

Application of Poisson – Gumbel Distribution to Design Windspeed Calculation for Wind Turbines in the Chinese SE Seaboard

Zhang Rongyan¹⁾, Zhang Xiuzhi²⁾ and Cai Lianwa³⁾

¹⁾ Fujian Provincial Climate center, Fuzhou 350001; ²⁾ National Climate Center of China, Beijing 100081; ³⁾ Dongshan Meteorological Bureau of Fujian, Dongshan 363400

Abstract: The annual number, intensity and tracks of western North-Pacific tropical cyclones (CT) are erratic so that the yearly number of recorded CT differs from one station to another along the SE seaboard, thus constituting a particular discrete pattern while maximum winds under CT impacts forms a continuous pattern. The paper is devoted to the calculation of TC associated maximal winds as turbine design values for multi-yr return periods by use of Shanghai Typhoon Institute provided 1961-2006 winds in the near-center TCs in conjunction with related gales recorded in each of the stations concerned in the TC season, dealt with by the Poisson-Gumbel distribution of extreme winds. Calculations show that for 53% of these stations in a 50-yr return period the strongest winds are below 25m/s, and the stations to experience >42.5 m/s are distributed in the Dachen Island, Shengshan, and Shipu of Zhejiang Province, Beijiao and Taishan of Fujian, Zhelang and the Shangchuan Island of Guangdong as well as the Xisha Island of Hainan, where risks are great if wind turbines are set up for electricity production.

Keywords: tropical cyclone Poisson-Gumbel distribution of extremes WTGS security parameters

I. INTRODUCTION

Following the state specified Norm of Security of Wind Turbines (IEC 61400-1)[1] the security parameters for a Wind Turbine Generator System (WTGS) are wind force 4, speed of 50, 42.5, 37.5 and 30 m/s. The extreme winds are mostly related to TC in the littoral belts of China, especially south of the Yangtze estuary, where the strongest TC winds reach ≥ 40 m/s, under which the danger to the coastal wind electricity development is considerably increased

In reality, TC effects on the wind turbines are both positive and negative. Weaker tropical depressions and storms as well as stronger TC outer-core winds allow the turbines to work

longer at a specified rotation rate whereas vigorous TC, e.g., typhoon, intense typhoon and super typhoon, would damage and even destroy these machines. For example, the 2006 strong typhoon “Pearl” coded 0601 in Chinese convention, passing through the Nanao Island early on May 18, landed on the Chenghai seaboard, with its wind force 12 at 35m/s, under whose effects a wind turbine unit at the island experienced winds in excess of 40 m/s in a longer period, with gusts of 56.5 m/s (measured before electricity failure), an intensity that has not occurred in the past 56-yr period, doing damage to many of the wind turbines. Another example is the typhoon Saomei as the super typhoon in 2006 made landfall on August 10 in the Fujian/Zhejiang bordering belt with 60 m/s speed and its central pressure of 920 hPa, the extreme of 68.0 (75.8 m/s) observed at Xiaguan, Cangnan of Zhejiang (at the Hezhangyan, ~700 m MSL, Fuding of Fujian) with the consequence that 28 turbines in Wenzhou of Zhejiang were all damaged, 5 of which collapsed.

Some efforts have been made of TC damage to wind turbines, as exemplified by Song et al. (2006)[2] who investigated the TC gales positive and negative impacts upon wind turbines, and TC gales are divided into 3 kinds, i.e., beneficial, defendable and destroyable. Song et al. also noted the provinces of Zhejiang, Fujian, Guangdong and Hainan under greater TC threats as well as the sharp shift of wind velocity and turbulence strength whenever the TC passes. As indicated in Clausenl et al. (2006; 2007)[3,4], the principal parameters of the International Standard ICE61400-1 are inapplicable to areas frequented by TC, and particularly for the western North Pacific they proposed the calculated sea wind extremes in a 50-yr return period by investigating TC central pressure and winds, with focus on the parameter for turbine design in the Philippines where the load security coefficient should be 0.35 higher than that for Europe and US, thereby implying that the investment would be expected to be 20~30% higher in western North Pacific countries.

It follows that through analysis of TC-related winds and the use of mathematic statistics it is possible to make probability pre-estimation of extreme winds to meet the needs of parameter design of wind turbines. The authors attempt to explore the pattern of TC-related wind frequency in the Chinese coastline in line with the WTGS security parameter by means of regional strong wind data treated by the Poisson-Gumbel Extremes distribution.

II. DATA SOURCE AND PROCESSING

2.1 Data Source

The source includes the 1961-2000 Yearbook of Typhoons and Yearbook of Tropical Cyclones compiled by Shanghai Typhoon Institute as well gales recorded by the associated coastal stations.

2.2 Data Processing

A warning line is set to be about 3 latitudes away from the coastline (Fig.1), within which the TC is defined as a threat, and the intensity is represented by the maximum winds in the near center that are separated according to recently published WMO version (Table 1). In 1961-2000 there are 428 TC of interest, of which 33.6 and 25.7% (totaling 59.5%) are typhoons and intense tropical storms, respectively; super and intense typhoons form 7.9 and 13.6%, respectively, which damaged the wind turbines; 10.3 and 8.9% (totaling 19.2%) are

tropical storms and tropical lows, in order, producing, typically, considerable benefits for the coastal wind turbine operation..

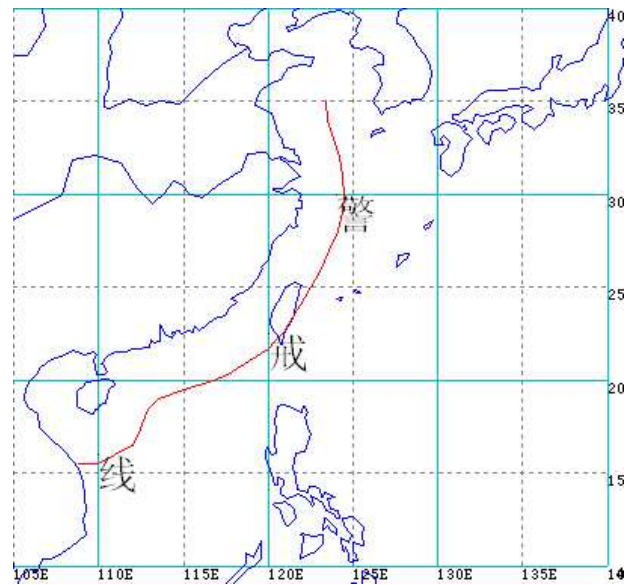


Fig.1. The warning line (full line) denoting a security zone to the west.

Table 1. The category of 1961-2006 TC of interest with their frequency

wind (m/s)	wind force	name	frequency (%)
≥ 51	≥ 16	super typhoon	34
41.5—50.9	14~15	intense typhoon	58
32.7—41.4	12~13	typhoon	144
24.5—32.6	10~11	strong tropical storm	110
17.2—24.4	8~9	tropical storm	44
10.8—17.1	6~7	tropical depression	38

III.COMPUTATIONAL METHOD

Both security and benefit are considered together in determining a maximal wind for the design of turbines. In view of a climate extreme changing as a function of the time and period it is inappropriate to take the observations into use. Normally the probability distribution is used to describe the extremes, in association with the fact that the probability of these extremes is steady (Ma et al., 1993; He et al., 2006)[7,8]. Through probability statistics inference, we can have maximum winds satisfying a certain probability value.

According to the Norm of Wind Turbine Design, typically, it is required that the extreme winds be to recur in a 100- 50-, 30- and 20-yr period, implying that these wind loads may happen to the related turbine units in these corresponding periods. Normally, for calculating the design wind recurring in a certain period of time, a sequence is formed by yearly maxima. Since TC tracks are random, their annual number and intensity vary even more greatly for a given station, with more TC attack in some years and none in the others, a situation that makes it difficult to construct a series of annual strongest winds, so that the common technique of extremes calculation does not serve the purpose. Instead, the Poisson-Gumbel probability

distribution meets the needs..

3.1 Calculation using the Poisson-Gumbel Extreme Wind Distribution

The erratic track, intensity and annual number of TC each year constitute a certain discrete distribution but instead TC-related coastal maximum winds can form a certain continuous pattern (Tang et al., 1985; Yan et al., 1993) [7,8] such that we can formulate the distribution function $G(x)$ of strongest wind ξ_n when the probability distribution of TC frequency n as P_k is obtained.

Assume TC frequency n in accordance with the Poisson distribution,

$$p_k = e^{-\lambda} \frac{\lambda^k}{K!} \quad (1)$$

where $\lambda = N/M$, with N = the total number of TC and M = the number of years.

Again, set the TC-related winds to follow the Gumbel distribution (Clausen et al., 2006),

$$G(x) = \exp\{-\exp[-\alpha(x - \delta)]\} \quad (2)$$

Consequently, we have the distribution function of Poisson-Gumbel extremes distribution in the form

$$F(x) = \sum_0^k p_k [G(x)]^k = \exp\{-\lambda[1 - G(x)]\} = P \quad (3)$$

so that

$$G(x) = 1 + \frac{1}{\lambda} \ln P \quad (4)$$

and

$$\exp\{-\exp[-\alpha(x - \delta)]\} = 1 + \frac{1}{\lambda} \ln P \quad (5)$$

Taking twice logarithmic form

$$\alpha(x - \delta) = -\ln\left[-\ln\left(1 + \frac{1}{\lambda} \ln P\right)\right] \quad (6)$$

we find the extreme gales at probability P

$$V_p = \delta + \frac{-\ln[-\ln(1 + \frac{1}{\lambda} \ln P)]}{\alpha} = \delta + \frac{-\ln[-\ln(1 + \frac{1}{\lambda} \ln(1 - \frac{1}{T}))]}{\alpha} \quad (7)$$

in which $\alpha = 1.28255/\sigma$, $\delta = \bar{x} - 0.57722/\alpha$, where $\bar{x}$ the mean of the sample sequence and σ the standard error of the series.

3.2 Case Calculation

In practically every year TC affects Congwu of Fujian Province, which is taken for calculating maximum wind recurring in a 50-yr return period by use of the Poisson-Gumbel extremes distribution. The procedure is as follows.

Step I. To choose the maximum winds of each TC hitting Congwu in 1960-2006 to guarantee inter-independence of samples of the gale sequence. In making the sequenced samples in conformity with Poisson distribution, a wind threshold value is determined in advance, beyond which the winds are selected into the series. In practice the threshold value should permit no TC influence to be only in 1/10 of the years, thereby leading to a sequence of strongest gales for the study station.

Step II. To test whether the TC frequency obeys Poisson distribution. The TC yearly frequencies are categorized (see Table 2), where f_i denotes the TC number for the category, n the total of years, P_i the (1)-given theoretical frequency, and k (=10) the number of categories, with $\lambda = 171/46 = 3.7174$.

Table 2. Test of TC frequency fitting for different categories

TC number	f_i	P_i	$\frac{(f_i - nP_i)^2}{nP_i}$
0	1	0.0243	0.0124
1	3	0.0903	0.3210
2	10	0.1679	0.6716
3	9	0.2080	0.0339
4	10	0.1933	0.1378
5	5	0.1437	0.3930
6	4	0.0891	0.0023
7	1	0.0473	0.6351
8	2	0.0220	0.9678
9	1	0.0091	0.8125
$\sum_{i=0}^k n_i \cdot f_i = 171$			3.9873

The $\chi^2 = \sum_{i=0}^k \frac{(f_i - nP_i)^2}{nP_i}$, with $i = 0, 1, 2, \dots, 9$ distribution is used to see whether TC

frequency follows the Poisson distribution (freedom $k - 3$). In this example, $\chi^2 = 3.9873$.

With confidence $\alpha = 0.05$ we look up the table of χ^2 with freedom = 7, we have $\chi^2_{0.05} = 14.07$, indicating $\chi^2 < \chi^2_{0.05}$, so that the TC frequency hitting the study station of Congwu obeys the Poisson distribution.

If the frequency fails to pass χ^2 test, it is needed to raise the threshold value to reduce the samples, after which calculation is made based on Table 1 till the χ^2 test is passed.

Step III. The (7) – calculated TC strongest winds is 33.6 m/s recurring in a 50-yr period for Congwu.

3.3 Comparison of the Gumbel Distribution for the Single-Station Yearly Maximum Wind Sequence to the Poisson-Gumbel Scheme for Multiple-Station TC Strongest Winds

To demonstrate the applicability of the results from the Poisson-Gumbel extremes distribution, the 1961-2006 series consisting of annual TC-related maxima taken from a given station of Zhejiang (Yuhuan), Fujian (Pingtan), Guangdong (Shanwei) and Hainan (Qionghai) is analyzed by the Gumbel distribution[6,9] (adding a maximum calculated from an associated weather system to the series for no TC in the year, Ma et al., 1993; Tang et al., 1985), with the results shown in Table 3. Evidently, except the Yuhuan station of Zhejiang, the other stations show results from the yearly multiple TC-related biggest winds treated by the Poisson – Gumbel (PG) scheme to be close to the results by the Gumbel scheme, thereby indicating that the PG distribution for calculating theoretical maxima in a multi-yr recurring period is effective and accurate. Note that the series consisting of inter- yearly typhoon gales and frequencies from each station concerned (when there is no typhoon the annual frequency is set to zero, with wind speed ignored) are used for Poisson - Gumbel distribution.

Table 3. Comparison between calculations of 1961-2006 sequenced annual maximum winds by the Gumbel method and yearly **multiple-station** TC maxima treated by Poisson – Gumbel scheme (denoted by PG), with difference by dif., and 20, say, for the recurring period of 20 years.

years	Gumbel	PG	dif.	Gumbel	PG	dif.	Gumbel	PG	dif.	Gumbel	PG	dif.
	Yuhuan			Pingtan			Shanwei			Qionghai		
20	35.9	33.7	2.2	31.8	32.1	-0.3	32.2	32.2	0	30.7	30.8	-0.1
30	38.1	35.3	2.8	33.8	33.8	0	34.5	34.2	0.3	32.9	32.7	0.2
50	40.8	37.3	3.5	36.4	35.9	0.5	37.3	36.7	0.6	35.7	35	0.7
100	44.4	40.1	4.3	39.8	38.8	1	41.2	40.1	1.1	39.5	38.1	1.4
non-TC yrs	3			2			1			7		
fixed number of year	1961~2006			1961~2006			1961~2006			1966~2006		

IV. DISTRIBUTION OF TC-RELATED MAXIMUM WINDS IN A MULTIPLE YEAR RETURN PERIOD

Statistics shows that there are 180 stations (close to the coastline or on islands) with their TC frequency subject to Poisson distribution passing χ^2 test at confidence of 95%. The distribution of maximal winds in a 20- and a 50-yr return period is presented for the purpose of the design of costal wind turbine units.

4.1 Pattern of 20-Year Recurring Maximum Winds

68.9% (5.6%) of the stations will have the strongest winds below 25 m/s (>37.5 m/s) in a 20-yr return period (Fig.2a), with the maximum of 47.6 (45.7) m/s in the Nanjishan Mountains of Zhejiang (Zhelang of Guangdong), next being 40.1 m/s at the Sengshan Mountains of

Zhejiang.

Following the 4 levels of WTGS, 27 stations will experience >30 m/s, distributed mainly along the coastal belts of central Zhejiang, Fujian/Zhejiang and Fujian/Guangdong bordering bands, the coastal eastern Guangdong including the Shangchuan Island and Zhapo, as well as the east of the Leizhou Peninsula, eastern Hainan and its Qionghai. together with Qianliyan of Shandong Province (as the northernmost station), with $37.5 \sim 42.5$ m/s over the projecting parts or islands of Zhejiang, Fujian, Guangdong and Hainan in addition to Sanmen in the Sanmen Gulf of Zhejiang. Winds in excess of 42.5 m/s will be found in Zhelang of Guangdong and the Nanjishan Mountains of Zhejiang.

4.2 Pattern of 50-Year Recurring Maximum Winds

53.3% (9.4%) of the littoral stations will experience maxima of <25 (>3.7 m/s) in a 50-yr return period (Fig.2b), with the strongest wind of 54.0 m/s to be at the Nanjishan station of Zhejiang, 51.5 m/s at the Zhelang station of Guangdong and 45.0 m/s at the Shengshan station of Zhejiang. The winds along Fujian central – southern coasts will be considerably smaller compared to those of the other stations.

The winds in a 50-yr return period will be distributed differently to those in a 20-year recurring period in that 13 more stations have >30 m/s winds, reaching the northernmost station Marine station far away in Liaoning, $37.5 \sim 42.5$ m/s stations will be found in the Putuo, Shipu, Shengsi, Dongshan and Yun'ao (the last two in the Fujian/Guangdong bordering belt), Zhapo and Shangchuan Island west of the Pearly River estuary, as well as Dongfang of Hainan Province, and 42.5 m/s winds over Nanjishan, Shengshan, Dachen Island and Sanmen of Zhejiang, Taishan and Beijiao of Fujian, Zhelang of Guangdong as well as the Xisha Island of Hainan Province.

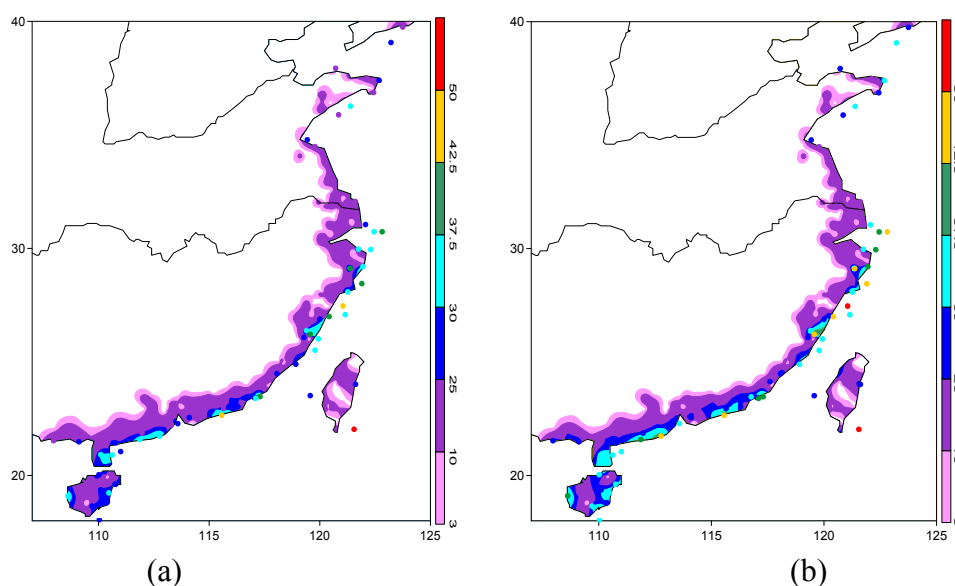


Fig.2. Calculated 10 min-mean maximum winds in a 20-yr (a) and 50-yr return period (b) for the coastal areas.

4.3 Analysis of Causes of Measured Winds Greater than the calculated Winds in a 50-Year Return Period

Fig.3 is the distribution of TC-related strongest winds in the Chinese littoral belt in 1961-2006. Comparison between Figs.3 and 2b shows that measured winds are greatly bigger than the calculated for a 50-yr recurring period. Therefore, the 180-station recorded TC-related maximal winds treated by χ^2 test show that 55% (25.6%) of the stations have the maxima higher than the calculations for a more than 100- (close to or more than 50-year) return period. According to the recurring time interval of measured maximum winds (Fig.4) there are >56% of the stations in each of the Provinces of Guangxi, Guangdong, Fujian and Jiangsu have the values greater than the calculated for a 100-year recurring period and about 54% of the stations in Shandong and Liaoning will experience the strongest winds bigger than the calculated in a 50-yr recurring period, which was mainly ascribed to super typhoons. Historically, the strongest CT occurring in a 100-year return period (the TC intensity referring to that of the landfall) include 8509 typhoon hitting the Shandong Peninsula, 8807 typhoon striking the Gulf of Hangzhou of Zhejiang, 0608 super typhoon lashing Zhejiang and Fujian ravaging the bordering coast, 6122 super typhoon battling the mid Fujian coast, 6903 and 9107 super typhoons battering the Fujian/Guangdong bordering coast and 7908 and 8309 super typhoons lashing coastal eastern Guangdong and the Pearly River Delta area, respectively.

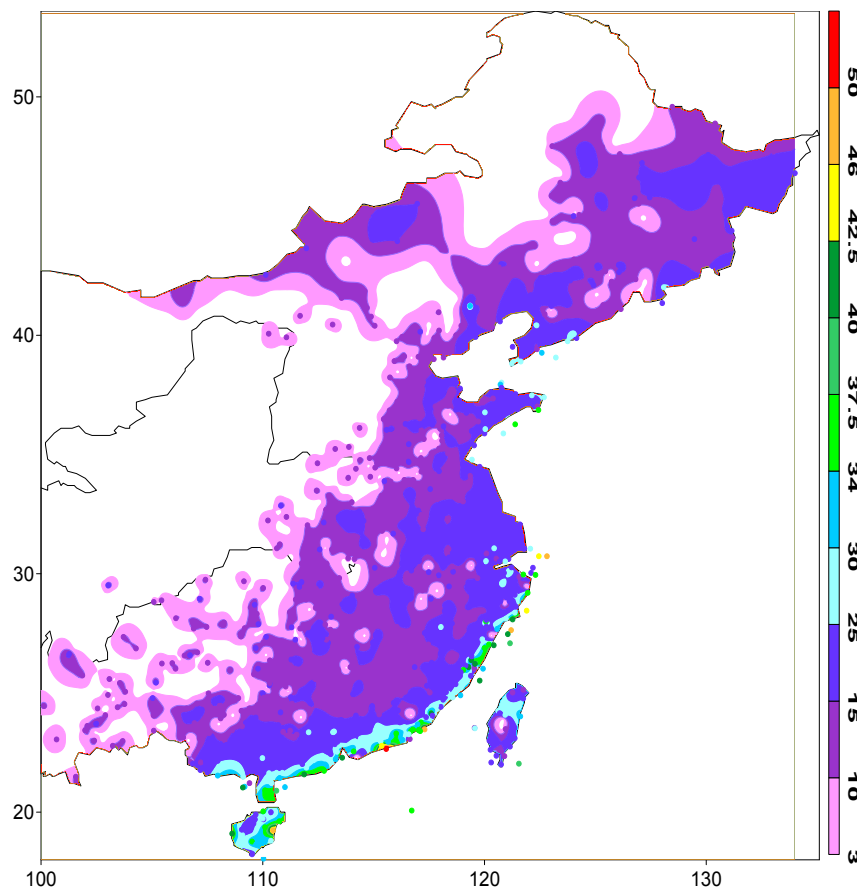


Fig.3. Distribution of TC-related maximal winds in the Chinese seaboard.

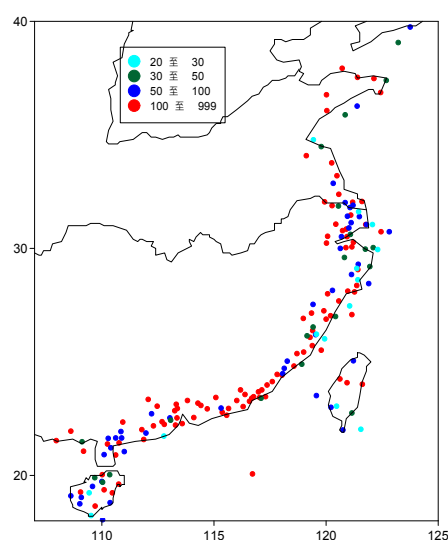


Fig.4. The recurring periods of measured TC-associated maximal winds.

V. SUMMARY

Based on the analysis, the following are of note.

- a) In 1961-2006 the typhoons and strong tropical storms in the main come inside the warning zone, making up 59.5% of total, the frequency of 7.9 (13.6%) being for super (intense) typhoons. Most of the TC-related maximum winds are utilizable.
- b) 53.9% of the stations hit by the calculated maxima in a 50-yr return period will experience <25 m/s winds, with >30 m/s winds over central – northern coastal Zhejiang, littoral zone between Fujian and Zhejiang and between Fujian and Guangdong, Zhelang, the Shangchuan Island and the Leizhou Peninsula of Guangdong, and Dongfang of Hainan Province. These areas are islands or projecting land exposed to vast waters, whereto we should pay much attention, when intending to develop wind turbine site.
- c) The Poisson-Gumbel scheme-given gale distribution in a multi-yr recurring periods conforms to reality. χ^2 tests indicate that 55% of the 180 stations show the measured maxima to be higher than the calculations found in a >100 year return period which was caused by super typhoons.

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