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The Annual Rate of Independent Events for the analysis of the extreme wind speed

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ABSTRACT

The statistical modeling of the extreme mean wind speed is a very controversial subject. Several models are currently being applied in the literature, based on different assumptions and supplying quite different results. This paper takes a step back towards the common root of many extreme value models: the Annual Rate of Independent Events (ARIE). Starting from an analysis of large datasets of synthetic wind observations, the ARIE is inspected from a new point of view and some features so far hidden are brought to light. Based on that, a new effective approach to model the distribution of the extreme mean wind speed is proposed. The reliability of the proposed model is discussed processing both large datasets of synthetic wind observations, and small-sized datasets representative of real conditions. ARIE sensitivity to uncertainties in the parent distribution is also evaluated and critically discussed.

1. Introduction

In the last 50 years, a great effort has been made to establish efficient statistical models to fit the extreme mean wind speed. The relevance of extreme value (EV) analysis on the economic assessment of the design wind speed and reliability of structures subjected to wind actions justifies the ongoing debate about the most suitable distribution model (Kumar et al., 2015). So far, however, the wind engineering community has not yet reached a common viewpoint and the EV distributions typically applied to predict design wind speed lead to scattered results, with uncertainties that increase progressively as the duration of the wind record decreases or the length of the return period increases (Lagomarsino et al., 1992; Lombardo, 2012). Working in this field, the authors have carried out a research program aimed at creating synthetic case studies through extensive Monte Carlo (MC) simulations of long-term time series of the mean wind speed.

Initially, a large dataset consisting of thousands of years of synthetic mean wind speed observations was generated (Torrielli et al., 2011) through a simulation algorithm (Masters and Gurley, 2003) that matches the target power spectral density function (PSDF) perfectly, while the probability distribution function (PDF) slightly deviates from the target one. Such observations were fitted to some of the most common EV distributions (Torrielli et al., 2013), in order to evaluate and discuss their effectiveness by removing any dummy effect due to the limited number of observations. Later, refined studies were carried out on modeling and simulating the macro-meteorological component of the mean wind speed (Torrielli et al., 2014). Particular attention was paid to the main harmonics associated with the spikes of the spectrum. In addition, a simulation algorithm able to generate sample functions with exact PDF and very accurate PSDF was implemented (Nichols et al., 2013). In such a framework it was proved that the stochastic or deterministic modeling of the main harmonics has a limited impact on EV analysis; on the contrary, the adoption of a simulation algorithm that perfectly matches the target PDF substantially improves the quality of the simulation with special regard to the tail of the parent distribution.

This paper takes a step back from the common EV analysis, towards the base that gave origin to many EV distributions, i.e. the Annual Rate of Independent Events (ARIE). The ARIE is a cloudy concept and some confusion exists about its estimation, basically depending on the features of the source data and the processing method (Davenport, 1967; Cook and Harris, 2004; Torrielli et al., 2013). So, inspired by a contribution from Harris (2014) and starting from the analysis of large datasets of synthetic wind observations, the ARIE is inspected from a new point of view and some features so far hidden are brought to light. Based on that, a new effective approach to model the distribution of the extreme mean wind speed is proposed.

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In such a framework, Section 2 presents the MC simulation of two large datasets, each consisting of 12,740 years of synthetic wind observations that reproduce two different reference wind climates. Section 3 focuses on the ARIE, discussing its physical meaning in the light of its variability as a function of the mean wind speed; based on an analysis of the simulated large datasets, a simple analytical model of the ARIE is also presented, which is the key point of a new technique for modeling the distribution of the extreme mean wind speed. The accuracy of this technique is measured in Section 4 through the evaluation of design mean wind speed in realistic cases, where only a few decades of wind observations are available. Section 5 investigates the sensitivity of this approach to the uncertainties in the parent distribution. Section 6 summarizes the main conclusions and draws some perspectives for future research.

2. Mean wind speed simulations

This section illustrates two extensive MC simulations of 10-min mean wind speeds, corresponding to two ideal wind climates characterized by the same macro-meteorological spectrum and by different parent distributions.

The macro-meteorological spectrum originates from the wind climate of an area in the central part of Italy of approximately 200 km in diameter. A full description of this wind climate and of the spectral combination technique adopted to derive its PSDF (Fig. 1(a)) are provided in Torrielli et al. (2011, 2013, 2014).

The Hybrid Weibull (HW) model (Takle and Brown, 1978) is used to describe the parent distribution of the two simulations, whose cumulative distribution function (CDF) is given by

$$F_V(v) = F_0 + (1 - F_0)\left\{1 - \exp\left[-\left(\frac{v}{c}\right)^k\right]\right\} \tag{1}$$

where F_0 is the rate of the wind calms, c and k are the scale and shape parameters, respectively, estimated by processing only the non-null wind observations. Table 1 lists the parameters and the first order moments adopted for the two simulations. The first simulation (SIM1) uses the parameters estimated by real observations consistent with the macro-meteorological spectrum, i.e. F_0=0.118, c=3.091 m/s and k=1.155. This last value is quite low with respect to the values usually adopted in the U.K. and in other Northern European countries (Torrielli et al., 2011) whereas it matches previous estimates of the Italian wind climate (Castino et al., 2003; Freda and Solari, 2010; Solari et al., 2012; Burlando et al., 2013) and with other analyses carried out by Holmes (2015).

Table 1
Parameters and first order moments of the HW distribution.

	F_0	k	c [m/s]	μ_V [m/s]	σ_V^2 [m²/s²]
SIM1	0.118	1.155	3.091	2.592	6.637
SIM2	0	2	5.561	4.928	6.637

The second simulation (SIM2) disregards wind calms, F_0=0, and considers a shape parameter representative of Northern European countries, k=2. The scale parameter c is determined by inverting the following equation under the assumption that the variance of SIM2 coincides with that of SIM1:

$$\sigma_V^2 = c^2\left\{\Gamma\left(1+\frac{2}{k}\right) - \left[\Gamma\left(1+\frac{1}{k}\right)\right]^2\right\} \tag{2}$$

$\Gamma\{\bullet\}$ being the Gamma function.

Two datasets consisting of 12,740 years of continuous 10-min mean wind speeds were generated through the MC algorithm described in Torrielli et al. (2014). This algorithm is based on the shuffling technique proposed by Nichols et al. (2010) for the simulation of spectrally colored non-Gaussian processes. Such a technique allows the generation of sample functions with a marginal PDF that perfectly matches the target one, while the PSDF approximates the target spectrum almost exactly.

The original algorithm has been modified in order to suitably handle harmonics associated with annual and diurnal cycles.

Fig. 1(b) shows the PDF of single samples of SIM1 and SIM2 on a probability paper that involves $\ln\{v\}$ on the abscissa and $\ln\{-\ln[(1-F_V)/(1-F_0)]\}$ on the ordinate, $\ln\{\bullet\}$ being the natural logarithm. In this figure, lines are used for the target PDFs whereas symbols are used for the empirical distributions. The empirical distributions are modeled through the plotting positions of the order statistical median, as explained in Torrielli et al. (2011). The matching between the empirical and target distributions for both SIM1 and SIM2 is perfect over the entire speed range; only slight deviations from the target distribution occur on the upper-tail region. Such deviations are due to the unavoidable statistical uncertainties deriving from the generation of large but finite-size samples.

3. The Annual Rate of Independent Events

Given the random variable V with parent distribution F_V, for the Law of Compound Probability (Cramer, 1946) the distribution of

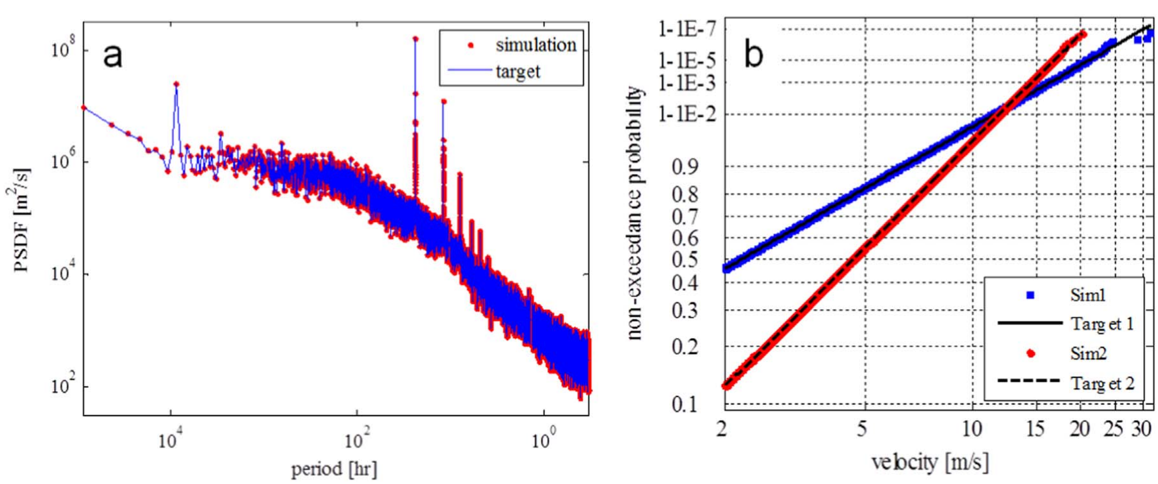

Fig. 1. Macro-meteorological spectrum of the mean wind speed (a) and Hybrid Weibull plot of the parent distribution (b).