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A refined analysis and simulation of the wind speed macro-meteorological components

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ABSTRACT

The authors have recently developed a Monte Carlo simulation algorithm able to generate thousands of years of synthetic wind speed values. In this study, however, two points have not received adequate attention: the presence of underlying periodic deterministic components embedded into the time series of the velocity and the generation of time series having exactly the desired marginal distribution. In principle, both these issues may have relevant consequences on the distribution of extreme values. This paper investigates and discusses the presence of underlying deterministic components in the wind records, develops a refined simulation algorithm for non-Gaussian colored wind speed stationary processes, and finally inspects how much these advances affect the analysis of extreme values. An extensive simulation consisting of more than 12,740 years of synthetic wind speeds is performed, based on the synoptic wind climatology of the central part of Italy. The results demonstrate that the use of a refined simulation algorithm improves the quality of extreme values analysis. On the other hand, it is not easy to express a definite opinion on the random or deterministic nature of some periodic cycles; it is shown, however, that dealing with such cycles as random or deterministic has very limited consequences on extreme values analysis.

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1. Introduction

The first step for generating time series of the mean wind speed is to characterize the wind speed macro-meteorological component to be simulated in terms of both its marginal probability distribution function (PDF) and its power spectral density function (PSDF). The authors have worked out a procedure to perform an extensive simulation of long-term time series of the mean wind velocity with target PDF and PSDF (Torrielli et al., 2011). The autocorrelation of the resulting time series matches perfectly the target autocorrelation, i.e. the PSDF, while the PDF slightly deviates from the target parent distribution in the upper tail region. Over 12,000 years of synthetic wind speeds were generated and different types of extremes were extracted. This wide dataset of extremes was fitted to some of the probabilistic models commonly applied in the analysis of extreme values (EV) and a wide critical comparison was carried out pointing out the merits and the limits of the different models (Torrielli et al., 2013).

This novel approach disclosed new prospects on EV analysis. Nevertheless it missed to investigate with sufficient attention two important issues. The first concerns the presence of possible periodic deterministic components, embedded into the macro-meteorological component of the wind speed, as argued by Harris (2008) for the first time; in particular, Harris warned against the impact of such periodic deterministic components on the probability distribution of the annual maximum speeds. The second issue concerns the slight deviations from the target parent that occur in the upper tail region of the distribution of the simulated time series. In particular, since extremes belong to the tail of the parent, it is not clear how much such deviations influence the distribution of extreme values. Both these two issues deserve refined analyses and simulations.

The first part of this paper investigates the presence of the underlying periodic deterministic components embedded into the registrations of the mean speed relative to a temperate wind climate, similarly to the study carried by Harris (2008). Section 2 introduces the set of wind measurements acquired in the central part of Italy, which are processed to characterize the mean wind speed to be simulated. Particular attention is paid to study the harmonics associated with the annual and diurnal periodic cycles. Section 3 provides a critical discussion on the random or deterministic nature of such cycles.

The second part of this paper is devoted to develop a refined simulation procedure of the wind speed macro-meteorological component. Section 4 carries out an extensive simulation of the mean wind speed process, by means of an algorithm that assigns the exact target probability distribution to the synthetic time series. A comparison with the simulation technique applied by Torrielli

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et al. (2013) is provided. Section 5 discusses the influence of the periodic deterministic components embedded within the wind speed records on the probability distribution of the extreme values drawn out from the time series. Section 6 draws the main conclusions and points out some prospects for the present research.

2. Mean wind speed

This paper resumes the case study presented in Torrielli et al. (2011, 2013). The description of the mean wind velocity $V(t)$ is based on the measurements recorded by 6 anemometers spread out over an area of approximately 200 km in diameter in the central part of Italy (Table 1).

Such measurements comprehend both historical and modern records. The historical records, provided by the Air Force and Ente Nazionale per l'Assistenza al Volo (Flight Control Agency), are a collection of speeds taken over a 33 years period at 3 h intervals. The modern records, provided by the new instrumental network of Rete Ferroviaria Italia (Italian Railway Company), are a collection of speeds taken over a 1 year period at 10 min intervals. In both cases, the velocity values are averaged over 10 min intervals. Even if the raw historical records were 50 years long, a single segment presenting minor gaps in the data is selected for each anemometer. The length of 33 years results from a compromise between the intents of including long-term variations in the analysis and of limiting the missing data. Finally, the percentage of missing data on the selected segments is quite small, ranging between 0.7% and 1.8%. The features of the local terrain where the anemometers are sited are taken into account by transforming the wind data – affected by local roughness and topography – into speed values corresponding to a unique reference condition, i.e. 10 m height on a flat homogeneous terrain with roughness length $z_0 = 0.05$ m (Burlando et al., 2010, 2013). Satisfying this requirement is considerably simple because all sensors are put in flat open territories, sufficiently far from mountains and the sea coast. This also reduces the possibility that local up/downhill winds or breezes compromise greatly data homogeneity.

Significant efforts have been made to identify wind speeds not ascribable to synoptic scale cyclonic events, e.g. related to thunderstorms, instrument errors or anomalous anthropic events. The detected non-synoptic/wrong speed values, rated between 1% and 3% of the real missing data, have been removed from the databases. Thus, in terms of extremes, all datasets are made as representative as possible of a unique type of wind mechanism.

The 6 wind records are processed to characterize the PDF and the PSDF of the stochastic mean speed process $V(t)$. The resulting wind speed model is referred to as ‘probable’ wind climate (Torrielli et al., 2011).

2.1. Marginal distribution

The Hybrid Weibull (HW) model (Takle and Brown, 1978) is used to describe the marginal distribution of $V(t)$. The cumulative distribution function (CDF) of the HW model is

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

where F_0 is the rate of zero values, while c and k are the Weibull parameters.

The HW distribution is preferred to the classically applied 2-parameter Weibull distribution because the presence of wind calms is taken into account through the extra parameter F_0; this ensures consistency between the marginal distribution and the time correlation, as $V(t)$ is treated as a single stochastic process consisting of speed values equal or greater than zero.

Only the 3 historical records, collecting 33 years of measurements, are used to estimate the parameters of the HW parent distribution. A probabilistic technique has been worked out to correct false wind calms of the older wind registrations, through the analysis of the more recent ones (Torrielli, 2011). The historical datasets, suitably homogenized, are merged into a single dataset associated with a so-called superstation (Peterka, 1992; Simiu and Filliben, 1999). Excluding the presence of systematic errors, the distribution of the missing data within the wind records can be considered as random and uncorrelated from record to record. Therefore it is reasonable to assume that the presence of missing data does not affect the modeling of the parent distribution from the superstation dataset. The fitting of such a dataset to the HW parent distribution provides the estimates of the parameters reported in Table 2 together with the related first four central moments, i.e. the mean, the variance, the skewness and the kurtosis.

2.2. Macro-meteorological spectrum

One of the goal of this analysis is to extend as much as possible the range of the frequencies over which the PSDF of the mean wind speed process $V(t)$ is defined. For this reason, the spectral estimates from the historical and the modern records are suitably combined together.

Each record is treated as a continuous stationary stochastic process and the PSDF is estimated through the Blackman and Tukey (1959) method: the autocorrelation function is first calculated from the data, then it is Fourier transformed to obtain the power spectrum. The Blackman and Tukey method is chosen mainly because it is suitably applied also in the presence of missing data, with a small loss of accuracy in the autocorrelation estimates. The possibility of estimating the PSDF by Fourier transforming the continuous segments of the wind records was set aside because in this case the spectrum would miss the long-period harmonics. One could argue that the tail of the autocorrelation function,

Table 2
Parameters of the HW distribution and relative moments.

F_0	k	c [m s^{-1}]	μ_V [m s^{-1}]	σ_V^2 [m^2 s^{-2}]	γ_1	γ_2
0.118	1.155	3.091	2.592	6.637	1.611	6.631

Table 1
Anemometer stations.

Station	Lat.	Long.	Location	Sampling time	Start record	End record	Continuous record
Capodichino	40.89°N	14.30°E	Airport	3 h	1 July 1965	30 June 1998	5 yr
Ciampino	41.78°N	12.58°E	Airport	3 h	1 July 1975	30 June 2008	10 yr
Grazzanise	41.05°N	14.07°E	Airport	3 h	1 July 1974	30 June 2007	2 yr
Capua	41.11°N	14.16°E	Rail/embank	10 min	1 January 2006	31 December 2006	66 d
Mignano 1	41.40°N	13.97°E	Rail/cut	10 min	1 January 2006	31 December 2006	70 d
Mignano 2	41.39°N	13.97°E	Rail/viaduct	10 min	1 January 2007	31 December 2007	137 d

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