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MEAN RECURRENCE INTERVALS OF ULTIMATE WIND LOADS

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ABSTRACT

The attention of wind engineers and extreme value climatologists has been focused in the last few decades on estimates of basic wind speeds, that is, wind speeds with 50- or 100-yr mean recurrence intervals (MRIs). Recently, however, efforts have been reported on MRI estimation for speeds inducing the design strength or causing member failure. These efforts have benefited from progress in extreme value theory, notably the development of 'peaks over threshold' methods used in conjunction with the Generalized Pareto Distribution. According to results based on such methods extreme wind speeds are best fitted by extreme value distributions of the reverse Weibull type which, unlike other distributions used in the past, have finite upper tails. We note results according to which the ASCE 7-93 Standard and its 1980s predecessors specify wind load factors that place structures in hurricane-prone regions at substantially higher risk than structures in non-hurricane regions, and comment on changes required in Standard provisons in this respect. We also review results on the effects of wind directionality. On average, estimates of wind loads with relatively short MRIs, obtained by disregarding wind directionality effects, are conservative in relation to estimates that take directionality into account. However, the conservatism decreases as the MRIs increase and may become marginal for speeds associated with wind-induced failures. We report and comment on the result that estimated tails of distributions that best fit samples of hurricane wind speeds are somewhat shorter than estimated tails for samples of squares of hurricane wind speeds. An Appendix provides instructions for accessing electronic files containing wind speed data and computer program listings.

INTRODUCTION

The last two decades have witnessed a veritable revolution in extreme value theory. Its main focus was the development of the 'peaks over threshold' approach used in conjunction with the Generalized Pareto Distribution (GPD). One useful feature of this approach is that it includes in the analysis all data observed during the period of record that exceed a sufficiently high threshold. In contrast, in the epochal approach, the period of record is divided into equal epochs (e.g., years), and the data used in the analysis consist of the maximum observed value in each epoch (e.g., the maximum yearly speeds). For example, suppose that the two largest speeds exceeding the 35 m/s threshold are 35.1 m/s and 36.4 m/s during year 1, and 36.3 m/s, 42.7 m/s and 45.2 m/s during year 2. For those two years, the epochal approach makes use of two data points (36.4 m/s and 45.2 m/s). For a 36 m/s threshold, the ' peaks over threshold approach' makes use of four data points (36.3 m/s, 36.4 m/s, 42.7 m/s, and 45.2 m/s); for a 35 m/s threshold, it makes use of five data points. The 'peaks over threshold' approach can thus result in larger extreme data samples for any given record length. In addition, for any given set of observations, more realistic estimates are obtained by conducting analyses of a set of samples -- rather than of a single sample -- each sample in the set corresponding to a distinct threshold.

In the next section we review briefly the 'peaks over threshold' approach and the estimation methodology used to obtain the results reviewed in this paper, and describe the data used to obtain those results. We also review results on wind speed distributions reported by Simiu and Heckert (1996) and Heckert, Simiu and Whalen (1998). The third section reviews estimates, conditional on epistemic uncertainties being negligible, of MRIs of wind loads inducing the design strength, as specified by the ASCE 7-93 Standard (1993) and similar standards. According to these results, for extratropical regions those MRIs appear to be satisfactory from a safety point of view. However, for hurricane-prone regions, the MRIs can be one or even two orders of magnitude shorter than for extratropical regions. This inconsistency with respect to risk in the ASCE 7-93 Standard and its 1980s predecessors is the result of the implicit assumption by Ellingwood et al. (1980) that wind load factors for hurricane-prone regions can be estimated on the basis of statistics of extratropical winds. The fourth section reviews results which confirm that, on average (though not in all cases), for 50-yr or 100-yr MRIs, wind directionality effects are significant, that is, estimates that do not account for directional effects are conservative. The results show, however, that the conservatism decreases as the MRIs increase, and that for the long MRIs associated with member failures the conservatism is marginal. The fifth section presents and comments on results according to which tail length parameters are slightly lower for samples of extreme wind speeds than for samples derived from the latter by squaring the wind speeds. The final section presents a summary and our conclusions.

BASIC THEORY, ESTIMATION METHOD, WIND SPEED DATA, AND WIND SPEED DISTRIBUTIONS

The exceedances y of a sufficiently high threshold u are rare events to which the Poisson distribution applies. Asymptotically, the exceedances y can be shown to be fitted by the Generalized Pareto Distribution (GPD), whose expression is

$$G(y)=\mathrm{Prob}[Y \leq y]=1-\{[1+(cy/a)]^{-1/c}\} \quad a>0,(1+(cy/a))>0 \qquad (1)$$

where a and c are the location and the tail length parameter, respectively. Equation 1 can be used to represent the conditional cumulative distribution of the excess $Y=X-u$ of the variate X over the threshold u, given $X>u$ for u sufficiently large (Pickands, 1975). The cases $c>0$, $c=0$ and $c<0$ correspond respectively to Fréchet (Type II Extreme Value), Gumbel (Type I Extreme Value), and reverse Weibull (Type III distribution of the largest values) domains of attraction. For $c=0$ the expression between braces is understood in a limiting sense as the exponential $\exp(-y/a)$ (Castillo, 1988, p. 215). For the reverse Weibull distribution the upper tail is finite.

Our estimates were based on analyses of sets of data exceeding various thresholds u. They were obtained by using the de Haan procedure (de Haan, 1994; see Simiu and Heckert, 1995 or Simiu and Scanlan, 1996 for a review). Note that the smaller the threshold, the larger is the sample size and the smaller are the sampling errors (i.e., the narrower the confidence bands). Consider, for example, Fig. 1, which shows the estimated wind speeds corresponding to various thresholds for milepost 150 on the Gulf coast, a location near Port Isabel, Texas. For a 38 m/s threshold the sample size is 26, whereas for a 36 m/s threshold the sample size is 42. On the other hand, the smaller the threshold, the larger is the deviation from the assumption inherent in extreme value theory that the data are asymptotically large. If this deviation is too large the extreme value model is no longer appropriate (Castillo, 1988). In view of the dependence of the estimates upon threshold, the estimation is performed subjectively on the basis of plots such as those of Fig. 1, as discussed, for example, in de Haan (1994) or Simiu and Heckert (1996) and references quoted therein. Given the errors associated with high thresholds on the one hand and low thresholds on the other, an optimum threshold in principle exists near which the graph is approximately horizontal (see Simiu and Heckert, 1995 for additional details). When choosing a reasonable value for the estimated value of the tail length parameter c on the basis of our inspection of the graphs, it should be recalled that a larger estimate implies a longer tail and is therefore conservative from a structural engineering viewpoint. Finally, we note that for very long MRIs sampling errors are large, and estimates based on an individual sample are unreliable. However, estimates for large numbers of samples can yield useful insights on average trends.

The following wind speed data were used:

1. Hurricane wind speed data obtained by simulation for each of 16 azimuths. (These data, obtained by Batts et al. (1980), were previously used to develop the wind speed map included in the ASCE 7-93 Standard, and ASCE load factors for combined wind and flood (K. Mehta, 1997, personal communication).
2. Observed extratropical daily wind speed data sets for periods of up to 26 years, and maximum yearly wind speed data sets for periods of up to 54 years. These data represent maxima regardless of wind direction.
3. Observed extratropical maximum yearly wind speed data for each of 8 azimuths.

The data are described in some detail in Heckert, Simiu and Whalen (1998), Simiu and Heckert (1996), Simiu et al. (1979) and Changery et al. (1984). They are listed in public files, which also include information on the data sets and computer programs for their statistical analysis (see Appendix).

Results reported by Simiu and Heckert (1996) and Heckert, Simiu and Whalen (1998) lend strong support to the hypothesis that extreme wind speeds are best fitted by reverse Weibull distributions in both extratropical storm and hurricane-prone regions. The results show that, while the effect of the tail's finiteness can be modest for estimates of basic wind speeds (i.e., speeds with a 50- or 100-yr MRI), it can be significant for estimates of speeds with long MRIs.

WIND LOAD FACTORS

We review an assessment of wind load factors specified by the ASCE 7-93 Standard and its 1980s predecessors for the simple case where (1) the design of the structure or element is governed by the wind load, the other loads being negligible, (2) wind directionality effects are not significant, and (3) epistemic uncertainties are not taken into account (the implications of the latter assumption are discussed subsequently). For this case the design strength is proportional to the wind load factor times the wind load associated with a 50-year wind speed. In view of the fact that wind load factors were developed in Ellingwood et al. (1980) on the basis of records of extratropical storm winds, without any consideration being given to statistics of hurricane wind speeds, the question arises whether the wind load factors specified in the ASCE Standard 7-93 for hurricane-prone regions are consistent from the point of view of risk with those specified for extratropical regions.

We first discuss the consequence of neglecting epistemic uncertainties. Probability distributions of wind loads are functions of epistemic uncertainties with respect to the aerodynamic force coefficient, the oncoming aerodynamic flow characteristics, and the probabilistic estimate of the wind speed. The larger these uncertainties, the longer are the tails of the wind load distributions, that is, the shorter are the estimated MRIs of a specified wind load. Estimates of MRIs that do not account for epistemic uncertainties are upper bounds for estimates that do. Therefore, if the former estimates -- the upper bounds -- are unsatisfactory, so, *a fortiori*, are the latter estimates.

Assessments reported by Whalen (1996) were based on estimated ratios of wind loads corresponding to various long MRIs, R, on the one hand and the 50-year wind load on the other. Since the estimates are conditional upon the epistemic uncertainties being negligible, and we assume loads other than those induced by wind to be negligible, the estimated load ratios are equal to the squares of the ratios between the estimated R-yr and 50-yr speeds. On average we found that MRIs of hurricane loads inducing the design strength are of the order of 500 years, while the corresponding estimates for extratropical storms are longer by as much as two orders of magnitude or more. As previously mentioned, our estimates yield longer MRIs than those that would be obtained if the epistemic uncertainties were accounted for. Therefore, according to our results, the load factors inherent in the provisions of the ASCE 7-93 Standard correspond, on average, to MRIs of the wind load inducing the design strength that are less than 500 years.

We mentioned earlier that according to our results wind speeds in both extratropical regions and hurricane-prone regions have reverse Weibull distributions, i.e., distributions with limited upper tail. For hurricane winds this conclusion is consistent with recent findings acccording to which the intensity of hurricanes has a limited upper bound. Note that if an Extreme Value distribution with longer upper tail (e.g., the Type I distribution) were assumed to fit hurricane wind speeds, the MRIs of the wind speeds inducing the design strength would be even shorter than those estimated on the basis of the reverse Weibull distribution. As noted by Whalen (1996), this would also have been the case had the simulated hurricane wind speeds of Vickery and Twisdale (1996) been used instead of those of Batts et al. (1980).

DIRECTIONAL VERSUS NON-DIRECTIONAL ESTIMATES OF EXTREMES

In this section we review estimates for various mean recurrence intervals, R, of ratios, r_R, between estimates of equivalent extreme wind speeds, x_{Req}, obtained by taking wind directionality effects into account, and estimates of extreme wind speeds, x_R, obtained by disregarding such effects.

We now define equivalent extreme wind speeds, or for short, equivalent wind speeds, and review the method for estimating them. The method is applicable provided that the wind effects depend on wind speed and direction in the form

$$p(\theta)=(\rho/2)C(\theta)x(\theta)^2 \tag{2}$$

where ρ = air density, C=aerodynamic pressure or force coefficient (or other wind effect coefficient independent of wind speed), p=pressure or force (or other wind effect), x=wind speed, and θ=wind direction. The estimation method makes use of the set of N time series

$$P_j(\theta_i)=C(\theta_i)x_j(\theta_i)^2/\max_i[C(\theta_i)] \tag{3}$$

TABLE 1. DIRECTION-DEPENDENT AERODYNAMIC COEFFICIENTS

	i	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
Set 1	$C(\theta_i)$	1.1	1.0	0.5	0.6	0.7	0.6	0.5	0.9	1.8	**3.3**	1.1	0.6	0.1	0.2	0.2	0.8
Set 2	$C(\theta_i)$	0.9	0.8	0.5	0.4	1.2	0.7	0.6	0.5	0.5	0.6	0.6	0.9	**1.4**	0.8	0.8	0.4

where i=1,2,...,N denotes the direction, j=1,2,..,M, M is the number of storm events, x_j denotes wind speed in event j, $\max_i[C(\theta_i)]$ is the largest of the values $C(\theta_i)$, and $\max_i$ denotes the maximum over all i's. For non-hurricane regions data are available for a number of directions N=8. For hurricane-prone regions N=16. From these time series we form the single time series

$$P_j=\max_i[\{[P_j(\theta_i)]\}. \tag{4a}$$

To within a constant factor, P_j is the largest wind effect in event j. Rather than analyzing the time series P_j, we analyze the time series of equivalent wind speeds

$$x_{eq\,j}=(P_j)^{1/2}\,. \tag{4b}$$

The analysis yields the extreme values x_{Req}, where R denotes the MRI. The extreme wind effect for the MRI of interest is

$$p_R=(\rho/2)\{\max_i[C(\theta_i)]\}(x_{Req})^2. \tag{5}$$

For the case where directionality is not taken into account, estimates of pressure are obtained by following exactly the same steps used to estimate p_R, except that in Eq. 3 the factor $[C(\theta_i)]$ is replaced by the factor $\max_i[C(\theta_i)]$. For this case we will refer to R as the nominal MRI, as opposed to the MRI, and the counterpart of the time series of the equivalent extreme wind speeds $x_{eq\,j}$ is therefore the time series of the extreme wind speeds x_j.

We considered two typical sets of aerodynamic coefficients, shown in Table 1. Set 1 corresponds to a roof corner location. Set 2 corresponds to a location at the approximate center of a building facade. Note that the ratios between the largest aerodynamic coefficient (shown in bold type) and the other coefficients are on average much smaller for set 1 than for set 2. From each of these two sets seven additional sets of aerodynamic coefficients were used, which were obtained from those listed above table via rotation of the building by 45 , 90 , ..., 270 , 315 degrees. For example, for a 45-degree rotation, for the N, NNE, NE...,NW, NNW directions, the aerodynamic coefficients for set 1 are 0.2, 0.8, 1.1,....,0.1, 0.2.

For set 1 of Table 1, Figs. 2a and 2c (corresponding to a coastal location near Corpus Christi, Texas, and identified as milestone 250) show estimated tail length parameters c of the best fitting

TABLE 2. MEAN AND STANDARD DEVIATIONS OF r_R.

	r_{50}	r_{2000}	$r_{10\,000}$	$r_{100\,000}$
Mean	0.71 (0.82)	0.85 (0.88)	0.90 (0.90)	0.96 (0.95)
Standard dev.	0.12 (0.04)	0.11 (0.05)	0.12 (0.09)	0.18 (0.10)

NOTE. Values not between parentheses and values between parentheses correspond to aerodynamic coefficient sets 1 and 2, respectively.

extreme value distributions, and their 95% confidence bounds, for x_R and x_{Req}, respectively. Figures 2b, 2d show estimates x_R and x_{Req}, respectively, as functions of threshold. From Figs. 2b, 2d we estimate, roughly, $x_{50}=34$ m/s, $x_{50eq}=20$ m/s, and $x_{5000}=45$ m/s, $x_{5000eq}=45$ m/s. It can be seen in Fig. 2 that, while the estimates of the 50-yr speeds vary slowly as a function of threshold, for the 5,000-yr speeds the variability is larger. *We strongly emphasize that individual estimates for very long MRIs are unreliable because of large sampling errors,* the period over which hurricane data are available in the U.S.being only about 100 years. However, if such estimates are obtained for a large number of locations (in our case 55 locations located at successive intervals of about 70 km), they can, on average, provide useful approximate indications of trends. This is, in our opinion, the case for Table 2, which lists sample statistics of $r_R = x_{Req}/x_R$ than would be admissible for any individual estimate.

Note in Fig. 2 that the 50-yr estimates are significantly smaller for x_{Req} than for x_R. However, in many cases, including the case of Fig. 2, this is less and less the case for estimates with increasingly large MRIs. According to Table 2, for both sets of aerodynamic coefficients, for very large MRIs the estimated ratios are, on average, close to unity.

To understand these results qualitatively, consider the simple example of the time series $x_j(\theta_i)$ $(i=1,2;\ j=1,2,3)$: $x_j(\theta_1)=\{52,41,47\}$, and $x_j(\theta_2)=\{48,46,39\}$. Let us assume $C(\theta_1)=0.5$, $C(\theta_2)=1$. By Eq. 4b, the time series of the equivalent wind speeds $x_{eq\,j}$ is identical to the time series $x_j(\theta_2)$. Its mean and standard deviation are 44.33 and 4.33, respectively. On the other hand, for the nondirectional time series (i.e., the time series of the largest wind speeds, regardless of direction), we have $x_j=\{52,46,47\}$, with mean and standard deviation $48.33>44.33$ and $3.21<4.33$, respectively. From the fact that the mean is larger and the standard deviation is smaller for the time series x_j than for the time series $x_{eq\,j}$, and from typical expressions of percentage points as functions of population means and standard deviations, it follows in many situations that, for very short MRIs, x_R can be significantly larger than x_{Req}, while for very long MRIs this is no longer the case.

Designs are governed by loads with large MRIs, rather than by the 50-yr loads. Therefore, our results appear to indicate that, contrary to common belief, ultimate loads obtained by the non-directional method (i.e., from the time series x_j) may be only marginally conservative.

In accordance with the ASCE Standard 7-93, for hurricane-prone regions near the coastline, wind loads inducing the design strength are defined as the loads with a 50-yr nominal MRI multiplied by an effective wind load factor (1.3×1.05^2). These nominal MRIs were found to be, on average, of the order of 500 years. For Fig. 2 the nominal MRI and the MRI of the ultimate wind load are estimated as follows. The speed inducing the design strength is $(1.05)(1.3)^{1/2} \times x_{50} \approx 1.2 \times 34$ m/s$=40.8$ m/s. From Fig. 2b, the nominal MRI of that speed is about 300 yrs (see also Simiu and Heckert, 1997). From Fig. 2d, the MRI of the 40.8 m/s speed (and, therefore, the MRI of the ultimate wind load) is about 3,000 yrs. Similar estimates were made for 55 mileposts with 8 distinct building orientations at each milepost. It was found that estimated MRIs were larger that nominal MRIs by a factor of about 3 to 15. A rough estimate of the average MRI for these 55x8 situations is 3,500 years. However, MRIs considerably smaller than 3,500 years can occur in some cases. Also, these estimates are conditional on the uncertainties in the estimation of the aerodynamic, micrometeorological, and climatological parameters that determine the wind loads being small. Unconditional estimates would lead to even smaller estimates of the MRIs. Our results may explain, at least in part, the large losses caused by many hurricane events compared to losses due to extratropical winds other than tornadoes. In light of these results it appears that the Standard specification of wind load factors in hurricane-prone regions needs to be reassessed and revised. A proposal currently before the ASCE 7 Standard Committee is to include, in addition to a basic wind speed map corresponding to a 50-yr MRI, a wind speed map corresponding to a higher MRI, to be used in lieu of speeds equal to the basic speeds multiplied by the square root of a wind load factor.

TAIL LENGTH PARAMETERS: WIND SPEEDS VERSUS WIND LOADS

The question has been raised among wind engineers of whether, for structural design purposes, is it more appropriate to fit probability distributions to data samples consisting of wind speeds, or to data samples consisting of the squares of the wind speeds. The answer depends on whether the distribution fitted to a sample of extreme variates is closer to the theoretical asymptotic distribution than is the case for the distribution fitted to the sample of the squares of those variates. No theoretical answer appears to be available at present.

For the hurricane wind speed data, regardless of their direction, we compared estimated tail length parameters for the best fitting distributions of the speeds and of the squares of the speeds. On average, we found that, for the squares of the wind speeds, the estimated tail length parameters are on average slightly larger than for the speeds themeselves. Typically, if the estimated tail length parameter for a sample of the wind speeds was $c=-0.25$, say, for the corresponding sample of squares of the wind speeds the estimated value was about $c=-0.1$. An example is shown in Fig. 3. We are currently performing research to confirm -- or possibly invalidate -- the common belief that analyses of extreme wind speeds yield results that are more realistic than those yielded by analyses of squares of extreme wind speeds.

SUMMARY AND CONCLUSIONS

According to estimates based on modern extreme value theory and the use of the 'peaks over threshold' estimation approach, extreme wind speeds are best fitted by extreme value distributions of the reverse Weibull type. Unlike other distributions used in the past, these distributions have finite upper tails. We noted that the ASCE 7-93 Standard and its 1980s predecessors specify wind load factors that place structures in hurricane-prone regions at substantially higher risk than structures in non-hurricane regions. We reviewed results on the effects of wind directionality. On average, estimates of wind loads with relatively short MRIs, obtained by disregarding wind directionality effects, are conservative in relation to estimates that take directionality into account. However, the conservatism decreases as the MRIs increase and may become marginal for speeds associated with wind-induced failures. We also reported the result that estimated tails of distributions that best fit samples of hurricane wind speeds are somewhat shorter than estimated tails for samples of squares of hurricane wind speeds.

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APPENDIX – INSTRUCTIONS FOR ACCESSING DATA AND COMPUTER PROGRAMS

To access data and programs type first:ftp ftp.nist.gov; >user anonymous; enter password >your e-mail address; >cd /pub/bfrl/emil. This places you in the main directory. Datasets and programs are stored in three subdirectories named maxyear, hurricane and directional. Each subdirectory has a readme file.

For example, to access the readme file for the hurricane directory, type from the main directory: >cd hurricane; >get readme. To get back to the main directory, type cd ../

To access hurricane datasets or programs, from the main directory type: cd hurricane/datasets (to access datasets) or cd hurricane/programs (to access programs). Then type >prompt off; >dir; >mget * (this copies all the data files). Once you are in the subdirectory hurricane/datasets, if you wish to get a specific file, type: get <nist.name> <local name> (example: get file35.dat file35.dat). To finish the session type: >quit

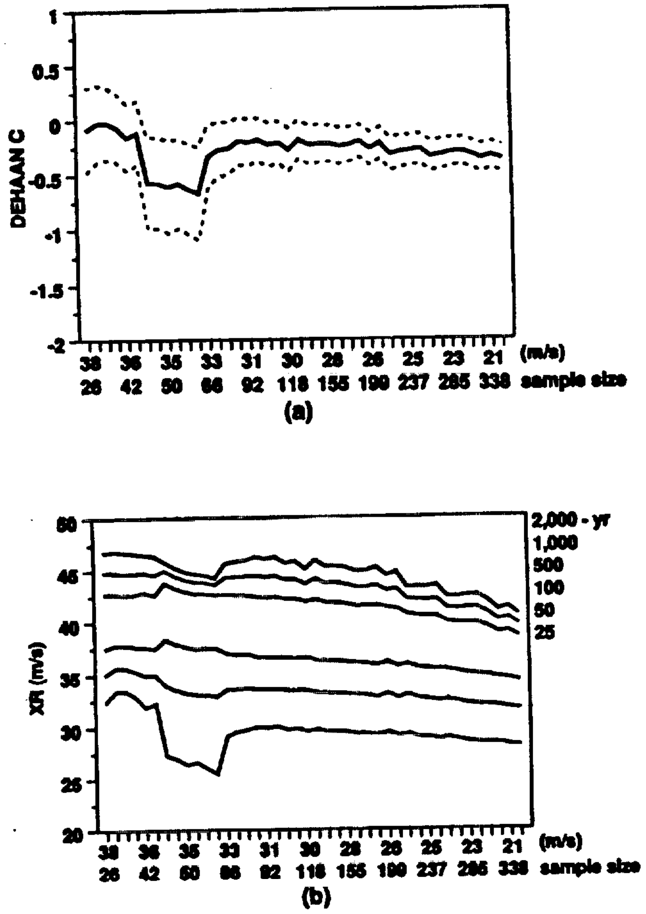

Fig. 1. (a) Estimates of parameter c and (b) estimates of speeds x_R with mean recurrence intervals R=25-yr to 2000-yr, as functions of threshold, milestone 150 (near Port Isabel, Texas).

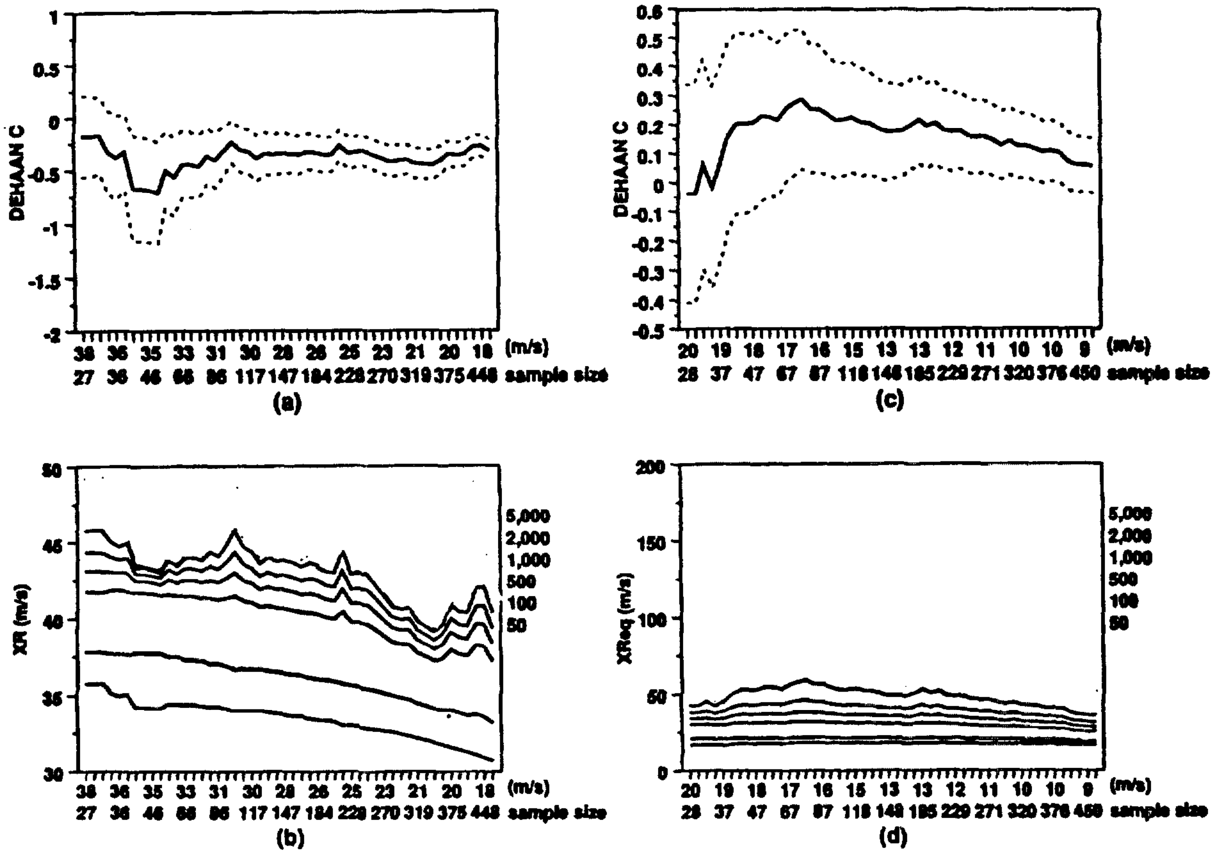

Fig. 2. Estimates of parameter *c* and wind speeds with 50- to 5000-yr mean recurrence intervals: (a), (b) wind directionality effects not taken into account, (c), (d) wind directionality effects accounted for. Coastal location near Corpus Christi, Texas (milepost 250).

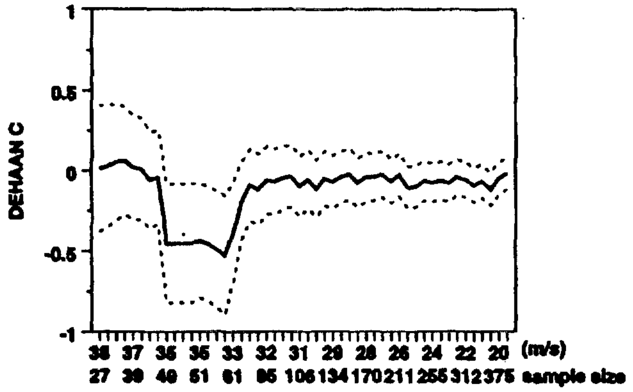

Fig. 3. Estimates of parameter *c* based on squares of data used in Fig. 1 (coastal site near Port Isabel, Texas). Note that overall estimate of *c* is larger than for Fig. 1.