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Three issues concerning the statistics of mean and extreme wind speeds

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ABSTRACT

In the calibration of statistical models for mean and extreme wind speeds, data coming from historical series measured at meteorological stations are used. In most of the cases, these do not comply with characteristics of the model to be calibrated. In particular, this is due to a finite onset wind speed of anemometers and to the discontinuous sampling. As a result, the mean wind speeds are often underestimated. In addition, when the extreme wind speeds are described through the Gumbel model, these are overestimated due to the non-perfect fitting of the data. In this paper the three issues related to the existence of a measurement threshold of anemometers, of the discontinuous sampling of mean wind speed, and of the appropriateness of the Gumbel distribution for the description of extreme wind speeds are discussed, based on the analysis of the historical records available to the Meteorological Service of the Italian Air Force, using an empirical approach. An estimate of the inaccuracies associated with each of the approximations above, is given.

1. Introduction

The analysis of wind speeds statistics is the first step towards the definition of design wind loads on structures. Though well established procedures exist to this aim, this remains a crucial point mainly for the dependency of wind load on the square of wind speed, which brings that even a small error in the prediction of the latter results in a considerable error in the load value, with consequent either underdesign or excessive cost of the structure.

In practical design situations, one can chose between using design wind speeds taken from Codes of Practice, or performing statistical analyses from available measurements. The first approach quite often brings an overestimation of the design load, due to several reasons; among these the coarse zoning of extreme wind maps, the lack of directional values, the neglecting of local attenuation effects, can be listed. On the other hand, the calculation of the design wind speed based on recorded data potentially gives much more accurate estimates, but requires expertise and, of course, the availability of reliable measurements. Both for the purpose of defining extreme wind maps to be incorporated in Codes of Practice, and for the analysis of the wind climate at a specific site, some assumptions are usually made, deriving from the nature of the wind data commonly available.

The 600 s-averaged or the 3600 s-averaged wind speed (the so-called *mean wind speed*) is usually modeled through a Weibull distribution, which is also the parent distribution for extreme wind speeds. In practice, due to the existence of wind calms and because of the finite onset wind speed of anemometers (thus generating false wind calms), the Weibull cumulated distribution is usually modified through the addition of a constant, accounting for true and false wind calms.

The statistical analysis of extreme winds is traditionally performed by processing recorded annual maxima by the Extreme Value Theory. This is based on three asymptotic distributions: the Gumbel, Frechet and reverse Weibull, also known as Type I, Type II and Type III Extreme Value distributions, respectively (Fisher and Tippett, 1928; Gumbel, 1958; Lagomarsino et al., 1992). The Generalized Extreme Value (GEV) distribution (Jeckinson, 1955) combines them into a single mathematical form, in which a shape factor defines the characteristics of the tail, and indicates which Extreme Value distribution (either Type I, II or III) fits best the recorded data. In particular, when the shape factor tends to zero the GEV distribution tends to the Gumbel distribution; with increasing positive values of the shape parameter, the GEV distribution tends to the Frechet distribution; finally, with increasing negative values of the shape parameter, the GEV distribution tends to the reversed Weibull distribution. A review of the methods available to calculate extreme wind speeds can be found in Palutikof et al. (1999).

Both the Gumbel and the Frechet distributions are characterized by an asymptotic right tail, whereas the reversed Weibull

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distribution is bounded to the right. As the wind speed cannot grow to infinity, the Gumbel and Frechet distributions are physically unacceptable (Gomes and Vickery, 1977; Simiu and Heckert, 1996). On the other hand, though limited to the right, the wind speed does not have a physical bound, which would be required by the Weibull distribution. The choice is then made based more on the ability of the three distributions to fit the experimental data, regardless of the physical consistency.

Simiu et al. (1978) concluded that the Gumbel distribution is the most appropriate model for predicting extreme wind speeds, whereas years later Simiu and Heckert (1996) concluded that the adoption of the Gumbel model is likely to result in an unrealistic assessment of structural reliability under wind loads, characterized by high failure probabilities (Ellingwood et al., 1980). This is due (at least in part) to the use of a distribution with an infinite right tail which suggests that a reasonable analytical model must have a finite right tail.

Galambos and Macri (1999) discuss the appropriateness of using the Gumbel distribution for modeling extreme wind speeds, as opposed to the reverse Weibull distribution. They show that the assumption of bounded wind speeds and the subsequent implementation of the Peaks Over Threshold method for estimating the required parameters from real data lead to contradictions, and that the Gumbel distribution in most cases is more realistic. Also Cook (1985) states that the Gumbel distribution is more appropriate than the Frechet and reverse Weibull distributions.

On the other hand, Harris (2004) points out the existence of right-limited parent distributions giving rise to a Type I asymptote, therefore eliminating the constrain that the maxima of a limited physical phenomenon must be necessarily described by the reverse Weibull distribution.

The possible use of the GEV distribution for describing the extreme wind speeds is also investigated by Harris (2006), who concludes that it brings an unacceptable ambiguity in defining the wind loads, and it is therefore not to be considered an alternative to the use of the Gumbel distribution.

Also Codes of Practice usually adopt a Gumbel distribution, except for few cases in which the Frechet distribution is preferred. This is, for example, the case of the 1972 version of the ANSI Standard (ANSI A58.1 1972) (American National Standards Institute (1972)), where the Frechet distribution is used for the omnidirectional extreme wind speeds in areas not prone to hurricanes.

When the Gumbel distribution is adopted, the distribution parameters can be calculated following the Gumbel fitting method (Gumbel, 1958), an improvement of which can be found in Harris (1996). The Gumbel method, however, is biased and gives distorted values for the high probabilities of non-exceedence. Several alternative methods have been developed in order to remove this bias; a simple and effective modification to the Gumbel procedure, which gives nearly unbiased estimates, is that of Gringorten (1963).

A method for estimating the GEV distribution parameters using the method of Probability Weighted Moments can be found in Hosking et al. (1984).

A major criticism to the application of the traditional Extreme Value Theory is put forward in International Organisation for Standardisation (2009), where it is clearly stated that "*in the general case, yearly extremes do not form an appropriate basis for the extreme value analysis of wind speeds. This is especially true if the respective storm phenomenon tends to occur in families or cluster. … the ensemble therefore should consist of independent extremes above an appropriate threshold for each storm type*". An analysis of only yearly extremes may, in fact, lead to the loss of important information if the second and third strongest storm in 1 year is stronger than the yearly extreme of another year. This is also shown by Kasperski (2011).

To overcome these restrictions, the model parameters can be estimated using the Gumbel distribution fitted to the first *n* annual maxima (Lagomarsino et al., 1992) or to monthly maxima (Simiu et al., 1982; Grigoriu, 1984). These estimates are based on an empirical model which assumes that the first *n* annual maxima and monthly maxima are independent and stationary. The assumption of independence seems satisfactory; in particular, Grigoriu (1984) showed that, for short wind records estimates of extreme wind speeds derived from monthly observations are more reliable than those based on yearly data, and provide the upper confidence limits for the development of probability-based specifications for wind design.

However, these approaches still consider only the largest event occurred in each epoch, and neglect all other events. In order to overcome this contradiction, alternative approaches based on reference periods shorter than a year, or on all recorded maxima have been developed (Gomes and Vickery, 1977; Cook, 1982; Harris, 1999; An and Pandey, 2005).

Harris (2009), on the other hand, also makes a criticism to the use of asymptotic models for extreme wind speeds, based on the observations that the data available to calibrate them are usually associated with an insufficiently large rate parameter; the effect of this being that a systematic error is introduced. To overcome this, he introduces a modified version of the Method of Independent Storms, which is not asymptotic.

Recently, another method for extreme value estimation based on the introduction of a conditional average exceedence rate has been proposed (Naess and Gaidai, 2009; Karpa and Naess, 2013); the method is designed to account for statistical dependence between the data points in a rational way.

An alternative to the use of the Extreme Value theory is the application of Process Analysis (or Threshold Crossing Method), which looks at the 600 s mean wind speed as a random process. For large values of the threshold, the upcrossing can be modeled as a Poisson process, and the probability that in one year a threshold is never exceeded coincides with the distribution of the annual maxima of the mean wind speed. For calibration of the distribution of the annual maxima obtained with the use of Process Analysis, knowledge of the Weibull parameters of the mean wind speed is needed; the calculation of these must be carried out such to obtain a good accuracy in the right tail, therefore standard techniques for fitting available experimental datasets are not necessarily the best option.

An exhaustive review of models commonly used to analyze extreme wind speeds is also available in Torrielli et al. (2013). The authors apply different models to the database and conclude that the GEV distribution provides a good description of the annual maxima if it is applied to very large datasets.

In this paper, three issues concerning the analysis of wind speed statistics are analyzed. The first is related to the possibility of improving the fitting the low values of the mean wind speed, thus eliminating false calms. The second is related to the comparison between the Gumbel, Frechet and reverse Weibull distributions for extreme wind speeds, through the use of the GEV distribution. The third is related to the discontinuous sampling of the 600 s mean wind speed for the application of Extreme Value Theory. The paper is meant at pointing out some weaknesses associated with the use of simple models implemented by Codes of Practice, and at quantifying the error that they bring; in addition it gives possible ways to allow for these inaccuracies.

The concepts put forward are validated through application to measurements taken from a database of 119 ground level stations, located as shown in Fig. 1, most of them belonging to the Italian Air Force meteorological network. About 55 stations are located at an altitude of more than 500 m above sea level and 25 of them at an altitude of more than 1000 m. Data collected starting from 1951 was digitized into an electronic database. All the data comply with the World Meteorological Organization (WMO) and International Civil Aviation Organization ICAO standards.