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Article

Estimation of extreme wind speed in SCS and NWP by a non-stationary model

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HIGHLIGHTS

- An enhancement trend of the extreme wind speed is found in the South China Sea (SCS) and the Northwest Pacific (NWP).
- Particular attention is paid to the non-stationary process of the extreme wind speed of tropical cyclone.

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ABSTRACT

In offshore engineering design, it is considerably significant to have an adequately accurate estimation of marine environmental parameters, in particular, the extreme wind speed of tropical cyclone (TC) with different return periods to guarantee the safety in projected operating life period. Based on the 71-year (1945–2015) TC data in the Northwest Pacific (NWP) by the Joint Typhoon Warning Center (JTWC) of US, a notable growth of the TC intensity is observed in the context of climate change. The fact implies that the traditional stationary model might be incapable of predicting parameters in the extreme events. Therefore, a non-stationary model is proposed in this study to estimate extreme wind speed in the South China Sea (SCS) and NWP. We find that the extreme wind speeds of different return periods exhibit an evident enhancement trend, for instance, the extreme wind speeds with different return periods by non-stationary model are 4.1%–4.4% higher than stationary ones in SCS. Also, the spatial distribution of extreme wind speed in NWP has been examined with the same methodology by dividing the west sea areas of the NWP 0°–45°N, 105°E–130°E into 45 subareas of 5° × 5°, where oil and gas resources are abundant. Similarly, remarkable spacial in-homogeneity in the extreme wind speed is seen in this area: the extreme wind speed with 50-year return period in the subarea (15°N–20°N, 115°E–120°E) of Zhongsha and Dongsha Islands is 73.8 m/s, while that in the subarea of Yellow Sea (30°N–35°N, 120°E–125°E) is only 47.1 m/s. As a result, the present study demonstrates that non-stationary and in-homogeneous effects should be taken into consideration in the estimation of extreme wind speed.

1. Introduction

The South China Sea (SCS) and the Northwest Pacific (NWP) are the sea areas most frequently hit by intense tropical cyclones (TC) in the world. And the reliability of offshore platforms design is heavily relied on the understanding of TC activities, which often bring about strong winds and destructive waves. An adequate accurate estimation of the TC parameters in the area is essential for offshore platform design and operation, especially in the context of climate change. Let us look at some of destructive TC events in recent years: Hurricanes Rita and Katrina were haunting about the Mexican Gulf in 2005 and caused one of the most destructive natural disasters in American history [1,2]; Typhoon Rammasun in 2014, with the maximum wind speed up to 72 m/s brought grievous loss to Philippine and China. The intensity of these superstrong TC beyond the engineers' expectation might imply the necessity of ocean engineering standard revision due to the enhancing trend of TC activity [3,4]. Thus, it is a pressing need to have a deep understanding in the characteristics and trend of TC activities in today's ocean engineering design.

The TC extreme wind speed of different return periods and the TC occurrence frequency are two crucial parameters for offshore structure design. A lot of works have been done to estimate these parameters. Liu and Ma [5] developed Poisson–Gumbel compound extreme value distribution to calculate wind speed and design wave height which seemed to be reasonable in short term. Shi and

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Zhou [6] used moment estimation method to derive parameters of wind speed distribution functions for practical purposes. Qi et al. [7] employed the 3-parameter Weibull distribution model to predict the extreme wind, wave and current with different return periods in the deep water areas of SCS. However, all of these studies were based on the assumption that the temporal variation of the TC activities is insignificant, which might be challenged for long term forecasting in the context of climate change.

Ongoing debate on the trend of TC activities in different oceans is still hot in the scientific community. Emanuel [3,8] found an observational enhancement of TC activities in terms of power dissipation index (PDI). Based on the design code, Liu et al. [9] introduced the extreme value theory to analyze the long-term data of TC related wind speed and simultaneous water levels of Mississippi river, finding that the return period of the hurricane Katrina should be 50 years instead of 200 years. Wang and Li [4] studied the typhoon and strong typhoon in the SCS areas and found a significant rising trend of the strong typhoon counts and intensity. Mika [10] reviewed the trend debate of TCs and suggested that the observed long-term increasing trend could be attributed to the advance in the observation capabilities. Fitchett and Grab [11] found an increasing trend of TC landfalls on the south of Madagascar in the past 6 decades, while no statistically significant trends in the frequency of overall TC landfalls over Madagascar and Mozambique could be established. Choi et al. [12] found a trend of rapidly decreasing frequency of TC affecting Japan since 1978. Dowdy [13] studied the satellite-checked TC data (1982–2013) in Australia and found a significant decreasing trend in TC numbers with high confidence level when the El Niño-Southern Oscillation induced variability is removed.

It should be noted that although the debate on the observed trend of TC activities and the mechanism behind it in the scientific community might last for some time, engineers should be aware that certain temporal and spatial variation (increase or decrease in different areas) of TC activities, whatever its reason is, does occur in the recent decades. Hence, the fact and corresponding consequences should be seriously considered, that is to say, we should ask whether the current stationary process-based methodology is still suitable for the determination of design parameters. In fact, Typhoon Rammasun in 2014, which is believed one of the top two landfall typhoons in China since 1973, achieved the maximum wind speed of 72 m/s [14] far beyond the 50-year return storm standard of 60 m/s. The other is Typhoon Marge of SCS in 1973 with minimum central pressure of 937.8 hPa and maximum wind speed more than 70 m/s. These two extreme events occurring in such a short term provide adequate reason for people to query the current stationary statistics model. Thus, it is extremely necessary to properly consider the temporal and spatial variation in engineering design in the context of climate change.

In this study, we are primarily concerned with temporal and spatial variation of TC activities in SCS and NWP. Based on the analysis of 71-year (1945–2015) TC database in these sea areas by the Joint Typhoon Warning Center (JTWC), the TC activity is found to be a non-stationary stochastic process. By establishing a non-stationary model, the extreme wind speed with different return periods and its spatial distribution in SCS and NWP are obtained. The paper is organized as follows: We at first briefly introduce the extreme value theory and corresponding parameter estimation method and then set up the non-stationary extreme value model for the maximum wind speed of typhoon. The stationary and non-stationary extreme wind speeds with different return periods in SCS are then calculated and compared. The following passage is devoted to the study of spatial distribution of extreme wind speed in NWP. Finally we come to the conclusion and implications by this study.

2. Theory and method

Extreme value theory is unique as a statistical discipline with distinguished feature to quantify the stochastic behavior of a process at unusually large or small level. In particular, extreme value analyses usually need to estimate the probability of events that are more extreme than others that have already been observed [15]. As part of its design criteria for offshore structures, the platform is required to withstand the strong wind and huge wave during its projected life span of a few decades. Hence, extreme value theory is focused on in this study to calculate TC extreme wind speed in SCS and NWP.

A brief introduction of extreme value theory is presented below. Let ξ represent a random variable with its distribution function being $G(x)$. Designate ξ_i as the ith independent observation value of ξ $(i = 1, 2, \dots, n)$, and define the random variable ζ as the maximum value of the observation $\xi_1, \xi_2, \dots, \xi_n$, namely,

$$\zeta = \operatorname*{Max}_{1\le i\le n}\{\xi_i\}, \quad i = 1, 2, \dots, n. \tag{1}$$

Let n be a random variable independent of ξ, with its range of value in positive integers, which denotes the number of the observation in one year. And let $P\{i = k\} = P_k (k = 1, 2, \dots)$. Then, the distribution function of ζ is

$$F(\zeta) = \sum_{k=1}^{\infty} P_k [G(\zeta)]^k = 1 - R. \tag{2}$$

When the extreme value distribution function is derived, the remaining work for practical application is how to solve the equation above for a given design frequency R. Generally speaking, we call $T = 1/R$ the return period of extreme values. If ζ_R satisfies $F(\zeta_R) = 1-R$, then ζ_R is called the value occurring once in T years. For instance, $\zeta_{0.01}$ is the extreme value occurring once in 100 years when $R = 0.01$.

The 71-year (1945–2015) TC data by JTWC are used in this paper. And the revised method by Emanuel [3] is employed to unify recorded TC wind speed data. There are 820 TC events totally in the SCS (4°N–25°N, 109°W–122°W in this study) according to the 71-year time series of TC database and almost half of the TCs with lifetime maximum wind speed (LMWS) are less than 30 m/s. As we focus on typhoon, only TCs with LMWS exceeding 30 m/s are considered below. In the following text, when we refer to TCs, it means TCs with LMWS larger than 30 m/s. Applying the conclusion of extreme value theory in the calculation of design extreme wind speed, the TC annual frequency is noted as a random variable n and the wind speed is denoted as ξ, their corresponding distribution functions are P_k and $G(x)$ respectively. So the annual maximal wind speed denoted as ζ follows the distribution as Eq. (2).

Since the numbers of TCs annual occurrence in the SCS are positive integers, the TC annual frequency forms a discrete distribution. Based on the statistical analysis of the TC database in the SCS, we found that the TC annual frequency follows Poisson distribution (Fig. 1):

$$P_k = \frac{\mathrm{e}^{-\lambda}\lambda^k}{k!}, \tag{3}$$

where λ is the average number of TC annual frequency with its mean value about 6 annually. Then, the extreme wind speed $\hat{V}$ can be represented in the form:

$$\begin{aligned} F(\hat{V}) &= \sum_{k=1}^{\infty} p_k [G(\hat{V})]^k = \sum_{k=1}^{\infty} \mathrm{e}^{-\lambda} \frac{\lambda^k}{k!} [G(\hat{V})]^k = \mathrm{e}^{-\lambda[1-G(\hat{V})]} \\ &= 1 - R. \end{aligned} \tag{4}$$

For a given design frequency R, the extreme wind speed with different return periods can be obtained from Eq. (4).