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Non-stationarity of extreme wind speeds in Hangzhou with time varying exposure

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Abstract

Extreme wind speed analysis has been carried out conventionally by assuming the extreme series data is stationary. However, time-varying trends of the extreme wind speed series could be detected at many surface meteorological stations in China. Two main reasons, exposure change and climate change, were provided to explain the temporal trends of annual maximum wind speed series data, recorded at Hangzhou (China) meteorological station. After making a correction on wind speed series for time varying exposure, it is necessary to perform non-stationary statistical modelling on the corrected extreme wind speed data series in addition to the classical extreme value analysis. The generalized extreme value (GEV) distribution with time-dependent location and scale parameters was selected as a non-stationary model to describe the corrected extreme wind speed series. The obtained non-stationary extreme value models were then used to estimate the non-stationary extreme wind speed quantiles with various mean recurrence intervals (MRIs), and compared to the corresponding stationary ones with various MRIs for the Hangzhou area in China. The results indicate that the non-stationary characteristics of extreme wind speed data should be carefully evaluated and reflected in the determination of design wind speeds.

Introduction

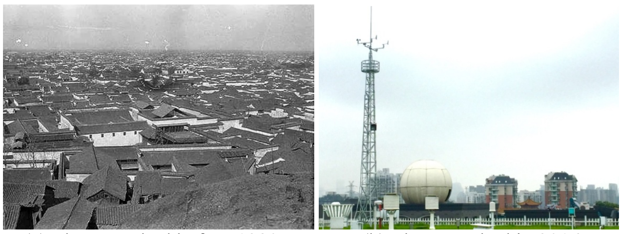
In the classical extreme value analysis, extreme wind speed data collected from a study area should be assumed to be independently and identically distributed in a stationary extreme wind speed climate [1]. However, several literatures in the meteorological and geophysical fields have revealed that the statistics of extreme climate variables (e.g. extreme temperature, extreme precipitation and extreme wind speed) were changing with time over the last decades and might continue to change in the near future under the background of global warming attributable to human activity [2-4]. In recent studies, Lombardo and Ayyub [3] analyzed the extreme wind and heat events in Washington, DC, area and observed a slight overall decrease in annual maximum gust wind speeds over the last 50-70 years. Mo et al. [4] carried out the regression and t-test analyses to the annual maximum 10-min mean wind speed series from 194 meteorological stations in China and revealed the existence of temporal trends in surface wind speed observations from 166 stations. The annual mean wind speeds over broad areas of China were also found temporally decreasing [5-8]. Therefore, it is necessary to investigate the non-stationarity of extreme wind speeds in China considering a changing climate.

The Chinese load code [9] specifies that the 10-min mean wind speed should be observed at the reference height of 10 m for open rural exposure in the meteorological stations. However, attributable to the rapid urbanization in China since 1980s, the terrain near the meteorological station might have changed dramatically so that the exposure category in the vicinity of the original anemometer site might become very different from the initial open rural exposure. Therefore it is questionable to directly utilize the original wind speed series for statistical modeling to estimate the basic design wind speed without any terrain correction. Chen et al. [10] tried to correct the annual maximum wind speed data from two meteorological stations in China based on the empirical relationship between the gust factor and the roughness length proposed by Ashcroft [11]. Mo et al. [4] applied this exposure correction procedure by considering the directional dependent adjustment for exposure and used the reanalysis data to explore the spatial and temporal trends of the extreme wind speed for 151 meteorological stations in China.

There are two main objectives in this study. One is aimed at investigating the existence of any temporal trend in the original wind speed data affected by the time varying exposure for the Hangzhou area in China and then attempting to correct these data series to obtain the adjusted wind speed data corresponding to the standard condition referenced in the Chinese load code (i.e., the 10-min mean wind speed at 10m height for open rural exposure). The other objective is to evaluate the non-stationarity of the extreme wind speed data series considering a changing climate. A non-stationary statistical modeling method that incorporates time as a covariate was used to model the distribution parameters of the extreme wind speeds in the presence of a temporal trend. Based on the adjusted annual maximum wind speed data, the non-stationary extreme wind speed quantiles were estimated and compared to the corresponding stationary ones with various MRIs.

Study area and wind speed data specification

The wind speed data series of the Hangzhou (China) meteorological station are publically available in the China Meteorological Data System (CMDS) (http://data.cma.cn/). Since the Hangzhou meteorological station belongs to the international exchange ground meteorological stations (IEGMS), standard practice for data quality control is warranted. According to the meteorological data specification, the collected wind speed data has been carefully calibrated by adjusting the observation height, observation time interval and so on to the standard condition. Wind speed data measured at 10 m height in the Hangzhou meteorological station over the period from 1968 to 2013 were utilized to estimate the extreme wind speeds in Hangzhou area with various MRIs. The topographical change nearby Hangzhou meteorological station is shown in Figure 1(a-b). Two photos were shot at the same location at the Hangzhou meteorological station and the buildings in the photos were both located in the east of the Hangzhou station. As shown in Figure 1(a-b), most of low-rise buildings built before 1980s were removed and replaced by modern high-rise buildings. Therefore, a qualitative conclusion can be made that the existing exposure category for the Hangzhou meteorological station is far from the open rural exposure attributable to the rapid urban development and construction.



(a) Photographed before 1980s (b) Photographed in 2016

Figure 1. Topographical change in the east of Hangzhou meteorological station

The recorded data series include daily maximum 10-min mean wind speed at 10 m height, along with its corresponding wind direction sector and the 3-s gust mean wind speed. The incident wind direction sectors for the Hangzhou meteorological station are defined in Figure 2, where the 16 Arabic numerals are the archived wind direction sectors defined in the meteorological data specification and the 4 Roman numerals are the classified major direction sectors in order to increase the wind speed data sample size in each considered azimuth range for analyzing the gust factors and roughness lengths, which would be used for exposure correction. Given the daily maximum 10-min mean wind speed series obtained from the Hangzhou meteorological station, the annual maximum wind speed series can also be extracted.

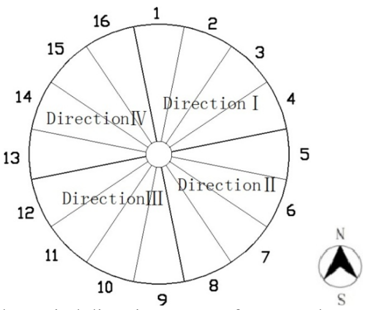


Figure 2. Incident wind direction sectors for Hangzhou meteorological station

Exposure correction

As shown in Figure. 1, the existing terrain of the Hangzhou station is quite far from the standard exposure category (i.e., Category B specified in GB 50009-2012). It is necessary to implement the exposure correction for the original wind speed records. In the work of Ashcroft [11], the observed wind speed data series were obtained from 14 British meteorological stations. The surrounding terrain of the selected stations covered a variety of terrain categories, and the obtained wind speed series were mainly affected by the cold front weather processes, which is one of the main weather processes in China. Therefore, it is practical to utilize the simplified empirical relationship between the gust factor and the roughness length advocated by Ashcroft [11] to correct the original wind speed series of the Hangzhou station.

Given the daily maximum 10-min mean wind speed series $V_{10\min}$ and 3-s gust wind speed series $V_{3\sec}$ of Hangzhou meteorological station obtained from the CMDS, the daily 3-s gust factor $G_{3\sec,d}$ can be calculated. The calculated daily 3-s gust factors were then grouped into 4 major wind direction sectors shown in Figure 2 in Roman numerals in order to increase the sample size in each considered direction for estimating the median value of the time series of the gust factors for each year (denoted as $G_{3\sec}$). The estimated 3-s gust factors for each year can be related to the roughness length (denoted as z_0). The empirical relationship between the turbulence intensity (denoted as I_z) and $G_{3\sec}$ can be expressed as [11]:

$$G_{3\sec} = 1 + \gamma I_z = \hat{A}_1 + \frac{\hat{A}_2}{\ln\left(z/z_0\right)} \quad (1)$$

where the notations γ, $\hat{A}_1$ and $\hat{A}_2$ are the empirical parameters and the approximated value of $\hat{A}_1$ and $\hat{A}_2$ have been given in Ashcroft [11] with $\hat{A}_1 = 1.08$, $\hat{A}_2 = 2.32$. It is well known the computed values of z_0 vary significantly even in the same wind direction sector which could significantly affect corrections [12]. For simplicity, z_0 could be estimated by equation (1).

Given the empirical relationship in equation (1), the time-varying roughness length z_0 of the 4 major wind direction sectors can be estimated year by year. The relationship between roughness length and wind profile exponent defined in GB 50009-2012 was given in Chen *et al.* [10], in which the roughness length corresponding to the standard terrain (Category B in GB 50009-2012) is equal to 0.05 m associated with the mean wind profile exponent of 0.16.

Figure 3 shows the estimated time varying roughness length for the Hangzhou meteorological station. Since no gust wind speeds are reported over the years from 1988 to 2001, exposure correction was simply made for that period by assuming the homogeneous behavior of the change of the terrain. From Figure 3, it can be observed that before 1980 the values of roughness length for the 4 major wind direction sectors are smaller than or close to 0.05 m while after 1980, attributable to the rapid urban development, the roughness lengths corresponding to 4 major wind direction sectors become greater than 0.05 m. For example, along Direction IV the roughness length over the period from 2002 to 2010 is larger than 0.3 m corresponding to Category C in GB 50009-2012 [10]. Such time-dependent variations of roughness lengths indicate that it is necessary to adjust the original wind speed series to the standard exposure category.

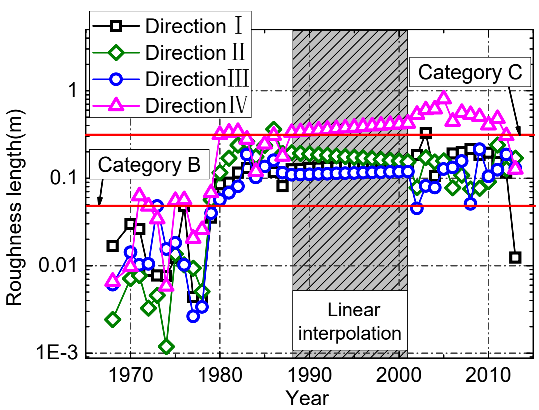


Figure 3. Time varying roughness length of Hangzhou meteorological station

The next step is to correct the mean wind speed series based on the estimated roughness length z_0 to the standard roughness length of 0.05 m. With the available daily maximum 10-min mean wind speed series $V_{10\min}$ for the time-varying exposure, the mean wind speed at the reference height of 10 m for the open rural exposure (denoted as V_0) can then be estimated as [13]:

$$V_0 = \frac{V_{10\min}}{k_T \ln(10/z_0)} \tag{2}$$

where k_T is the terrain factor and can be calculated by $k_T = 0.19(z_0/0.05)^{0.07}$ [14].

By using equation (2), the corrected annual maximum wind speed series can be obtained. Since the roughness length values are slightly smaller than or close to 0.05 m before 1980 as shown in Figure 3, it is reasonable to speculate that the terrain around Hangzhou meteorological station was kept the same as the standard exposure of Category B in GB 20009-2012 during that period. That is to say, only the estimated roughness lengths for the 4 major wind direction sectors after 1980 were utilized to correct the original wind speed series in this paper. The comparison between adjusted and original annual maximum wind speed series for Hangzhou station is shown in Figure 4. The regression trend line of the adjusted annual maximum wind speed series support the presence of downward trends. The presence of downward trends in the adjusted wind speed series of Hangzhou station may be attributed to non-climate and climate factors. For non-climate factors, although the exposure correction procedure has been conducted on the original wind speed data, it is difficult to completely remove exposure influences. Furthermore, other non-climate factors may still exist. For climate factors, the potential change of winter monsoons may lead to the decreasing trend in the wind speed data series [5-6]. It may be necessary to take into account such a non-stationary property of extreme wind speed series in the estimation of design wind speeds with various MRIs for the Hangzhou area.

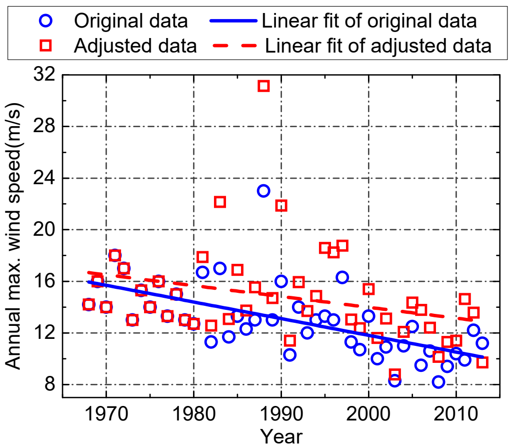


Figure 4. Comparison between adjusted and original annual maximum wind speed series for Hangzhou station

Non-stationary statistical modeling of extreme wind speed

In the classical extreme wind speed analysis, the generalized extreme value (GEV) distribution incorporating Gumbel's type I, Frechet's type II and Weibull's type III distributions is commonly used with constant parameters. Denote the annual maximum wind speed as a random variable V, the cumulative distribution function of which can be modeled by the GEV distribution as:

$$F_V(v) = P(V \le v) = \exp\left\{-\left[1 - \frac{\kappa(v-\mu)}{\xi}\right]^{1/\kappa}\right\} \quad \kappa \ne 0$$
$$= \exp\left\{-\exp\left[-\frac{(v-\mu)}{\xi}\right]\right\} \quad \kappa = 0 \tag{3}$$

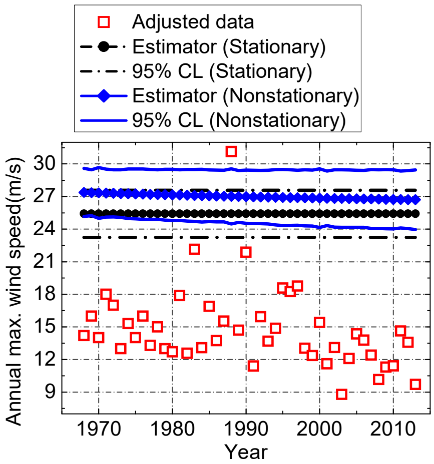
in which μ, $\xi > 0$ and κ are the location, scale and shape parameters, respectively. $\mu + \xi/\kappa \le v < +\infty$ when $\kappa < 0$ (Frechet); $-\infty < v < +\infty$ when $\kappa = 0$ (Gumbel) and $-\infty < v \le \mu + \xi/\kappa$ when $\kappa > 0$ (Weibull).

In the non-stationary analysis, the time-varying trend detected in the adjusted extreme wind speed series of Hangzhou station can be taken into account by the GEV model with time-dependent parameters [1]. Specifically, the location parameter μ_t and the logarithm of the scale parameter $\ln(\xi_t)$ in the non-stationary GEV analysis are assumed to be polynomial functions of covariates $t = 1, 2, \ldots, n$ and the shape parameter κ_t is assumed to be a constant κ, the general form of model parameters can be expressed as:

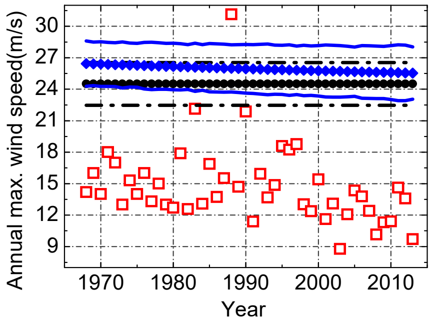
$$\begin{cases} \mu_t = \beta_0 + \beta_1 t + \beta_2 t^2 + \cdots \\ \ln(\xi_t) = \delta_0 + \delta_1 t + \delta_2 t^2 + \cdots \\ \kappa_t = \kappa \end{cases} \tag{4}$$

where the notations β_0, β_1, β_2, δ_0, δ_1, δ_2 are the constant parameters to be estimated. The use of logarithm of the scale parameter instead of itself is aim to ensure the positive value of the scale parameter. The shape parameter is always difficult to estimate with precision, so that it is usually unrealistic to model κ_t as a polynomial function of time. The parameters of the non-stationary GEV model can be approximated by maximizing the log-likelihood function. Given the estimated parameters of the non-stationary GEV model, the non-stationary extreme wind speed quantile $V_{R,t}$ with a MRI of R years can be estimated.

Figure 5 shows the estimated "time-dependent" extreme wind speed quantiles and 95% confidence limits by using the non-stationary Gumbel model for MRIs of 50/100 years. The design wind speeds were also estimated by the classical stationary statistical modeling and plotted in Figure 5. The determined non-stationary Gumbel model is able to take into account the time variation of the adjusted extreme wind speed data series. As a whole, downward trends are displayed for the time varying extreme wind speed quantiles with different MRIs. By comparing the estimated quantiles between using the stationary and non-stationary Gumbel models, it was found that the non-stationary model yields larger values of design wind speed. When the MRI=50/100 years, the design wind speed by using the stationary model is 24.5/25.4 m/s. The corresponding latest value by using the non-stationary model is 25.5/26.7 m/s respectively, which is 4%/5% larger than those estimated by the stationary model. That is to say the conventional stationary statistical modeling may underestimate the design wind speeds associated with common used 50 and 100 MRIs.



(a) MRI=100 years



(b) MRI=50 years

Figure 5. Estimated quantiles and their confidence limits using the stationary and non-stationary Gumbel models

Conclusions

Based on the surface wind observations of the Hangzhou meteorological station in China, obvious downward trends were detected in the original annual maximum wind speed series. The presence of temporal trends in the extreme wind speed series of the Hangzhou station may be partially attributed to the non-climate factors such as time varying exposure, problems with standardization of the wind speed data and so on. An exposure correction procedure was adopted in this paper attempting to correct the original extreme wind speed series to the standard exposure category.

In order to take into account the time-varying trends of extreme wind speed series in Hangzhou area, non-stationary statistical modeling of the adjusted annual maximum wind speed series were implemented using the GEV model with time-dependent parameters. Based on the determined non-stationary models of extreme wind speed, the extreme wind speed quantiles (i.e., time-dependent “design wind speeds”) with various MRIs were estimated. The estimated time-dependent design wind speed results show that the conventional stationary extreme value modeling may underestimate design wind speed estimations in Hangzhou area associated with common used 50 and 100 MRIs. Although this finding is mainly concerned about Hangzhou area, the similar non-stationary statistical modeling process can be used for extreme wind speed estimation in other area. Since the temporal trends of the surface wind speed observations were detected from many meteorological stations in China, it is necessary to carefully consider the non-stationary property of extreme wind speed observations for particular regions.

Acknowledgments

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