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Extreme wind speed distribution in a mixed wind climate

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ABSTRACT

The meteorological services of mid-latitude countries record wind speeds averaged over 10 min or 1 h periods and peak wind speeds for the same averaging period or a full day. Design wind speeds based on the statistical analysis of this data in a mixed wind climate may prove to be imprecise and unsafe due to the occurrence of intense, small and rapid extreme wind events such as thunderstorm outflows. Considering the 6 year continuous high-frequency records registered in two Port areas of the Upper Tyrrhenian Sea, a preliminary but representative analysis of the extreme wind speed distribution has been carried out in a mixed wind climate area frequently struck by thunderstorms. Results show that wind speeds with a high return period are always related to thunderstorm outflows. The mixed extreme distribution asymptotically overlaps with that for thunderstorms for high return periods and always provides the highest wind speeds. Gathering the ensemble of all extreme values into a single set leads to underestimating of the extreme wind speed. The Italian code provides conservative estimates of the extreme wind speed that protect designers from thunderstorms as well. However, refined analyses of the local wind climate that ignore thunderstorm events may lead to severe underestimations of the design wind velocity.

1. Introduction

Defining the design wind speed is a key step in evaluating the wind loading of structures and their safety with regard to the wind. In the meanwhile, it is one of the most debated and controversial issues in scientific and technical literature on modern wind engineering.

Following the original assessment provided by Davenport (1968), the wind loading models and codes of countries in mid-latitude areas traditionally adopt design wind speeds related to the synoptic extra-tropical cyclones that develop over a few thousand kilometres on a horizontal plane, with a duration of a few days. This facilitates the acquisition of several pieces of data, providing a complete picture of these events and justifying the development of refined extreme wind speed statistical analyses (Gomes and Vickery, 1977; Cook, 1982; Lagomarsino et al., 1992; Simiu and Heckert, 1996; Holmes and Moriarty, 1999; Cook and Harris, 2004; Harris, 2009, 2014; Torrielli et al., 2013, 2014).

Like extra-tropical cyclones, thunderstorms also occur almost everywhere at the mid-latitudes causing extreme wind speeds that often exceed those of extra-tropical cyclones (Gomes and Vickery, 1976; Choi, 1999; Letchford et al., 2002). They consist of a set of mesoscale convective cells that develop within a few kilometres on the horizontal plane and evolve in about 30–60 min. Each cell involves an updraft of warm air followed by a downdraft of cold air that impinging over the ground produces transient radial outflows and a vortex ring. The short duration, sporadic occurrence, and small size of thunderstorm cells make a limited data available, thus preventing a clear representation of these phenomena and the development of reasonable extreme wind speed analyses (Solari, 2014).

Gomes and Vickery (1977/1978) defined a mixed wind climate as a climatological condition in which different wind phenomena occur, in particular extra-tropical cyclones and thunderstorm outflows, and formulated a ground-breaking method to determine the extreme wind speed distribution in such a mixed condition. Evolutions of this method were proposed by Twisdale and Vickery (1992), Cook et al. (2003), and Harris (2017). The applications carried out by Riera and Nanni (1989), Kasperski (2002), and Lombardo et al. (2009) pointed out the shortcomings of separating different events based on a limited information, and of gathering a representative data related to mesoscale events.

The studies carried out in this paper originate from “Wind and Ports” (WP) (Solari et al., 2012) and “Wind, Ports and Sea” (WPS) (Repetto et al., 2017, 2018), two European Projects carried out between 2009 and 2015 with the aim of forecasting the wind for the safe management of

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seaport areas. These areas often have a conflictual relationship with the wind. Overlooking the sea, they are lashed by more intense winds than those experienced in protected areas; in cases in which the ports are surrounded by mountainous reliefs, they are also subject to intense channelling phenomena. These elements are crucial as ports are home to a variety of activities the safe conduct of which essentially depends on the actions and effects of wind. In particular, wind gusts, combined with waves generated by them, affect the entry and docking of ships in ports and terminals operability; port structures, especially cranes, container unloaders, light towers and wind turbines are often damaged and sometimes disrupted; stacked containers can be overturned by wind.

In order to cope with this reality, among many other actions an extensive in-situ wind monitoring network has been set in the main commercial ports of the Upper Tyrrhenian Sea. This network is made up of about 40 ultrasonic anemometers, for some of which the duration of the data logging is now over 6 years, and 3 LiDAR scanners, installed in 2015. Thanks to the continuous operating mode with high sampling frequency, this set of sensors offers a huge and perhaps unprecedented amount of high quality data. This creates a unique opportunity to obtain a large amount of high resolution wind records and to open the doors to refined analyses of extreme wind speed distribution in a mixed climate.

This paper provides a preliminary but representative contribution to this topic by focusing on the data detected by 4 anemometers of the WP & WPS monitoring network in the Ports of Livorno and La Spezia. Each anemometer has been detecting continuous data for nearly 6 years. Section 2 provides a brief description of the wind monitoring network and of the dataset that it has generated. Section 3 illustrates the procedure applied to separate the data gathered during different intense wind events into selective homogeneous datasets; it also describes the difficulties encountered due to the presence of intermediate events; it goes on to discuss the creation of historical series of independent extreme wind speeds related to extra-tropical cyclones, thunderstorm outflows and intermediate events. Section 4 evaluates the extreme wind speed distributions by means of various criteria. Section 5 discusses the evaluation of the extreme wind speed distribution of the thunderstorm outflows by making recourse, comparatively, to peak wind speeds and to the maximum values of the slowly-varying mean wind velocity multiplied by an average gust factor (Holmes et al., 2008; Kwon and Kareem, 2009; Lombardo et al., 2014; Solari et al., 2015). Section 6 compares the results provided by this study with the extreme wind speed values assigned by codes or obtained in previous investigations carried out disregarding the issue of mixed statistics. Section 7 summarizes the main conclusions and provides some prospects for future research.

2. Wind monitoring network and dataset

WP (Solari et al., 2012) and WPS (Repetto et al., 2017, 2018) are two projects financed by the European "Italy–France Maritime 2007–2013" Cross-border program that dealt with the problem of safe wind management and risk assessment for the Ports of Genoa, Livorno, Savona and Vado, La Spezia, Bastia and L'Île-Rousse. This aim was pursued using an integrated set of tools among which an extensive in-situ wind monitoring network set up for the purpose. Fig. 1 shows its main features.

WP created a network made up of 23 ultrasonic anemometers (yellow circles in Fig. 1), some of which are tri-axial and the others bi-axial, located 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. WPS enhanced this network by means of 5 new ultrasonic

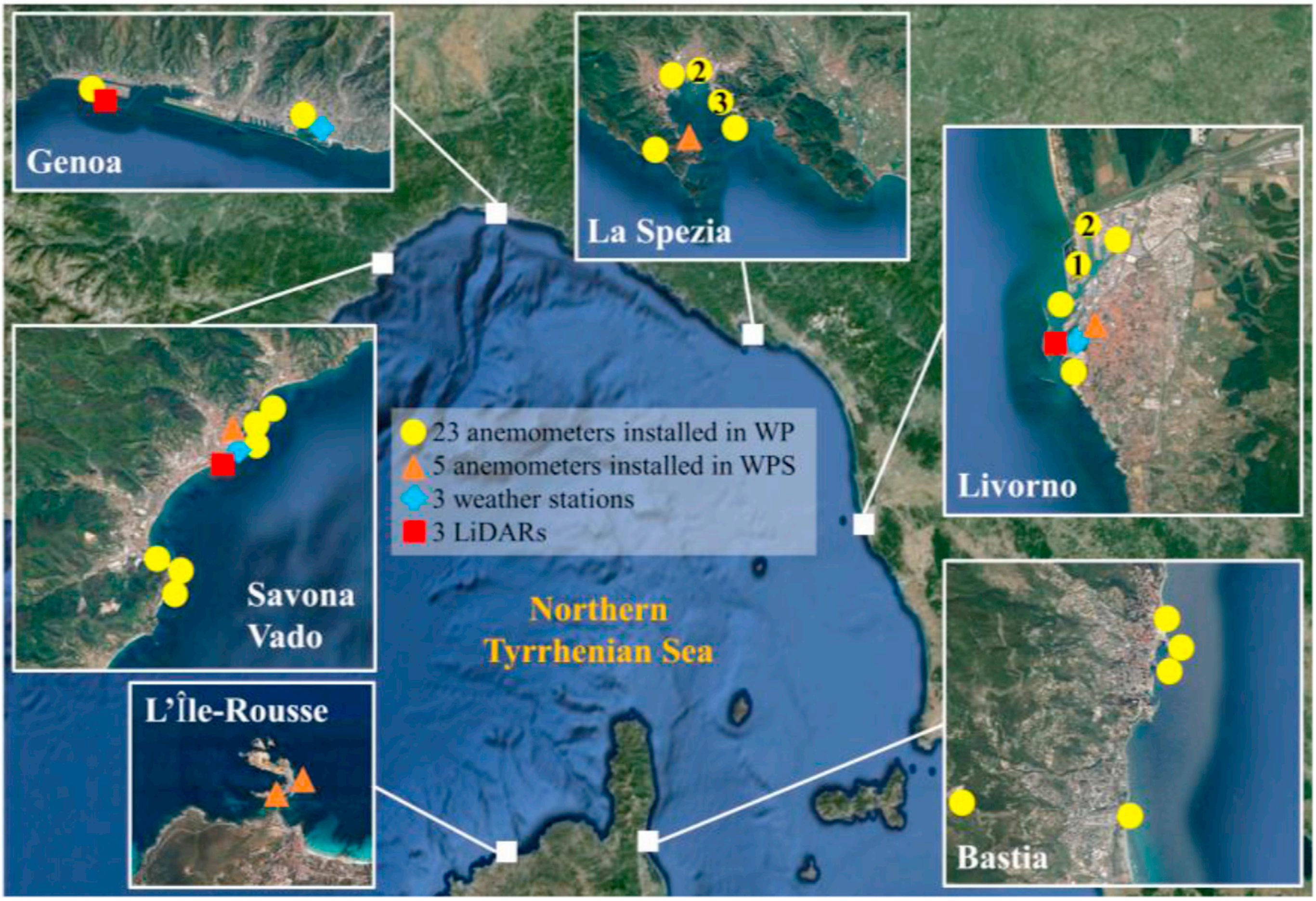


Fig. 1. WP & WPS wind monitoring network (basic pictures extracted from Google Earth).

anemometers (orange triangles) in the Ports of Savona (1), La Spezia (1), Livorno (1) and L'Île Rousse (2), 3 LiDAR (Light Detection And Ranging) scanners (red squares), and 3 weather stations (blue diamonds), each of which includes another ultrasonic anemometer, a barometer, a thermometer and a hygrometer. Other sensors autonomously installed by individual Port Authorities are in the process of becoming parts of the WP and WPS network.

The ultrasonic anemometers detect the wind speed and the wind direction with a precision of 0,01 m/s and 1°, respectively. Their sampling rate is 10 Hz with the exception of one sensor in the Port of Savona, with a sampling frequency of 1 Hz, and those in the Ports of Bastia and L'Île Rousse, with a sampling frequency of 2 Hz. To avoid local effects contaminating the measurements and to register undisturbed wind speeds, all instruments are homogeneously distributed in the port areas and mounted on high-rise towers and on some antenna masts at the top of buildings, at a height of at least 10 m above ground level (AGL). A set of local servers, placed in the headquarters of each port authority, receives the records acquired by the anemometers in their own port area, and processes basic statistics over 10 min periods, that is, the mean and the peak wind speed and the mean wind direction. Each server automatically sends this information and all raw data recordings to the central server located in the Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genoa, where a preliminary check of the data received is done, before storing it in a database.

In order to establish a preliminary but robust procedure and discuss its outcomes concisely, the analyses carried out in this paper are limited to the data gathered by anemometers 01 and 02 in the port of Livorno (LI) and by anemometers 02 and 03 in the port of La Spezia (SP) (Fig. 2). The main properties of these anemometers are shown in Table 1, in which *h* is the height of sensors AGL. It is worth noting that, despite the anemometers have been installed for more than 6 years, the period for which valid data is available is shorter (on average 80%). This is due to periods during which measurements were not taken out due to accidents or malfunctioning of instruments, as well as to the existence of periods in which recordings were not reliable enough to be examined (Cook, 2014a, 2014b).

3. Separation of the dataset into selective SUB-DATASETS

In order to carry out an appropriate statistical analysis of the extreme wind speed in a mixed climate, intense wind events should be extracted from the original dataset including all data, and they should be allocated to selective sub-datasets covering homogeneous families of wind events (Thom, 1968a; Gomes and Vickery, 1977/1978). This operation was done here in two successive steps. Firstly, only records with 1 s peak wind speed $\hat{v}$ greater than 18–20 m/s were extracted from the whole dataset. The actual censoring threshold was chosen in order to obtain a reasonable number of extreme wind speeds, for each family of homogeneous events. Secondly, extra-tropical cyclones or depressions (D), thunderstorm outflows (T) and intermediate events (IN) were separated using the semi-automatic procedure described by De Gaetano et al. (2014). This procedure implies a mix of a massive number of quantitative checks, and a few qualitative expert judgments. The former compares the ratio between the peak wind speed $\hat{v}$ and the mean wind speed over different time intervals, with the classic gust factor for synoptic wind speeds (Solari, 1993). The latter was refined here by selecting thunderstorm outflows based not only on 10 min and 1 h duration records, but also on 10 h records centred around the 10 min record selected (Duranona, 2015; Zhang et al., 2017).

Table 1
Main properties of the anemometers selected to perform statistical analyses.

Port	Anemometer No.	*h* (m)	Type	Period of analysis (days)	Valid data (%)
Livorno (LI)	01	20	tri-axial	2010.10.01–2017.03.05 (2348)	81%
	02	20	tri-axial	2010.10.01–2017.03.05 (2348)	71%
La Spezia (SP)	02	13	bi-axial	2010.10.29–2016.10.22 (2186)	87%
	03	10	bi-axial	2011.02.05–2016.09.16 (2051)	84%

As an example, Figs. 3–5 show the records for an extra-tropical cyclone, a thunderstorm outflow and an intermediate event, respectively, detected by anemometer 03 of the Port of La Spezia. In each figure, schemes (a,b), (c,d) and (e,f) refer, respectively, to 10 min, 1 h and 10 h long records for the same event, centred around its peak wind speed. Schemes (a,c,e) and (b,d,f) correspond to the wind speed and direction, respectively. Schemes (a) and (b) provide the measured data (symbols) and related mean values over a 10 min period (solid lines). Schemes (c) and (d) provide measured data (symbols) and related mean values over 1 h (solid lines) and 10 min periods (dotted lines). Schemes (e) and (f) provide measured data (symbols) and related mean values over 10 min periods (dotted lines). In addition, schemes (a) and (c) show the 1 s peak wind speed $\hat{v}$ (red circles) and the maximum value $\overline{v}_{max}$ (orange squares)

(a) (b)

Fig. 2. Position of the anemometers selected for this analysis (basic pictures extracted from Google Earth): (a) Livorno; (b) La Spezia.

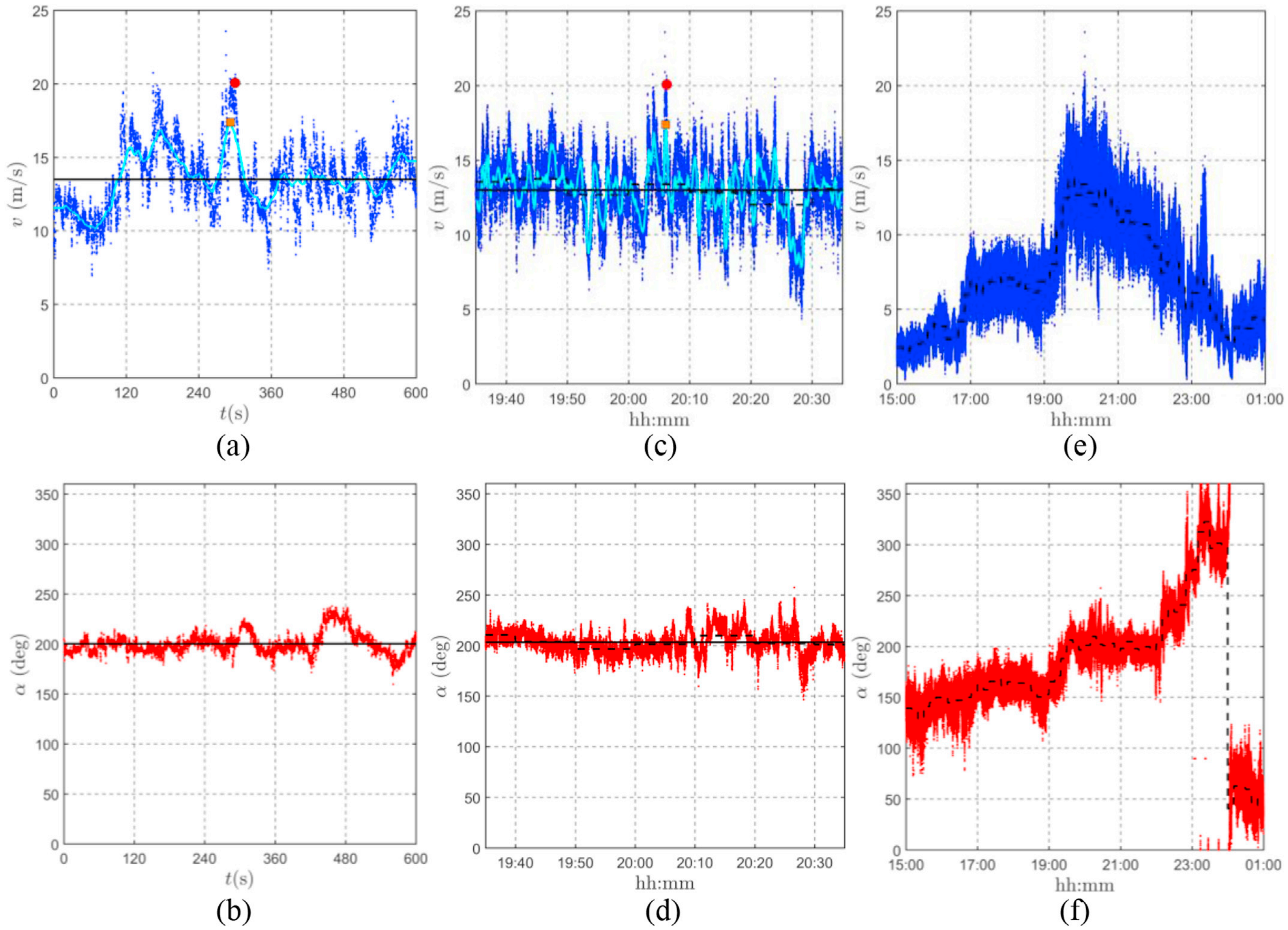


Fig. 3. Extra-tropical cyclone recorded on 2nd March 2016 by the anemometer 03 of the Port of La Spezia: wind speed time-history in10-min (a), 1-h (c), and 10-h (e); wind direction time-history in 10-min (b), 1-h (d), and 10-h (f).

of the slowly-varying mean wind speed over a period of $T = 30$ s.

The record of the depression (Fig. 3) shows a relatively high mean wind speed and a gust factor, of around 1.5, typical of neutral atmospheric conditions. This signal is nearly stationary and Gaussian. The thunderstorm outflow record (Fig. 4) shows a relatively low mean wind speed and a very high gust factor. This signal is strongly non-stationary. The intermediate event record (Fig. 5) shows a low mean wind speed and a gust factor significantly higher than those typical for neutral atmospheric conditions. This signal is nearly stationary but the fluctuations are clearly non-Gaussian. More details may be found in De Gaetano et al. (2014).

Once highly controlled selective sub-datasets have been generated, independent extreme wind speeds are extracted in terms of the following criterion: Extra-tropical cyclones and intermediate events are considered as independent provided they are separated by a time interval longer than 3 days and 1 day, respectively. Thunderstorms are considered as independent if they are separated by an interval longer than 4 times their duration (Solari et al., 2015). This criterion works in most cases, except for some complex situations in which two or three different types of events occur close to one another. In some cases this happens only due to actually different independent events occurring at the same time (Figs. 6 and 7). In other cases the separation criterion provided by De Gaetano et al. (2014) results in the creation, within the same record, of an unrealistic sequence of alternating different events (Figs. 8–10). Fortunately, this is not very frequent.

Fig. 6 shows an intermediate event followed by a thunderstorm outflow, both of which with peak wind speed greater than the censoring threshold. In this case both the maximum peak wind speeds of these events are included in the appropriate series of the independent extreme values.

Fig. 7 shows two intense events, labelled as thunderstorm outflows, which occurred quite close to one another. They are taken as being independent due to their short duration. Following the separation procedure, a qualitative expert judgement was required for the former, and it was labelled as a thunderstorm outflow after having ascertained the presence of lightning and thunder over La Spezia during its occurrence.

Figs. 8–10 show three wind speed time-histories characterised by a sequence of records labelled as depressions and intermediate events. Fig. 8 depicts a case in which an intermediate event seems to be embedded within an extra-tropical cyclone. Accordingly, both the maximum peak wind speeds for these events are retained in the series of independent extreme values. Fig. 9 shows a sequence of alternating records labelled as depressions and intermediate events. Observing that the 10 min mean wind speed is relatively large for the entire intense part of this event, almost 20 m/s, the maximum peak wind speed for this sequence is labelled as a depression. Similarly, Fig. 10 shows a sequence of alternating records labelled as depressions and intermediate events. Unlike the previous case, however, the 10 min mean wind speed oscillates between 5 and 10 m/s. Accordingly, the maximum peak wind speed for this sequence is labelled as an intermediate event.

Tables 2 and 3 summarize, the number of data and the maximum value in each series of the peak wind speeds related to the 3 phenomena

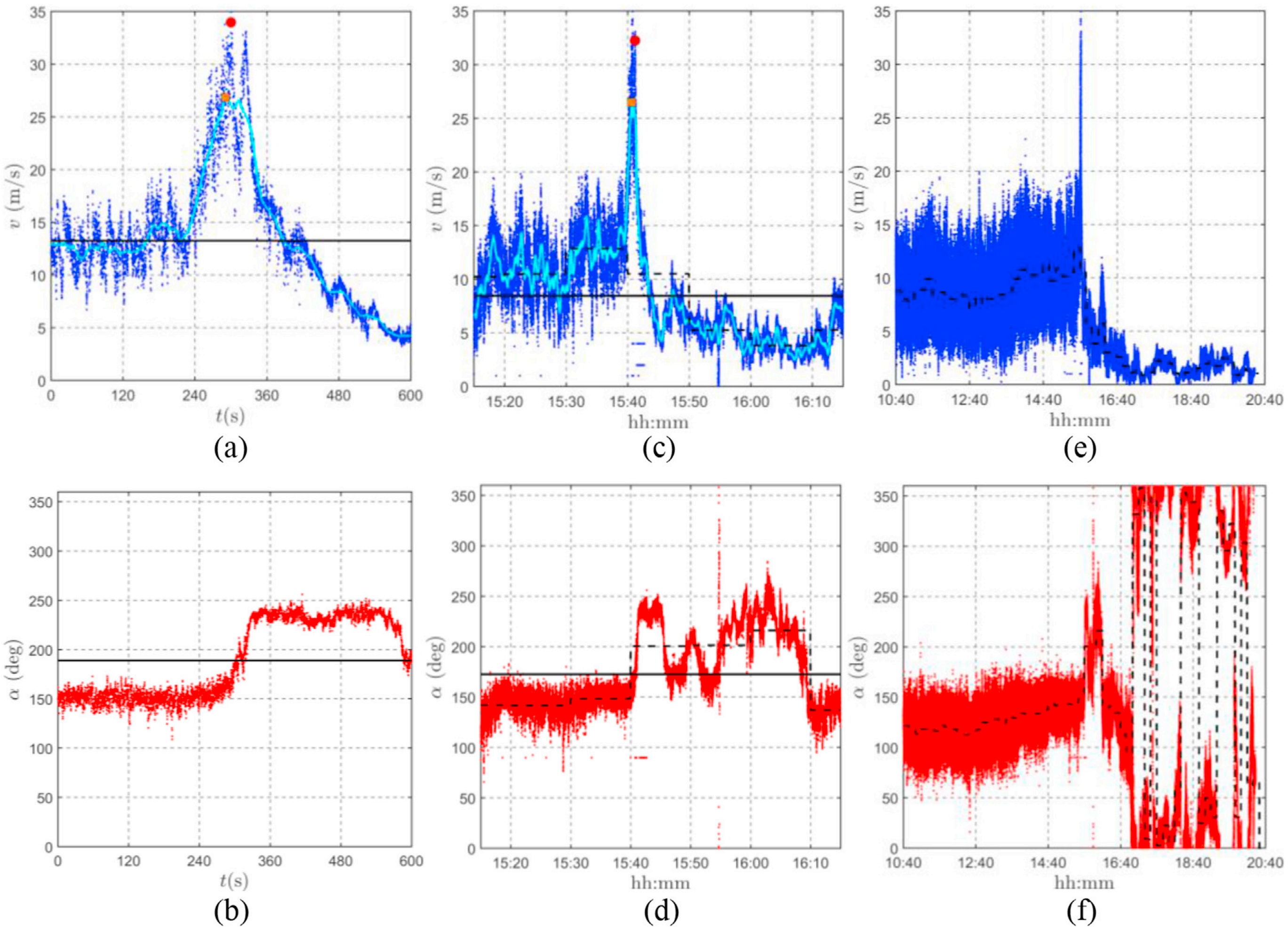


Fig. 4. Thunderstorm outflow recorded on 25th October 2011 by the anemometer 03 of the Port of La Spezia: wind speed time-history in10-min (a), 1-h (c), and 10-h (e); wind direction time-history in 10-min (b), 1-h (d), and 10-h (f).

(D, T, IN) and to the 4 anemometers (LI_01, LI_02, SP_02, SP_03) examined, respectively. Tables 4–7 provide the full series of the peak wind speed values $\widehat{v}$ and of the corresponding maximum values of the slowly varying mean wind speeds $\overline{v}_{\max}$ detected during the thunderstorm outflows.

4. Extreme wind speed distribution

The extreme wind speed distribution in a mixed climate should be evaluated by firstly investigating each wind phenomenon that strikes that area separately, with the aim of obtaining its own extreme distribution. Then, depending on their use, these distributions can be included in a comprehensive model referred to as a mixed extreme distribution (Gomes and Vickery, 1977/1978), or they can be kept separate, in order to provide independent wind loading conditions for each wind phenomenon (Solari, 2014).

Within the framework of a preliminary study still based on a limited number of years of acquisition, the use of advanced models (Harris, 2014; Torrielli et al., 2013, 2014) may prove to be disproportionate to the actual data available and, in addition, it may lead to results that are distorted or endowed with a false level of accuracy. Hence, the extreme distribution of the peak wind speed is reported here as being classic Fisher-Tippett Type I or Gumbel distribution for all the phenomena involved in the mixed climate.

In addition, since the limited number of the available years of wind measurements makes it impossible regress each extreme value distribution by its yearly maxima series, based on the monthly maximum (Simiu et al., 1982) and storm (Cook, 1982) methods, the cumulative distribution function (CDF) for the yearly maximum peak wind speed for each wind phenomenon is given by:

$$F^{(K)}_{\widehat{v}}(\widehat{v}) = \left[F^{(K)}_{\widehat{v},e}(\widehat{v})\right]^{N_K} \tag{1}$$

$$F^{(K)}_{\widehat{v},e}(\widehat{v}) = \exp\{-\exp[-a_K(\widehat{v}-u_K)]\} \tag{2}$$

where $K = D, T, IN$ denotes the wind phenomenon, N_K is the average number of independent extreme peak wind speed values in one year for the K phenomenon, $F^{(K)}_{\widehat{v},e}$ is the CDF for the extreme peak wind speed of the K phenomenon, and u_K and a_K are the mode and the scale factor for type I distribution.

The u_K and a_K parameters are inferred here using the measured data and the order statistics method. Accordingly, the series of the extreme peak wind speeds is ordered from the smallest $\widehat{v}_1$ to the greatest $\widehat{v}_{N_K}$ value and the empirical estimate for $F^{(K)}_{\widehat{v},e}(\widehat{v}_m)$, referred to as the plotting position, is determined based on the ranked position of $\widehat{v}_m$ (Guo, 1990) by means of the equation:

$$F^{(K)}_{\widehat{v},e}(\widehat{v}_m) = \frac{m}{N_K+1} \tag{3}$$

where m is the ranking of each value in the population (Cook, 1982). The

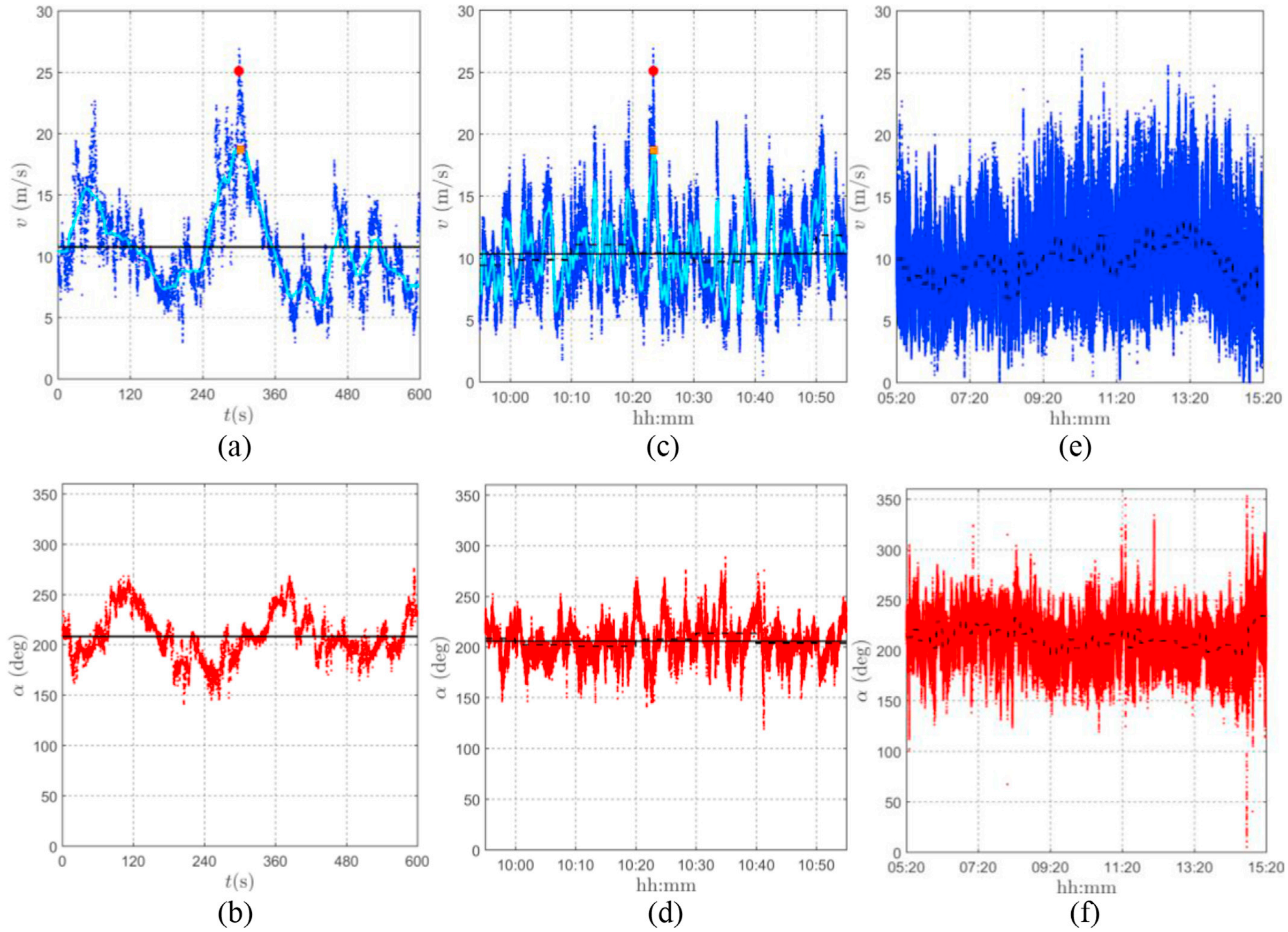


Fig. 5. Intermediate event recorded on 16th December 2011 by the anemometer 03 of the Port of La Spezia: wind speed time-history in10-min (a), 1-h (c), and 10-h (e); wind direction time-history in 10-min (b), 1-h (d), and 10-h (f).

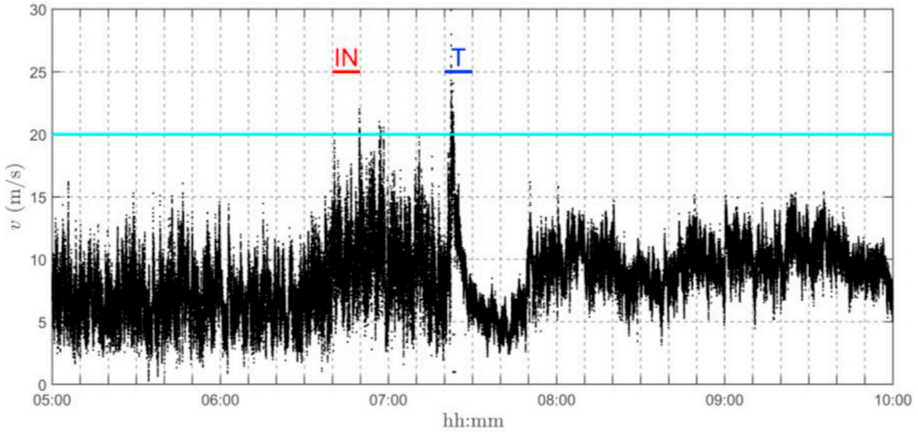


Fig. 6. 5-h wind speed time-history measured on 26 December 2013 by the anemometer 03 of the Port of La Spezia.

estimation of the u_K and a_K parameters is done using the least squares technique, so that Eq. (2) best approximates Eq. (3) in a “Gumbel probability paper”, that is, in a diagram in which the coordinate axes are such that Eq. (2) becomes linear. Also, in this case different weights are not applied to the sequence of the ordered values, nor are refined inference methods (Lieblein, 1974; Hoaglin et al., 1983) used, due to the limited number of data. Table 8 shows the values of the u_K and a_K parameters together with the N_K values estimated by taking the actual number of valid data into account (Section 2, Table 1).

Figs. 11–14 show the CDF for the maximum yearly peak wind speed as detected by the 4 anemometers (LI_01, LI_02, SP_02, SP_03) respectively. Schemes (a), (b), (c) refer to the D, T and IN events, respectively. Each diagram is a Gumbel plot that provides the peak wind speed $\widehat{v}$ as a function of the return period $R = 1/[1 - F_{\widehat{v}}(\widehat{v})]$. Type I distribution (solid

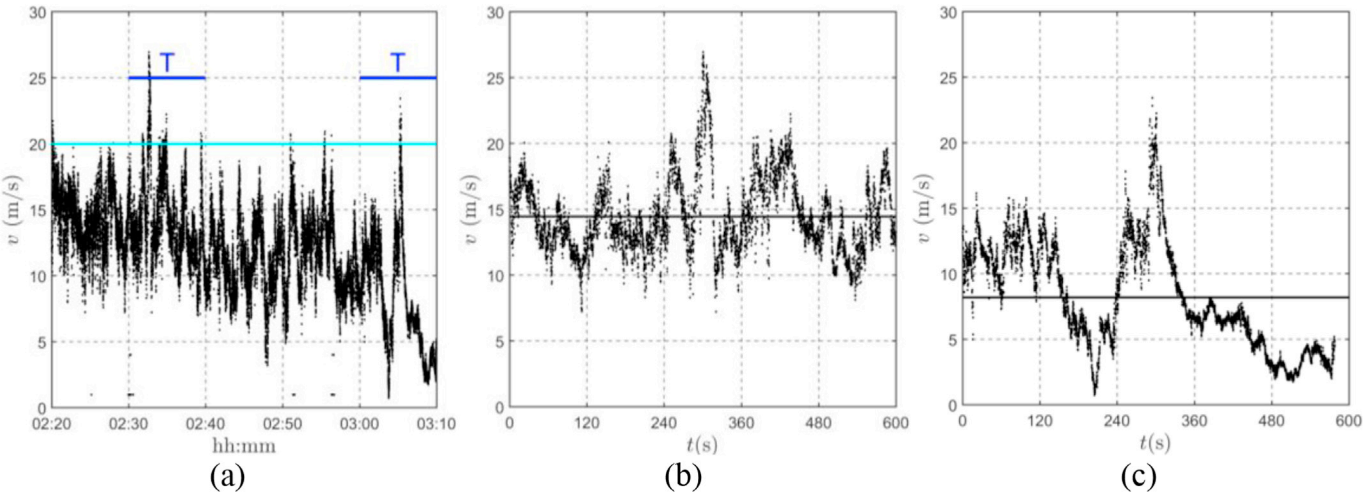


Fig. 7. (a) 50-min wind speed time-history measured on 9 February 2014 by the anemometer 03 of the Port of La Spezia; (b, c) subsequent 10-min intervals in which two transient events occur.

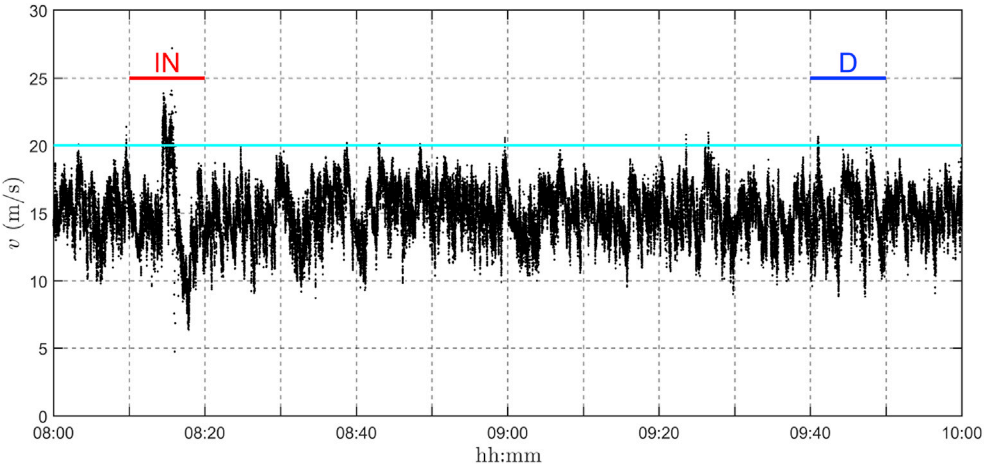


Fig. 8. 2-h wind speed time-history measured on 26 November 2010 by the anemometer 01 of the Port of Livorno.

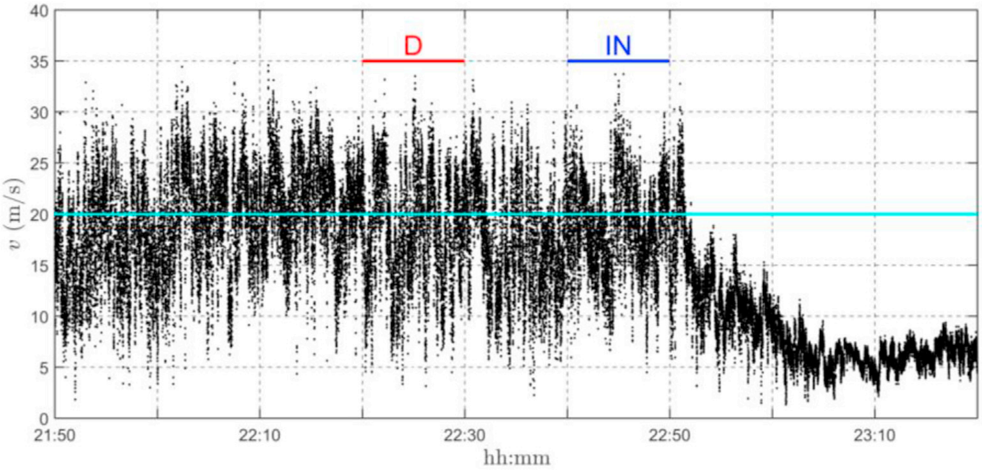


Fig. 9. 1 and a half-h wind speed time-history measured on 16 December 2011 by the anemometer 02 of the Port of Livorno.

lines) represents a reasonable fit for the experimental points (circles) except for the presence of a clear outlier, the maximum value of the peak wind speed in Fig. 11(a) (LI_01, D) and of two other suspicious bits of data, the maximum values for the peak wind speed in Fig. 11(b) (LI_01, T) and in Fig. 14(b) (SP_03, T).

The correctness of the above data has been carefully checked with

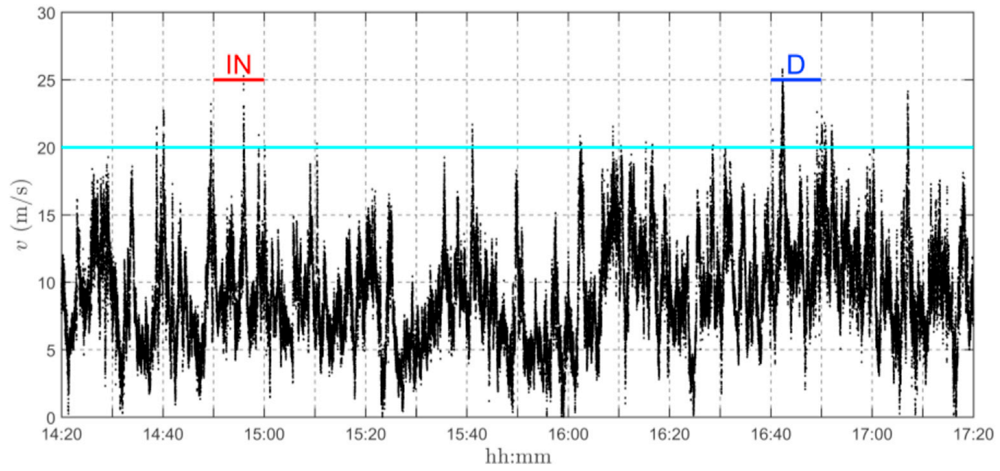


Fig. 10. 3-h wind speed time-history measured on 8 November 2010 by the anemometer 02 of the Port of La Spezia.

Table 2
Number of data in each series of peak wind speed values.

Event Anemometer	D	T	IN
LI_01	47	19	17
LI_02	44	10	12
SP_02	10	9	20
SP_03	15	16	19

Table 3
Maximum value of the peak wind speed $\hat{v}$ (m/s) in each series.

Event Anemometer	D	T	IN
LI_01	33.01	33.65	24.23
LI_02	31.49	29.44	26.47
SP_02	25.97	30.03	26.94
SP_03	26.54	33.98	25.60

Table 4
Extreme wind speeds detected in thunderstorm outflows by the anemometer 01 of Port of Livorno.

No.	Date	Time	$\hat{v}$ (m/s)	$\bar{v}_{max}$ (m/s)
1	20101108	19:00	22.70	20.08
2	20110904	15:50	22.83	20.98
3	20111216	22:50	33.65	27.58
4	20121111	5:00	22.87	16.07
5	20121202	18:20	27.30	25.72
6	20130525	13:00	20.57	18.33
7	20131121	23:30	20.49	18.76
8	20140323	21:40	24.01	21.51
9	20140721	3:40	21.05	18.22
10	20141013	14:30	22.78	20.69
11	20141116	0:30	23.44	21.38
12	20141117	20:10	21.48	18.32
13	20141227	15:50	28.50	25.37
14	20151004	5:10	22.03	19.15
15	20151015	22:20	23.74	21.96
16	20151016	1:40	25.75	23.34
17	20151016	2:00	23.30	20.25
18	20160906	17:40	22.14	19.07
19	20170113	13:20	21.92	19.87

Table 5
Extreme wind speeds detected in thunderstorm outflows by the anemometer 02 of Port of Livorno.

No.	Date	Time	$\hat{v}$ (m/s)	$\bar{v}_{max}$ (m/s)
1	20110904	15:50	22.73	20.13
2	20120120	10:50	19.14	13.81
3	20121111	5:00	19.84	15.31
4	20121207	13:40	18.29	14.60
5	20131121	10:10	18.51	15.57
6	20151004	5:30	21.75	19.23
7	20151028	19:30	23.29	16.30
8	20160906	17:40	24.96	20.78
9	20160916	23:20	29.44	20.67
10	20170113	13:40	20.49	16.52

Table 6
Extreme wind speeds detected in thunderstorm outflows by the anemometer 02 of Port of La Spezia.

No.	Date	Time	$\hat{v}$ (m/s)	$\bar{v}_{max}$ (m/s)
1	20110605	14:50	23.10	18.11
2	20120411	7:20	30.03	23.39
3	20120419	12:50	23.61	16.62
4	20121027	12:30	21.56	15.24
5	20131103	11:10	27.78	18.94
6	20141013	15:50	20.00	16.49
7	20141227	13:30	26.21	20.04
8	20150130	1:20	20.62	16.20
9	20111203	13:00	21.86	15.25

regard to both the individual records from which they were extracted and the records registered simultaneously by other anemometers in the monitoring network in the same port area, including those not examined in this paper. In the case of the peak wind speed $\hat{v} = 33.01$ m/s in Fig. 11(a) (LI_01, D), the other four anemometers in the port of Livorno detected similar wind conditions, with peak wind speeds always higher than 30 m/s. In the case of the peak wind speed $\hat{v} = 33.65$ m/s in Fig. 11(b) (LI_01, T), the corresponding record shows a transient event embedded in an intense synoptic condition. The other four anemometers in the port of Livorno detected similar synoptic conditions without clear transient events as for LI_01, this having been probably caused by a local phenomenon. In the case of the peak wind speed $\hat{v} = 33.98$ m/s in Fig. 14(b) (SP_03, T), this refers to an isolated transient gust front. SP_02 detected a similar situation, delayed by about 5 min, with a lower peak wind speed of the order of 20 m/s.

Fig. 15 shows the CDF of the maximum yearly peak wind speed detected by the 4 anemometers, for each wind phenomenon. The statistical analysis of depressions highlights rather good agreement between different anemometers in the same area. Small differences can be related to the local roughness of the terrain around the anemometric stations. On the other hand, significant differences occur between the areas of Livorno and La Spezia despite their proximity (about 75 km). This is probably due

Table 7
Extreme wind speeds detected in thunderstorm outflows by the anemometer 03 of Port of La Spezia.

No.	Date	Time	$\widehat{v}$ (m/s)	$\overline{v}_{max}$ (m/s)
1	20110605	14:50	20.70	17.68
2	20110724	0:00	21.18	17.33
3	20111019	21:10	23.63	18.82
4	20111025	15:40	33.98	26.86
5	20120411	7:10	23.40	18.46
6	20120924	13:50	23.69	19.94
7	20121015	0:20	22.53	20.31
8	20131110	10:10	20.33	14.97
9	20131226	7:20	26.31	18.75
10	20140209	2:30	26.39	20.62
11	20140209	3:00	21.55	16.48
12	20141013	15:50	25.18	20.33
13	20141201	0:10	21.37	18.03
14	20141227	13:40	22.24	15.29
15	20150117	2:40	22.80	17.55
16	20160305	13:00	22.89	16.74

Table 8
Model parameters of the CDF of different wind phenomena.

Anemometer	K wind phenomenon	a_K (s/m)	u_K (m/s)	N_K
LI_01	*D*	0.49	21.40	9.02
	T	0.32	22.08	3.65
	IN	0.56	19.17	3.26
LI_02	*D*	0.49	21.83	9.63
	T	0.28	20.10	2.19
	IN	0.45	19.92	2.63
SP_02	*D*	0.62	21.82	1.92
	T	0.28	22.14	1.73
	IN	0.49	21.35	3.84
SP_03	*D*	0.51	21.40	3.18
	T	0.30	21.90	3.39
	IN	0.58	21.73	4.03

to the different properties of the two sites both in terms of orography and of roughness length: Livorno, which is characterised by higher wind speed values, has the sea to the west and a flat open area all around it, whereas La Spezia is surrounded by the mountain range of the Liguria Apennines in all directions, apart a small sector facing the sea towards the south. The situation is different for thunderstorm outflows, where data gathered by different anemometers in different areas lead to similar results: This may be due to the fact that thunderstorm cells frequently move from the sea towards inland and the roughness length plays a secondary role (Solari et al., 2015; Zhang et al., 2017). Intermediate events are characterised by intermediate properties.

Once the CDF for the maximum yearly peak wind speed has been evaluated for each wind phenomenon at each anemometer, the method of mixed statistics (Gomes and Vickery, 1977/1978) provides a tool for estimating a comprehensive CDF for the maximum yearly peak wind speed at each anemometer. Assuming that the extreme wind speeds of different wind phenomena are statistically independent, the mixed (M) CDF for the maximum yearly peak wind speed is given by:

$$F^{(M)}_{\widehat{v}}(\widehat{v}) = F^{(T)}_{\widehat{v}}(\widehat{v})\cdot F^{(D)}_{\widehat{v}}(\widehat{v})\cdot F^{(IN)}_{\widehat{v}}(\widehat{v}) \tag{4}$$

$F^{(K)}_{\widehat{v}}$ (Eq. (1)) being the CDF for the maximum yearly peak wind speed for the K phenomenon.

For each anemometer, Figs. 16 and 17 show the CDF for the maximum yearly peak wind speed for each phenomenon (D, T, IN) and for mixed statistics (M). In addition, following Lombardo et al. (2009), the results obtained by gathering the ensemble (E) of all the extreme values into a single set are also shown as a reference. Table 9 provides a synthetic overview of these results.

Figs. 16 and 17 and Table 9 point out that wind events with a high return period, which are the most important for structural safety, are always related to thunderstorms. This finding confirms, at least in the area examined here, similar results reported worldwide (Whittingham, 1964; Davenport, 1968; Thom, 1968b; Gomes and Vickery, 1976; Twisdale and Vickery, 1992; Choi, 1999; Letchford et al., 2002; Lombardo et al., 2009). On the other hand, contrary to what was observed by Kasperski (2002) in Germany, intermediate events do not seem to have a determinant role in extreme wind speeds. In every case, gathering the ensemble of all extreme values into a single set leads to underestimating the mixed CDF especially for high return periods, where the mixed CDF tends to coincide with that for thunderstorms.

Coming to a more detailed examination of the two port areas examined here, the wind climate of the Port of Livorno is dominated by thunderstorm outflows, depressions are usually secondary, and intermediate events definitely have a marginal role. However, while for LI_01 thunderstorm outflows dominate depressions for any return period over 1 year, for LI_02 thunderstorm outflows exceed extra-tropical depressions in terms of importance, only for return periods over about 20 years.

As far as the wind climate of the Port of La Spezia is concerned, this is dominated by thunderstorm outflows for any return period over 1 year, whereas intermediate events are comparable with depressions for SP_03 and slightly exceed the same for SP_02.

5. Extreme mean VS peak wind speed distribution

The assignment of the extreme wind speed for synoptic extra-tropical cyclones is a key topic in wind engineering in relation to research, applications and codes. In some cases, the extreme wind speed is evaluated in terms of mean values usually averaged over a time interval $\Delta T = 10$ or 60 min. In other cases, such as in this paper, it is carried out in terms of

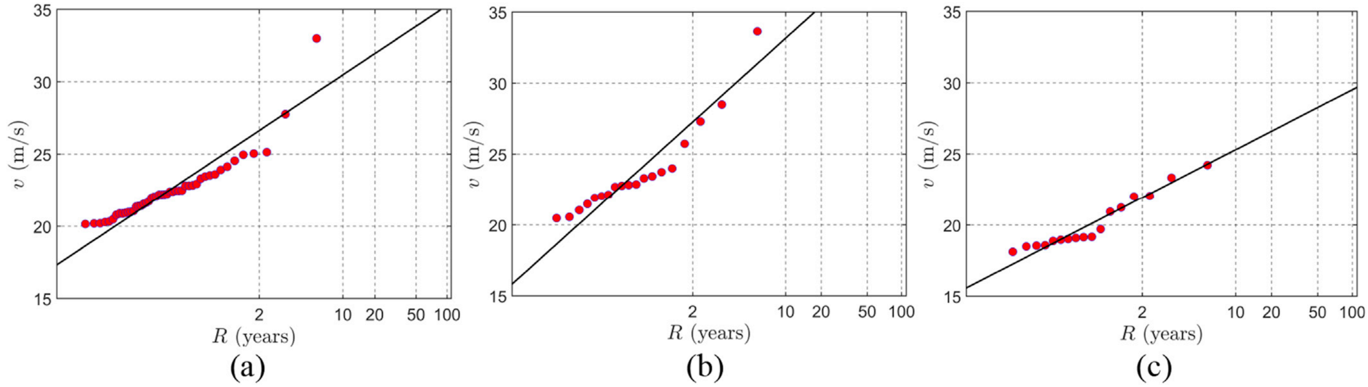


Fig. 11. Plotting positions and fitting line for the extra-tropical depressions (a), thunderstorm outflows (b), and intermediate events (c) detected by the anemometer 01 in the Port of Livorno.

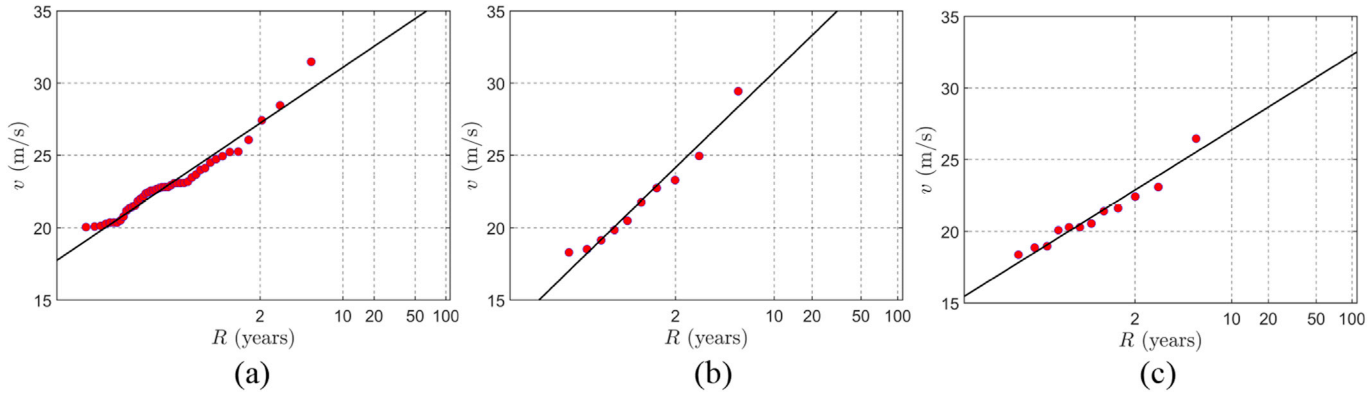


Fig. 12. Plotting positions and fitting line for the extra-tropical depressions (a), thunderstorm outflows (b), and intermediate events (c) detected by the anemometer 02 in the Port of Livorno.

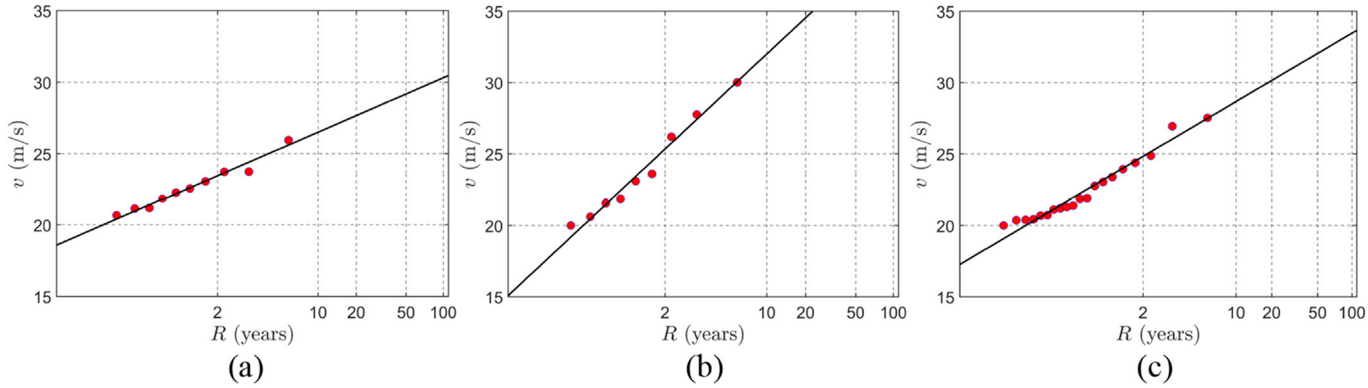


Fig. 13. Plotting positions and fitting line for the extra-tropical depressions (a), thunderstorm outflows (b), and intermediate events (c) detected by the anemometer 02 in the Port of La Spezia.

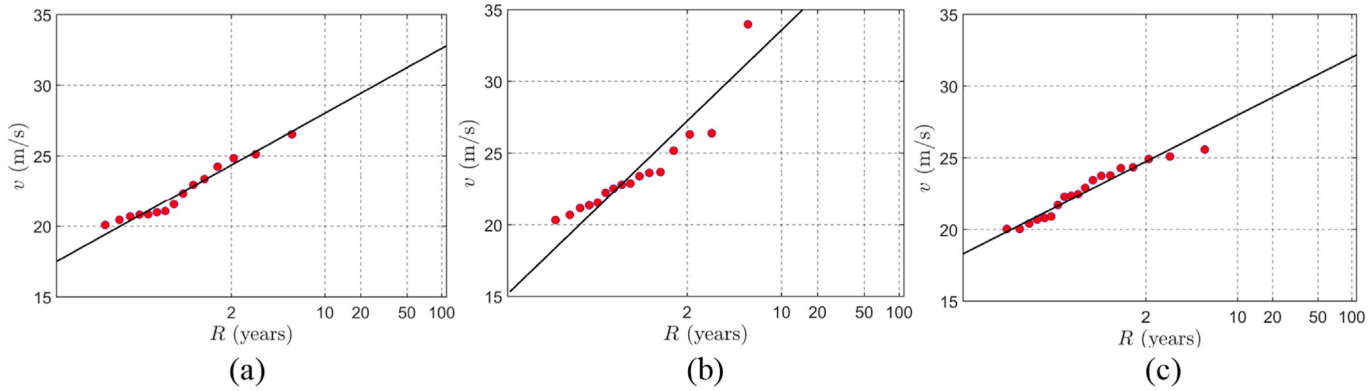
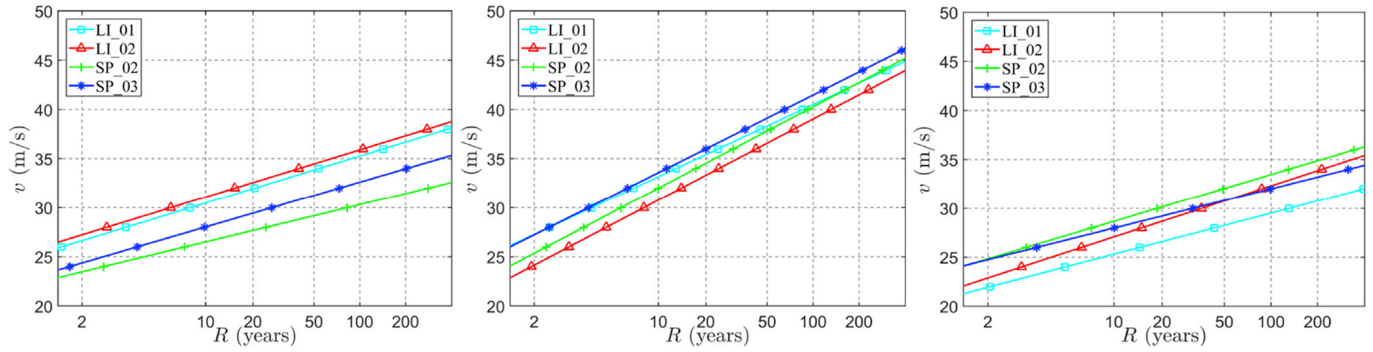


Fig. 14. Plotting positions and fitting line for the extra-tropical depressions (a), thunderstorm outflows (b), and intermediate events (c) detected by the anemometer 03 in the Port of La Spezia.

peak values averaged over a time interval $\tau = 1$ or 3 s (in this paper $\tau = 1$ s). In both cases, the passage from one evaluation to the other occurs by means of a velocity gust factor referred to as the ratio between the peak and the mean wind speed (Durst, 1960; Greenway, 1979; Solari, 1993; Holmes et al., 2014; Kwon and Kareem, 2014). The longstanding literature on this topic bears testimony to the inherent achievement of a relevant level of confidence in the application of this procedure.

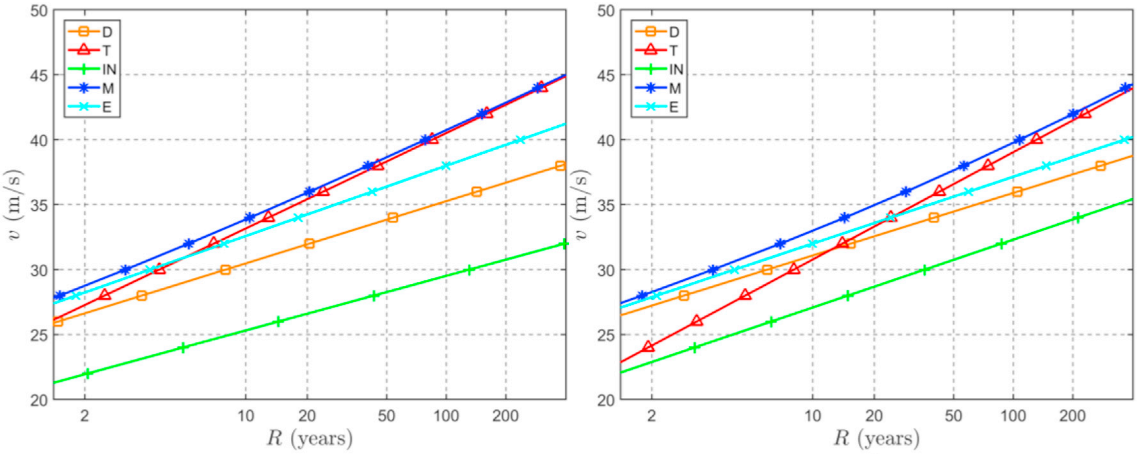
The situation is quite different for thunderstorm outflows. Firstly, due to their transient character, the mean wind speed is no longer representative and should be replaced by a suitable value for the time-varying mean wind speed (Chay et al., 2008; Holmes et al., 2008; Lombardo et al., 2014). Since this quantity depends on the moving average period T, the gust factor of thunderstorm outflows is in turn a function of T (Choi, 2000; Choi and Hidayat, 2002; Holmes et al., 2008; Lombardo et al., 2014). Solari et al. (2015) defined three noteworthy velocity ratios that play a key role in thunderstorm loading and response of structures. In this context, the ratio between the peak wind velocity $\hat{v}$ and the maximum value of the slowly-varying mean wind velocity $\overline{v}_{\max}$ corresponds to the most common definition of the gust factor for a thunderstorm outflow:

$$G_v = \frac{\hat{v}}{\overline{v}_{\max}} \tag{5}$$



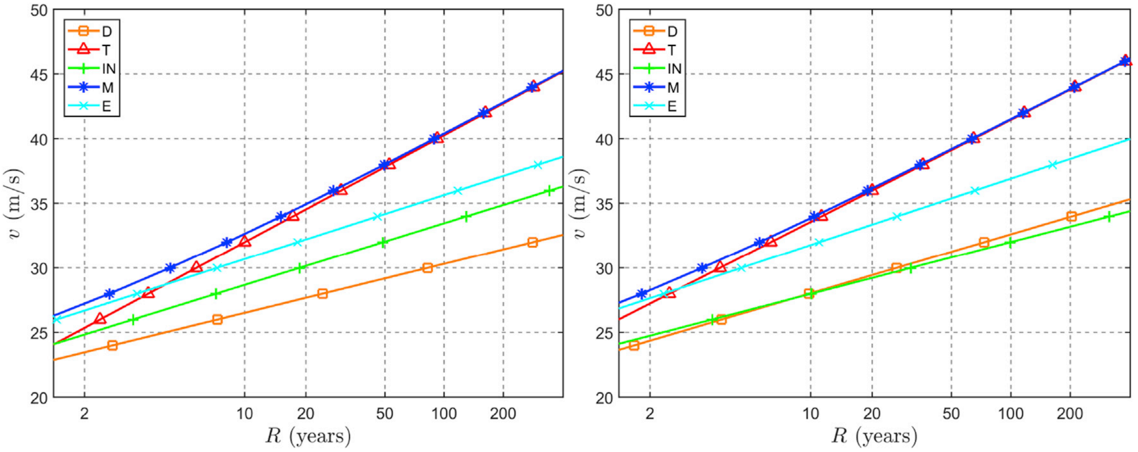
(a) (b) (c)

Fig. 15. CDF of the yearly maximum peak wind speed for extra-tropical depressions (a), thunderstorm outflows (b), and intermediate events (c) in correspondence of the 4 anemometers analysed.



(a) (b)

Fig. 16. Peak wind speed as a function of the return period for the anemometers 01 (a) and 02 (b) of the Port of Livorno.



(a) (b)

Fig. 17. Peak wind speed as a function of the return period for the anemometer 02 (a) and 03 (b) of the Port of La Spezia.

Table 10 shows the mean values for the gust factors of the thunderstorm outflows recorded by each of the four anemometers examined here.

Despite these definitions and the values for the gust factors estimated being rather recent, they are shared by the wind engineering community more and more. However, to the Authors' knowledge, no evaluation has been carried out to evaluate the reliability of using G_v in order to move from the extreme wind speed distribution in terms of $\hat{v}$ to the one based on $\overline{v}_{\max}$, and vice-versa.

In order to fill this gap and to provide some preliminary remarks on this issue, the CDF for the yearly maximum value of $\overline{v}_{\max}$ (dotted blue line in Fig. 18) is estimated for each anemometer using the method described

Table 9
Peak wind speed (m/s) as a function of the return period.

Analysis	Anemometer	*R* (years)					
		2	5	10	20	50	100
D	LI_01	26.64	28.95	30.48	31.95	33.85	35.27
	LI_02	27.23	29.55	31.09	32.56	34.47	35.90
	SP_02	23.47	25.30	26.51	27.68	29.18	30.31
	SP_03	24.36	26.57	28.03	29.44	31.25	32.61
T	LI_01	27.27	30.82	33.17	35.42	38.33	40.52
	LI_02	24.15	28.14	30.78	33.31	36.59	39.04
	SP_02	25.35	29.35	32.00	34.54	37.82	40.28
	SP_03	27.24	31.05	33.57	35.99	39.13	41.48
IN	LI_01	21.94	23.97	25.31	26.60	28.27	29.52
	LI_02	22.89	25.41	27.08	28.68	30.76	32.31
	SP_02	24.84	27.15	28.68	30.15	32.05	33.47
	SP_03	24.75	26.70	27.98	29.22	30.82	32.01
E	LI_01	28.24	30.85	32.58	34.24	36.39	38.00
	LI_02	27.88	30.36	32.00	33.58	35.62	37.15
	SP_02	26.69	29.09	30.68	32.21	34.18	35.66
	SP_03	27.65	30.14	31.78	33.36	35.40	36.93
M	LI_01	28.75	31.77	33.86	35.92	38.65	40.74
	LI_02	28.27	31.04	32.99	34.95	37.64	39.77
	SP_02	27.22	30.37	32.64	34.93	38.03	40.41
	SP_03	28.27	31.55	33.86	36.16	39.21	41.52

Table 10
Mean value of the gust factor of the thunderstorm outflows.

Anemometer	LI_01	LI_02	SP_02	SP_03
$\langle G \rangle$	1.14	1.27	1.34	1.27

in Section 5 with regard to $\hat{v}$ (full red line in Fig. 18). In addition, the CDF for the yearly maximum value of $\hat{v}$ is determined by multiplying the extreme values of $\overline{v}_{\max}$ by the gust factors in Table 9 (dashed and dotted black line in Fig. 18). The agreement between these two methods is excellent. Also, this procedure is easy to apply due to the weak dependence of the thunderstorm gust factor on roughness length. This means that directionality effects can be disregarded, despite being important for synoptic depressions.

The persisting limited knowledge of intermediate events prevents development of similar studies in their regard.

6. Comparison with classic analyses

The results described in Section 4 are compared with the extreme wind speed values provided by the Italian Guide for Wind Actions and Effects on Structures (CNR-DT 207/2008, 2008) in the two areas examined here. In addition, a comparison is carried out with the results of some detailed analyses of the wind climate of Pisa (Ballio et al., 1999), 20 km from Livorno, and of La Spezia (Castino et al., 2003). All these studies concern the historical ensemble of the mean wind speed values over 10 min periods, so they are based on many more years of measurements than those considered here. On the other hand they do not take into account either the occurrence of thunderstorms or mixed statistics.

Using the Italian Guide for Wind Actions and Effects on Structures (CNR-DT 207/2008, 2008), the Port of Livorno lies in Area 3 (Tuscany Zone) at sea level, so its basic reference wind velocity, i.e. the mean wind velocity over a 10 min interval at a height of 10 m above flat homogeneous open terrain with roughness length $z_0 = 0{,}05$ m and return period $R = 50$ years, is $v_b = 27$ m/s. This document also provides the return coefficient c_r that multiplied by v_b provides the reference wind velocity v_r as a function of R. Besides, it assigns exposure category II to the seaport area of Livorno. Accordingly, the mean wind velocity at anemometers at a height $z = 20$ m (Table 1) is $v_m = 1.138 \cdot v_r$, whereas the peak wind velocity is the mean wind velocity multiplied by the gust factor $G_v = 1.471$, namely $v_p = 1.674 \cdot v_r$.

Similarly, the Port of La Spezia lies in Area 7 (Liguria Zone) at sea level, so $v_b = 28$ m/s. This makes it exposure category III. Accordingly, the mean wind velocities at anemometers at a height $z_2 = 13$ m and $z_3 = 10$ m (Table 1) are $v_{m2} = 0.973 \cdot v_r$ and $v_{m3} = 0.921 \cdot v_r$, respectively, whereas the gust factors are $G_{v2} = 1.572$ and $G_{v3} = 1.603$; thus, $v_{p2} = 1.530 \cdot v_r$ and $v_{p3} = 1.476 \cdot v_r$.

The wind climate of Pisa, extrapolated here from the seaport area of Livorno, was determined during the studies that led to the Italian wind map (Ballio et al., 1999) still provided by the Italian wind code (CNR-DT 207/2008, 2008). The wind climate of La Spezia was evaluated in the framework of a pilot study for micro-zoning of the Liguria Region (Castino et al., 2003). These investigations, which took wind directionality effects into account, provided $v_b = 24{,}7$ m/s and $v_b = 25$ m/s, respectively. The local wind velocities at the anemometers have been scaled accordingly.

Fig. 19 compares the above results with those provided in Section 4 based on mixed statistics. Firstly, at least in the areas examined here, the Italian code (CNR-DT 207/2008, 2008) provides conservative estimates of the extreme wind speed. A comparison between the results of previous analyses based on long historical series but ignoring thunderstorms, and the new investigations based on a limited number of years but taking thunderstorms into account, shows different trends in Livorno and La Spezia. In Livorno (Fig. 19(a)), the results by Ballio et al. (1999) are always cautious when compared with the evaluations here. In La Spezia (Fig. 19(b)), the occurrence of intense thunderstorm outflows leads to equating (anemometer 02) or exceeding (anemometer 03), the results of the micro-zoning analysis performed by Castino et al. (2003), for high/medium return periods. In any case, further analyses are necessary.

7. Conclusions and prospects

Extra-tropical cyclones are the most typical events that strike mid-latitude areas. Thunderstorms, like extra-tropical cyclones, occur almost everywhere in these areas. The European wind climate and that of many other parts of the world is dominated by these two phenomena. In addition, intermediate events occur. In such a genuine multi-mechanism mixed wind climate, a reasonable extreme wind speed analysis cannot be done without separating the data related to different phenomena. How this data is combined in a mixed statistical scheme depends on the aim of the analyses to be carried out.

In this paper, preliminary statistical analyses of the extreme peak wind speed recorded by the continuous high-frequency monitoring system of the “Wind and Ports” and “Wind, Ports and Sea” Projects are done

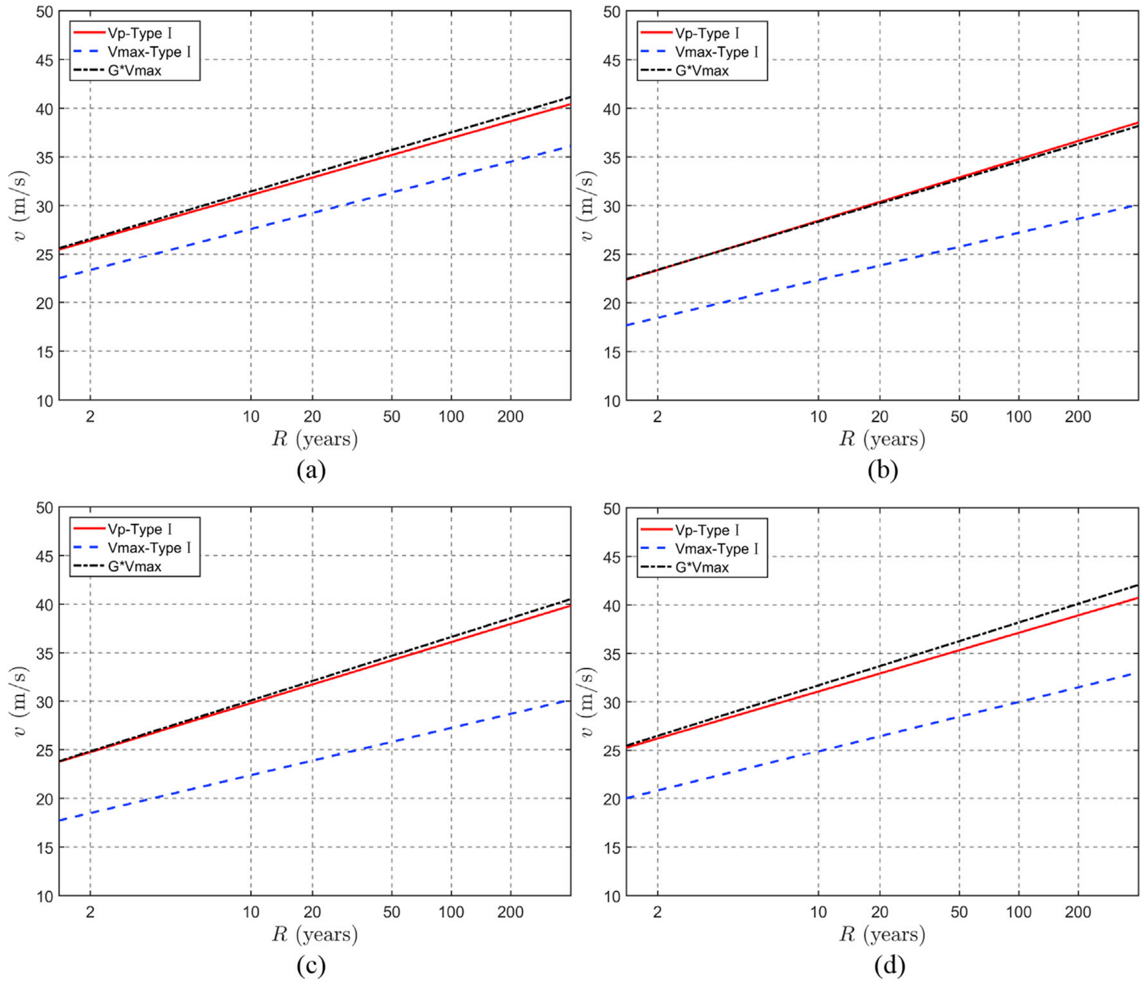


Fig. 18. Extreme mean vs peak wind speed distributions of thunderstorm outflows: anemometers 01 (a) and 02 (b) of the Port of Livorno; anemometers 02 (c) and 03 (d) of the Port of La Spezia.

over a 6 year period, with regard to anemometers 01 and 02 of the Port of Livorno and to anemometers 02 and 03 of the Port of La Spezia. Firstly, records with a peak wind speed greater than a given censoring threshold are extracted from the data population. Secondly, depressions, thunderstorm outflows and intermediate events are separated and stored in selective datasets. Thirdly, independent extreme wind speeds are selected based on the time interval that separates successive extremes. Fourthly, the extreme distribution of the peak wind speed for each wind phenomenon is given by the Type I extreme value model. Finally, the information on the extreme distribution of the peak wind speed is completed by mixed statistics and by gathering the ensemble of all the extreme values into a single set.

At least in the seaport areas examined here, the results show that wind events with a high return period, the most important for structural safety, are always related to thunderstorm phenomena. Depressions play a relevant role only in some cases and always with reference to low return periods related to serviceability analyses. Intermediate events are still very uncertain phenomena. According to this study, however, they do not seem to be so relevant for assessing extreme wind speeds. The mixed extreme distribution asymptotically tends to coincide with thunderstorm distribution for high return periods and always provides the highest extreme wind speed values. In every case, gathering the ensemble of all the extremes into a single set leads to underestimating the extreme peak wind speed especially for high return periods.

As with synoptic depressions, for thunderstorm outflows too the passage from the distribution of the peak wind speed to the distribution of the maximum value of the slowly varying mean wind speed, and vice-versa, may be suitably performed using appropriate velocity gust factor. In the case of thunderstorms this procedure is even easier due to the weak dependence of the gust factor on the roughness length, which means that directionality effects can be disregarded, despite being very important for synoptic depressions.

The results provided by mixed statistics are compared with the extreme wind speed values taken from the Italian Guide for Wind Actions and Effects on Structures, and with the results of previous wind climate analyses concerning the historical ensemble of the wind speeds averaged over 10 min periods. These results derive from many more years of measurements than those considered in this paper. On the other hand they do not take into account either thunderstorms or mixed statistics.

The Italian Guide provides estimates of the extreme wind speed that are so conservative that they protect designers against thunderstorms as well. Previous analyses of the local wind climate provide extreme wind speeds that are always lower than those indicated in the Italian Guide. In Livorno, where thunderstorms seem to be less intense than in La Spezia, these results are also conservative compared to these evaluations. In La Spezia, on the other hand, the occurrence of intense thunderstorms leads to results that equate or exceed those provided by micro-zoning analyses done ignoring these phenomena, for high return periods. This finding confirms the risks involved in relation to studies based on data or on methods that are not suitable for recognizing or evaluating the occurrence of thunderstorms.

The prospects for improving these analyses relate to three different issues. The first focuses on gathering and analysing new data to strengthen and refine the results above. However, in this way, only the

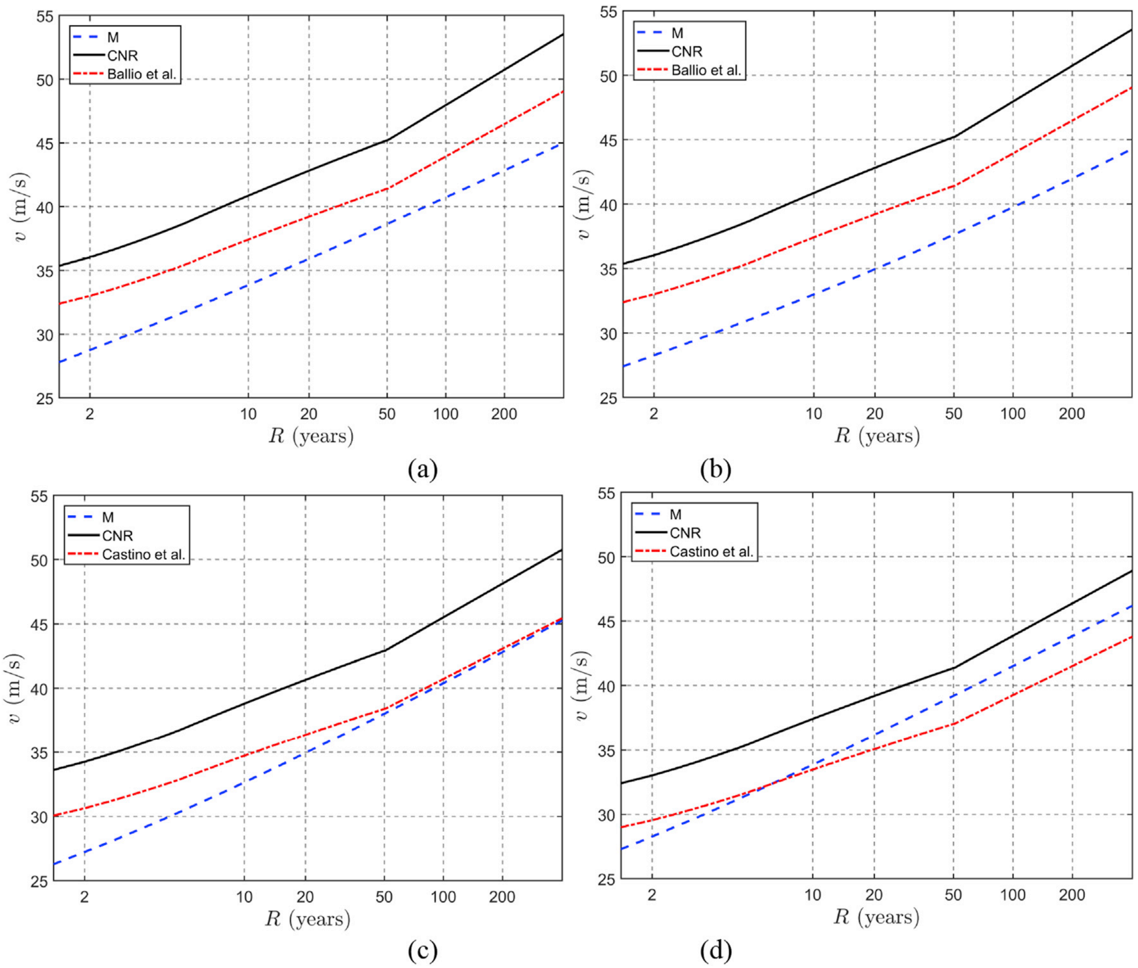


Fig. 19. Peak wind velocity extreme distributions for the anemometer 01 (a) and 02 (b) of the Port of Livorno, and the anemometers 02 (c) and 03 (d) of the Port of La Spezia.

passage of a lot of time may really produce relevant improvements deriving from assembling richer datasets and using refined statistical models, which are unjustified at this stage due to the scarcity of available data. The second consists of pursuing a different strategy based on collecting and analysing the set of the data detected by different anemometers in the same seaport area together, in order to create statistical models of the extreme wind speed that take into account the frequency of occurrence and the plan distribution of thunderstorm outflows with different intensity. The third deals with comprehension of intermediate events with reference to the meteorological viewpoint even before their statistical assessment. In any case further research is necessary.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jweia.2018.03.019.

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