown in the bottom left picture in Figure 5, which represents the vertical wind profile of the slowly-varying mean wind velocity, $\bar{v}(t)$, at 295 s (see the red line in the upper picture). The profiles are calculated by means of the moving average period $T = 30$ s (black line), as well as other two different averaging periods for comparison (red and green lines). The nose-like shape disappeared at about 320 s, lasting in total approximately 1.5 min. Note that the absolute maximum wind speed was at 485 s, when the nose-like shape had already disappeared. The missing values after this maximum are likely due to the heavy rain that followed the downburst, which left the air exceptionally clear. Finally, the bottom right picture shows the wind direction in terms of wind barbs (in knots), which was from west along the whole profile. The clockwise rotation of the wind direction occurred in the ramp-up period, then it lasted until the high wind speed had ceased.

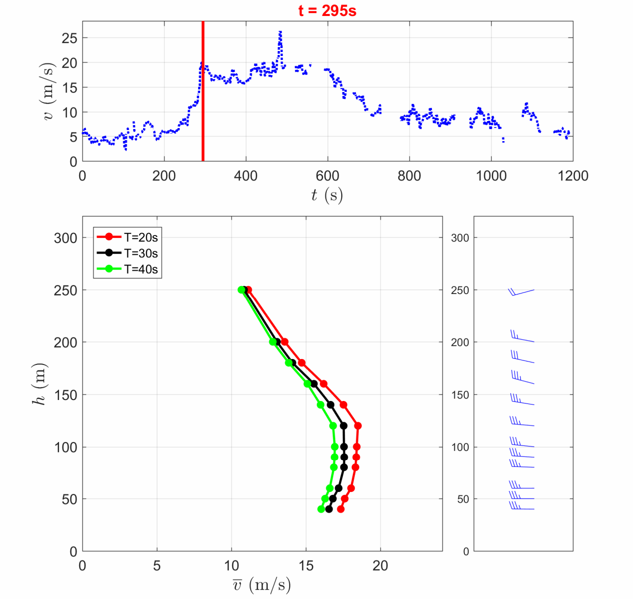

Figure 5. Wind speed and direction measurements recorded by the LiDAR of the Port of Livorno: 1-Hz wind speed values at 120 m AGL (upper picture); vertical profiles of slowly-varying mean wind velocity (bottom left); vertical profiles of wind barbs (bottom right).

Figure 6 shows the 10-Hz measurements of wind speed and direction recorded by the anemometer LI.04 in the Port of Livorno. Note that the time-scale in this figure is 1 h, which allows to capture the strongly transient nature of this event.

For this event, according to the LiDAR measurements, the 10-min mean wind speed from 11:00 to 11:10 UTC at 120 m AGL was 11.7 m/s and the corresponding gust factor G_{10} was 2.26 (this is the maximum along the whole profile). As mentioned above, however, the storm passage lasted globally more than 10 minutes. The gust factor defined on 1 h is $G_{60} = 3.29$, as the 1-h mean wind speed at 120 m AGL was 8.01 m/s.

As far as the anemometer LI.04 is concerned, the 10-min mean wind speed was 13.1 m/s and $\mathrm{G}_{10} = 1.56$, whereas the 1-h mean wind speed was 7.5 m/s and $\mathrm{G}_{60} = 2.71$.

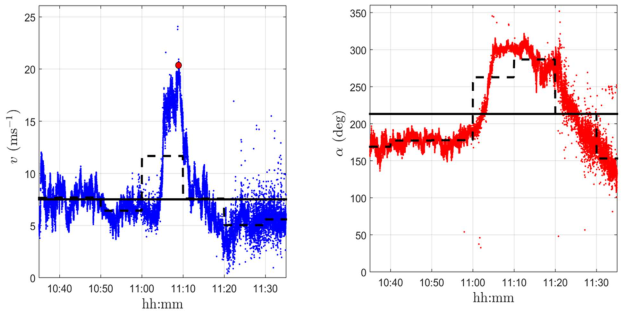

Figure 6. Wind speed (left) and direction (right) measurements recorded by the anemometer LI.04 of the Port of Livorno.

Main characteristics of the nose-like shape wind profiles

From all the events selected according to the criterion presented above, i.e. $\bar{v}_{10} \geq 18$ m/s and $G_{10} \geq 1.5$, a subset has been extracted based on a subjective analysis of the LiDARs' wind profiles and the cross-checking with satellite images and lightning occurrence in order to be sure that the profiles refer to thunderstorm events.

Table 2 shows the range of variability of the gust factor, G_{10}, height AGL of the maximum wind speed, $h_{\max}$, maximum directional shift during the storm, $\Delta\theta$, and duration of the nose-like shape, *T*. All evaluations are based on the analysis of the slowly-varying mean wind velocity $\bar{v}(t)$. Overall, 8 thunderstorms have been selected, none in the Port of Savona.

Port	N	G_{10}	$h_{\max}$ (m)	$\Delta\theta$ (°)	T (s)
Savona	-	-	-	-	-
Genoa	5	1.59-3.90	60-120	60-130	15-140
Livorno	3	1.73-2.87	50-120	30-90	30-50

Table 2. Main characteristics of the LiDARs nose-like shape profiles: gust factor, G_{10}, height of the maximum wind speed, $h_{\max}$, maximum directional shift, $\Delta\theta$, and duration, *T*.

Conclusions

In the present paper, the wind vertical profiles measured by means of three LiDARs during strong thunderstorms are analysed and described qualitatively and quantitatively. Such events are selected preliminarily trough an automatic procedure based on fixed thresholds of the 10-min mean wind speed and gust factor. Then, a subset of these events is chosen according to the subjective analysis of the anemometric signals measured by the LiDARs as well as cross-checking with other meteorological information, e.g. satellite images and lightning occurrence.

In particular, the thunderstorm event that occurred the 13 September 2015 is presented in detail in order to describe qualitatively the main characteristics of the anemometric signals during thunderstorms and the procedure of cross-checking between anemometric signals and other meteorological data. Signals similar to the one of the 13 September have been selected from the whole LiDARs' databases and compared each other in order to report the range of variability of some important features of the nose-like shape, i.e. duration, gust factor, directional shift, height of the maximum wind speed.

From the 8 thunderstorms compared, a rather high variability of these parameters appeared: gust factors have been found in the range 1.59-3.90; the height of the maximum was observed in the range between 50 and 120 m AGL; the duration was from a minimum of 15 s to a maximum of 140 s; the maximum directional shift during the storm passage was from 30° to 130°.

Acknowledgments

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