Separation and classification of extreme wind events from anemometric data

Patrizia De Gaetano\textsuperscript{1}, Maria Pia Repetto\textsuperscript{1}, Teresa Repetto\textsuperscript{1} and Giovanni Solari\textsuperscript{1}

\textsuperscript{1}Department of Civil, Chemical and Environmental Engineering, University of Genova, Italy, 

\texttt{patrizia.degaetano@unige.it}

Abstract

The separation and classification of intense wind phenomena into homogeneous families is a key topic to interpret the events of engineering interest, to study the wind-excited response of structures, to determine the distribution of extreme wind velocities and wind-induced effects. This paper is aimed at separating and classifying independent extreme wind phenomena through a semi-automated procedure involving a mix of quantitative controls and assisted expert judgment. The proposed method is applied to an extensive dataset provided by a wide and high quality monitoring network realized in the Ports of the Northern Tyrrhenian Sea with reference to the European Project “Wind and Ports”.

1 Introduction

The separation and classification of intense wind phenomena into homogeneous families is a key topic to interpret the events of engineering interest, to study the wind-excited response of structures, to determine the distribution of extreme wind velocities and wind-induced effects (Solari, 2013).

Thom (1967) first proposed to deal with the mixed populations of extra-tropical and tropical cyclones by means of two combined distributions, then showed that one third of the yearly peak wind velocities in US occur during thunderstorms (Thom, 1968). Gomes and Vickery (1976) carried out a study of the extreme wind velocities in Australia, where they separated thunderstorm from non thunderstorm winds, determined the distributions of these two phenomena and derived a mixed distribution later extended to more different phenomena (Gomes and Vickery, 1977/1978). Analogous aspects were discussed by Riera and Nanni (1989), Twisdale and Vickery (1992), Holmes (1999), Choi and Tanurdjaja (2002) and Cook et al (2003). Kasperski (2002) introduced the idea that in temperate climates thunderstorms cannot be clearly distinguished from frontal depressions, since a third class of phenomena exist, called gust fronts, with intermediate properties; he also proposed a criterion to subdivide the data belonging to different phenomena, whose application is strongly conditioned by effectively available measures. Choi and Hidayat (2002), Chen and Letchford (2004), and Chay and Albermani (2005) discussed the different dynamic response of structures subjected to different wind phenomena. Lombardo et al (2009) implemented an automated algorithm to separate thunderstorm from not thunderstorm winds in U.S.; this criterion was later applied in the framework of a dataset assisted design of structures in mixed climates (Yeo, 2011; Lombardo, 2012).

This paper is part of a research activity aimed at investigating extreme wind events in port areas (Solari et al., 2012). A wide and high quality monitoring network has been realized in the main ports of the Northern Tyrrhenian Sea, which collects data continuously with a sampling rate of 10 Hz. The measured data are first analysed in order to extract 10-minutes intervals characterized by large mean or/and peak wind velocity. For each event, 10-minutes interval statistical wind features are inspected with reference to 1-hour (centred on the 10-minutes interval), 10-minutes and 1-minute intervals. This information is jointly processed in order to separate and classify extreme wind phenomena by a semi-automated procedure involving a suitable mix of quantitative controls and assisted expert judgments. Independent extreme wind events associated to different wind phenomena are finally extracted.
2 Monitoring network and dataset

Figure 1 shows the anemometric monitoring network realized for the project “Wind and Ports” – the forecast of the wind for the safety and the management of port areas (Solari et al, 2012). The project, financed by the European Territorial Cooperation Objective, Cross-border program “Italy–France Maritime 2007–2013”, involves the Port Authorities of the five main ports in the High Tyrrhenian Sea, namely Genova, La Spezia, Livorno, Savona (Italy) and Bastia (France). The Department of Civil, Chemical and Environmental Engineering (DICCA) of the University of Genova is the scientific actuator. The network is constituted by 22 ultrasonic anemometers (circles), most of them tri-axial and the others bi-axial. Besides, 9 anemometers co-financed by the Port Authority of Genova will be added soon (squares in Figure 1), leading to a network of 31 instruments.

![Figure 1: Anemometer stations installed in the port areas involved in the project.](image)

The position of the instruments has been chosen in order to cover homogeneously the port areas and to register undisturbed wind velocity histories. The instruments are generally mounted on high rise towers or at the top of buildings, at least at 10 m height above ground level, with particular attention to avoid local effects affecting the measures. The sampling rate of the anemometers is set to 10 Hz, with the exception of the anemometers in the Port of Bastia, which are set to 2 Hz. Wind measurements are collected with a precision of 0.01 m/s and 1° for intensity and direction, respectively.

A set of local servers, placed in each port authority headquarter, receives the measures acquired by the anemometers in their own port area, and elaborates the basic statistics on 10 minute periods, namely the mean and peak wind velocity and the mean wind direction. Each server automatically sends this information to the central server located in DICCA. Two files are sent every 10 minutes containing, for each anemometer, the raw data and the statistical values of the previous 10-minutes periods. The operational centre of DICCA receives these data and stores them into a central dataset, after having systematically checked and validated the data received. The real time transfer is crucial for the short term forecasting (Burlando et al, 2013).

3 Classification of events

An examination of the huge amount of the available data shows that wind events can be classified into three families characterized by different properties: 1) stationary (S) Gaussian (G) synoptic events, corresponding to neutral atmospheric conditions, with relatively large mean velocities and small gust factors; such events are referred to as extended pressure systems by Gomes and Vickery (1976, 1977/1978) and strong frontal depressions by Kasperski (2002, 2009); they are called herein extra-tropical depressions (D); 2) non stationary (NS) non Gaussian (NG) events, corresponding to thunderstorms (T), with large peak velocities and gust factors but relatively small mean velocities; 3) stationary (S)
non Gaussian (NG) events, corresponding to unstable atmospheric conditions, with relatively small mean velocities but large peaks and gust factors; such events are referred to as gust fronts (F) or intermediate events (Kasperski, 2002).

Figures 2, 3 and 4 show three typical events, referred to a 1-hour period centred on the gust peak, of the type described above. For each event, the scheme (a) shows the diagrams of the wind speed raw data (cyan line), the mean value (blue dotted line) and the instantaneous peak (red circle) (obviously larger than the 1-s peak); the scheme (b) shows the histogram of the wind speed measures, compared with the ideal Gaussian density function matching the mean wind speed and the standard deviation.

Figure 2 shows a typical 1-hour record of a SG event corresponding to a depression D. It is characterized by a relatively high mean wind velocity $V_{m60} = 15.03 \text{ m/s}$, a 1-s gust peak $V_{p10} = 22.46 \text{ m/s}$ and a classic gust factor $G_{60} = 1.49$. The skewness $\gamma_{60} = 0.02$ and the kurtosis $\kappa_{60} = 3.08$ denote a typical Gaussian process; the Gaussian density function $f_v(v)$ is almost perfectly superimposed on the histogram of the recorded velocity $v$.

Figure 3 shows a typical 1-hour record of a NS NG event corresponding to a thunderstorm T. It is characterized by a relatively low mean velocity $V_{m60} = 7.33 \text{ m/s}$, a very high 1-s gust peak $V_{p10} = 33.36 \text{ m/s}$ and a very high gust factor $G_{60} = 4.55$. The skewness $\gamma_{60} = 1.20$ and the kurtosis $\kappa_{60} = 5.60$ denote a typical non-Gaussian distribution. The diagram of the wind direction, not reported here, shows a sudden change just in correspondence of the gust peak.
Figure 4 shows a typical 1-hour record of a S NG event corresponding to an unstable gust front F. It is characterized by a low mean velocity \( V_{m60} = 5.51 \text{ m/s} \), a relatively intense 1-s gust peak \( V_{p10} = 15.68 \text{ m/s} \) and a high gust factor \( G_{60} = 2.85 \). The skewness \( \gamma_{60} = 0.63 \) and the kurtosis \( \kappa_{60} = 3.61 \) denote a moderately non-Gaussian distribution.

Figure 5 shows the conceptual scheme of the procedure by means of which the original base of raw data is transformed into more datasets associated with the different wind events described above.

a) Starting from the raw data, for each anemometer of the monitoring network a dataset is created, denoted by 1, which contains, for subsequent time intervals \( T = 10 \text{ minutes} \), the mean direction \( \alpha \), the peak velocity \( V_{p10} \) averaged on \( \tau = 1 \text{ s} \), and the mean velocity \( V_{m10} \). The series of the mean velocities is processed by the method of the storms (Cook, 1982); the threshold used to separate subsequent storms is chosen in such a way as to identify, for each anemometer, about 100 storms per year.

b) Starting from the dataset 1, two datasets denoted by 2 and 3 are created. The dataset 2 contains the peak velocities \( V_{p10} \geq V_{p10}^* \); the dataset 3 contains the mean velocities \( V_{m10} \geq V_{m10}^* \); in this case \( V_{p10}^* = 15 \text{ m/s} \) and \( V_{m10}^* = 10 \text{ m/s} \). Besides the mean wind direction \( \alpha \), both datasets are completed by the following parameters: gust factor \( G_{10} = V_{p10}/V_{m10} \), turbulence intensity \( I_{10} \), skewness \( \gamma_{10} \) and kurtosis \( \kappa_{10} \) in the \( T = 10 \text{-minutes interval} \); mean wind velocity \( V_{m60} \), gust factor \( G_{60} = V_{p10}/V_{m60} \), turbulence intensity \( I_{60} \), skewness \( \gamma_{60} \) and kurtosis \( \kappa_{60} \) in the 60-minutes interval centred around \( T \); maximum value in \( T \) of the mean wind velocity averaged over 1-minute \( V_{m1} \) and gust factor \( G_{1} = V_{p10}/V_{m1} \).
c) Starting from the datasets 2 and 3, two datasets denoted by 4 and 5 are created. These contain, respectively, the maximum (independent) values of $V_{p10}$ and $V_{m10}$ for each storm, irrespective of any separation into families of homogeneous events.

d) Starting from the dataset 2, three datasets denoted by 6, 7 and 8 are extracted. The dataset 6 contains all the $V_{p10}$ values associated with S G synoptic events corresponding to extra-tropical depressions (D). The dataset 7 contains all the $V_{p10}$ values associated with NS NG events corresponding to thunderstorms (T). The dataset 8 contains all the $V_{p10}$ values associated with S NG events corresponding to gust fronts (F). The classification of each event into one of the categories D, T or F is illustrated in Section 4.

e) In a similar way to point d), starting from the dataset 3, three datasets denoted by 9, 10 and 11 are extracted. These datasets contain all the $V_{m10}$ values associated with S G (D), NS NG (T) and S NG (F) events, respectively. The dataset 9 corresponds, in terms of mean wind velocities, to the dataset 6 in terms of peak wind velocities. On the other hand, unlike the datasets 7 and 8, obtained from the peak velocities $V_{p10} \geq V^*_{p10}$, the datasets 10 and 11, obtained from the mean velocities $V_{m10} \geq V^*_{m10}$, contain a very limited sub-set of thunderstorm and gust fronts; as such, they provide no more than some elements for a non exhaustive cross-check with the datasets 7 and 8.

f) Starting from the datasets 6, 7, 8 and 9, four datasets denoted by 12, 13, 14 and 15 are extracted. The datasets 12 and 15 contain, for each subsequent storm, the maximum independent $V_{p10}$ and $V_{m10}$ values associated, respectively, with S G (D) events. The datasets 13 and 14 contain the maximum independent $V_{p10}$ and $V_{m10}$ values associated, respectively, with NS NG (T) and S NG (F) events; the concept of independence is discussed in Section 5.

4 Separation algorithm

Each anemometer is qualified via a card that reports its position, height $z$ over ground and main technical characteristics. This card also provides, at height $z$ and as a function of the direction $\alpha$ of the oncoming wind, the turbulence intensity $I_u$ and the three reference gust factors $G_{10}, G_{60}$ and $G_{1}$; the apex 0 indicates that such values are evaluated numerically assuming, as it is classical, that intense wind velocities occur in atmospheric neutral conditions and are stationary Gaussian processes.

![Image](image.png)

Figure 6: a) Roughness length $z_0$ of the area of the Port of Livorno; b) turbulence intensity $I_u$ at 10 m height above ground, when the wind blows from $\alpha = 90^\circ$.

As an example, Figure 6(a) shows the roughness length $z_0$ attributed to the area of the Port of Livorno; Figure 6(b) shows the intensity $I_u$ of the longitudinal component of turbulence, at 10 m height above
ground, when the wind blows from $\alpha = 90^\circ$. These results are obtained by the procedure formulated by ESDU (1993), in an advanced version developed at DICCA (Solari et al, 2012). The reference gust factors $G_{0.10}^0, G_{0.60}^0$ e $G_{0.1}^0$ are evaluated through the method proposed by Solari (1993).

The separation among the depressions (D), the thunderstorms (T) and the gust fronts (F), indicated in Figure 5 as the extraction of the datasets 6, 7 and 8 from the dataset 2, and of the dataset 9, 10 and 11 from the dataset 3, is carried out through a semi-automated procedure shown by the flow-chart in Figure 7. Such procedure is a mix of quantitative controls, based on the comparison between measured gust factors and their reference values described above, and qualitative controls, formulated through an assisted expert judgment inspired by the visual examination of the time histories and the measured skewness and kurtosis values.

![Flow-chart](image)

Figure 7: Flow-chart of the semi-automated algorithm by means of which the depressions (D), the thunderstorms (T) and the gust fronts (F) are separated.

a) Events for which the following rule (first quantitative control) applies are classified as depressions (D):

$$\frac{G_{0.60}}{G_{0.60}^0} \leq 1.10$$

They are strongly stationary and Gaussian over 1-hour intervals.

b) Events for which the following rule (second quantitative control) applies are classified as depressions (D):

$$\frac{G_{0.60}}{G_{0.60}^0} \leq 1.25 \cap \frac{G_{0.10}}{G_{0.10}^0} \leq 1.10$$

They are strongly stationary and Gaussian over 10-minutes intervals, although they exhibit some variability over 1-hour intervals.

c) Events for which the following rule (third quantitative control) applies are classified as thunderstorms (T) or gust fronts (F):

$$\frac{G_{0.10}}{G_{0.10}^0} > 1.25$$

The classification of such events into the category of thunderstorms (T) or gust fronts (F) is carried out through a following qualitative control.

d) Events for which the following rule (fourth quantitative control) applies are classified as depressions (D):

$$\frac{G_{0.60}}{G_{0.60}^0} < 1.25 \cap \frac{G_{0.10}}{G_{0.10}^0} > 0.80$$
Those events that do not satisfy such Eq. (4), are classified as thunderstorms (T), gust fronts (F) or depressions (D) through following qualitative controls.

A discriminating factor for classifying an event not attributable to a depression (D) as a thunderstorm (T) or a gust front (F) is the ratio $G_{10}/G_{60}$: when it is less than 0.90, the event is usually a thunderstorm (T); when it is greater than 0.90, the event is usually a gust front (F). The skewness and the kurtosis are discriminating factors for classifying an event, on the one side, as a depression (D), on the other, as a thunderstorm (T) or a gust front (F).

5 Independent events

Once the depressions (D), the thunderstorms (T) and the gust fronts (F) are separated in different datasets (6, 7, 8 or 9, 10, 11 in Figure 5) by the criterion described in Section 4, it remains to extract, from each of them, a suitable series of independent maxima.

The maximum values of the depressions associated with different successive storms are dealt with as independent, provided that they are separated by at least 72 hours. In a very preliminary way, the maximum values of the thunderstorms are dealt with as independent provided that they are separated by at least 1 hour. Analogously, the maximum values of the gust fronts associated to different successive storms are dealt with as independent provided that they are separated by at least 24 hours.

It remains an open question whether it is permissible to take independent maximum values associated with different events close together or even consequential.

6 Conclusions

This paper formulates a semi-automated criterion to separate and classify independent extreme wind phenomena, based upon a suitable mix of quantitative controls and assisted expert judgments. Two aspects are worth noting. First, as Kasperski (2002) pointed out for the first, it is not possible to separate clearly S G (D) from NS NG (T) events. At least there is a third class of wind phenomena, defined herein as S NG (F) events, which greatly complicate the “binary” approach that prevails in the literature. Second, in order to apply the classification criterion discussed in this paper, several parameters not commonly available should be used and recourse should be made to expert judgment. This throws quite a few shadows on some automated or semi-automated extraction and classification criteria reported in the literature. Since the separation of wind events in different classes is functional to carry out more refined analyses, their meaning becomes somewhat questionable if it is not equally accurate the preliminary separation process. Both these aspects have profound impact on the dynamic wind-excited response of structures and the mixed statistics of extreme wind velocities and wind-induced effects.

References


