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Extreme wind events in a complex maritime environment: Ways of quantification

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ABSTRACT

The rising demand of energy consumption in isolated locations such as in islands leads in the expansion of on and off-shore wind farms. The optimization of the structural design of wind turbines for such applications requires a risk analysis that is made by using the definition of return periods of extreme events with respect to the lifespan of wind turbines. This work is focusing on the estimation and the analysis of extreme wind speeds by means of the corresponding return periods based on two methods: the Peaks Over Threshold and the Annual Maxima. In addition, different methodologies and tools are tested in order to achieve more accurate results. The data used for the application are both: observations (measurements from Met Stations located on Greek islands) and modeling (a 10-year model hindcast database). The sensitivity test results were used to adjust the methodologies and make 50-year extreme wind speed maps for Northeast Mediterranean (focusing on the sea and the islands). The outcome should be used as a guide for on and off-shore wind energy applications and other construction activities.

1. Introduction

In the structural design of wind turbines, probabilistic approaches of risk assessment are adopted in order to optimize the constructions in terms of profit and durability and avoid time and cost overruns that can compromise the economic viability of the project. To this end different approaches are used for estimating conditions that contribute to or form potential threats for wind turbines such as extreme wind speed. Such conditions can be evaluated through risk analysis, a methodology that combines the magnitude and the likelihood of occurrence of an extreme event.

In this direction, risk can be expressed through the concept of return period that is a statistical estimator for extreme phenomena reoccurrence based on data of shorter range. Although, there are different approaches proposed for the estimation of the magnitude and reoccurrence interval of events, Annual Maxima and Peaks Over Threshold methods (Coles, 2001) meet great acceptance for their effectiveness. Cook (1985) suggested that for Annual Maxima method, extreme wind speed is often well represented by Gumbel distribution. The same author (1982) used the dynamic pressure to achieve a faster convergence and better distribution fitting. A more recent study was held by Larsén et al. (2011) where an extreme wind speed atlas is created based on the principles of Generalized Extreme Value (GEV) theory and the Annual Maxima (AM) method. Peaks Over Threshold (POT) methodology is employed for studies based on smaller time series and the use of exponential is supported (Abild et al., 1992). As in the first case, the wind speed square is found to fit better, especially in areas with low wind speeds and in cases where the wind speed distribution is not skewed enough for an exponential quick convergence to the distribution tail (Caires and Sterl, 2004; Galambos, 1987; Cook, 1982). These extreme value analysis methods are also used to more targeted studies of extremes based on similar characteristics such as the year season or the direction (Cook, 1982). The necessity for bigger datasets that do not violate the principles of Extreme Value (EV) theory led to the introduction of other methodologies such as the Method of Independent Storms (MIS) (Harris, 1998) and the EV theory based on the largest annual events (Smith, 1986). At the same time different approaches are proposed by Lopatoukhin et al. (2000) for the estimation of extreme wind wave heights such us the Initial Distribution Method (IDM). Breivik et al. (2014) studied wind and wave extremes using large ensembles and computed a non-parametric Direct Return Estimate (DRE) from the tail of the fitted distribution function. This was used for the estimation of the 100-year marine wind speed over the Globe.

The purpose of this work is to study ways of estimating the likelihood of occurrence of extreme wind speed events and to apply them over the area of Greece. More specifically, different methods and tools are applied over multiple datasets and the convergence (or not) of the results is further discussed. Through this procedure the uncertainties on the estimation of extreme

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winds are presented and the appropriateness of the methods/tools used is studied.

Towards this direction, the two approaches mentioned above and used are the Peaks Over Threshold (POT) and the Annual Maxima method (AM) (Palutikof et al., 1999; Larsén et al., 2011). The data employed for the application consists of both measurements from nine different stations and modeled time series. The selected area is characterized by a complex land–water distribution and the existence of several islands (smaller or bigger) where wind energy production is considerable. The reason for this selection is the local climatic and geographic characteristics. More specifically, an almost constant Boundary Layer (BL) depth ($\sim$300 m) is observed over the sea during day and night. This BL depth can change dramatically from night to day over islands that can lead to strong vertical wind components (over the islands) during day-time especially on the warmer period of the year. In addition, close to laminar flow conditions are observed near the water surface while more turbulent over the land and downwind. Moreover, strong dominant effects can take place at the wake part of the islands and at the same time wind shading can be the case in areas surrounded by island clusters.

The modeled time series are extracted from a database created by the Atmospheric Modeling and Weather Forecasting Group (AM&WFG) of the University of Athens within the framework of Marina Renewable Integrated Application Platform project (Kallos et al., 2012) (MARINA – http://forecast.uoa.gr/proj_marina.php). The advantage of the use of the database is the fact that a wide area is represented and wind speed is recorded in five levels within the boundary layer.

2. Materials and methods

Two of the most known methodologies to estimate return periods, are the Block Maxima and the Peaks Over Threshold method. A quick description of them is provided below.

2.1. Block (Annual) Maxima method

The Block Maxima method uses the GEV theory (Jenkinson, 1955). For this application the time series are divided in same-size blocks and the maximum value of each block is used to create the dataset for the application.

The choice of the block size is of major importance since a very small can lead to overestimation and increased bias. On the other hand, very large blocks will lead to smaller datasets, large variability (Coles, 2001) and rather unreliable estimation. These reasons led to the use of annual blocks (Annual Maxima) because shorter periods may violate the principles of the GEV theory (Coles, 2001). The sample created by selecting the annual maximum values, is used to fit a distribution that belongs to the GEV family.

It is widely accepted that wind speed is well described by the Weibull distribution (Hennessey, 1977), while the extremes (AM) are often approached by the first type of GEV (Cook, 1985). The later, combined with the fact that Gumbel's Probability Density Function:

$$F(x) = \frac{1}{\alpha} e^{-z - e^{-z}} \tag{2.1.1}$$

where $z = \frac{x-\beta}{\alpha}$, β=location parameter, α=scale parameter, requires the estimation of only two parameters, led to this selection.

The estimation of the parameters of the fitting distribution is based on two methods. The first one is the Maximum Likelihood (ML) Method (Cramér, 1946; Hazewinkel, 2001) and the second is the Method of Moments (MoM) (Cramér, 1946; Kendall and Stuart, 1987). Using the ML Method, the location (β) and the scale (α) parameter can be estimated through the numerical solution of the following equations simultaneously:

$$\tilde{x} - \frac{\sum_{t=1}^{n} x_t \exp(-x_t/a)}{\sum_{t=1}^{n} \exp(-x_t/a)} - a = 0 \quad \text{and} \quad -a \cdot \log\left[\frac{1}{n} \sum_{i=1}^{n} \exp\left(-\frac{x_i}{a}\right)\right] - \beta = 0 \tag{2.1.2}$$

where $x_1, ..., x_n$ is a random sample, $\tilde{x}$ is the sample mean and α, β the scale and location parameter respectively.

Using the MoM, the location (β) and the scale (α) parameters can be calculated by:

$$\alpha = \frac{s \cdot \sqrt{6}}{\pi}, \quad \beta = \tilde{x} - 0.57721 \cdot a \tag{2.1.3}$$

where $\tilde{x}$ and s are the sample mean and standard deviation, respectively.

In order to verify the appropriateness of the distribution selection, the raw data under study (modeled or observed) is compared with the corresponding values of the theoretical distribution. There are different approaches either graphical or analytical such as Probability plots (P–P plots), Quantile plots (Q–Q plots) (Coles, 2001) and the Kolmogorov–Smirnov test (Marsaglia et al., 2003).

The next step is to estimate extreme wind speed (U_T) with the preferred return period (T) through the relation $F(U_T)=1 - (1/T)$ leading to the following results (Palutikof et al., 1999):

$$U_T = \begin{cases} \beta + \frac{\alpha}{k}\left\{1 - \left[-\ln\left(1 - \frac{1}{T}\right)\right]^k\right\} & k \neq 0 \\ \beta - \alpha \ln\left[-\ln\left(1 - \frac{1}{T}\right)\right] & k = 0 \end{cases} \tag{2.1.4}$$

where α, β and k are the scale, location and shape parameter respectively.

The extreme wind speed uncertainty is normally distributed and expressed through the 95% confidence interval that equals to $1.96 \cdot \sigma(U_T)$, where $\sigma(U_T) = \pi \bullet \alpha \sqrt{\frac{1 + 1.14 k_T + 1.10 {k_T}^2}{6n}}$, n is the number of maxima, $k_T = \frac{\sqrt{6}(\ln T - \gamma_E)}{\pi}$ and γ_E is the Euler's constant.

For the successful implementation with respect to the principles of Extreme Value theory, events should be independent and identically distributed (Palutikof et al., 1999). It is also assumed that a stationary extreme wind speed climate characterizes the study area. The main disadvantage regarding the AM method is that only one value per year is used. This reduces the amount of the analyzed data significantly. For this reason, the original time series must be large enough. Cook (1985) suggests the use of 20 years of data for reliable results, and argues that the method cannot be applied to time series of less than 10 years.

2.2. Peaks Over Threshold method

To overcome the above mentioned shortcomings, a second approach for the estimation of return periods has been used through the Peaks Over Threshold method that is based on the Generalized Pareto Distribution (GPD) that is used to estimate the values exceeding a threshold.

The great advantage of POT method is the utilization of more data for the application that can be achieved also by smaller time series. For this reason, in contrast to AM, a period of 5–6 years is statistically adequate (Coles and Walshaw, 1994).

The first step for creating the dataset is to apply a high threshold and form wind speed clusters above it. The problem that arises with the selection of the threshold is similar to the block selection for the Block Maxima. Low thresholds may lead to violation of the asymptotic behavior of the distribution, while high will create fewer exceedances and will lead to an increase of variance. Therefore, the threshold should be high enough so as to converge to GPD and avoid the coexistence of different