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Investigations on coefficient of variation of extreme wind speed

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Abstract. The uncertainty of extreme wind speeds is one key contributor to the uncertainty of wind loads and their effects on structures. The probability distribution of annual extreme wind speeds may be characterized using a classical Gumbel Type distribution. The expression that establishes the relationship between the extreme wind speeds at different recurrence periods and the corresponding coefficients of variation is formulated, and its efficacy is validated. The coefficients of variation are calibrated to be about 0.125 and 0.184 according to defined Chinese and US design specifications, respectively. Based on the wind data of 54 cities in China, 49 meteorological stations in the US, 3 stations in Singapore, the coefficients span intervals of (0.1, 0.35), (0.08, 0.20) and (0.06, 0.14), respectively. For hurricanes in the US, the coefficients range approximately from 0.3 to 0.4. This convenient technique is recommended as one alternative tool for coefficient of variation analyses in the future revisions of related codes. The sensitivities of coefficients of variation for 49 meteorological stations in the US are quantified and demonstrated. Some contradictions and incompatibilities can be clearly detected and illustrated by comparing the coefficients of variation obtained with different combinations of recurrence period wind data.

Keywords: extreme wind speed; coefficient of variation; recurrence coefficient; sensitivity analysis; design code

1. Introduction

The statistical parameters for extreme wind speeds play significant roles for structural wind-resistant performance evaluation, reliability analysis, and risk assessment. For extreme wind data, time durations of 3-sec, 10-min, and 60-min may be individually adopted by codes and/or specifications in different countries and/or areas. For instance, the 3-s gust extreme wind speed has been used to quantify the destructive effects of strong extreme winds in the US since 1996, whereas the 10-min one has been used in China (JTG/G D60-01-2004). Traditionally, Type I Gumbel, Type II Frechet, and Type III reverse Weibull distributions are adopted for delineating the extreme wind speed (Simiu and Heckert 1996, Cook 1998, Holmes and Moriarty 1999, Cheng and Yeung 2002, Cook *et al.* 2003). The Type II Frechet distribution is usually abandoned for its low fitting accuracy. Theoretically, the extreme wind speed is physically bounded, and the Type III distribution seems to be more reasonable than the Type I distribution for depicting the properties of extreme wind speeds. The Gumbel Type method is a simple and straightforward one, adopted

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worldwide by many national design codes. The Gumbel Type distribution is used to fit a sample of annual maximum wind speeds (An and Pandy 2007). In some cases, the Type I distribution generates more satisfactory results than the Type III distribution. This is verified by many studies (Simiu *et al.* 2001; Cheng and Yeung 2002, Lee *et al.* 2012). Therefore, the Type I distribution is recommended and adopted in the Chinese Code (JTG/G D60-01-2004).The applicability of a Gumbel Type distribution for modeling the wind speed and wind pressure was also justified by Chen and Huang (2010). In addition, the extreme wind pressure was considered as a Gumbel Type variable in some publications (Choi and Tanurdjaja 2002, Cheng and Yeung 2002). The extreme wind pressure may be predicted by the classical Gumbel, Gumbel-Lieblein, modified Gumbel, and the Modified Independent Storm techniques, and the corresponding results may be slightly different. It is worth mentioning that for the same sets of wind data, the speeds and pressures may not in theory simultaneously be subject to the Gumbel Type distribution. Although they cannot be ensured perfect theoretically, the errors may be minor and practically negligible.

The coefficient of variation (denoted as δ) is usually defined as the ratio of the standard deviation to the average value. It is a normalized measure of dispersion of a probability distribution compared to its expectation. Furthermore, for the same set of annual extreme wind speeds, if different distribution types are used to fit the data series, the average, standard deviation, and coefficient of variation may be different. Intrinsically, the relative weights of each data set vary with the adopted mathematical model. In wind response reliability and risk analysis, the coefficient of variation for extreme wind speeds is a significant parameter for determining the reliability index (or failure probability) and for evaluating the hazard loss. Therefore, it is quite important to accurately determine the value of the coefficient of variation. Using the Gumbel Type distribution, δ=0.2 was empirically assumed by Ge *et al.* (2000) for flutter reliability analysis for long span bridges. If standard deviation data are not available, can the wind-induced reliability and/or risk analysis be performed only in terms of the mean extreme speeds for different recurrence periods? What are the characteristics of the coefficients of variation of extreme wind speeds? These issues will be addressed in detail.

In this study, the characteristics of the coefficient of variation for extreme wind speed will be comprehensively investigated from both the theoretical and practical viewpoints. The inherent relations between the coefficient of variation and recurrence coefficient are studied. The coefficient of variation is calibrated based on the available data in certain Chinese and US codes. The manifold properties of extreme wind speeds are then demonstrated and expounded in terms of wind data collected on some stations in China, Singapore, and US. The related issues on typhoons, thunderstorms, and hurricanes respectively in three countries are also discussed. Finally, some concluding remarks are provided.

2. Relationship between the coefficient of variation and recurrence coefficient of Gumbel type extreme wind speed

If the annual extreme wind speed U is regarded as a Gumbel Type distributed random variable, the cumulative probability distribution function may be expressed as

$$F(U) = \exp\{-\exp[-a(U-b)]\} \tag{1}$$

where $F(U)$ is the cumulative probability of speed U, and a and b are the scale and threshold parameters, respectively, and may be estimated using the classical least-squares technique.

For two different recurrence periods of T_1 and T_2, the corresponding cumulative probability can be calculated by

$$1-1/T_1=\exp\{-\exp[-a(U_{T_1}-b)]\} \tag{2}$$

$$1-1/T_2=\exp\{-\exp[-a(U_{T_2}-b)]\} \tag{3}$$

where U_{T_1}, and U_{T_2} (unit: m/s) are extreme wind speeds related to recurrence periods T_1, and T_2 (unit: year), respectively. The parameters *a* and *b* may be derived from Eqs. (2) and (3) as

$$a=\{-\ln[-\ln(1-1/T_1)]+\ln[-\ln(1-1/T_2]\}/(U_{T_1}-U_{T_2}) \tag{4}$$

$$b=\frac{U_{T_1}\ln[-\ln(1-1/T_2)]-U_{T_2}\ln[-\ln(1-1/T_1)]}{\ln[-\ln(1-1/T_2)]-\ln[-\ln(1-1/T_1)]} \tag{5}$$

If the two extreme wind speeds U_{T_1}, and U_{T_2} at the two different recurrence periods T_1, and T_2 are determined, parameters *a* and *b* can be easily obtained from Eqs. (4) and (5), respectively. For most cases, *a* and *b* are usually determined based on many extreme wind speeds and their recurrence periods. With different combinations of the wind recurrence periods and speeds, different results of *a* and *b* can be obtained. The main reasons for this may be due to two aspects: one is that the original data may be affected by some unavoidable factors; the other is that the assumed Gumbel Type distribution is purely theoretical and cannot thoroughly characterize the exact property of the extreme wind speed.

For a Gumbel Type distribution, *a* and *b* can also be obtained by

$$a=1.2825/\sigma=1.2825/(\delta\mu) \tag{6}$$

$$b=\mu-0.5772/a=\mu-0.45\delta\mu \tag{7}$$

where μ, σ, and δ are the average, standard deviation, and coefficient of variation of the extreme wind speed, respectively. The parameter *a* is inversely proportional to the standard deviation σ, whereas *b* is proportional to the average μ. If δ is kept unchanged, *a* is also inversely proportional to μ.

From Eqs. (1), (6), and (7), the extreme wind speed U_T can be derived as

$$U_T=-\ln\{-\ln[F(U_T)]\}/a+b=-\ln\{-\ln[F(U_T)]\}\delta\mu/1.2825+\mu-0.45\delta\mu \tag{8}$$

For the extreme wind speed in structural wind engineering, the recurrence coefficient η of the recurrence period T is customarily defined as the ratio of U_{T_2} to either U_{100} or U_{50}. According to Eq. (8), η may be respectively computed by

$$\eta=U_T/U_{100}=\frac{-\ln[-\ln(1-1/T)]\delta/1.2825+1-0.45\delta}{-\ln[-\ln(0.99)]\delta/1.2825+1-0.45\delta} \tag{9a}$$

$$\eta=U_T/U_{50}=\frac{-\ln[-\ln(1-1/T)]\delta/1.2825+1-0.45\delta}{-\ln[-\ln(0.98)]\delta/1.2825+1-0.45\delta} \tag{9b}$$

Eq. (9) can be extended to a general form as

$$\eta_1/\eta_2 = U_{T_1}/U_{T_2} = \frac{-\ln[-\ln(1-1/T_1)]\delta/1.2825+1-0.45\delta}{-\ln[-\ln(1-1/T_2)]\delta/1.2825+1-0.45\delta} \tag{10}$$

For two periods of T_1 and T_2 (without loss of generality, assuming $T_1 < T_2$, and correspondingly, $U_{T_1} < U_{T_2}$, $\eta_1 < \eta_2$), if U_{T_1} and U_{T_2} are determined, δ can be obtained from Eq. (10) by

$$\delta = (U_{T_1} - U_{T_2})/V \tag{11}$$

where

$$V = \{U_{T_1}\ln[-\ln(1-1/T_2)] - U_{T_2}\ln[-\ln(1-1/T_1)]\}/1.2825 + 0.45(U_{T_1} - U_{T_2}) < 0 \tag{12}$$

The relationship between δ and the two annual extreme wind speeds (U_{T_1}, U_{T_2}) and their recurrence coefficients ($\eta_1 < \eta_2$) is established via the concise formulations of Eqs. (10) and (11). Once T_1, T_2, η_1, and η_2 are known, the value of δ can be uniquely determined. For certain T_1 and T_2, if the ratio of U_{T_1}/U_{T_2} (i.e., η_1/η_2) decreases, δ tends to be higher. For certain η_1 and η_2, if the ratio of T_1/T_2 decreases, δ tends to be lower.

The customary approach is to collect annual extreme data at a weather station and use classical statistical methods to determine the scale and threshold parameters. Only when these parameters have been determined can the return period values of wind speed for design purposes be determined. This process yields a coefficient of variation that is most definitely site-dependent. It is emphasized that the presented process and formulations (i.e., Eqs. (11 and 12)) for determining the coefficient of variation is not intended to replace the conventional approach. Instead, it offers an analytical solution that provides clear physical insight into the relationships between recurrence periods, extreme wind velocities, and coefficient of variation.

3. Calibration of the coefficient of variation based on the recurrence coefficient in one Chinese Code

For the recurrence periods of T =5, 10, 20, 30, and 50 yrs, the values of η (defined as U_T/U_{100}, i.e., 0.78, 0.84, 0.88, 0.92, and 0.95, respectively) are provided by the Wind-resistant Design Specification for Highway Bridges Code (JTG/G D60-01-2004). With different combinations of provided recurrence periods and their corresponding η in this code, the δ can be obtained by Eqs. (11) and (12), which are listed in Table 1. It can be observed that different values of δ can be obtained based on diverse combinations of recurrence periods, and most results are in the range of (0.11, 0.14). The maximum value is 0.1909 for T_1=20 and T_2=30, and the minimum value is 0.0954 for T_1=10 and T_2=20.

Fig. 1 displays the remarkable sensitivity of δ to η ($T_1 = 20$). It reveals that for different recurrence periods, the closer recurrence coefficients lead to a lower value of δ. For example, if T_1=20 and T_2=5 or 10, the δ increases with the increase of η_1; on the contrary, if T_1=20 and T_2=30, 50 or 100, the δ decreases with the increase of η_1. In addition, when η_1 varies in a narrow interval, the δ changes in almost a linear manner. The variation ratios ($\Delta\delta / \Delta\eta$) are 1.3, 2.7, -6.8 , -2.6, -1.6, 2.9, and 5.6, for the five cases (T_2, η_2) = (5, 0.78), (10, 0.84), (30, 0.92), (50, 0.95), and (100, 1), respectively, as shown in Fig. 1. Thus, the property of high sensitivity can be clearly observed.

Table 1 Calculated δ based on η offered in one Chinese Code (JTG/G D60-01-2004)

T_1 (Yr.) / T_2 (Yr.)	10	20	30	50	100
5	0.1452	0.1216	0.1339	0.1270	0.1274
10	/	0.0954	0.1253	0.1172	0.1203
20	0.1216	/	0.1909	0.1376	0.1342
30	0.1339	0.1909	/	0.0981	0.1148
50	0.1270	0.1376	0.0981	/	0.1290

When δ =0.1, 0.125, 0.15, 0.20, 0.25, 0.3, the corresponding η can be obtained by Eq. 9(a), and the η versus T curves are plotted in Fig. 2. The specified values of η in the code are also depicted in Fig. 2. It can be observed that the η values provided by the code are approximately in accordance with those of δ=0.125, which means 0.125 should be the maximum likelihood and appropriate value for δ. Correspondingly, for η, the values of 0.783, 0.836, 0.886, 0.915, and 0.951 should be more accurate than those listed in the Chinese Code (JTG/G D60-01-2004), and the new data are recommended for further revisions of the code.

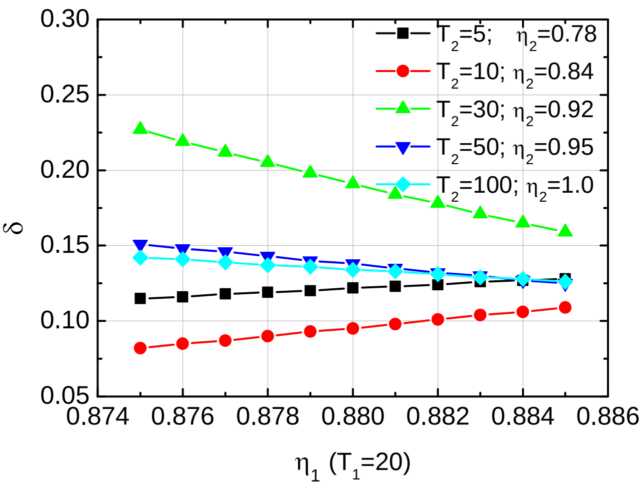

Fig. 1 δ versus η according to one Chinese Code (JTG/G D60-01-2004)

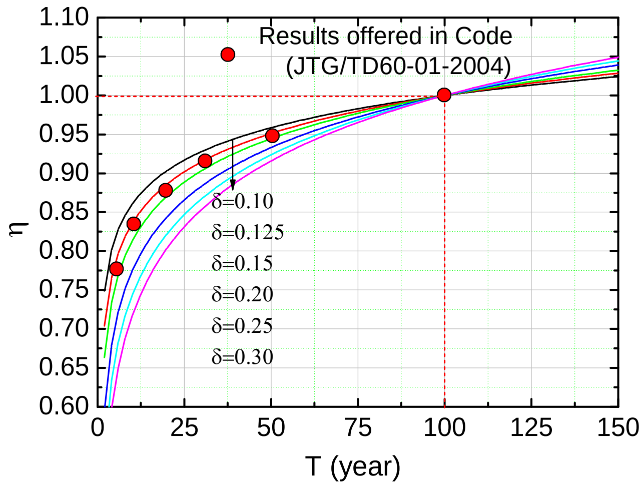

Fig. 2 Calibrated δ based on η in one Chinese Code (JTG/G D60-01-2004)

It may be concluded that the unified δ and η (for certain recurrence periods) is inappropriate for such a large-area country. In other words, δ should be site-dependent. For the coastal areas where the extreme winds may be dominated by typhoon winds, the value of δ should be much higher. Song *et al.* (2012) revealed that during the typhoon the wind characteristics in different stages varied remarkably, and the phenomena of enhanced levels of turbulence intensity, gust factors, turbulence integral length scale and spectral magnitudes in typhoon boundary layer were observed. The uncertainty of wind speed is the main contributor to the uncertainty of wind load and load effects. Interestingly, the same value of 0.125 is assumed or used for the extra-tropical storm wind speeds by Heckert *et al.* (1998). However, the distribution is not the Gumbel Type, but the reverse Weibull Type, with the tail length of c = -0.2.

4. Calculation and analysis of the coefficient of variation for extreme wind speeds in three countries

4.1 Some cities in China

As mentioned above, a unified set of recurrence coefficients of extreme wind speeds are given in the Chinese Code (JTG/G D60-01-2004). Evidently, they are statistics originally based on the enormous datasets from many stations distributed throughout the country. For the 10-yr, 50-yr and 100-yr recurrence periods, the 10-min wind speeds of 590 cities and/or districts in China are provided in the same code (JTG/G D60-01-2004). For the sake of brevity and without loss of generality, the wind data of 54 major and/or representative cities (as schematically marked in Fig. 3) are selected for analysis. Using Eqs. (11) and (12), the individual δ can be calculated from different combinations of the extreme wind speeds for individual recurrence periods, which are reported in Table 2. Coincidently, the data of Beijing and Jinan, Shenzhen and Haikou are identical.

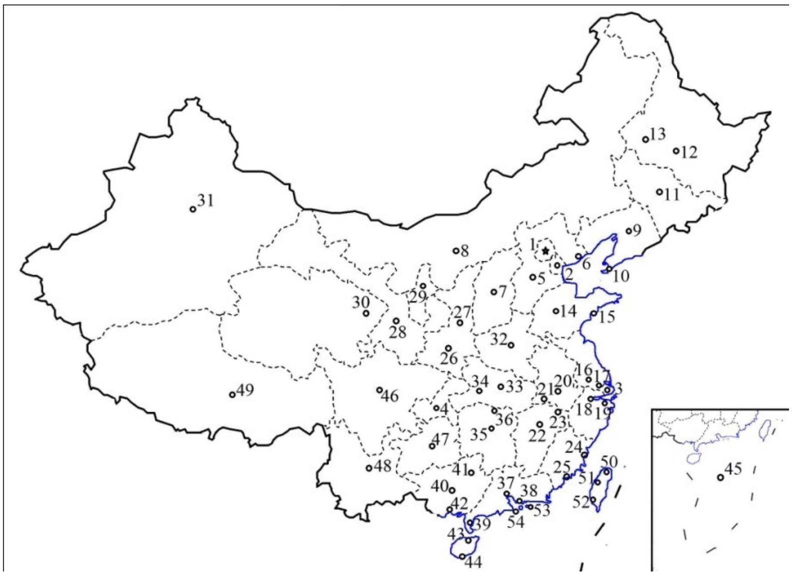

Fig. 3 Map showing locations of wind recording sites in China used in this study

Table 2 Wind speed details of China 54 major cities

No.	City	Altitude (m)	U_{10} (m/s)	U_{50} (m/s)	U_{100} (m/s)	η_{10}' /0.84	η_{50}' /0.95	$\delta(10,50)$	$\delta(10,100)$	$\delta(50,100)$
1	Beijing	54.0	22.2	27.2	28.6	0.92	1.00	0.2266	0.198	0.1252
2	Tianjin	3.3	22.1	28.6	31.3	0.84	0.96	0.3253	0.3229	0.315
3	Shanghai	2.8	23.9	31.3	33.8	0.84	0.97	0.3503	0.3207	0.2368
4	Chongqing	259.1	20.5	25.9	27.5	0.89	0.99	0.279	0.2462	0.1608
5	Shijiazhuang	80.5	20.3	24.0	25.7	0.94	0.98	0.1736	0.1791	0.1963
6	Qinhuangdao	2.1	23.9	27.1	28.6	0.99	1.00	0.1203	0.1248	0.1381
7	Taiyuan	778.3	23.0	26.6	28.2	0.97	0.99	0.1445	0.1471	0.1548
8	Huhehaote	1063.0	25.2	31.6	33.0	0.91	1.01	0.2655	0.2167	0.1031
9	Shenyang	42.8	25.6	30.0	31.4	0.97	1.01	0.1616	0.1474	0.1102
10	Dalian	91.5	25.7	32.7	35.2	0.87	0.98	0.2921	0.2738	0.2208
11	Changchun	236.8	27.4	33.0	35.4	0.92	0.98	0.2002	0.2012	0.2044
12	Harbin	142.3	24.1	30.2	32.8	0.87	0.97	0.2643	0.2652	0.268
13	Qiqihar	145.9	24.1	27.3	28.8	1.00	1.00	0.1191	0.1236	0.1367
14	Jinan	51.6	22.2	27.2	28.6	0.92	1.00	0.2266	0.198	0.1252
15	Qingdao	76.0	27.2	31.4	33.9	0.96	0.98	0.1421	0.163	0.2355

16	Nanjing	8.9	20.2	25.6	27.1	0.89	0.99	0.2847	0.2464	0.1493
17	Suzhou	7.1	22.1	27.1	28.2	0.93	1.01	0.2279	0.1875	0.0924
18	Hangzhou	41.7	22.2	27.2	28.6	0.92	1.00	0.2266	0.198	0.1252
19	Ningbo	4.2	22.1	28.6	31.3	0.84	0.96	0.3253	0.3229	0.315
20	Hefei	27.9	20.2	23.9	25.6	0.94	0.98	0.1746	0.1802	0.1976
21	Anqing	19.8	20.2	25.6	27.1	0.89	0.99	0.2847	0.2464	0.1493
22	Nanchang	46.7	20.3	25.1	27.2	0.89	0.97	0.2415	0.2448	0.2555
23	Jiujiang	36.1	20.2	23.9	25.6	0.94	0.98	0.1746	0.1802	0.1976
24	Fuzhou	83.8	25.7	33.9	37.4	0.82	0.95	0.3661	0.3677	0.3731
25	Xiamen	139.4	28.8	36.4	39.7	0.86	0.97	0.2797	0.2828	0.293
26	Xi’an	397.5	20.6	24.4	26.1	0.94	0.98	0.1762	0.1799	0.1915
27	Yan’an	957.8	21.2	25.1	26.8	0.94	0.99	0.1756	0.1776	0.1836
28	Lanzhou	1517.2	19.5	23.9	25.8	0.90	0.98	0.2271	0.229	0.235
29	Yinchuan	1111.4	27.0	34.4	37.0	0.87	0.98	0.2946	0.2746	0.2169
30	Xining	2261.2	22.6	26.8	28.6	0.94	0.99	0.1778	0.1787	0.1814
31	Wulumuqi	917.9	26.8	32.8	35.4	0.90	0.98	0.2249	0.227	0.2339
32	Zhengzhou	110.4	23.3	27.3	28.7	0.97	1.00	0.1614	0.1515	0.1246
33	Wuhan	23.3	20.2	23.9	25.6	0.94	0.98	0.1746	0.1802	0.1976
34	Yichang	133.1	18.2	22.3	24.1	0.90	0.97	0.2267	0.23	0.2408
35	Changsha	44.9	20.2	24.0	25.6	0.94	0.99	0.1805	0.1802	0.1794
36	Yueyang	53.0	20.3	25.6	27.2	0.89	0.99	0.2757	0.2448	0.1634
37	Guangzhou	6.6	22.1	28.6	31.3	0.84	0.96	0.3253	0.3229	0.315
38	Shenzhen	18.2	27.1	35.0	38.4	0.84	0.96	0.3212	0.3237	0.332
39	Zhanjiang	25.3	28.6	36.2	39.4	0.86	0.97	0.2824	0.2819	0.2804
40	Nanning	73.1	20.3	24.0	25.6	0.94	0.99	0.1736	0.175	0.1794
41	Guilin	164.4	18.2	22.3	24.1	0.90	0.97	0.2267	0.23	0.2408
42	Beihai	15.3	25.6	33.8	36.2	0.84	0.98	0.3682	0.3205	0.1971
43	Haikou	14.1	27.1	35.0	38.4	0.84	0.96	0.3212	0.3237	0.332
44	Sanya	5.5	28.6	37.3	41.4	0.82	0.95	0.3414	0.3585	0.4237
45	Xishadao	4.7	41.4	54.2	59.9	0.82	0.95	0.3496	0.3577	0.387
46	Chengdu	506.1	18.5	22.7	24.5	0.90	0.98	0.229	0.2302	0.234
47	Guiyang	1074.3	19.1	23.4	25.2	0.90	0.98	0.2265	0.2256	0.223
48	Kunming	1891.4	19.9	24.3	26.3	0.90	0.97	0.2213	0.2277	0.2486
49	Lasa	3658.0	21.7	26.6	28.7	0.90	0.98	0.2274	0.2286	0.2324

50	Taipei	8.0	25.6	33.8	37.3	0.82	0.95	0.3682	0.3698	0.3752
51	Taizhong	78.0	28.7	36.3	38.5	0.89	0.99	0.281	0.2462	0.1565
52	Tainan	14.0	31.3	37.3	40.4	0.92	0.97	0.1847	0.2001	0.2526
53	Hongkong	50.0	35.8	38.4	39.5	1.08	1.02	0.0609	0.0609	0.0609
54	Macau	57.0	35.1	37.4	38.4	1.09	1.03	0.0545	0.055	0.0563

It should be mentioned that some wind data concerning typhoons and even tornados may be included, especially in the coastal areas. In other words, due to the limited technical skill and inadequate management, the Mixed climatic wind data are used altogether. Many typhoon datasets cannot be clearly distinguished and therefore excluded for many coastal areas. Frankly, the Independent Storms Method may be more rational for characterizing such extreme events. Therefore, further investigations should be conducted to present more accurate results and to revise the code. For the coastal areas, the winds produced by tropical cyclone (typhoons) events are comparatively stronger and more turbulent than those generated by monsoon winds. Therefore, the typhoon winds are important sources of strong winds in the coastal areas. If the extreme wind data are roughly categorized into two types: strong monsoon and typhoon (hurricane, cyclone, thunderstorm, tornado), the coefficients of variation in non-typhoon regions may be much lower than those in the typhoon regions. If there is not a separation of the type of climatological event which generated each registered velocity, a thunderstorm, an extratropical pressure, or even a tropical cyclone have to be treated without any discrimination (Loredo-Souza 2012).

In addition, the parameter η' in Table 2 is calculated using the available data from different cities. η is the statistically specified value in the code (i.e., η_{10}=0.84, η_{50}=0.95), and η'/η reflects the recurrence coefficient deviation between the site-dependent results and the unified values. In other words, it characterizes the conformity of the recurrence coefficient from the specified value in the code and the actual value based on local wind data. It should be admitted that the "representative" value of η cannot accurately quantify all cities wind data throughout the country. After all, the recurrence coefficient should be site-dependent to great extent. Two sets of η'/η and three sets of δ for the selected 54 cities are shown in Figs. 4 and 5, respectively.

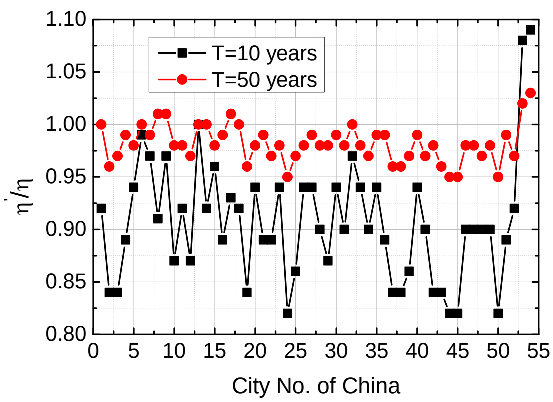

Fig. 4 China 54 cities η ratios with different recurrence periods

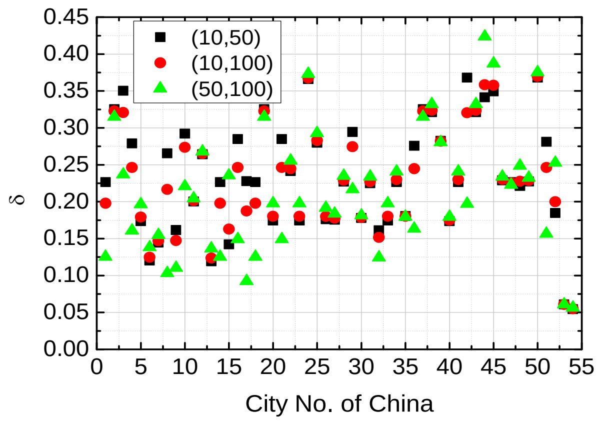

Fig. 5 China 54 cities δ with different combinations of recurrence periods

Noticeable discrepancies between η' and η can be detected for some cities. Compared with the 10-yr case, the η' of the 50-yr case is relatively closer to the corresponding η. Except for Hong Kong and Macau where η'/η are larger than 1.0, the η'/η span the intervals of (0.95, 1) and (0.8, 1) for the 50-yr and 10-yr cases respectively. Obviously, when T<100, according to U_{100} and η, the calculated U_T are higher than the tabulated values of each city, especially for the 10-yr case. It is easily accepted that a much wider safety margin should be kept for the unified design value.

The δ values are different for different cities, and most of them range from 0.1 to 0.35. For some cities, δ behaves very stable, and for the rest, the δ changes a lot as conditions vary. If δ fluctuates severely under different combination conditions, there are two possible reasons: (i) The Gumbel Type distribution is inappropriate for modeling the extreme wind speed; (ii) Significant errors occur in the statistical parameters of extreme wind speeds. Thus, it is a clear indication that the assumption may be wrong, and an alternative model should be selected for the fluctuation cases.

The δ values in Hong Kong and Macau are very stable and low, and can be considered as outliers. Apparently, the extreme wind speeds fit the Gumbel Type distributions, and the wind speeds are relatively close for different recurrence periods. Admittedly, the data are directly quoted from the Chinese Code (JTG/G D60-01-2004), no additional information (e.g., storm type, elevation, anemometer type, topographical condition, statistical time duration) are available.

Strangely, differences can be noticed among the three sets of δ. For one site, since the Gumbel Type model is adopted, the δ should be independent of the recurrence coefficients. The different value of δ with various combinations of recurrence periods indicates that the extreme wind speed cannot be modeled by the Gumbel Type distribution. This paradox or puzzle deserves to be solved to provide for a correction of the design code. The data sources and processing method, especially the data sources, need to be carefully examined. Because it is limited by technological ability, many extreme typhoon events may not be excluded, which increase the potential of data deviation.

Generally, the δ value increases with the increasing of extreme wind speed, especially in the coastal areas. For example, if U_{100}> 30 m/s, most δ are higher than 0.25, even reaching 0.35. It is easily understood that many typhoons may appear in these areas, and the data are incorporated. Subsequently, the wind speed fluctuates dramatically, which will be demonstrated by the hurricane cases in the US in the following section. For comparison, the wind speeds in the interior location cities of Huhehaote (No. 8), Shenyang (No. 9), Changchun (No. 11), and Wulumuqi (No. 31) are also relatively higher. The δ are not similar to those of coastal areas, which are not influenced by the extreme climatic events. For one area, if the value of δ is too low (e.g., $\delta < 0.05$) or too high (e.g., $\delta > 0.25$), deviating from the calibrated value of 0.125, perhaps the wind conditions of this area may be very complex, and the extreme wind speed cannot modeled by the Gumbel Type distribution. In this case, the statistical data accuracy may be challenged.

4.2 Several meteorological stations in Singapore

Singapore is located in the equatorial belt at about 1° north of the equator, and the wind climate is dominated by two monsoon seasons and the inter-monsoon thunderstorms. This area is subjected to the frequent onslaught of tropical thunderstorms. Although the thunderstorms are localized phenomena, they often generate significant strong and gusty winds (Choi 1999, Choi and Tanurdjaja 2002). The mixture of the different weather systems in Singapore indicates that the estimation of design wind speed cannot be done in a straightforward manner. Generally, the Gumbel Type method and the Independent Storm method can be used to characterize the extreme wind speed. The comparative appropriateness and/or competence of the above two methods is not within the scope of this paper. In consideration of the theme in this study, only the Gumbel Type method is used. Regardless of the weather system, if all the data can be treated as one population, then it is defined as the Mixed data pattern. In addition, if the data are sorted into the large- and small-scale weather systems or the non-thunderstorm and thunderstorm events, and they are separately analyzed to obtain each extreme distribution, then the data may be defined as the more appropriate Sorted data combined probability pattern (Choi 1999, Choi and Tanurdjaja 2002). With different time durations (e.g., 3-sec, 10-min, 60-min), the statistical properties may behave independently, and the common monsoons and thunderstorms exert different weights. For the Changi (east), Tengah (west), and Seletar (central-north) meteorological stations in Singapore, the 50-yr and 100-yr recurrence speeds for 60-min, 10-min and 3-sec time durations are listed in Table 3. The δ values can be calculated by Eqs. (11) and (12), which are also reported in Table 3.

For the Changi and Tengah stations, the extreme speeds from the long data period are higher than those from the short data period for both 60-min and 10-min time durations. The 3-s case does not follow this rule. For the Seletar station, the statistics are independent of the length of data period. For the Changi station, δ from short and long data periods are different for both the 60-min and 10-min time durations. The length of the data period plays a minor role on δ for other cases. For both Changi and Tengah stations with short data periods，δ decrease with the increase of time durations. For other cases, δ reach maximum when the time duration is 10 minutes.

For the 10-min cases, except for the case of the Changi station with a short data period, δ span the interval of (0.11, 0.13), which is very close to the calibrated result of 0.125 based on Chinese Code (JTG/G D60-01-2004). Generally, δ is fairly stable for three sites. After all, the three stations are not far away with each other, and the terrain conditions are almost similar. For the case of combined probability that are based on the Sorted data, δ are almost close to those of the Mixed data, which means δ is almost independent of the Mixed or the Sorted data pattern.

It should be pointed out that Singapore is a location where the extreme wind speeds are a result of tropical thunderstorms, which typically are of short duration with very different relationships between peak and mean wind speeds. The statistical data are related to the thunderstorms and non-thunderstorms. Based on 13 years (shorter than those of in Table 3) of wind records for Changi Station, the weather events were classified into the thunderstorms and non-thunderstorms categories. Choi (1999) fit the extreme wind speeds with the 3-sec and 60-min time durations for the recurrence periods of 10 and 50 yr, and the results are listed in Table 4.

For the 3-sec time duration, the gust speeds from the thunderstorms are higher than those of the non-thunderstorms. However, they reverse for the 60-min time duration. For the first case, 9 yrs out of the 13 yr have the highest gusts come from the thunderstorms, and for some years the first 6-7 highest gusts all come from the thunderstorm events. By contrast, only 3 yrs out of the 13 yr come from the thunderstorms, and they are only marginally higher than the non-thunderstorm ones in those 3 years. There are several years in which the top 20 mean wind speeds were all non-thunderstorms (Choi 1999).

For the non-thunderstorms, the coefficients of variation are about 0.13 and 0.09 for the 3-sec and 60-min time durations, which are consistent with the results in Table 3. However, for the thunderstorms, the coefficients of variation are 0.1155 and 0.1488 for the two cases, which is not anticipated. On one hand, the δ for the 3-sec case is lower than that of 60-min case. On the other hand, the δ for both cases are lower than 0.15, which are much lower than the 0.3 to 0.4 calculated by both the US hurricanes (in the following section) and the coastal areas (e.g., China mentioned above) prone to typhoons. Two possible causes may be included: one is the peculiarity of the local weather system, and the other is the short-term wind data. Choi himself mentioned that further studies should be carried out to confirm the findings if long-term wind data are available (Choi 1999).

Table 3 Wind speed details of Singapore three stations δ

Time duration	Location	Mixed data (short data period)			Mixed data (long data period)			Sorted data (Combined probability)		
		U_{50} (m/s)	U_{100} (m/s)	δ	U_{50} (m/s)	U_{100} (m/s)	δ	U_{50} (m/s)	U_{100} (m/s)	δ
60-min	Changi	10.5	10.8	0.0607	11.6	12.1	0.0996	10.5	10.9	0.0855
	Tengah	11.0	11.5	0.1066	11.5	12.0	0.1007	11.1	11.6	0.1053
	Seletar	10.9	11.2	0.0582	10.9	11.2	0.0582	11.1	11.5	0.0799
10-min	Changi	14.3	14.8	0.0771	16.2	17.0	0.1186	14.4	14.9	0.0764
	Tengah	15.8	16.6	0.1226	17.0	17.9	0.1300	15.9	16.7	0.1215
	Seletar	17.5	18.3	0.1073	17.6	18.4	0.1066	18.2	19.1	0.1188
3-sec	Changi	26.8	27.9	0.0937	26.0	27.1	0.0973	26.3	27.5	0.1071
	Tengah	32.0	33.8	0.1411	29.3	30.8	0.1244	31.9	33.8	0.1527
	Seletar	25.9	27.0	0.0978	25.9	27.0	0.0978	26.1	27.2	0.0969

Table 4 Changi Station δ under different conditions

Time duration	Thunderstorms			Non-Thunderstorms		
	U_{10} (m/s)	U_{50} (m/s)	δ	U_{10} (m/s)	U_{50} (m/s)	δ
3-sec	23.2	26.2	0.1155	20.9	23.8	0.1254
60-min	8.1	9.4	0.1488	9.5	10.5	0.0915

4.3 Some meteorological stations in the US

In Section C6.5.4 of the Commentary to ASCE 7-05 (ASCE 2006), they specify a wind load factor of 1.5 to estimate a wind speed effect with an MRI of 500 yrs and 50 yrs. The wind speed factor is defined as (e.g., Diniz and Simiu 2005) $U_{500}/U_{50}=\sqrt{1.5}=1.2247$. Correspondingly, the coefficient of variation of δ is 0.184, which is not in agreement with the calibrated result of 0.125 based on the Chinese Code (JTG/G D60-01-2004) as discussed earlier.

On the hurricane coast, the non-hurricane speeds are insignificantly different from those in the interior regions (Peterka and Shahid 1998). For non-hurricane speeds in the continental United States and in Alaska, they suggested the recurrence coefficient can be respectively calculated by

$$\eta_T = U_T / U_{50} = 0.36 + 0.10\ln(12T) \tag{13}$$

$$\eta_T = U_T / U_{50} = 0.45 + 0.085\ln(12T) \tag{14}$$

The δ are calibrated to be around 0.19 and 0.14, respectively. In addition, if the hurricane speeds are fitted by a Gumbel Type distribution, for the recurrence periods of 5, 10, 25, 100, and 500 yrs., the recurrence coefficients are 0.68, 0.77, 0.90, 1.105, and 1.36, respectively (Peterka and Shahid 1998). Correspondingly, the δ approximately spans the interval of (0.3, 0.4).

The 3-sec gust wind speed data collected annually in 143 weather stations were selected and processed for conformity by Cheng and Yeung (2002). In their studies, for the sake of consistency, the stations affected by hurricanes and tornadoes were therefore excluded. The results indicate that for the 143 stations considered, compared to the Type I Gumbel distribution, the Type III reverse Weibull distribution is more suitable for delineating the annual extreme gust wind speeds at 139 stations (Cheng and Yeung 2002). These results are also in agreement with the conclusions suggested by the studies for fastest-mile winds by Simiu and Heckert (1996). Interestingly, a simple statistical analysis revealed that the opposite results. For the majority of the stations considered, the Type I Gumbel distribution yielded a higher accuracy than the Type III distribution for gust winds with greater recurrence intervals. This result was further verified by Cheng and Yeung (2002) who fit the wind data at the 139 stations to both distributions. It can be concluded that the appropriateness of the optimum fitting criteria for the two distributions may be challenged. This complicated issue will not be further investigated, and only the Type I Gumbel distribution is attempted in this study.

Owing to the limitations of space, only the results of 49 stations that have a record length over 20 years are presented here. The initial information of Station No., Station abbreviation, record length, mean speed, standard deviation of speed, and the fitted extreme wind speed of record length and 50 years are respectively listed in columns of (1-7) Table 5. In column (8), the coefficient of variation is calculated using $\delta' = \sigma / m =$ Col(5)/Col(4). Inherently, each extreme wind dataset has the same weight for this δ' case, which is suitable for the Uniform Type distribution. In column (9), the δ are calculated using Eqs. (11) and (12), which involves columns (3, 6, 7) and the recurrence interval of 50 years. Column (10) is the difference between the two sets of coefficients of variation predicted by the two approaches.

Table 5 Wind speed details of US 49 stations

No.	Sta. No. (1)	Sta. Abv. (2)	N (yrs) (3)	Mean(m/s) (4)	STD (m/s) (5)	V_N (m/s) (6)	V_{50} (m/s) (7)	δ' (8)	δ (9)	δ' - δ (10)
1	3822	SAV	26	26.53	3.82	34.56	36.42	0.1440	0.1327	0.0113
2	3927	DFW	32	28.14	4.1	37.44	38.78	0.1457	0.1314	0.0143
3	3945	COL	21	30.44	4.71	39.59	42.65	0.1547	0.1431	0.0117
4	13743	DCA	38	28.03	4.36	38.49	39.35	0.1555	0.1367	0.0188
5	13865	MEI	20	24.56	3.7	31.62	34.16	0.1507	0.1393	0.0113
6	13874	ATL	21	28.01	4.24	36.24	39	0.1514	0.1404	0.0110
7	13880	CHS	22	26.61	2.94	32.44	34.25	0.1105	0.1030	0.0075
8	13897	BNA	21	26.68	4.82	36.05	39.19	0.1807	0.1670	0.0137
9	13957	SHV	38	27.74	4.47	38.44	39.32	0.1611	0.1412	0.0199
10	13966	SPS	27	29.33	3.9	37.64	39.43	0.1330	0.1228	0.0101
11	13967	OKC	21	29.98	4.3	38.34	41.14	0.1434	0.1332	0.0102
12	13968	TUL	21	26.99	3.52	33.83	36.12	0.1304	0.1212	0.0092
13	13994	STL	21	27.7	4.13	35.72	38.41	0.1491	0.1384	0.0107
14	13996	TOP	21	30.01	4.19	38.15	40.88	0.1396	0.1298	0.0098
15	14739	BOS	26	29.7	3.13	36.28	37.8	0.1054	0.0974	0.0080
16	14821	CMH	22	27.84	4.31	36.36	39.01	0.1548	0.1432	0.0116
17	14913	DLH	24	26.52	3.5	33.68	35.6	0.1320	0.1223	0.0097
18	14914	FAR	21	25.12	3.14	31.22	33.27	0.1250	0.1168	0.0082
19	14933	DSM	21	29.01	3.11	35.04	37.06	0.1072	0.0998	0.0074
20	23044	ELP	21	28.41	4.76	37.66	40.75	0.1675	0.1545	0.0131
21	23047	AMA	21	30.86	2.87	36.43	38.3	0.0930	0.0870	0.0060
22	23062	EDEN	35	25.54	1.96	30.1	30.61	0.0767	0.0699	0.0068
23	23155	BFL	20	21.23	3	26.95	29.02	0.1413	0.1317	0.0096
24	23160	TUS	21	27.8	4.13	35.83	38.52	0.1486	0.1379	0.0107
25	23169	LAS	20	30.35	4.83	39.56	42.88	0.1591	0.1473	0.0119
26	23174	LAX	40	21.85	2.85	28.79	29.24	0.1304	0.1131	0.0173
27	23185	RNO	21	31.65	4.16	39.72	42.42	0.1314	0.1218	0.0096
28	23788	SAN	21	20.46	3.24	26.75	28.86	0.1584	0.1468	0.0115

29	23234	SFO	40	28.62	5.35	41.66	42.5	0.1869	0.1585	0.0285
30	24011	BIS	21	27.57	3.38	34.13	36.33	0.1226	0.1142	0.0084
31	24033	BIL	21	28.88	2.75	34.21	36	0.0952	0.0890	0.0062
32	24127	SLC	36	29.29	4.11	38.79	39.95	0.1403	0.1578	-0.0175
33	24131	BOI	21	25.6	3.1	31.62	33.63	0.1211	0.1122	0.0089
34	24155	PEN	21	28.29	3.25	34.6	36.71	0.1149	0.1067	0.0081
35	24156	PIH	21	29.39	3.59	36.37	38.71	0.1222	0.1139	0.0083
36	24157	GEG	21	25.88	2.32	30.39	31.9	0.0896	0.0838	0.0058
37	24225	MFR	21	23.09	2.87	28.68	30.54	0.1243	0.1150	0.0093
38	24229	PDX	32	26.96	5.1	38.52	40.19	0.1892	0.1698	0.0194
39	24243	YKM	21	25.91	2.9	31.54	33.43	0.1119	0.1045	0.0074
40	93193	FAT	21	20.01	2.62	25.09	26.79	0.1309	0.1213	0.0096
41	93730	ATC	32	28.46	3.97	37.45	38.76	0.1395	0.1276	0.0119
42	93819	IND	23	31	8.13	47.36	52.08	0.2623	0.2385	0.0237
43	93821	SDF	20	28.25	5.39	38.52	42.23	0.1908	0.1761	0.0147
44	94008	GGW	21	29.65	3.89	37.21	39.74	0.1312	0.1219	0.0093
45	94224	AST	20	31.67	3.54	38.41	40.85	0.1118	0.1045	0.0073
46	94746	WOR	21	28.82	2.51	33.69	35.33	0.0871	0.0818	0.0053
47	94846	ORD	24	27.22	3.99	35.37	37.55	0.1466	0.1349	0.0117
48	94847	DTW	24	25.49	3.33	32.31	34.14	0.1306	0.1213	0.0094
49	94860	GRR	21	28.09	3.66	35.19	37.57	0.1303	0.1211	0.0092

The δ', δ and $\delta'-\delta$ are depicted in Fig. 6. Except for SLC Station (24127), $\delta<\delta'$. As mentioned in the Introduction, the statistical parameters are related to the variable distribution type. For the two different distribution types, the $\delta'-\delta$ mainly fall in the narrow interval of (0, 0.02). For most stations (except for IND Station (93819)), δ' and δ stay within the ranges of (0.08, 0.2), (0.07, 0.2), respectively. The maximum and minimum values of the δ are 0.2385 and 0.0699, respectively. They correspond to the IND Station (93819) and the EDEN Station (23062), respectively. In non-hurricane regions, δ is calculated to be within (0.18, 0.21) by Peterka and Shahid (1998). In addition, for the annual extreme wind speeds in the Netherlands, δ' are calculated to be in the region of (0.08, 0.18) by Carlos (2001).

According to Eqs. (11) and (12), δ changes with extreme wind speeds and recurrence periods, whereas some uncertainties cannot be avoided for both parameters. This means it is impossible to get an exactly accurate value of δ. Consider the following cases: U_{T_1}, U_{T_2}, T_1, and T_2 are individually increased by 1%, 1%, 10%, and 10% (such variation amplitude can be regarded as the possible upper threshold), and the new δ can be obtained by Eqs. (11) and (12). The absolute variation of $\Delta\delta$ may be easily determined (Fig. 7), by which the sensitivity of δ to U_{T_1}, U_{T_2}, T_1, and T_2 can be quantified. Some findings are given as:

For most stations, $\Delta\delta$ spans the region of (0, 0.06). For the DCA Station (13743), SHV Station (13957), LAX Station (23174), SFO Station (23234), and SLC Station (24127), δ are very sensitive to the related parameters. Even when $\Delta T_1 < \Delta T_2$, $\Delta\delta$ is more sensitive to T_1 than to T_2. Thus, the accuracy of T_1 seems to play a more significant role on δ than T_2 does. In addition, $\Delta\delta$ is more sensitive to U_{T_2} than to U_{T_1}. The differences are particularly obvious for the above five stations. The T_1 and T_2 are the most and least sensitive parameters, respectively.

Compared to in Singapore and United States, many cities in China have larger δ. The climatic and terrain conditions may be one cause, and the wind data collection method and analytical technique is another possible cause. Due to the first-hand data are not available, and the causes for the higher values cannot be thoroughly clarified in this paper. However, all data used in this paper are provided in the authorized codes or published documents, not based on speculations. Holmes (2009) mentioned that there is little consistency between neighboring economies with many places having codes and standards based on documents in the world, and a strategy for improving alignment of codes and standards in the future was outlined.

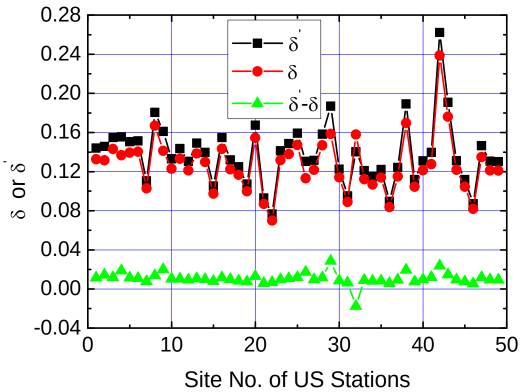

Fig. 6 Two sets of δ for the US 49 stations

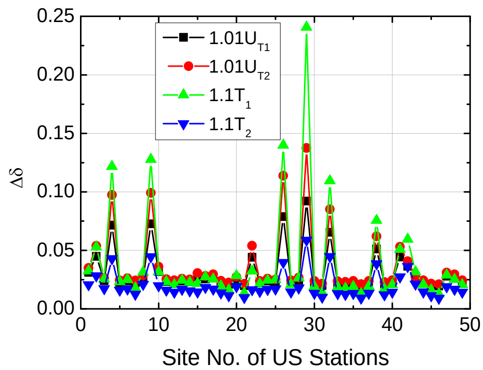

Fig. 7 Four sets of $\Delta\delta$ for the US 49 stations

5. Conclusions

This paper expounds the characteristics of the coefficients of variation of extreme wind speed that are modeled by a Gumbel Type distribution in both theoretical and practical aspects. Some findings and conclusions are summarized as follows.

- Once the two recurrence periods and the corresponding mean extreme wind speeds are given, the δ can be determined by the derived expression in a straightforward manner. One does not need to know the standard deviation. In general, the δ value is highly sensitive to the influencing parameters, i.e., it may be difficult to get an accurate estimation. For a single site, if the δ value is almost immune to combinations of different recurrence periods and the corresponding speeds, it presents a supportive proof that the extreme wind speeds can be modeled by a Gumbel Type distribution. The δ value may be considered and recommended as an effective diagnostic indicator for evaluating the modeling precision and statistical accuracy. If the value δ is not robust to different combinations of recurrence periods, it is unreasonable to model the extreme wind speeds using a Gumbel Type distribution, otherwise, intolerable errors may be induced.
- The δ value is calibrated to be about 0.125 according to certain Chinese specification, which contradicts the fact that it largely scatters in an interval of (0.1, 0.35) for 54 major cities in China. In comparison, based on 49 and 3 meteorological stations, the δ value spans intervals of (0.08, 0.20), and (0.06, 0.14) for the United States and Singapore, respectively. For hurricanes in the US, it approximately ranges from 0.3 to 0.4. For thunderstorms in Singapore, the δ values are close to those of non-thunderstorms, which may be related to the 13-year short-term data. The present convenient technique can be recommended as one alternative tool for wind speed coefficient of variation analysis in the future revisions of related codes.
- The sensitivity analyses on the coefficients of variation for 49 meteorological stations in US are carried out in theory and practice, and the different sensitivities are quantified and demonstrated. Some contradictions and incompatibilities for several stations can be clearly detected by cross-comparing the coefficients of variation obtained with different combinations of recurrence period wind data. Under this condition, some fitting errors are unavoidable if the Type I Gumbel distribution is used, and other probability distribution types should be attempted to reasonably characterize and model its features.

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