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NIST Technical Note 1416

Estimates of Hurricane Wind Speeds by the 'Peaks Over Threshold' Method

E. Simiu, N. A. Heckert, and T. Whalen

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[1] At Boulder, CO 80303.
[2] Some elements at Boulder, CO 80303.

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Sponsored by
National Science Foundation
Arlington, VA 22230

NATO Scientific Affairs Division
NATO, B-110 Brussels, Belgium

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Issued February 1996

U.S. Department of Commerce
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National Institute of Standards and Technology • Technical Note 1416
Natl. Inst. Stand. Technol. • Tech. Note 1416, 49 pages (February 1996)
CODEN: NTNOEF

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1996

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402–9325

ABSTRACT

We report results that lend support to the hypothesis that extreme hurricane wind speeds are described predominantly by reverse Weibull distributions, which have limited upper tails. The results are based on the analysis of hurricane wind speed data obtained in an earlier project and used for the development of the ASCE 7-83 and ASCE 7-93 Standard wind speed map. According to our results, wind load factors should be larger in hurricane-prone regions than the load factor specified in current standard provisions. However, the requisite increases are smaller than would be the case if the distributions were assumed to have infinite upper tails, as has been done so far in all principal studies of hurricane winds in the United States.

Key words: Building technology; building (codes); climatology; extreme value theory; hurricanes; load factors; structural engineering; structural reliability; threshold methods; wind (meteorology).

ACKNOWLEDGEMENTS

We acknowledge with thanks partial support by the National Science Foundation (Grant No. CMS-9411642 to Department of Civil Engineering, The Johns Hopkins University, subsequently transferred to the University of Colorado at Boulder), and partial support by the NATO Scientific Affairs Division for collaborative work with a team headed by Dr. S. Coles of the Department of Mathematics and Statistics, University of Lancaster, U.K. Useful interactions with Dr. Coles and with Prof. R.B. Corotis of the University of Colorado are also acknowledged with thanks.

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[1]Plots of Appendix I are not included in this list.

1. INTRODUCTION

A fundamental theorem in extreme value theory states that sufficiently large values of independent and identically distributed variates are described by one of three extreme value distributions: the Fréchet distribution (with infinite upper tail), the Gumbel distribution (whose upper tail is also infinite, but shorter than the Fréchet distribution's), and the reverse (negative) Weibull distribution, whose upper tail is finite (Castillo, 1988).

The consideration of the reverse Weibull distribution in wind engineering is the result of recent developments in extreme value theory, notably the use of the "peaks over threshold" approach. All principal studies of extreme hurricane winds in the United States published so far (Batts et al., 1980, Georgiou et al., 1983, and Vickery and Twisdale, 1995) have been based on the assumption that extreme wind speed distributions have infinite upper tail. The purpose of this report is to investigate the applicability of the reverse Weibull distribution to the modeling of hurricane wind speeds and the effect of using that distribution on the estimation of extreme wind speeds and wind load factors.

Simulations of hurricane wind speeds are based on censored probabilistic models of the various climatological parameters that determine the wind speeds (i.e., the pressure difference between center and periphery of the storm, the radius of maximum wind speeds, and the speed of translation of hurricanes) -- see Batts et al. (1980), or Simiu and Scanlan (1986). The censoring is based on physical considerations. It is in principle consistent with a tail-limited, rather than an infinitely tailed, probabilistic model of the extreme wind speeds.

The data used in this report were generated by simulation (Batts et al., 1980) to obtain estimates of hurricane wind speeds that were used to develop the wind speed map included in the ASCE 7-83 and ASCE 7-93 Standards. They are available on tape (Hurricane Wind Loads, Computer Program, Accession No. PB821 32259, National Technical Information Service, Springfield, VA, 1982), and are also available in anonymous files accessible to the reader as indicated in Appendix II of this report. The data are briefly discussed in Section 2.

Section 3 briefly discusses the "peaks over threshold" method of analysis used in this work and includes results obtained by that method. The results are discussed in Section 4, where a comparison is presented with other sets of available results. Section 5 presents our conclusions.

2. HURRICANE WIND SPEED DATA

As indicated earlier, the wind speed data analyzed in this report were obtained by simulation (Batts et al., 1980) and are directly accessible to the reader on disk (see Section 1) or in electronic form (see Appendix II). For each of 55 equidistant locations between mileposts 150 and 2850 (Fig. 1) and for each of 999 simulated hurricane events, data are available as maximum wind speeds within each of the sixteen half octants.[2] In addition, the estimated mean annual rates of occurrence of hurricanes events are available for each location.

In this study we analyze data sets in which each of the data points is the maximum wind speed in a hurricane event, regardless of direction. The data represent fastest one-minute hurricane speeds at 10 m above ground over open terrain at the coastline, in knots. To obtain the corresponding speeds in miles per hour (mph), the values in knots must be multiplied by 1.151 mph/knot. To obtain corresponding nominal hourly mean speeds in m/s (henceforth referred to simply as hourly mean speeds), the fastest one-minute hurricane wind speeds in mph must be multiplied by the factor 0.447 (m/s)/(mph), and by a conversion factor from fastest one-minute speeds to hourly mean speeds. For hurricane data it was found by Krayer and Marshall (1992) that the conversion factor from 10-min average speed to peak gust speed is about 10 percent higher than the factor proposed by Durst (1960) on the basis of extratropical storm data (see, for example, Simiu and Scanlan, 1986, p. 65). However, in our opinion, owing to the limited amount of data analyzed by Krayer and Marshall, this finding, and its implications for conversion factors pertaining to wind speeds averaged over other time intervals, are still somewhat tentative. For this reason we used in this report a conversion factor from fastest minute to hourly mean of 1.24, as proposed by Durst. A different value could be used if warranted by analyses of additional hurricane data. This, however, would not affect the main conclusions of this report, which pertain to the effect of the upper tail of the distribution on the estimation of extreme wind speeds and on ratios between wind speeds corresponding to different mean recurrence intervals.

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[2] For mileposts 450 and 500 the differences between the parameters used in the simulations were small, and the same set of simulations was assumed to be applicable to both mileposts.

FIGURE 1. Locator map with coastal distance intervals marked (nautical miles; 1 nautical mile≈1.9 km) (Ho et al., 1987).

3. ANALYSES AND RESULTS

3.1 Estimation of Tail Length Parameter of Generalized Pareto Distribution. The Generalized Pareto Distribution (GPD) is an asymptotic distribution whose use in extreme value theory rests on the fact that exceedances of a sufficiently high threshold are rare events to which the Poisson distribution applies. The expression for the GPD is

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

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 Extreme 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 mileposts 150 through 2850, Appendix I shows estimated values of the tail length parameter c and 95 percent confidence bounds[3] (top of each page), and mean hourly speeds X_R at 10 m elevation over open terrain at the coastline for mean recurrence intervals R= 25, 50, 100, 1000 and 2000 years. The estimates are based on analyses of sets of data exceeding various thresholds u. They were obtained by using the de Haan procedure (de Haan, 1994). The procedure is reviewed and the reasons for its choice are discussed in Simiu and Heckert (1995). The smaller the threshold, (a) the larger the sample size (for example, for milepost 150, for a 38 m/s threshold the sample size is 26; for a 37 m/s threshold the sample size is 36 -- see Appendix I), and (b) the smaller the sampling errors (i.e., the narrower the confidence bands). However, as the threshold decreases, there tends to be an increase in bias due to the stronger violation of the assumption -- inherent in the modeling by any extreme value distribution -- that the data are asymptotically large. Given the dependence of the estimates upon threshold, the estimation is performed subjectively on the basis of the plots of Appendix I, as discussed, for example, in Simiu and Heckert (1995).

Since, as the threshold becomes lower, the bias in the estimation of the variates increases while the sampling error decreases, an optimum threshold in principle exists. Over intervals where the bias error is small the graph is nearly horizontal; a downward slope of the graph is indicative

[3]These confidence bounds are associated with the sampling errors due to the limited number of wind speed data being analyzed. In addition to these sampling errors, the estimates are affected by climatological sampling errors, that is, sampling errors due to the limited number of climatological parameter data (pressure defect, radius of maximum wind speeds, traslation velocity) on the basis of which the simulation of the wind speed data was carried out. For the data of Batts et al. (1980) used in this report, the estimated standard deviation of the climatological sampling errors is about 10 percent (Batts, Cordes and Simiu, 1980).

of increasing bias. When choosing a reasonable value for the estimated value of 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.

Consider, for example, the graph for the estimate of the tail length parameter c, for milepost 850 (Appendix I). It is reasonable to infer from this graph that the estimated value of c is about -0.2. As a second example consider the graph for milepost 950. In this case a conservative choice for the estimated value of c is -0.25, say. From the results of Appendix I it is clear that the estimated values of the tail length parameter c are predominantly negative. This is an indication that the reverse Weibull distribution is a better model of the hurricane wind speeds than the Weibull (as opposed to reverse Weibull) or Gumbel distribution.

3.2 Estimation of Wind Speeds With Various Mean Recurrence Intervals. The mean recurrence interval R of a given wind speed, in years, is defined as the inverse of the probability that the wind speed will be exceeded in any one year. In this section we give expressions that allow the estimation from the GPD of the value of the variate corresponding to any percentage point $1 - 1/[\lambda(u)R]$, where $\lambda(u)$ is the mean crossing rate of the threshold u per year (i.e., the average number per year of data points larger than u). Note that, for any given location, $\lambda(u) = \mu_o n(u)/999$, where μ_o is the annual rate of occurrence of hurricane events at that location, n(u) is the number of wind speed data in excess of the threshold u, and 999 is the number of wind speed data in the set with the lowest possible threshold (i.e., the number of data obtained by simulation for each location). Set

$$\mathrm{Prob}[Y(u) < y] = 1 - 1/[\lambda(u)R] \qquad (2)$$

Using Equation (1)

$$1 - [1 + c(u)y(u)/a(u)]^{-1/c(u)} = 1 - 1/[\lambda(u)R] \qquad (3)$$

Therefore

$$y(u) = -a(u)[1 - [\lambda(u)R]^{c(u)}/c(u) \qquad (4)$$

(Davison and Smith, 1990). The value being sought is

$$X_R(u) = y(u) + u. \qquad (5)$$

Consider, for example, the graph showing estimated speeds for milepost 850 in Appendix I. Note a similarity between the dependence on sample size of the estimate of parameter c on the one hand and estimates of speeds with large mean recurrence intervals (say, R=2000 years and R=1000 years) on the other. The similarity is less pronounced for speeds with smaller mean recurrence intervals, say R=50 years. With relatively small error, it may be inferred from the graph that the mean hourly wind speeds are $X_{25} \approx 29$ m/s, $X_{50} \approx 32$ m/s, $X_{100} \approx 34$ m/s, $X_{500} \approx 38$

m/s, $X_{1000} \approx 40$ m/s, $X_{2000} \approx 41$ m/s. For milepost 950 the choices for the 100-yr and 2000-yr mean hourly speeds are about 32 m/s and 38 m/s, respectively.

Table 1 shows the estimated hourly mean hurricane wind speeds with 50-yr, 100-yr and 2000-yr mean recurrence intervals at 10 m above ground over open terrain near the coastline. Also shown in Table 1 are hourly mean speeds based on values estimated by Batts et al. (1980), Georgiou et al. (1983), and Vickery and Twisdale (1995). For consistency all conversions to hourly mean speeds in Table 1 were effected as indicated in Section 2. As indicated by Vickery and Twisdale's (1995) comparisons between fastest mile speeds estimated by these authors on the one hand and by Batts et al. (1980) on the other, our choice of conversion factor does not affect the comparability between the estimates of this report and the other estimates shown in Table 1. We note that the estimates of this report were not smoothed in Table 1 by averaging over three adjacent milepost locations, as was done in Batts et al. (1980).

Table 1. Estimated hourly mean hurricane wind speeds with 50-yr, 100-yr and 2000-yr mean recurrence intervals (MRI) at 10 m above ground over open terrain near the coastline, in m/s

	Coastal distance*	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
	Batts et al. (1980)	34	33	32	31	32	32	32	31	29	30	33	36	36	35	34	32	30	33	34	34	34	30	27	30	33	33	29
50-yr	This report	35	34	35	31	31	33	32	32	29	30	32	34	36	37	35	31	28	33	33	33	33	31	29	30	34	33	31
MRI	Georgiou et al. (1983)	33	31	32	33	33	33	35	34	31	34	35	36	39	38	35	31	31	33	32	33	33	30	29	30	32	31	28
	Vickery & Twisdale (1995)	34	31	33	32	**36**	**38**	**37**	35	**34**	33	33	34	38	38	34	34	31	34	36	36	35	30	32	31	32	34	32
	Batts et al. (1980)	37	36	35	34	35	35	35	34	31	32	36	38	39	38	37	34	33	36	36	37	36	33	32	34	36	36	33
100-yr	This report	38	36	37	34	35	35	35	34	31	31	35	37	39	39	38	32	31	35	36	34	37	34	32	33	37	36	35
MRI	Georgiou et al. (1983)	36	35	36	36	37	37	39	37	34	36	39	40	43	43	40	33	36	35	35	36	36	33	31	32	35	35	31
	Vickery & Twisdale (1995)	38	34	36	36	36	**39**	**41**	**38**	**37**	**36**	36	38	**43**	**43**	37	**37**	**35**	**39**	**40**	**40**	38	34	35	35	35	36	37
	Batts et al. (1980)	47	46	45	45	44	44	45	44	40	43	46	46	47	47	45	40	41	47	46	46	45	44	43	45	47	47	45
2,000-yr	This report	46	42	43	44	44	41	44	41	35	35	46	43	46	47	44	39	38	44	43	42	47	43	41	43	46	46	46
MRI	Georgiou et al. (1983)	51	47	48	49	49	50	51	50	46	48	51	55	57	56	54	45	46	49	48	49	48	45	43	47	50	48	45
	Vickery & Twisdale (1995)	49	46	46	46	**50**	**56**	**52**	**49**	**48**	**46**	**49**	**51**	**57**	**56**	**49**	**49**	**48**	**53**	**53**	**53**	**54**	**49**	**50**	**48**	48	49	49

* In hundreds of nautical miles (see Fig. 1).

Note. Bold numbers indicate estimated speeds based on (Vickery and Twisdale, 1995) which exceed speeds estimated in this report by more than 10 percent. (The estimates of this report are based on the reverse Weibull distribution, which has limited upper tail. All other estimates are based on distributions with infinite upper tail.)

4. DISCUSSION OF RESULTS

For wind speeds over the coastline the most significant difference between physical models used by the various authors listed in Table 1 involves the representation of the hurricane boundary layer. Unlike the other sets of estimates of Table 1, which used identical or similar empirical boundary layer models, the estimates by Vickery and Twisdale (1995) were based on the Shapiro boundary layer model. As indicated by Shapiro (1983, pp. 1995 and 1996), this model is not able to describe the detailed structure of the boundary layer, and its use entails, in addition to modeling errors, a truncation error of about 25 percent in the estimation of wind speeds for any simulated hurricane.

Modeling and computational errors notwithstanding, the various sets of estimates of 50-yr winds listed in Table 1 are by and large comparable. This is understandable in view of the informal calibration of the models effected in most investigations with a view to obtaining results that "make sense." We note, however, that there are differences of about +10 percent or -10 percent between the estimates of this report and those of Georgiou et al. for mileposts 200, 300, 400, 800, 1100, 1200, 1400 and 1800. The estimates based on Vickery and Twisdale (1995) are in most cases larger than the estimates of this report, although differences in excess of 10 percent occur only for a few locations (shown in bold figures in Table 1). Given the many uncertainties that affect each set of estimates, it is difficult in our opinion to argue that one set of 50-yr wind speed estimates is much better than another. However, the estimated 2000-yr speeds differ significantly in many cases between the various sets of Table 1. They are in most cases lowest for the set of estimates of this report, followed in increasing order by the sets of estimates based on Batts et al. (1980), Georgiou et al. (1983), and Vickery and Twisdale (1995). This is ascribed in part to the fact that these last three sets of estimates are based on distributions with infinite upper tails.

The highest estimated 2000-yr speed at 10 m over water near the coastline based on the results of this report is about 47 m/s x 1.24 x 1.2 = 70 m/s (157 mph). This is a point estimate, that is, it does not make allowance for sampling errors. Nor does this estimate make allowance for modeling errors.

It can be verified from the plots of Appendix I that, for the estimates of this report, the wind load factor $\phi_w = 1.3$ specified in the ASCE 7-95 Standard would in most cases correspond for wind-sensitive structures to nominal ultimate wind loads with mean recurrence intervals of, roughly, 500 years or less. This follows from the fact that the speeds associated with those ultimate wind loads would be equal to the 50-yr speeds times $(1.3)^{1/2}$. For the other sets of estimates of Table 1, the load factor $\phi_w = 1.3$ would correspond to nominal ultimate wind loads with even shorter mean recurrence intervals. The results of Table 1 therefore suggest that, for wind-sensitive structures, the wind load factor for hurricane wind speeds should be larger than 1.3. This would be the case even if (1) hurricane design wind speeds were multiplied by a factor of 1.05, as is done in the ASCE Standard 7-95 (see Commentary appended to the Standard), or (2) if conversion factors from fastest-minute speeds to hourly speeds different from the factor assumed in this report were used.

It follows from the results of Table 1 that, on average, load factors based on speeds modeled by the reverse Weibull distribution differ least from the value $\phi_w = 1.3$ currently specified in the ASCE Standard A7-95. To see this, note that the average estimated ratios of 2000-yr speeds to 50-yr speeds are about 1.3, 1.4, 1.45 and 1.5 for the sets based on this report, Batts et al. (1980), Vickery and Twisdale (1995), and Georgiou et al. (1983), respectively, so that the squares of these values are about 1.7, 1.95, 2.1, and 2.25, respectively. A similar ordering would be obtained if speeds with other large mean recurrence intervals were considered instead of the 2,000-yr speeds. Increases of the load factor based on the tail-limited distributional model supported by our results would therefore be smaller than the increases that would be called for if distributions with infinite upper tails were assumed to be appropriate, as has been the case for all other principal studies of hurricane winds in the United States.

5. CONCLUSIONS

The main conclusions of this work are:

1. The results of our analyses are consistent with the assumption that reverse Weibull distributions describe the probabilistic behavior of extreme hurricane speeds at most if not all locations along the Gulf Coast and the Atlantic Coast. Note that a similar conclusion was reached by Simiu and Heckert (1995) with regard to wind speeds in regions not affected by hurricanes.

2. For any specified reasonably long mean recurrence interval, say, 2000 years, hurricane wind speeds described by reverse Weibull distributions tend to be lower than speeds estimated by earlier procedures that use infinitely tailed distributions.

3. The nominal ultimate wind loads obtained through multiplication of the 50-year loads by the load factor $\phi_w = 1.3$ specified in the ASCE 7-95 Standard appear to have relatively short mean recurrence intervals, that is, to result in unsafe designs of wind-sensitive structures in hurricane-prone regions. Increases of the load factor based on the tail-limited distributional model supported by our results appear therefore to be warranted. These would be smaller than the increases that would be called for if distributions with infinite upper tails were assumed to be appropriate, as has been the case for all other principal studies of hurricane winds in the United States.

Our conclusions are subject to limitations inherent in the quality of the data and physical models used in the analyses. An effort aimed at carrying out improved simulations that would reduce those limitations is currently being envisaged.

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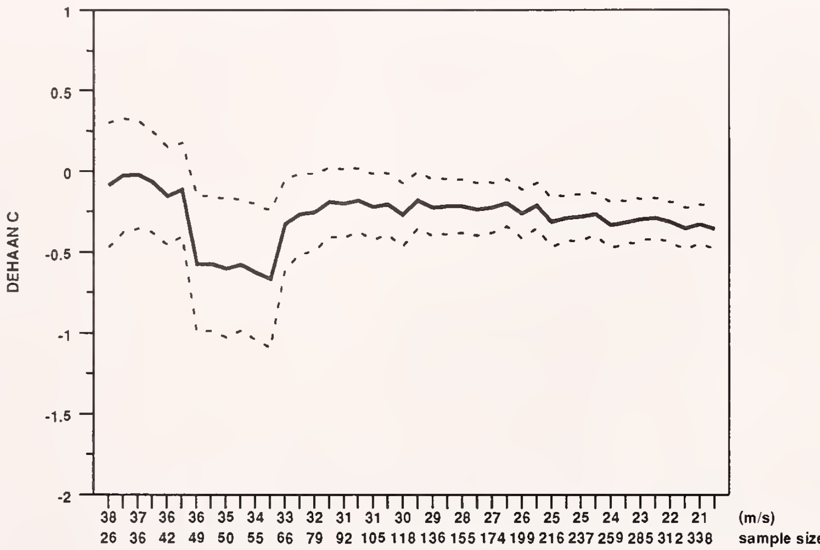
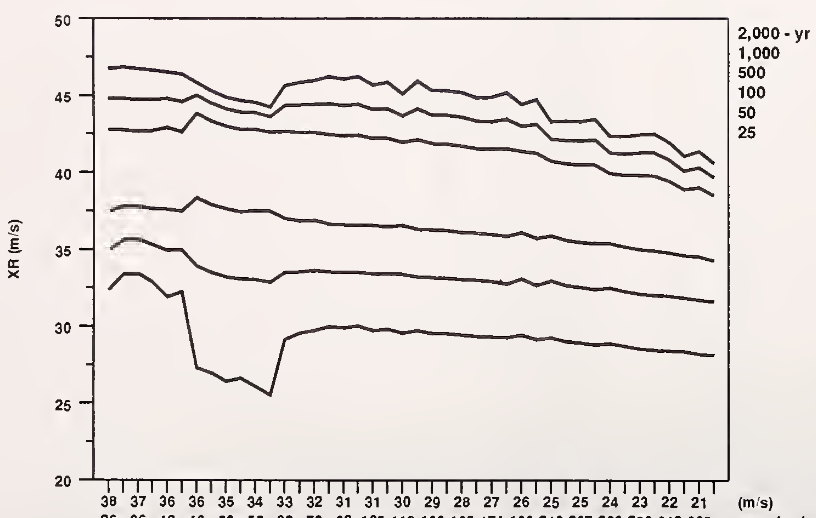
APPENDIX I

Estimated tail length parameter c and 95% confidence bounds, versus threshold and number of threshold exceedances (top of each page).

Estimated hourly mean speeds at 10 m above ground over open terrain for 25-yr, 50-yr, 100-yr, 500-yr, 1000-yr and 2000-yr mean recurrence intervals (bottom of each page)

MILEPOST 150





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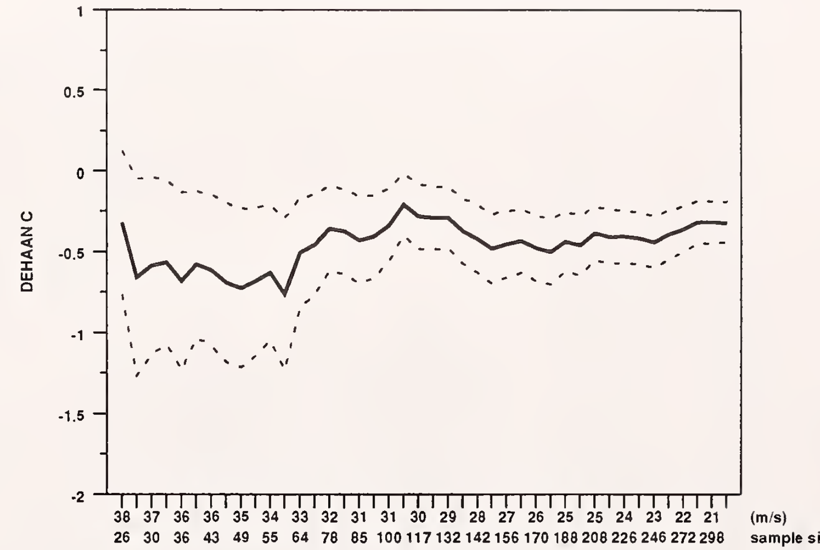

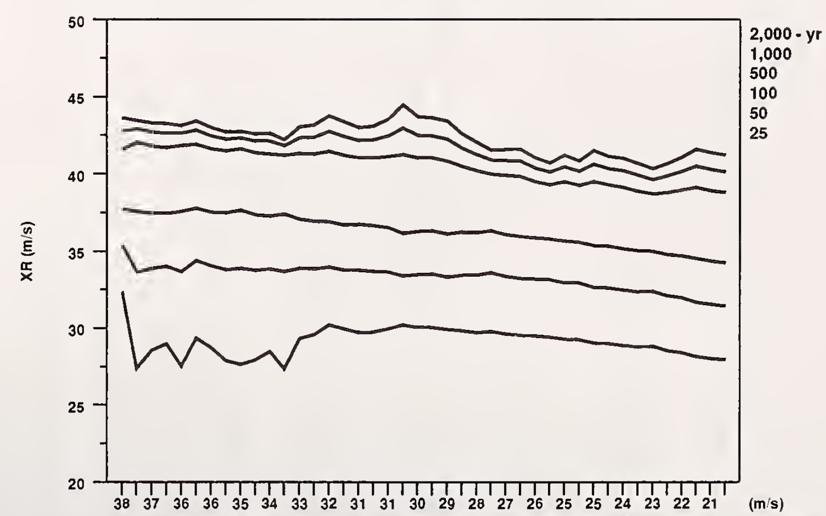

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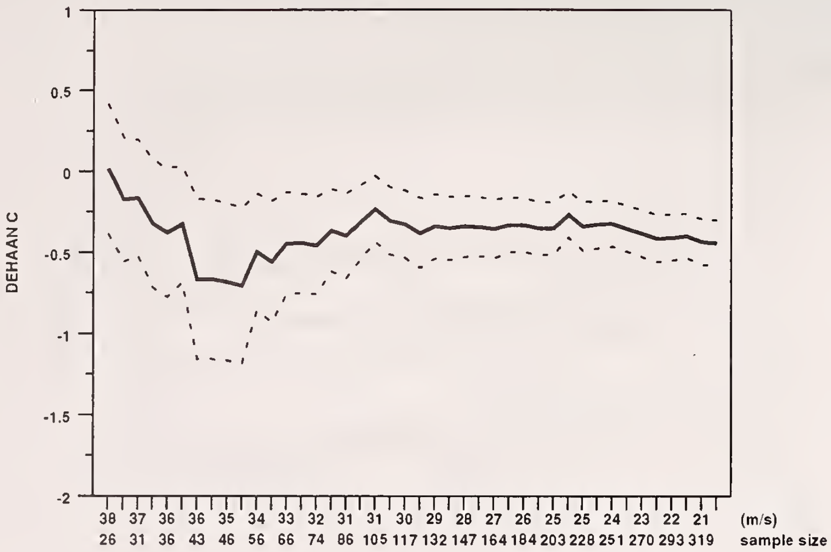

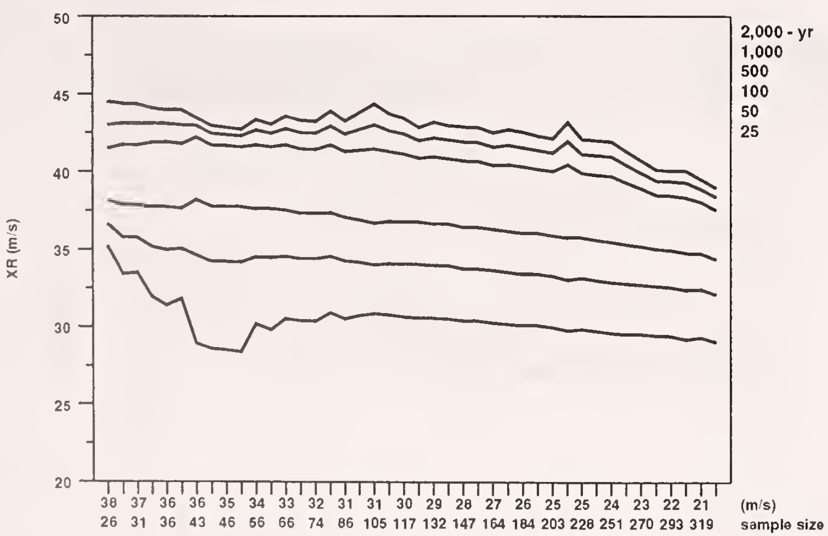

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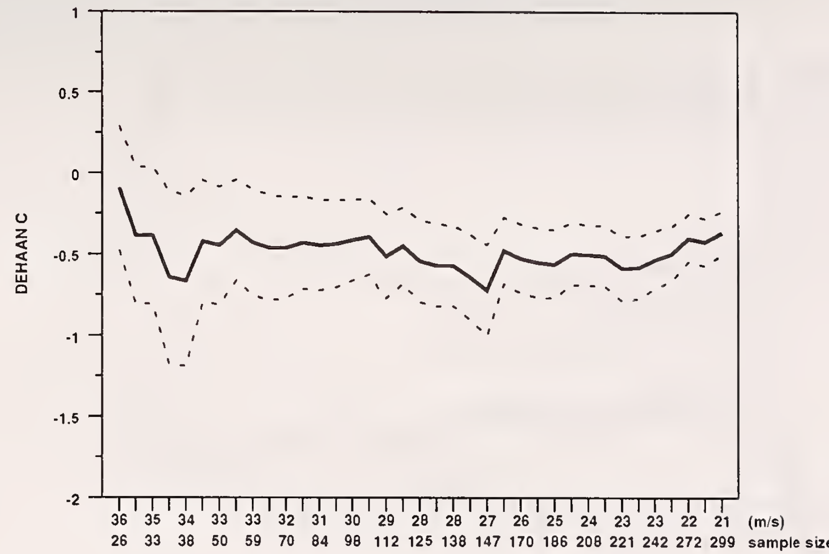

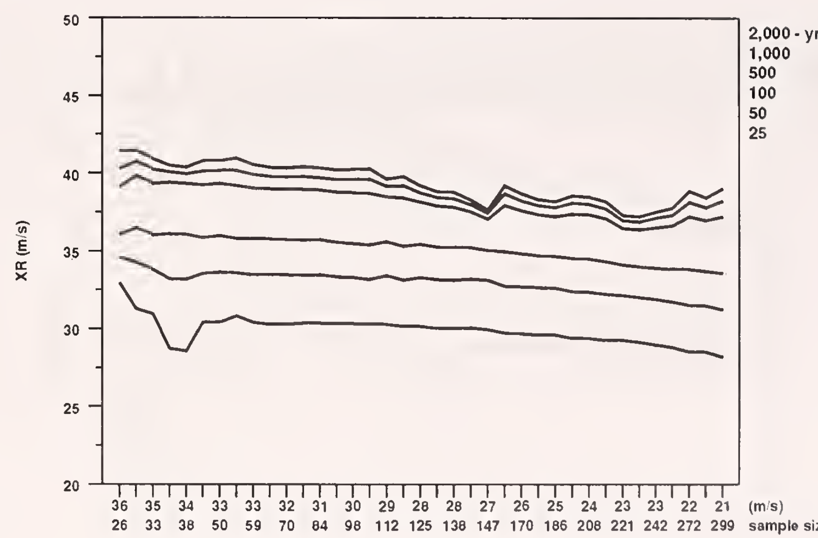

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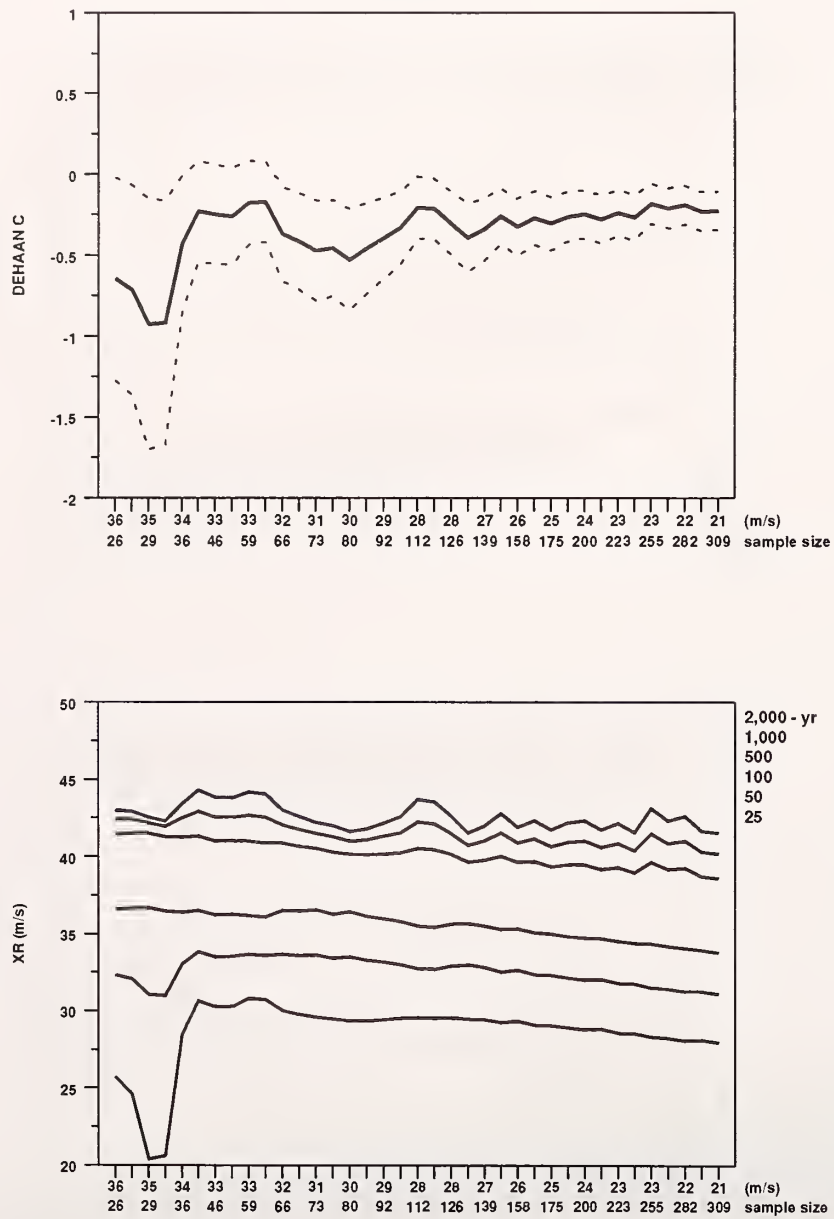

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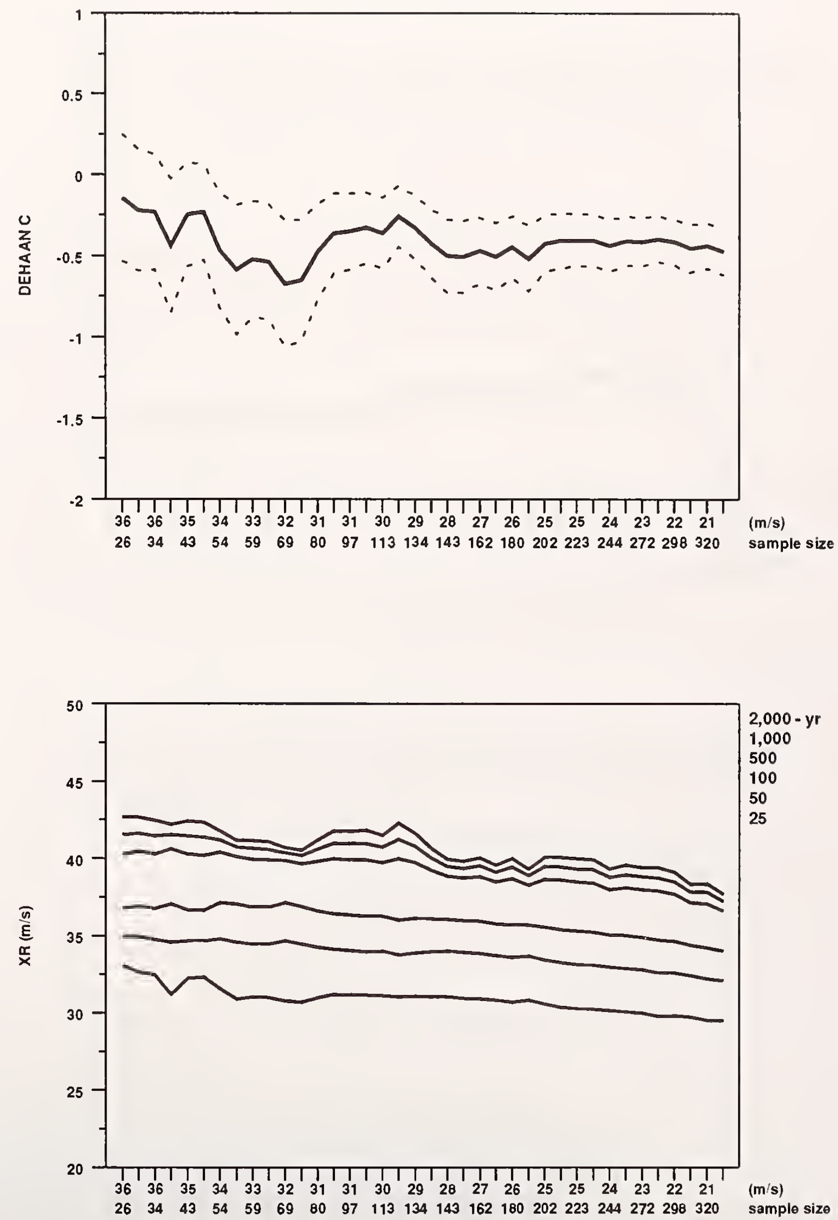

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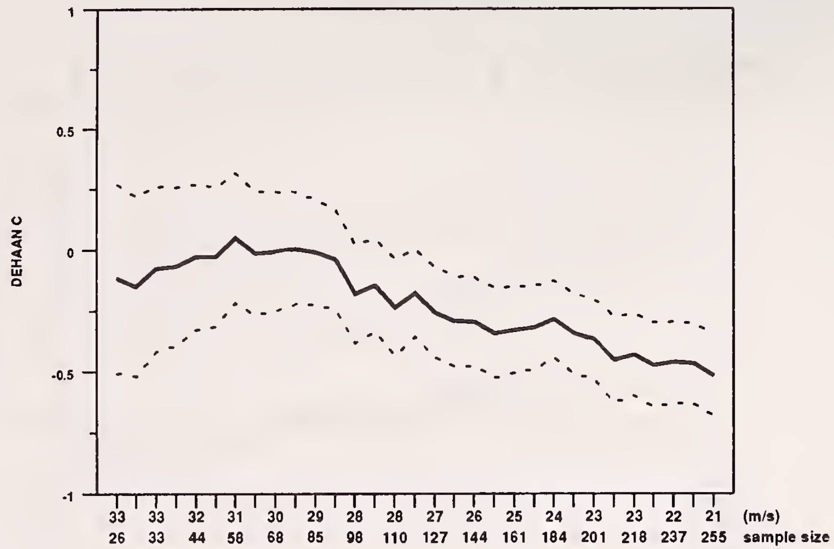

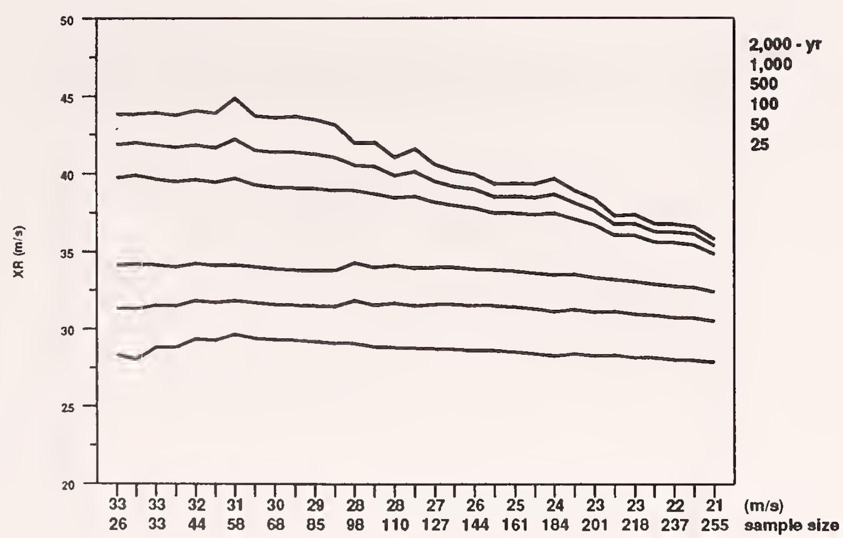

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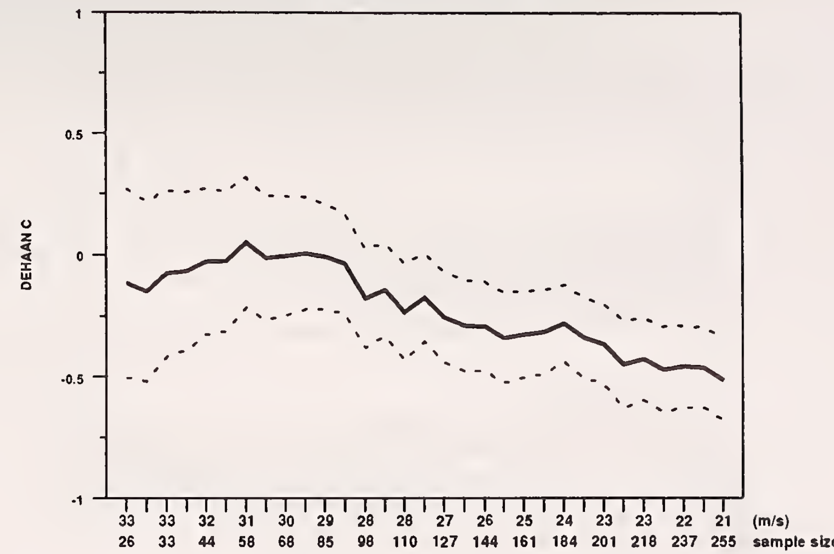

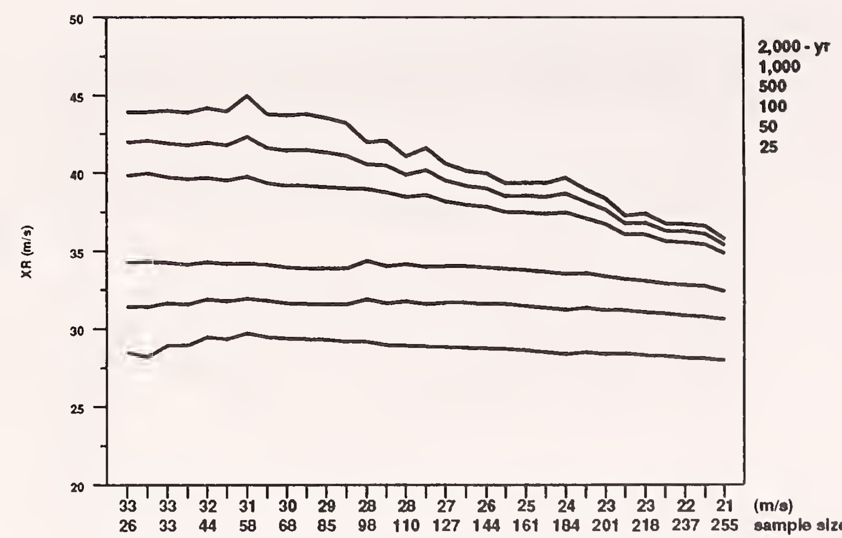

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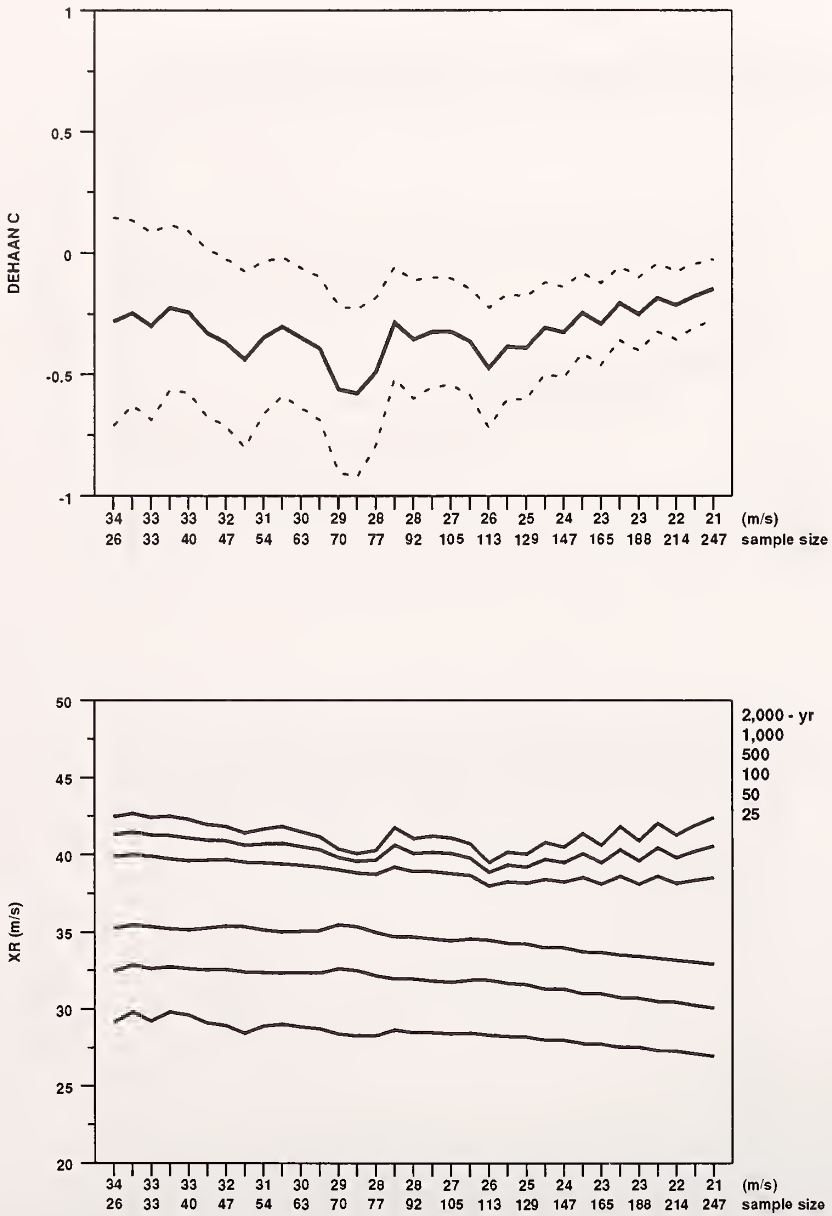

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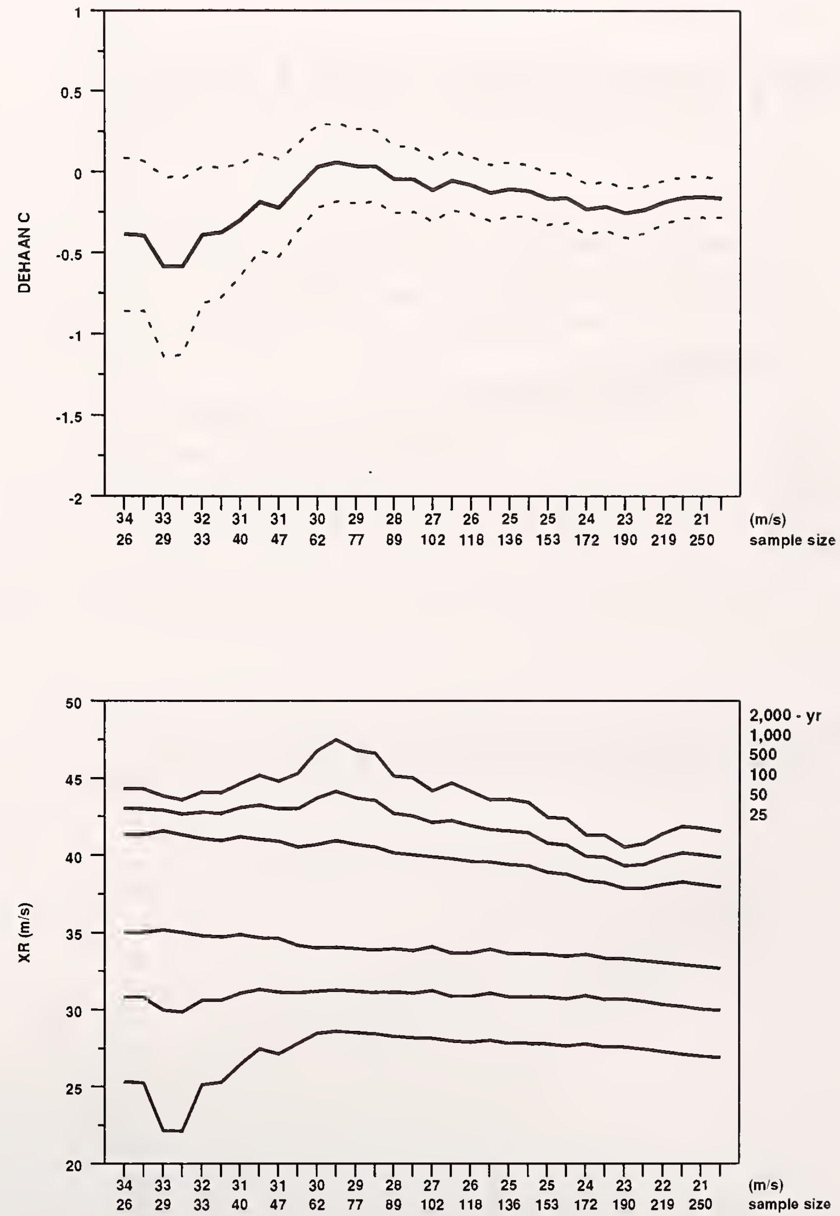

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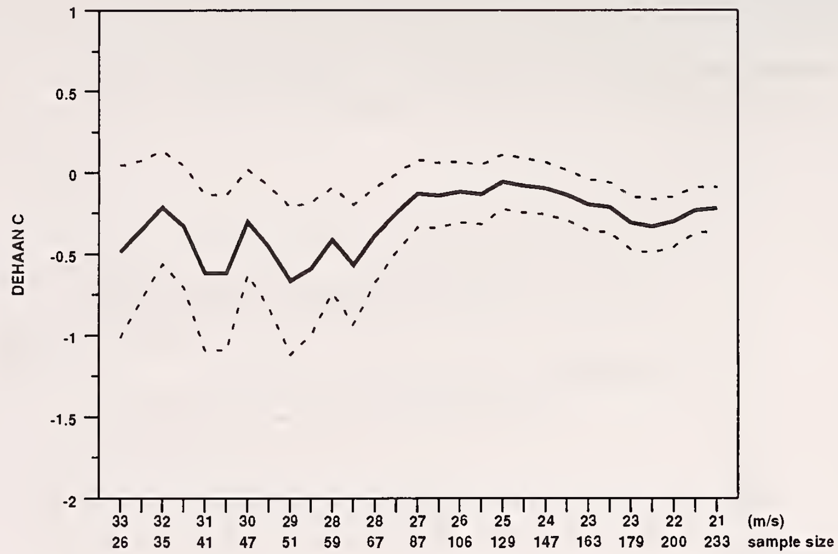

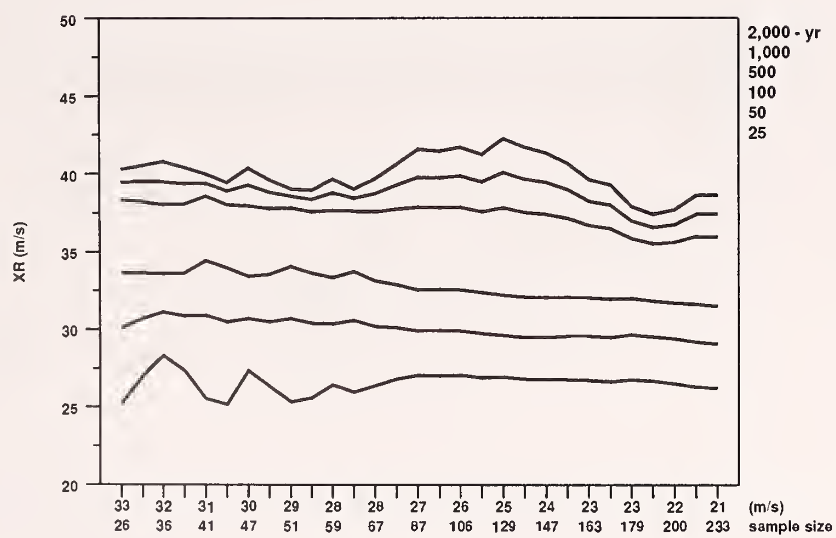

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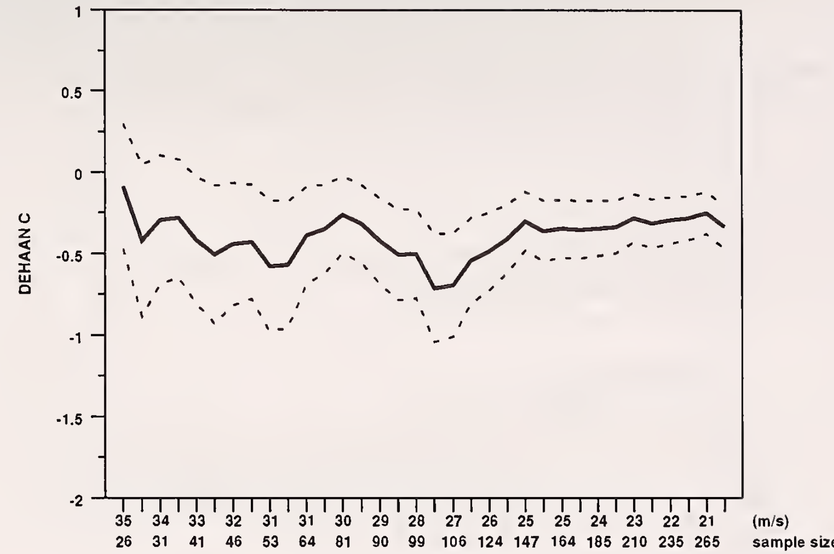

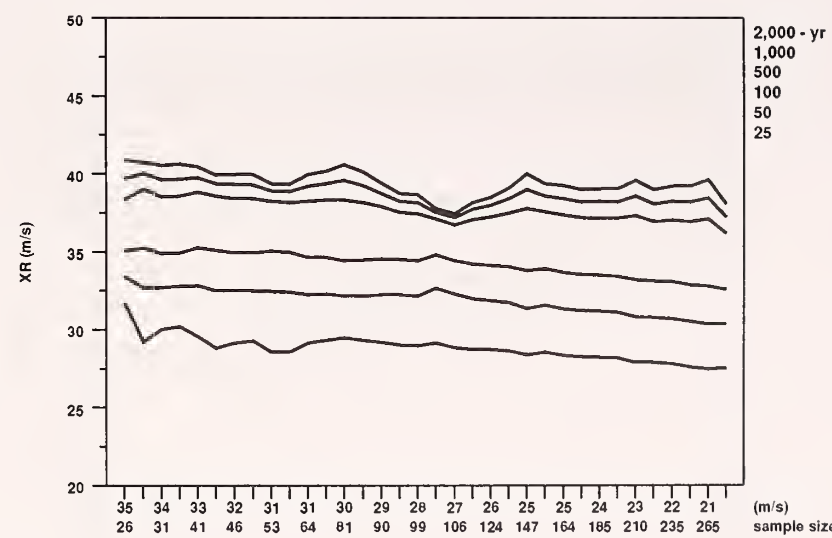

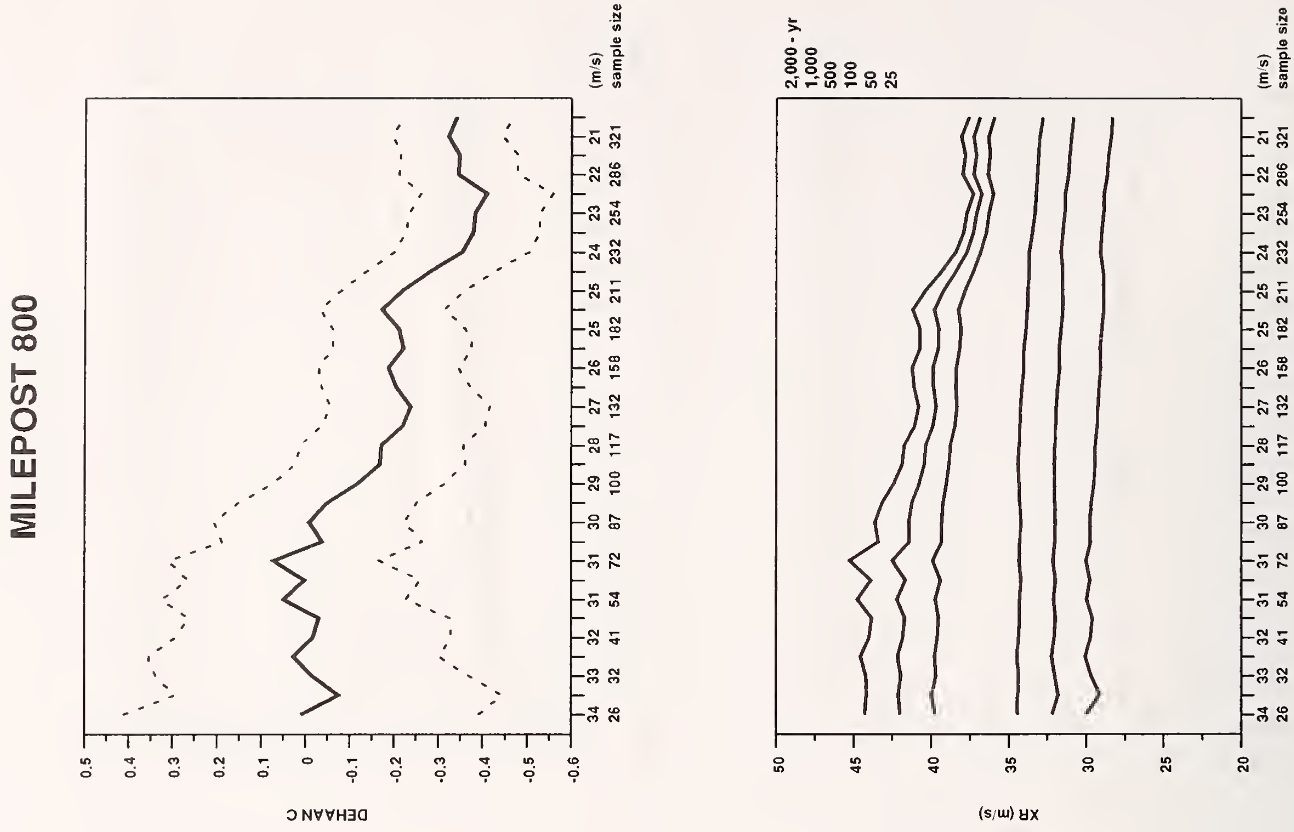
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XR (m/s)
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1,000
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100
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25
(m/s)
sample size
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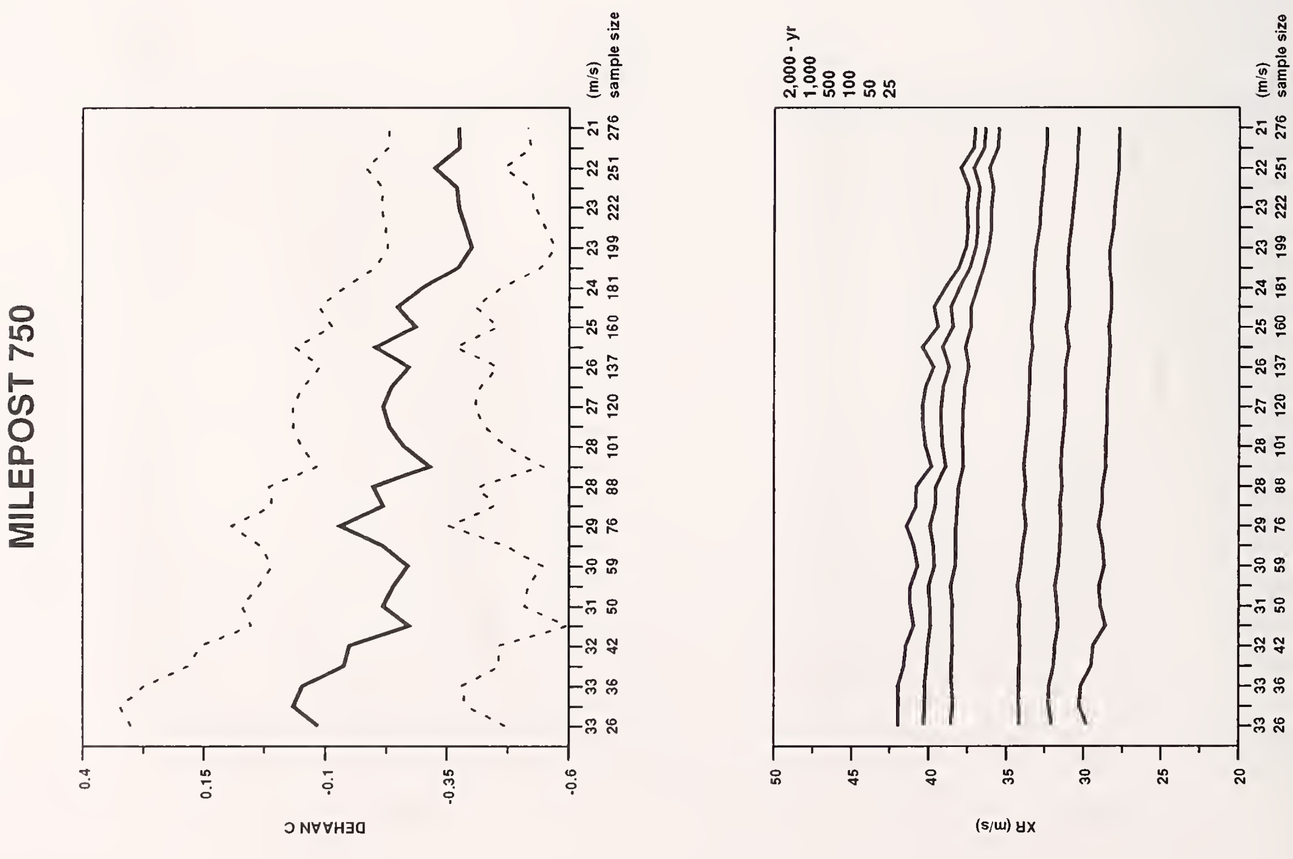
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XR (m/s)
2,000 - yr
1,000
500
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sample size
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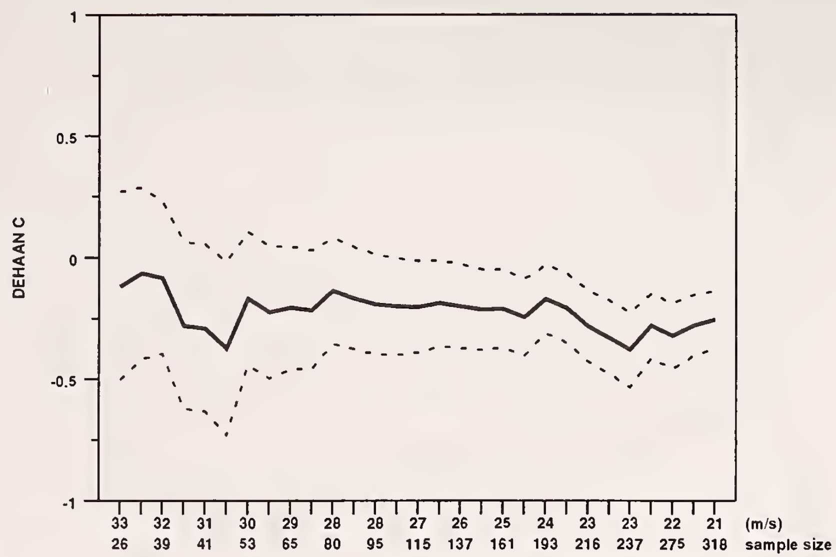

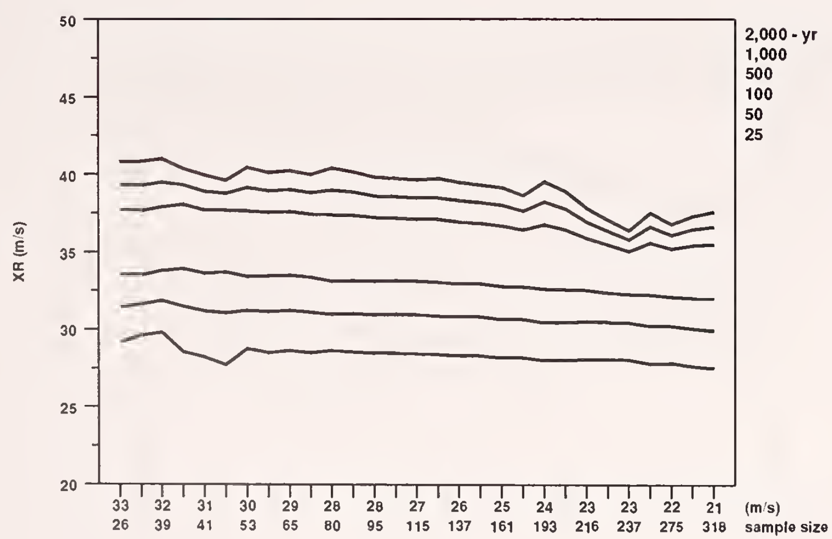

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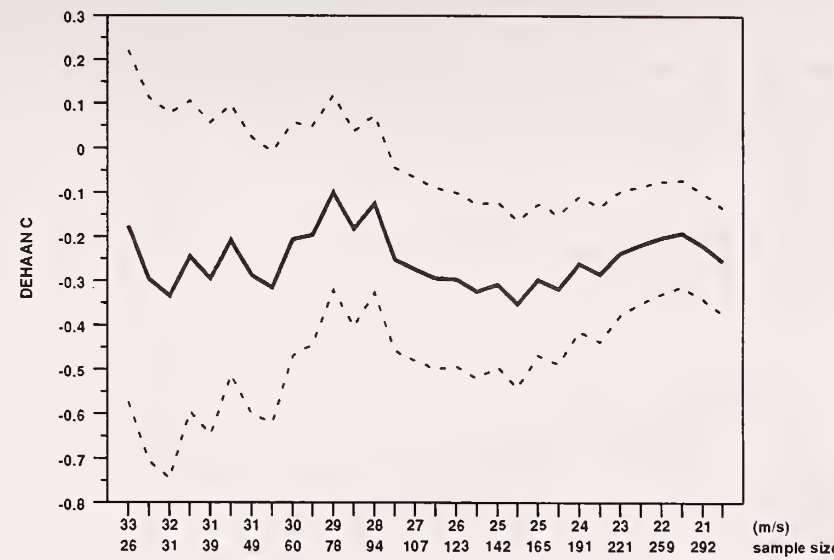

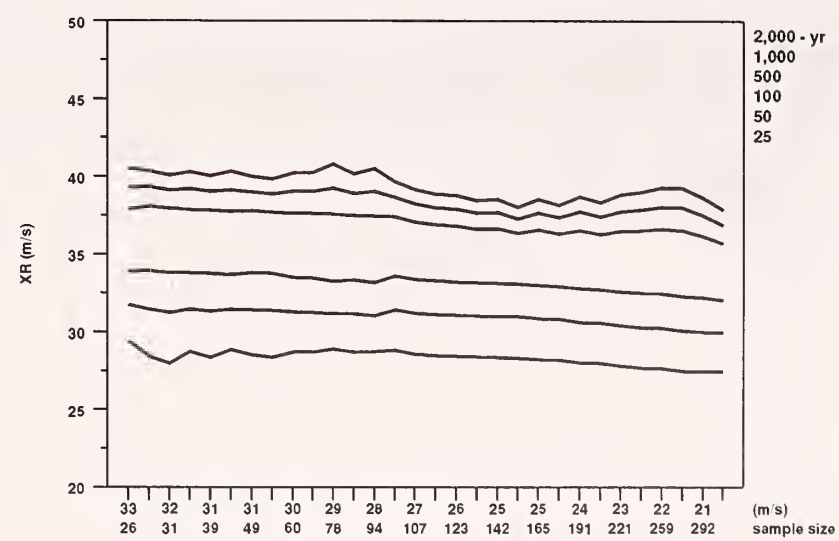

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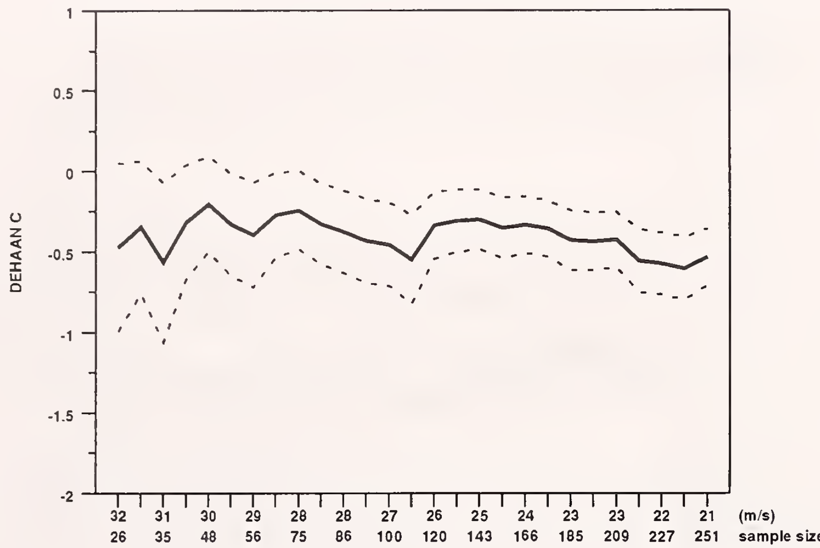

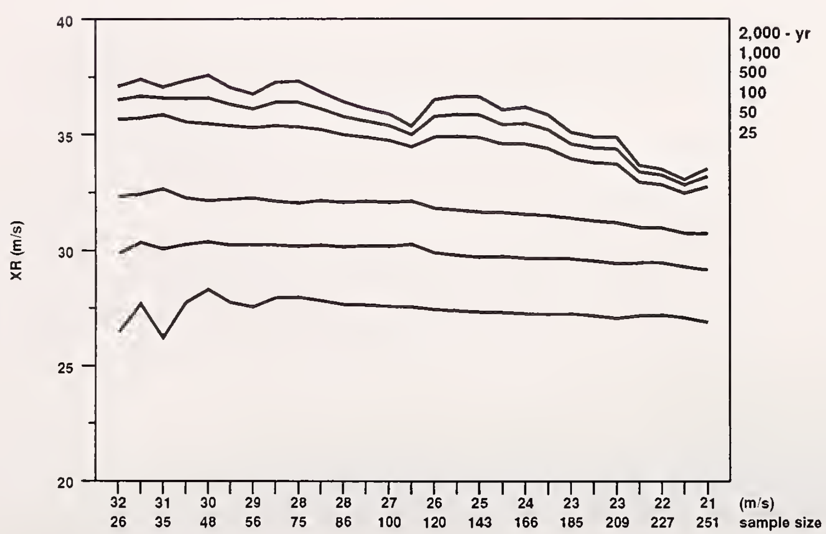

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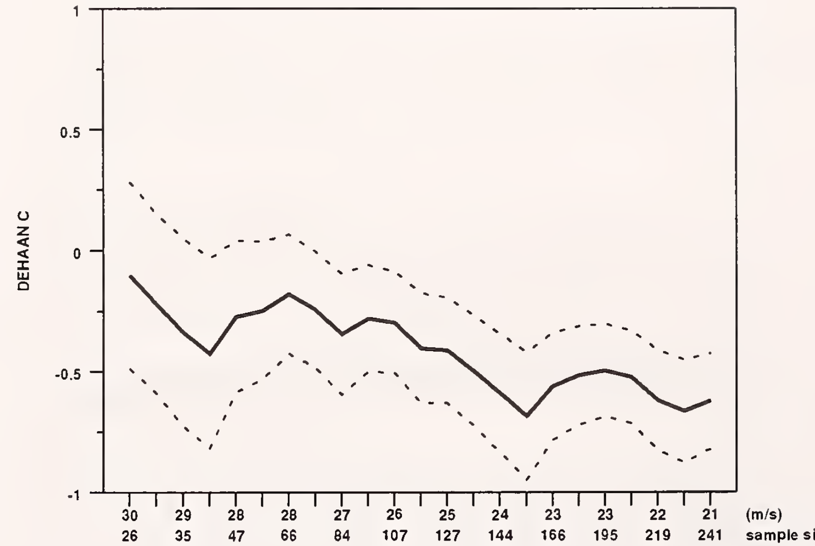

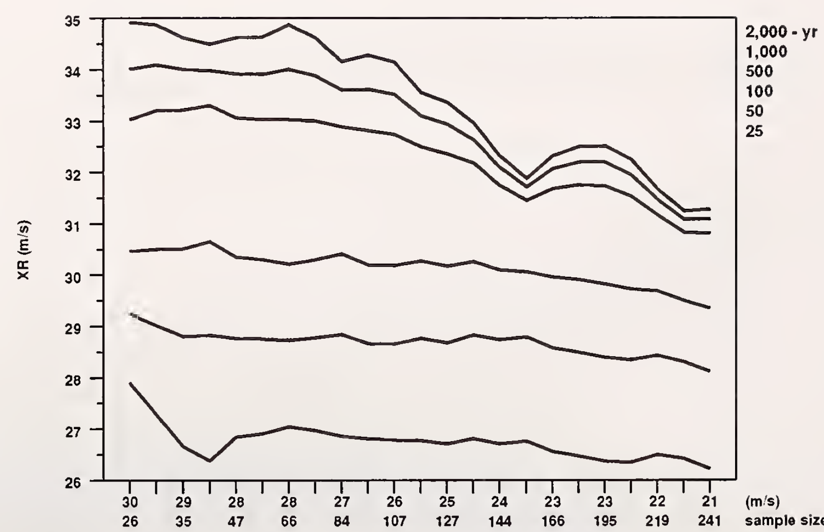

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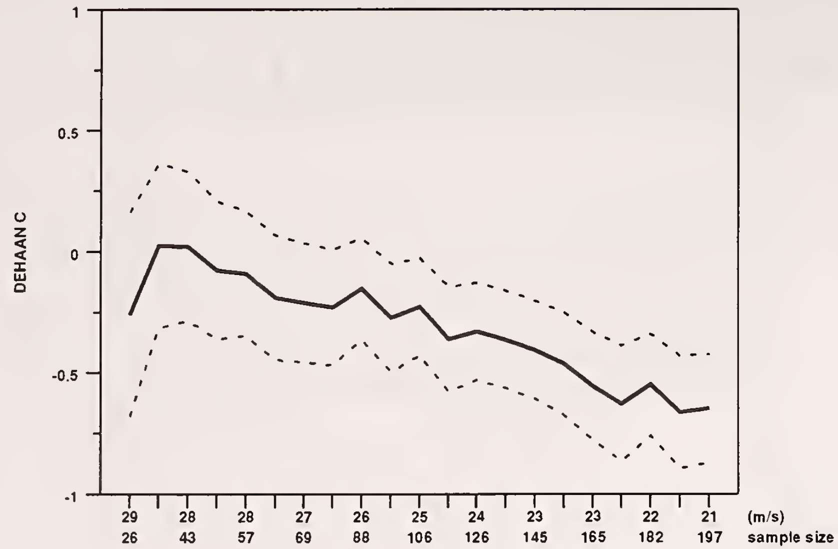

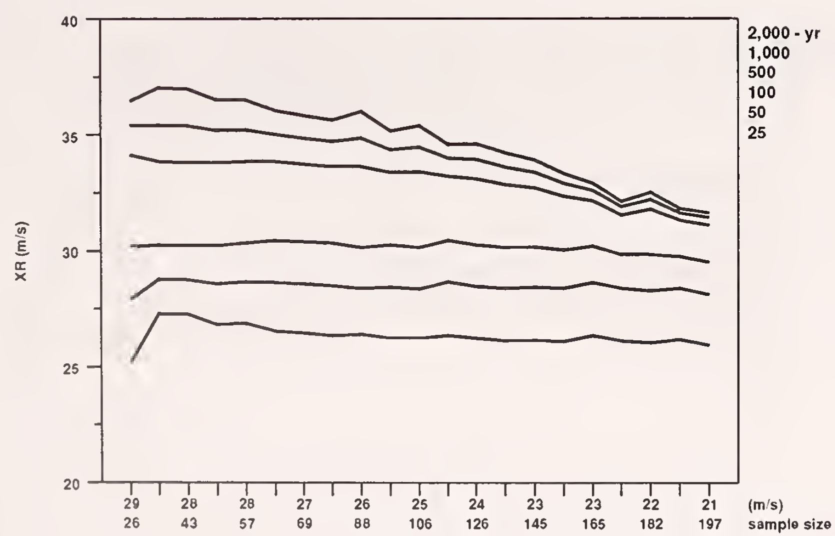

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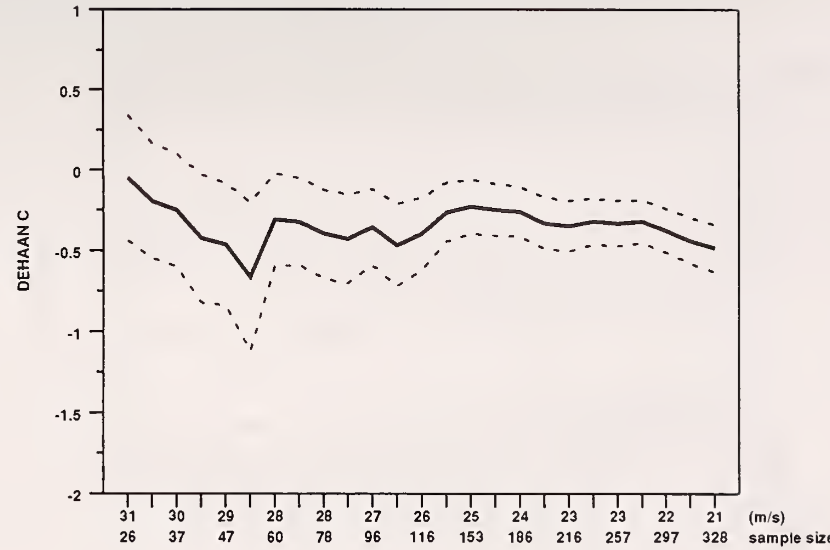

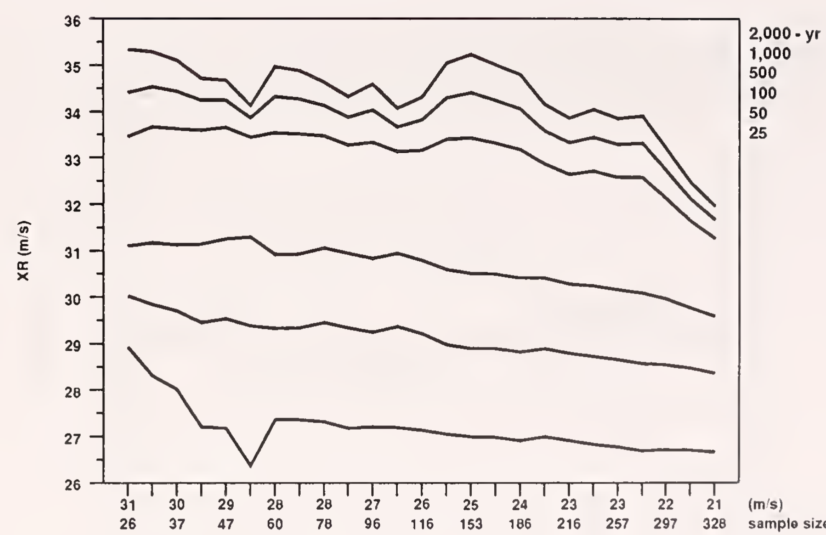

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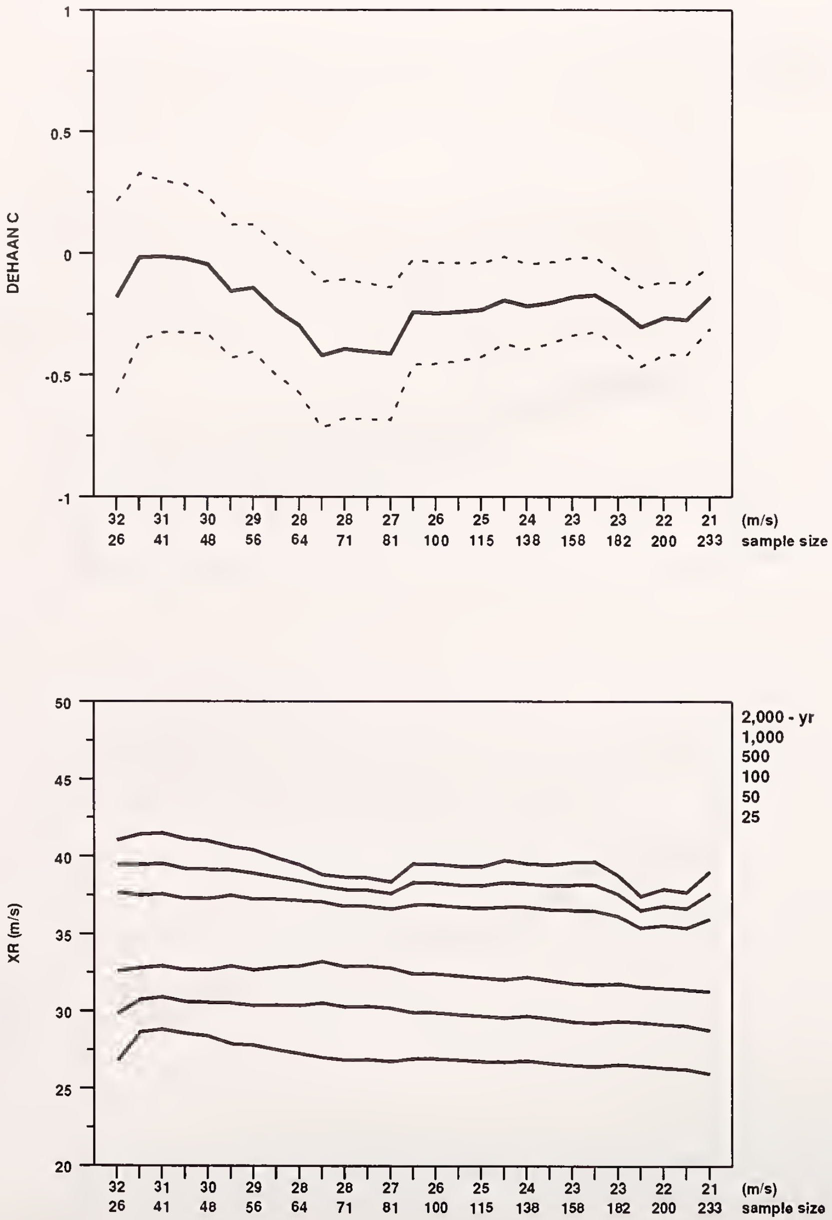

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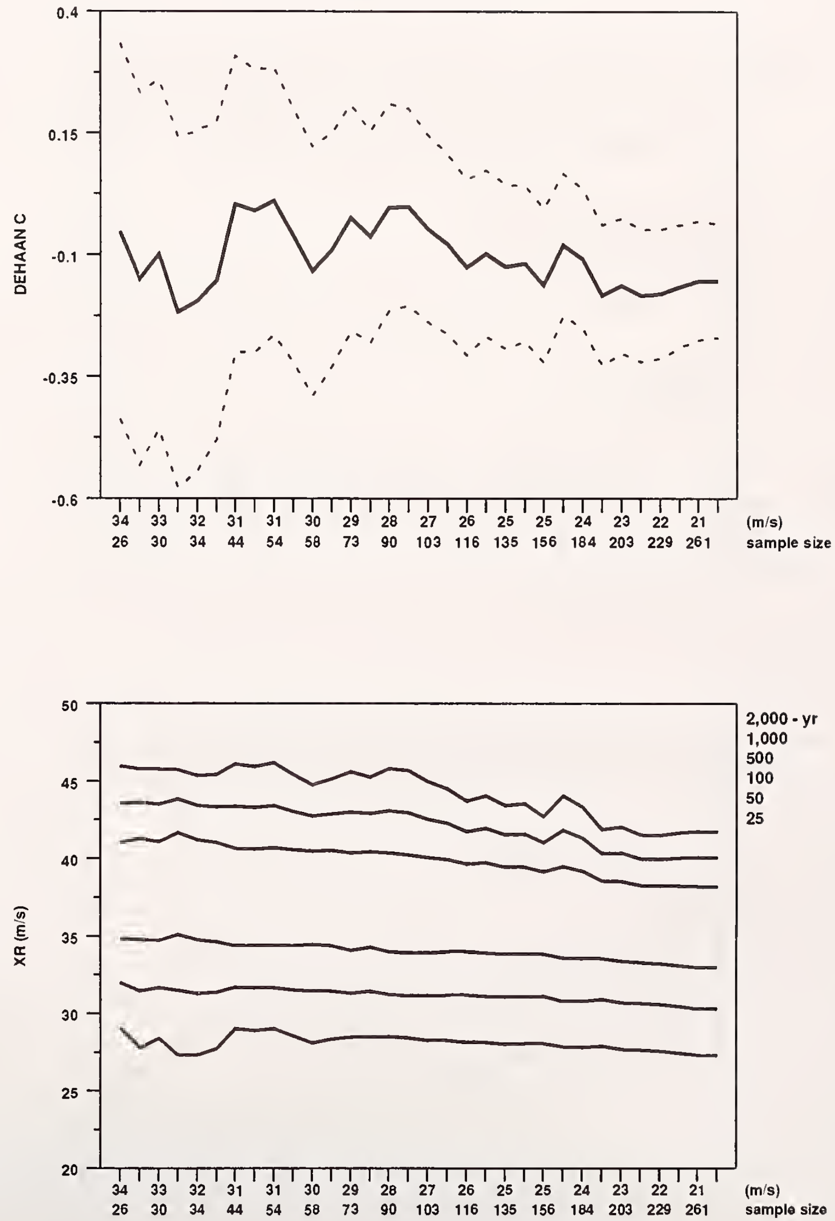

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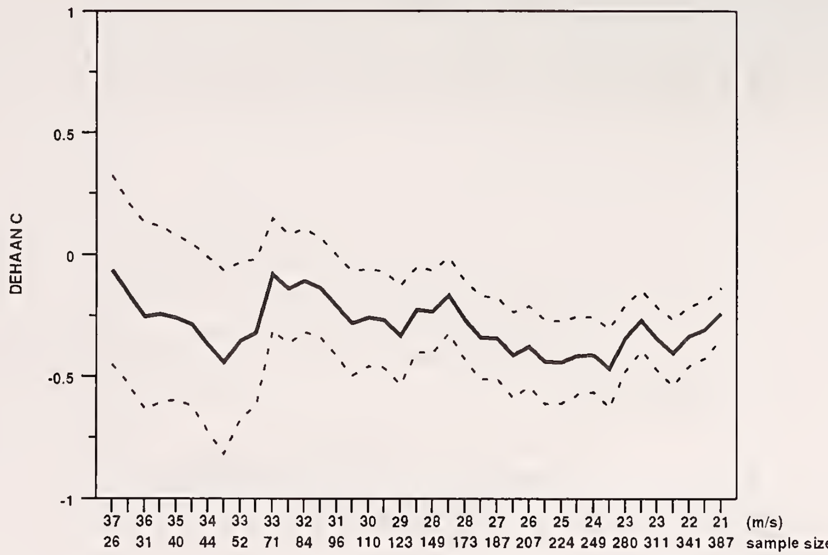

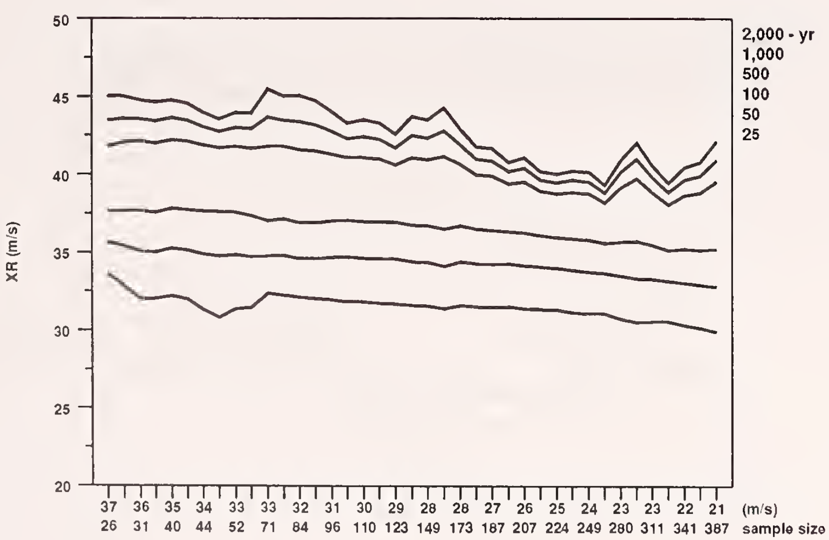

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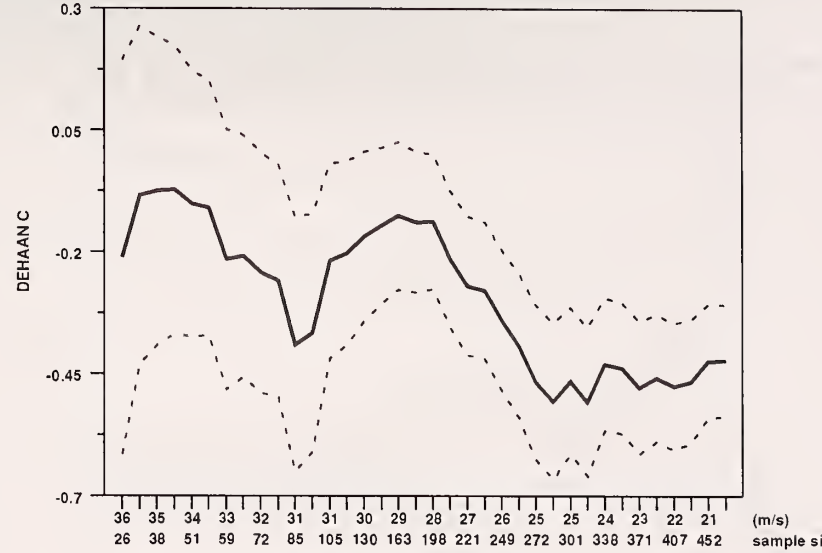

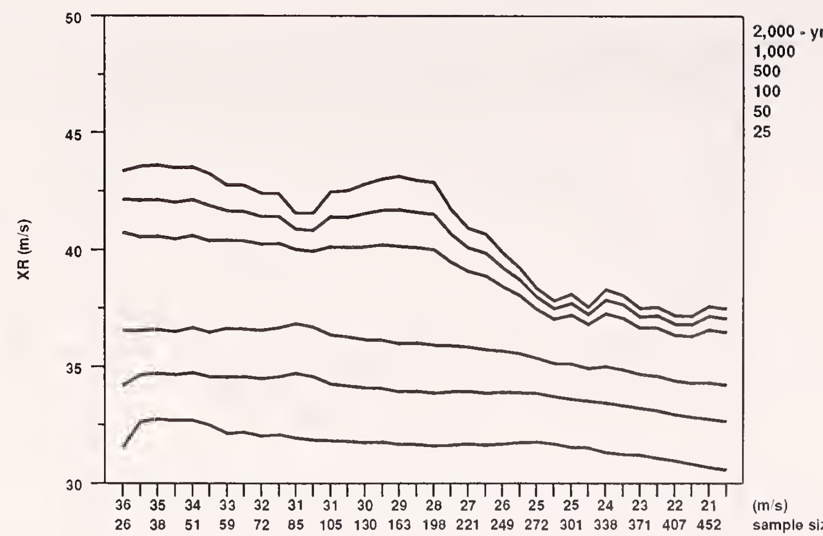

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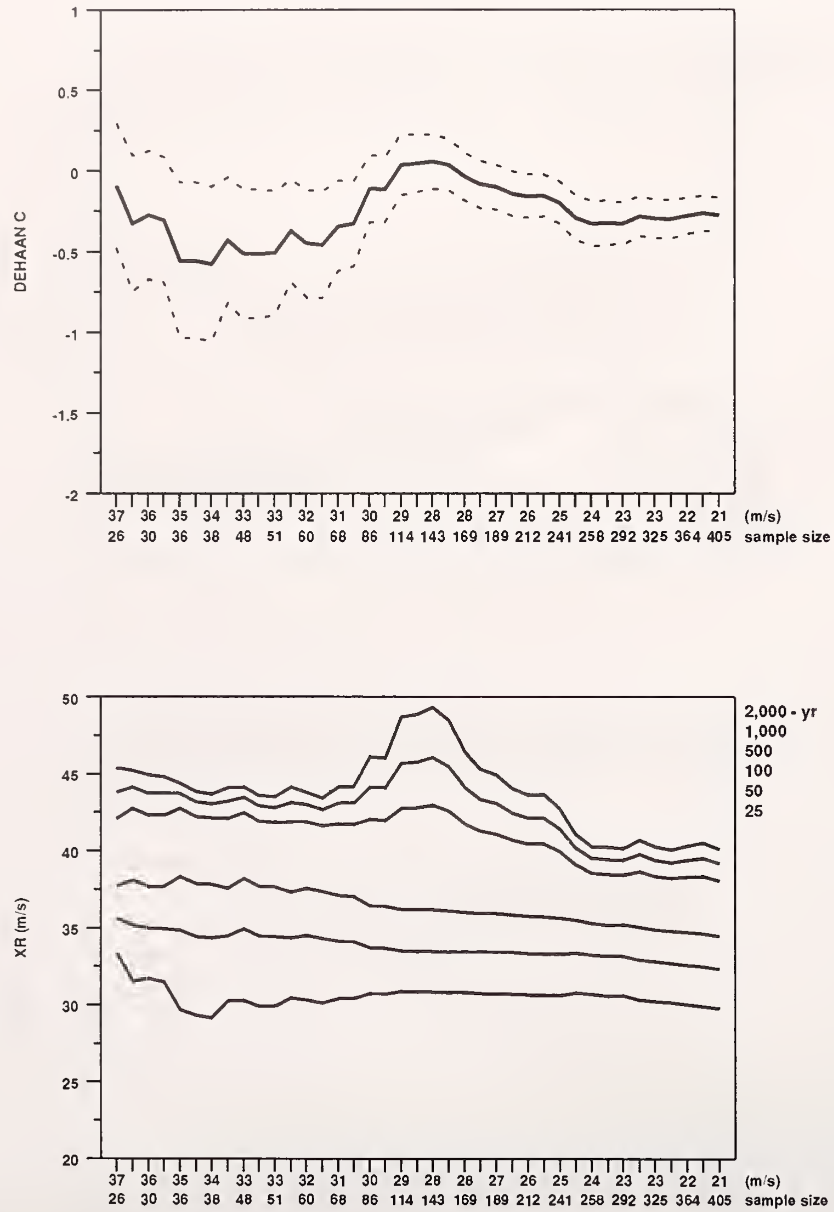

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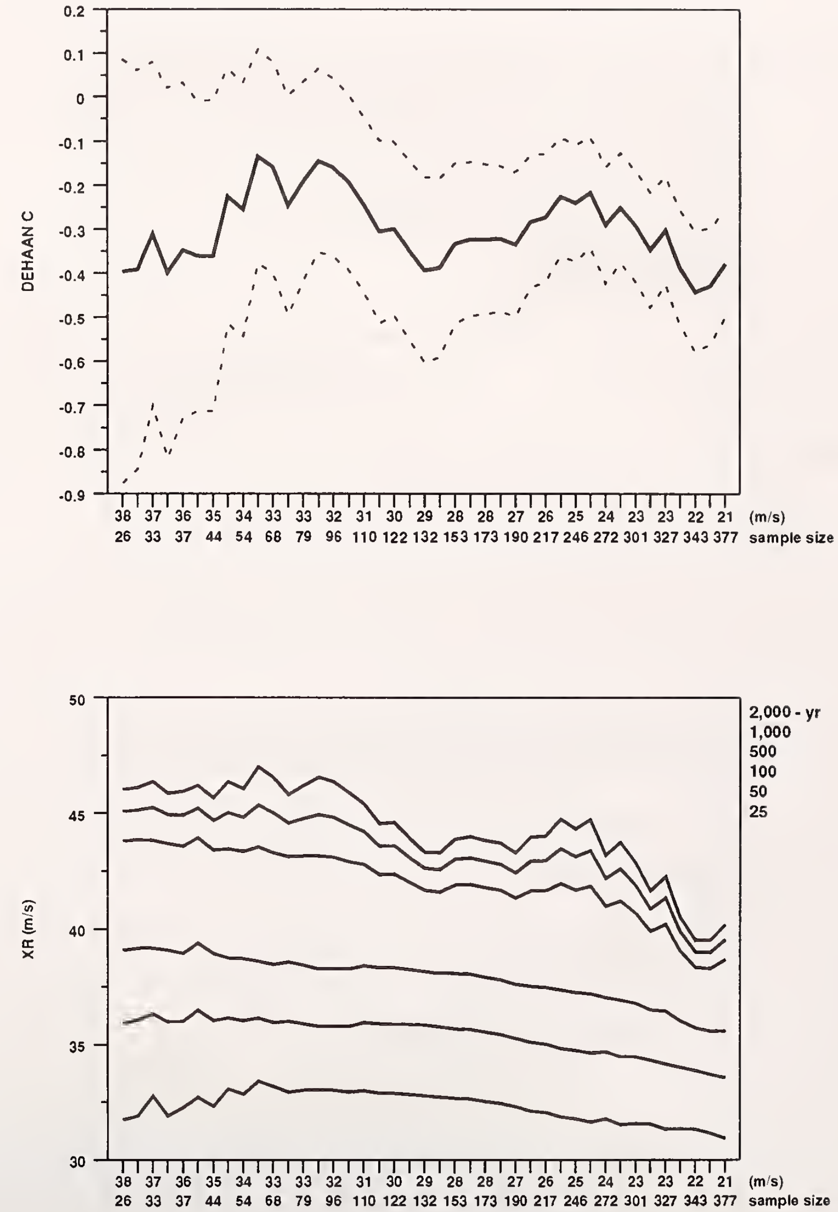

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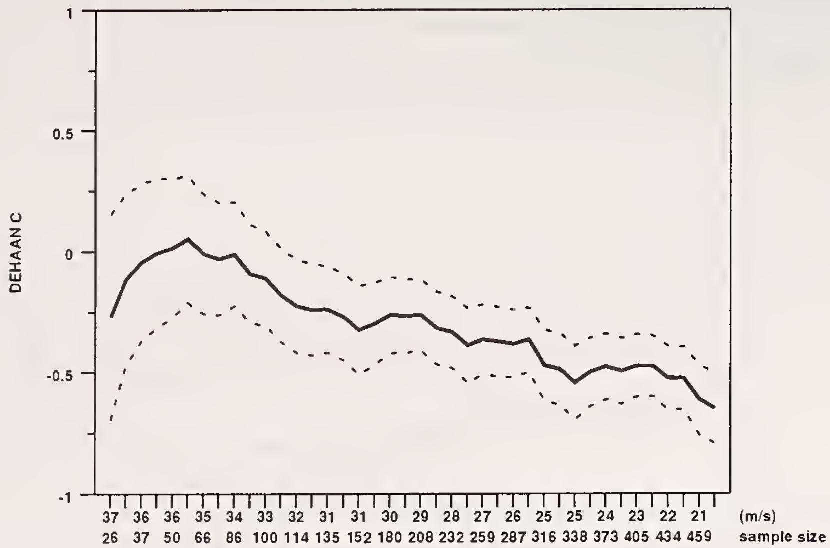

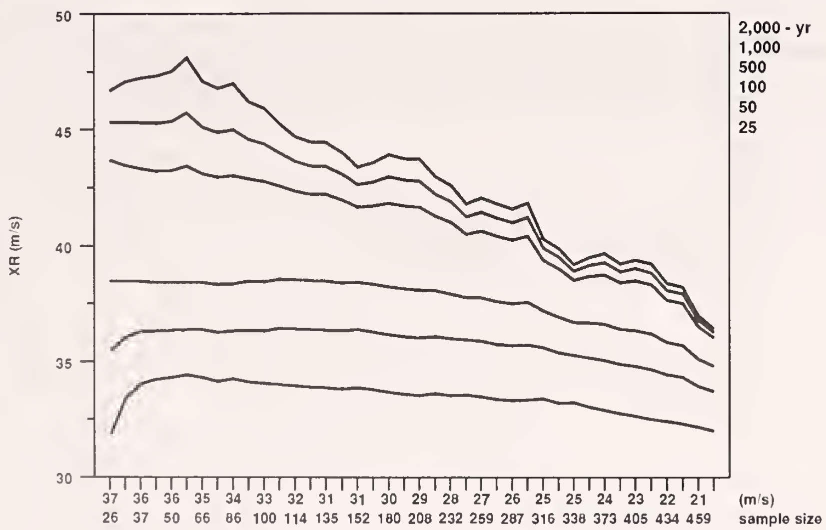

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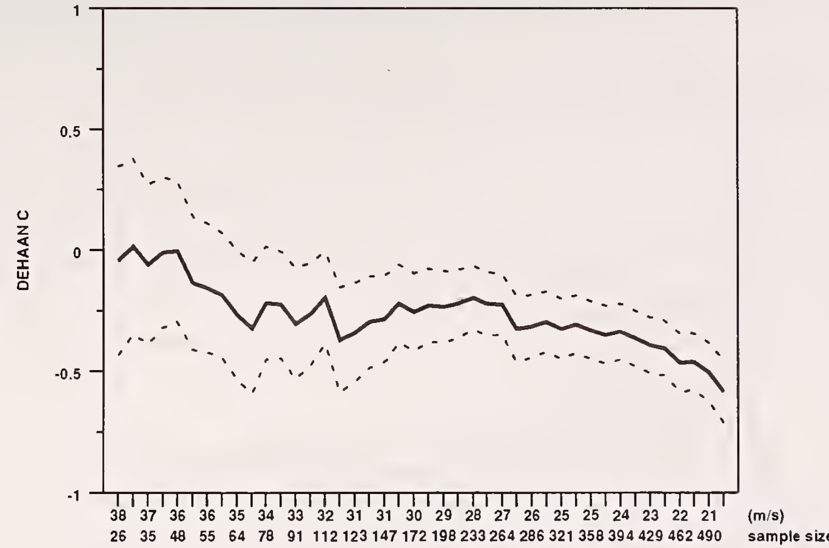

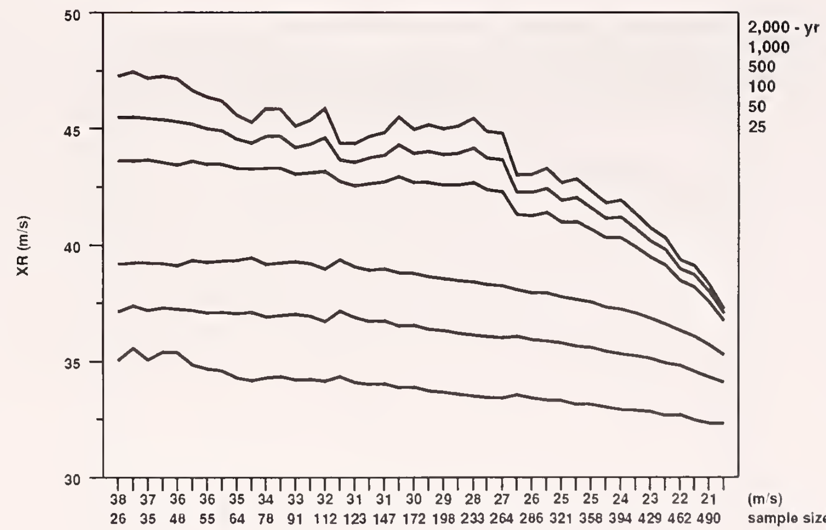

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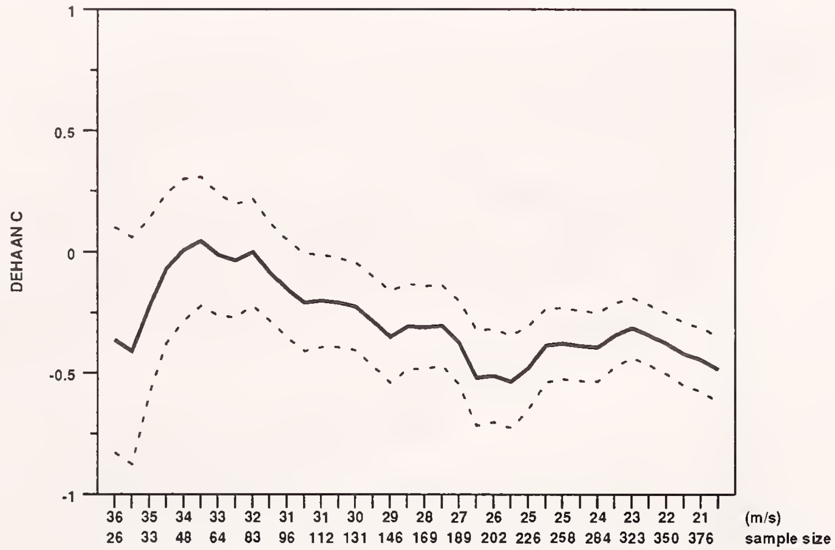

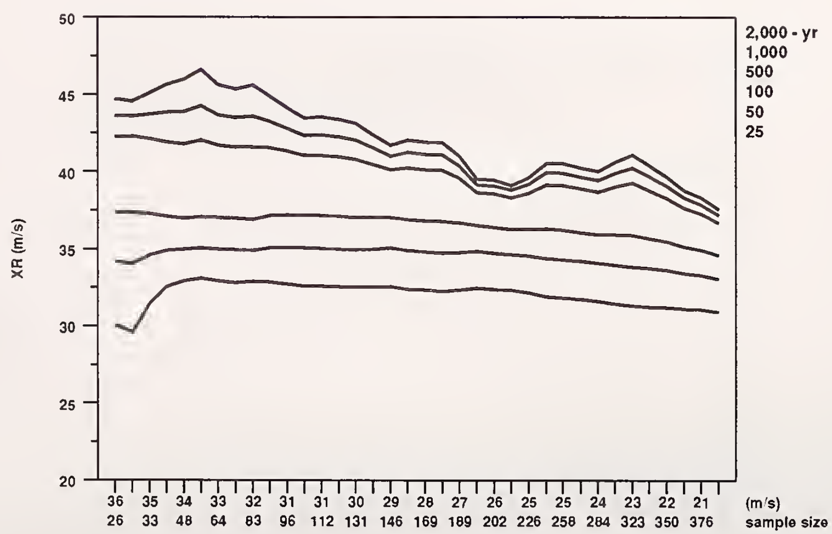

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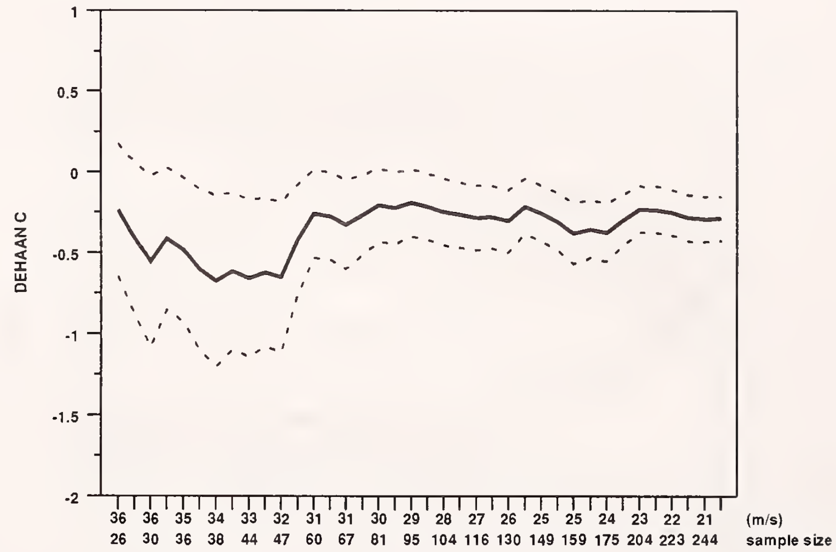

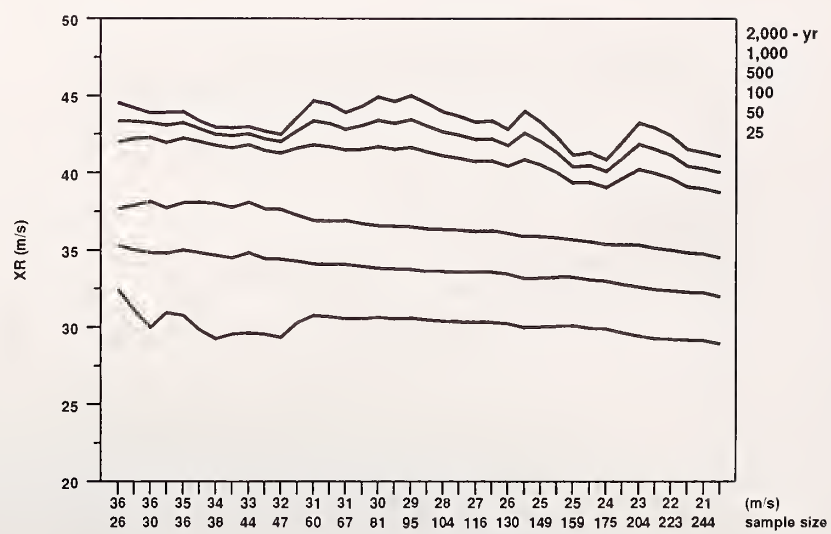

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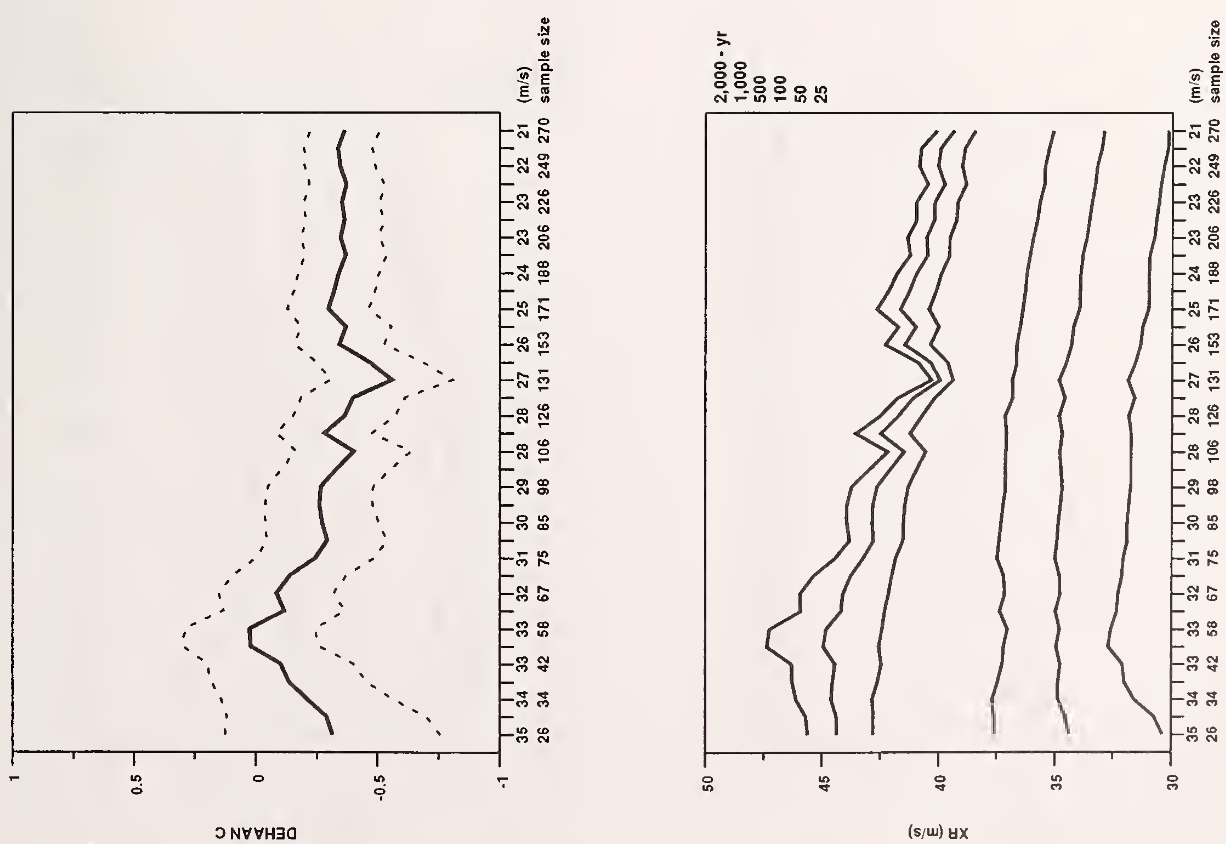

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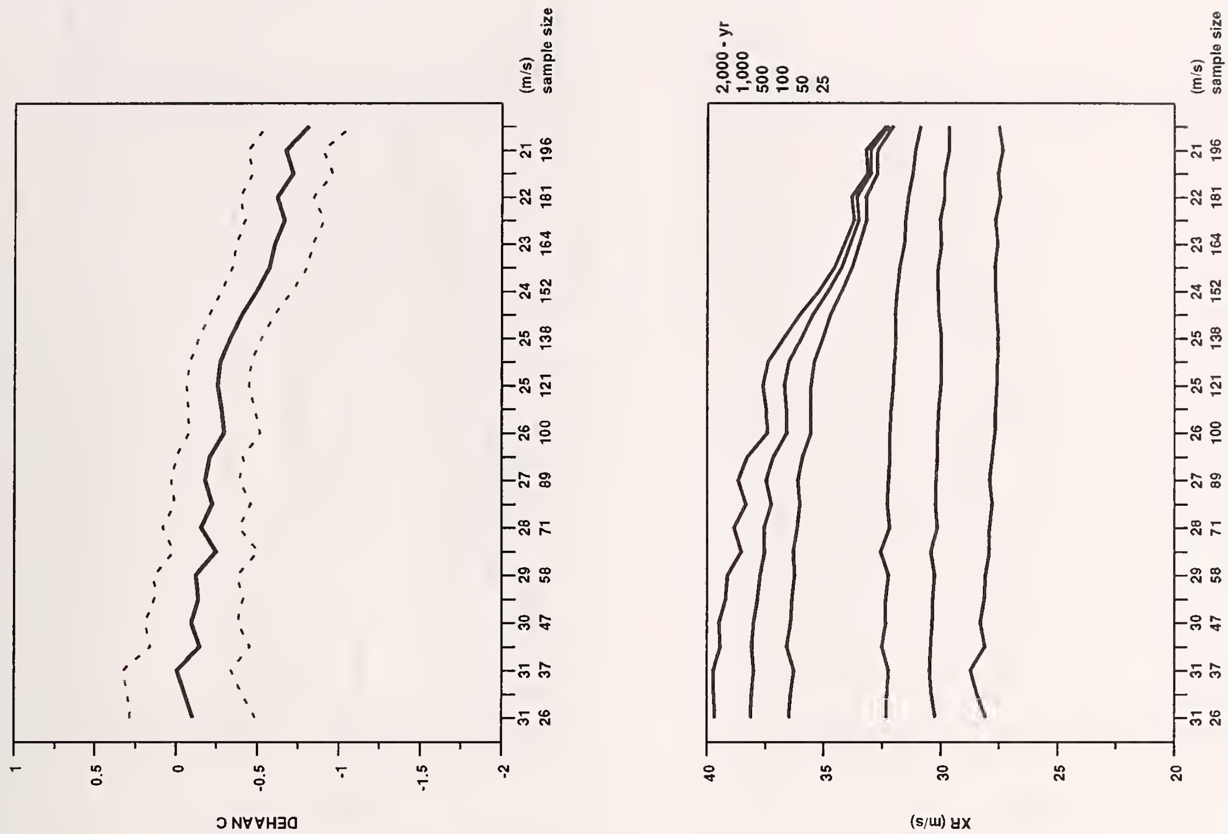

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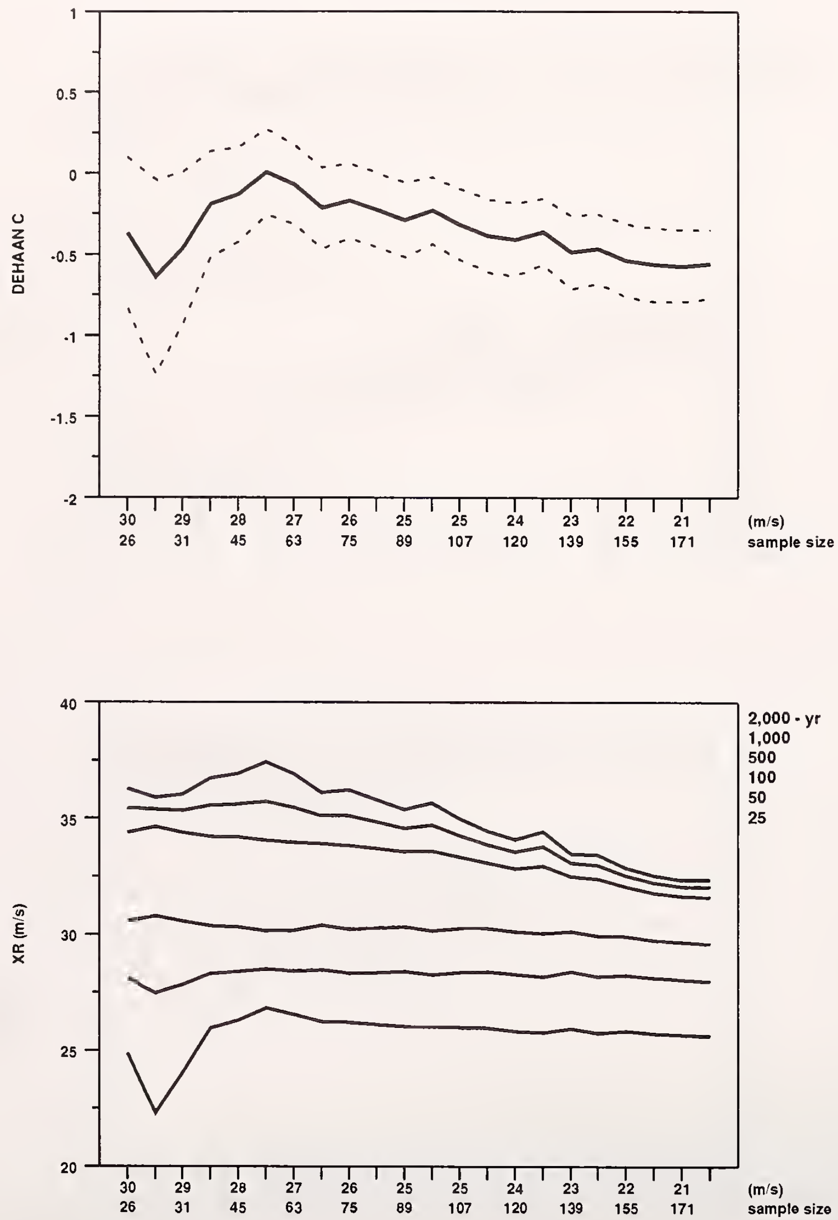

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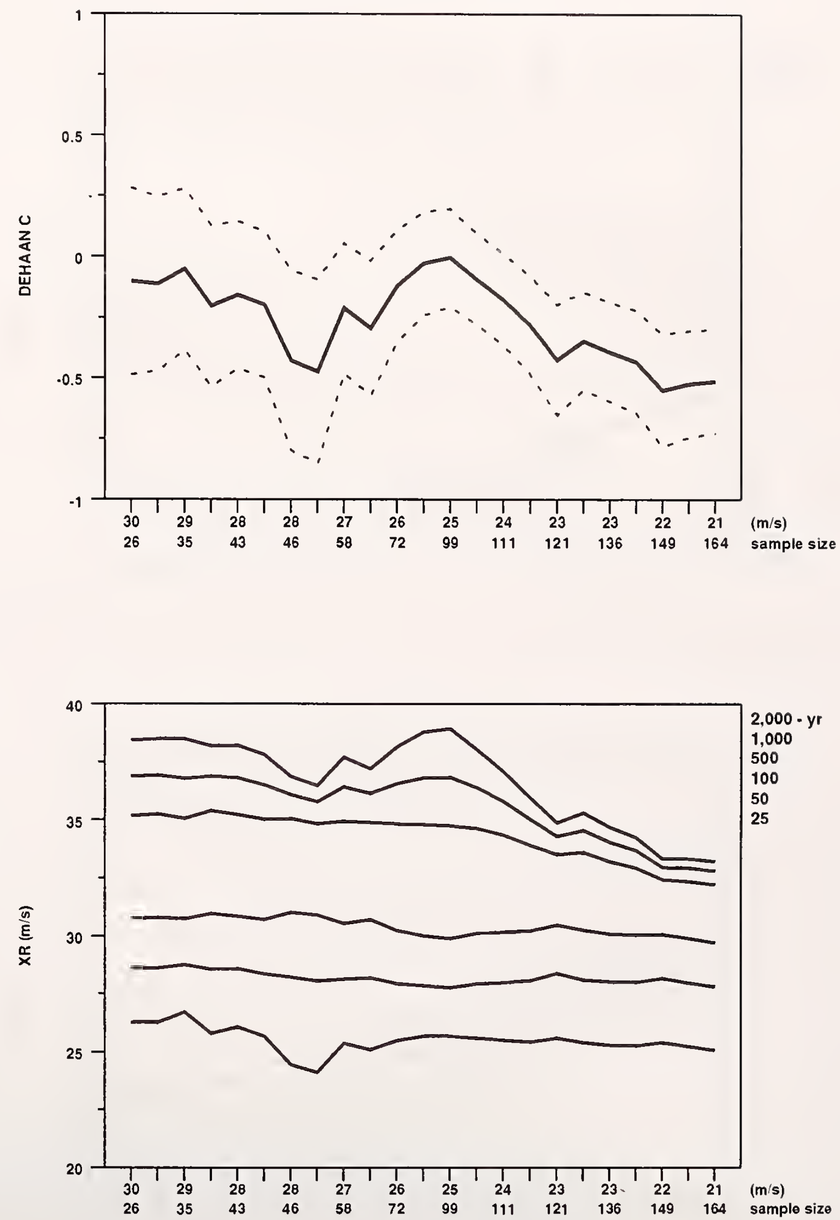

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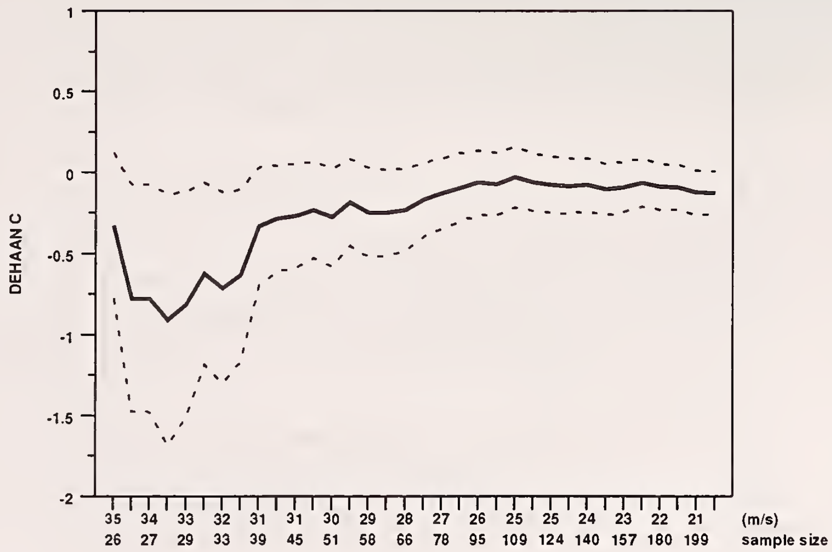

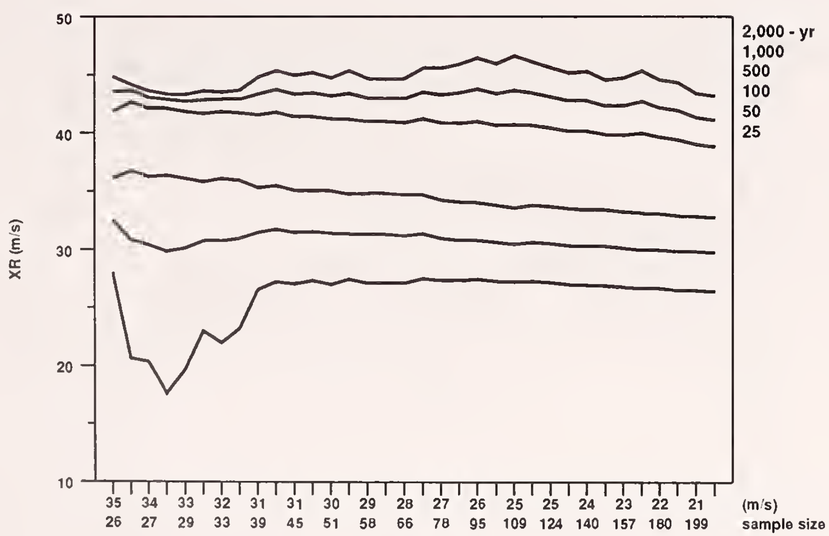

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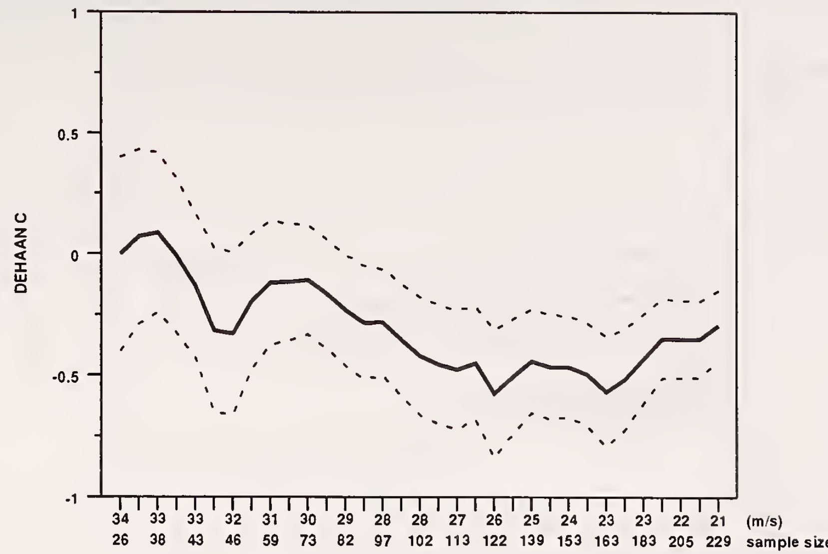

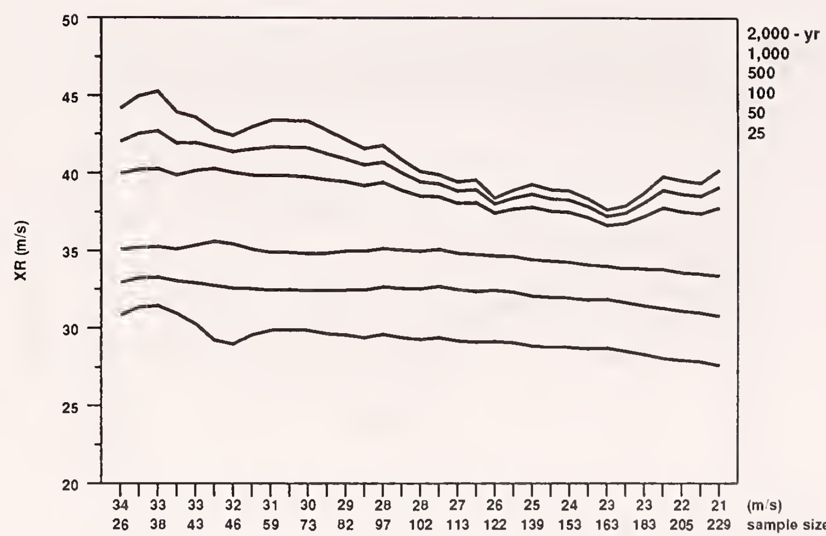

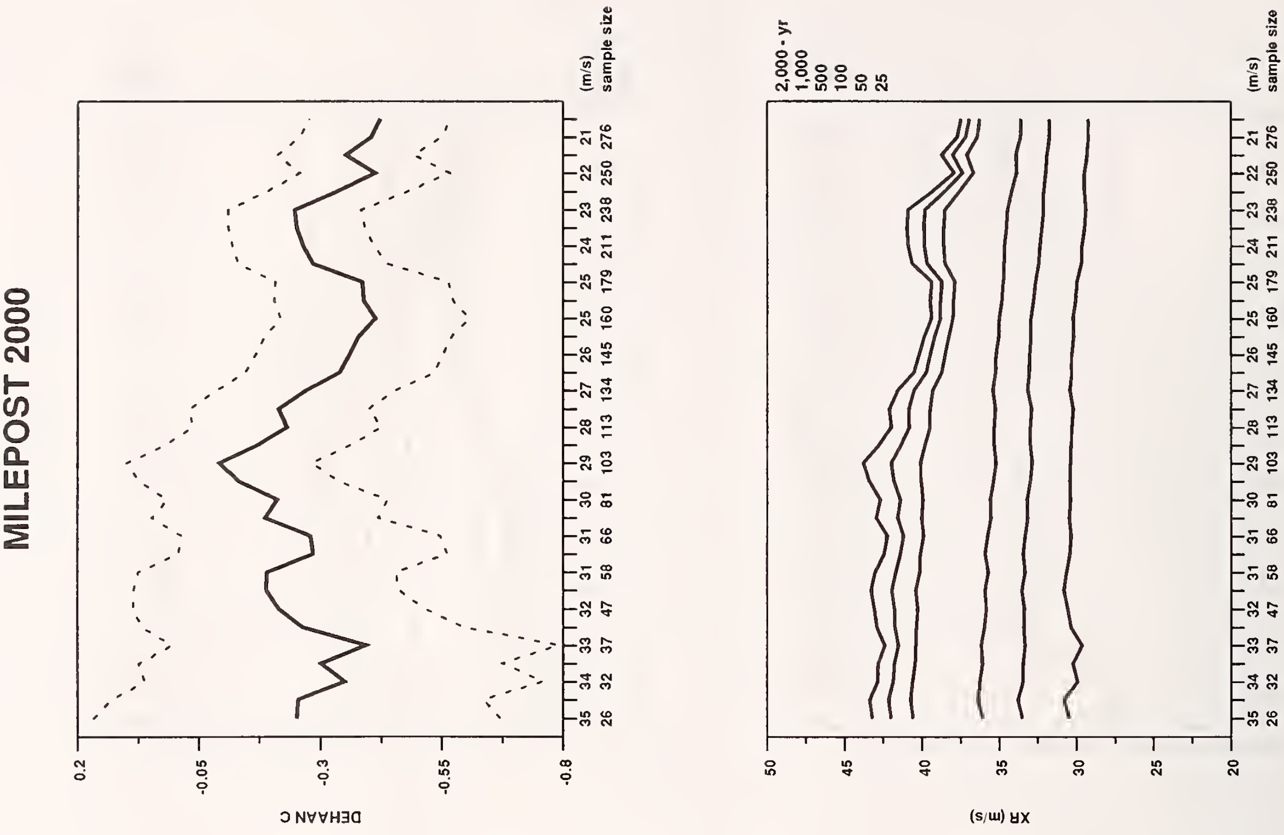
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XR (m/s)
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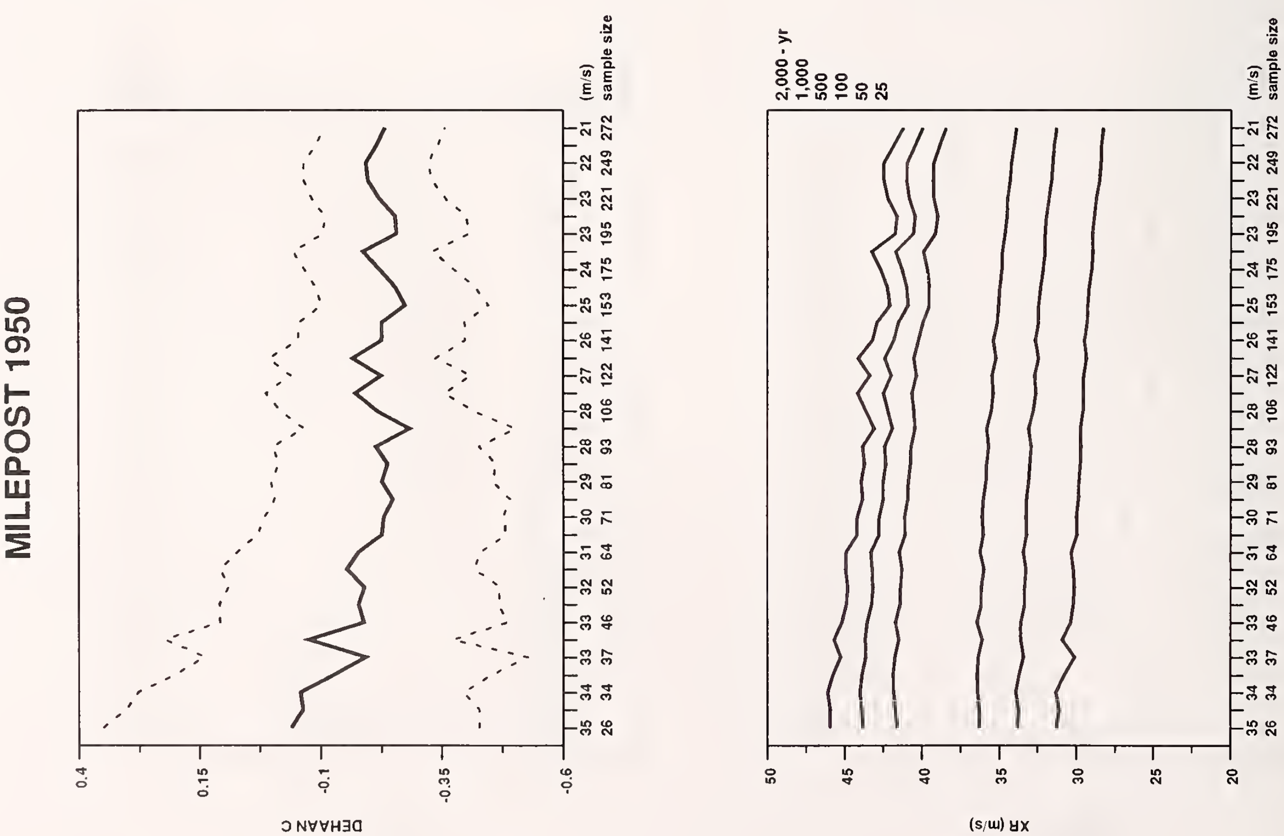
1,000
500
100
50
25
(m/s)
sample size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1,000
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100
50
25
(m/s)
sample size

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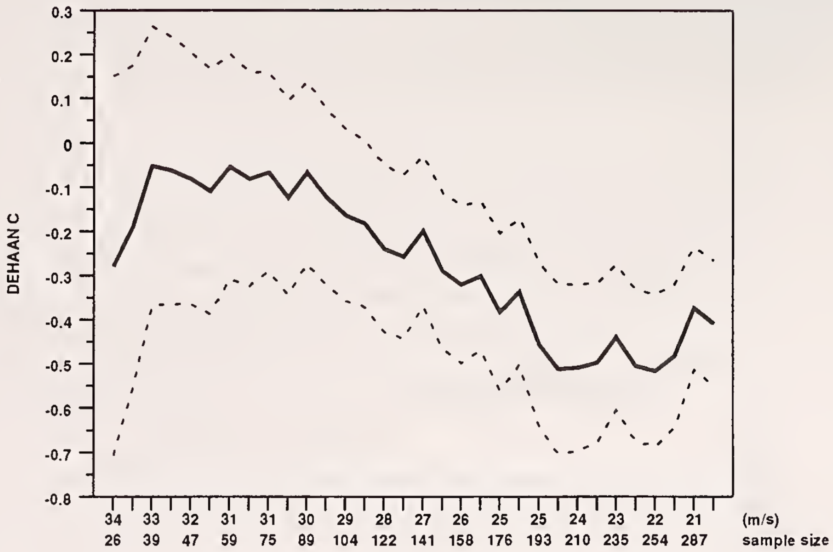

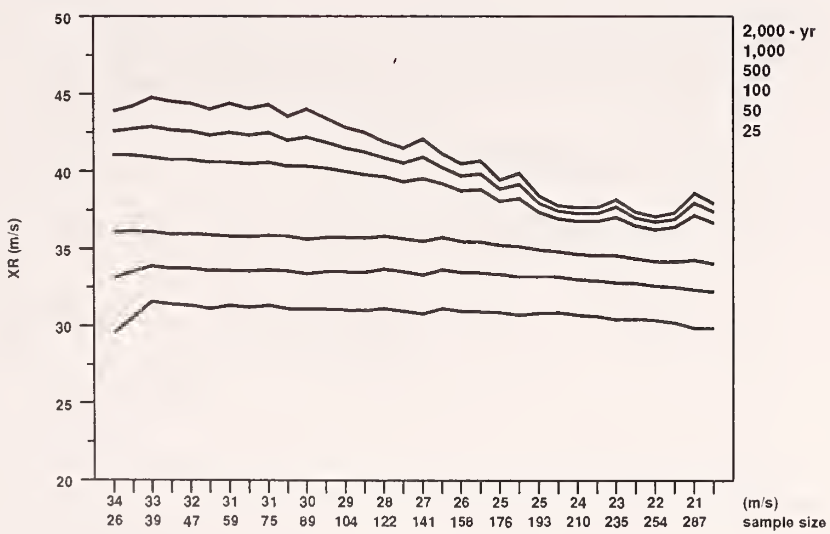

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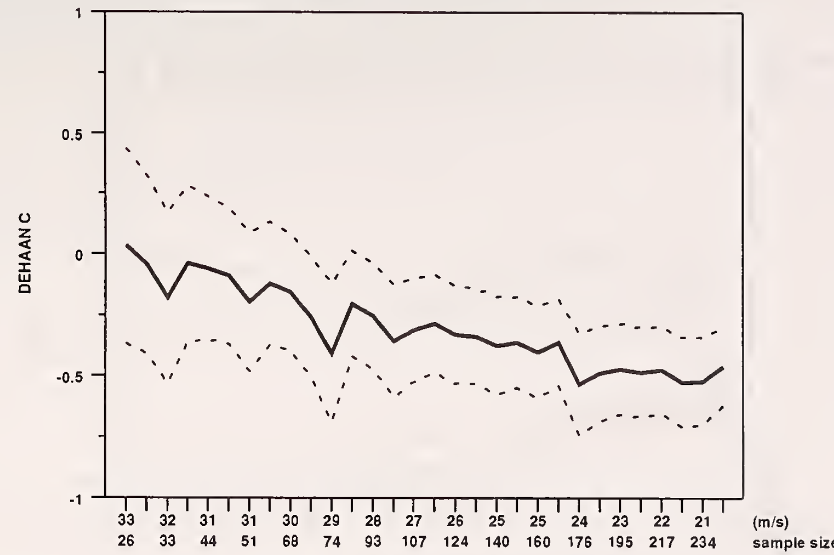

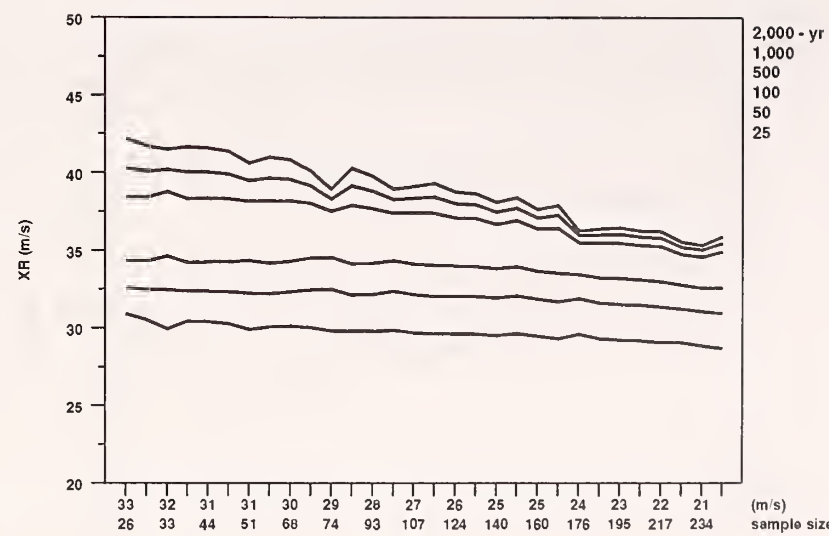

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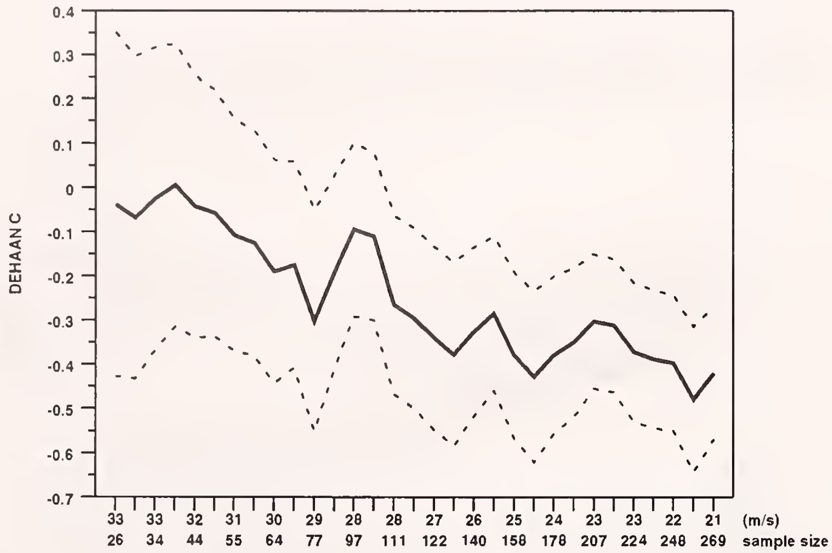

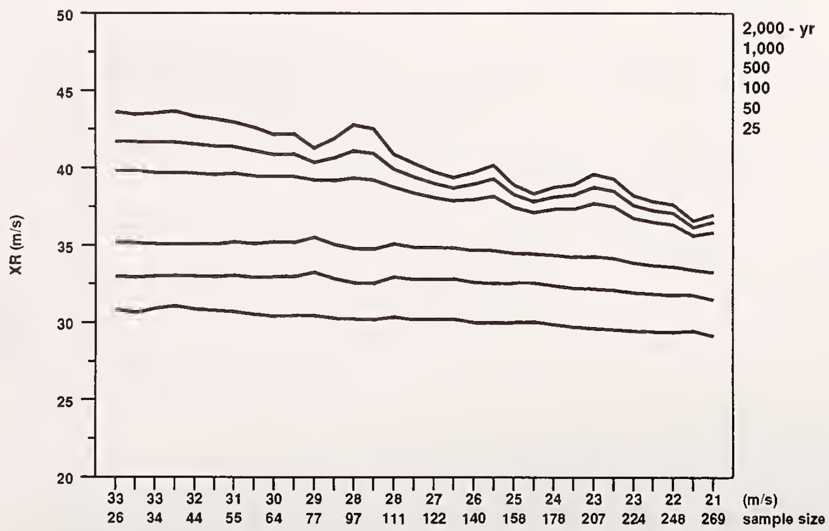

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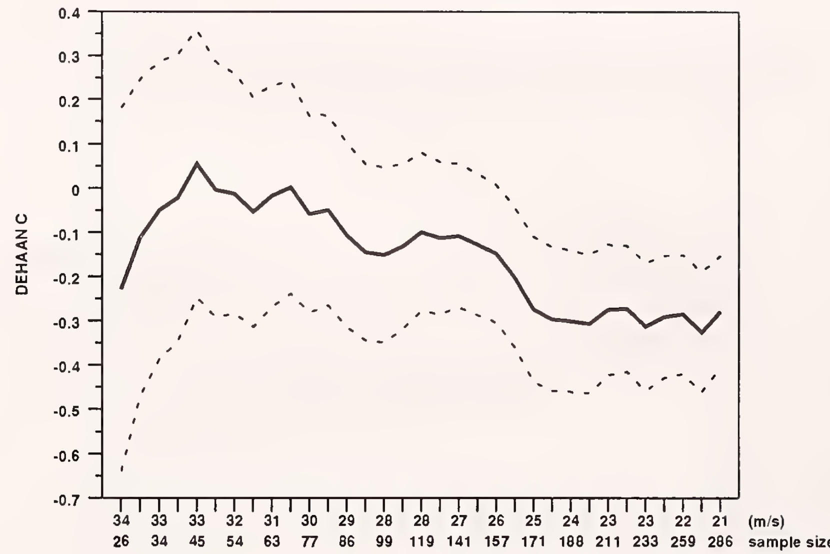

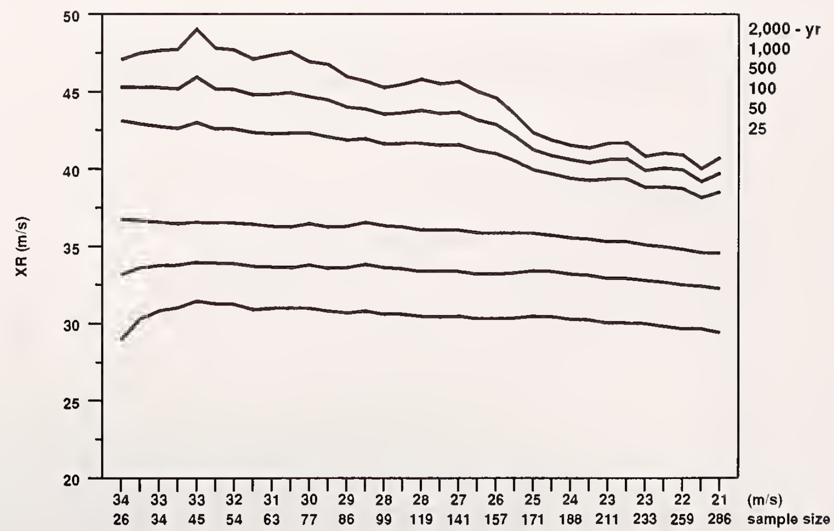

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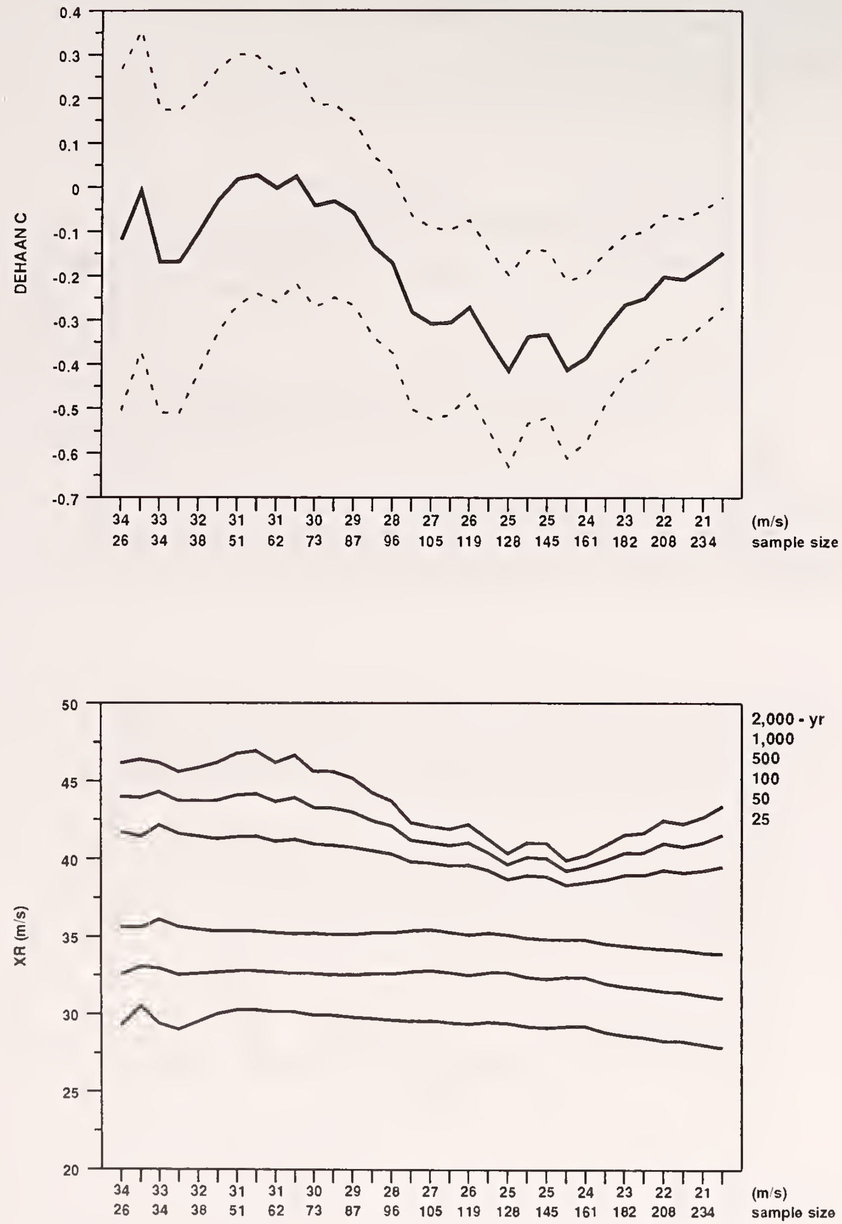

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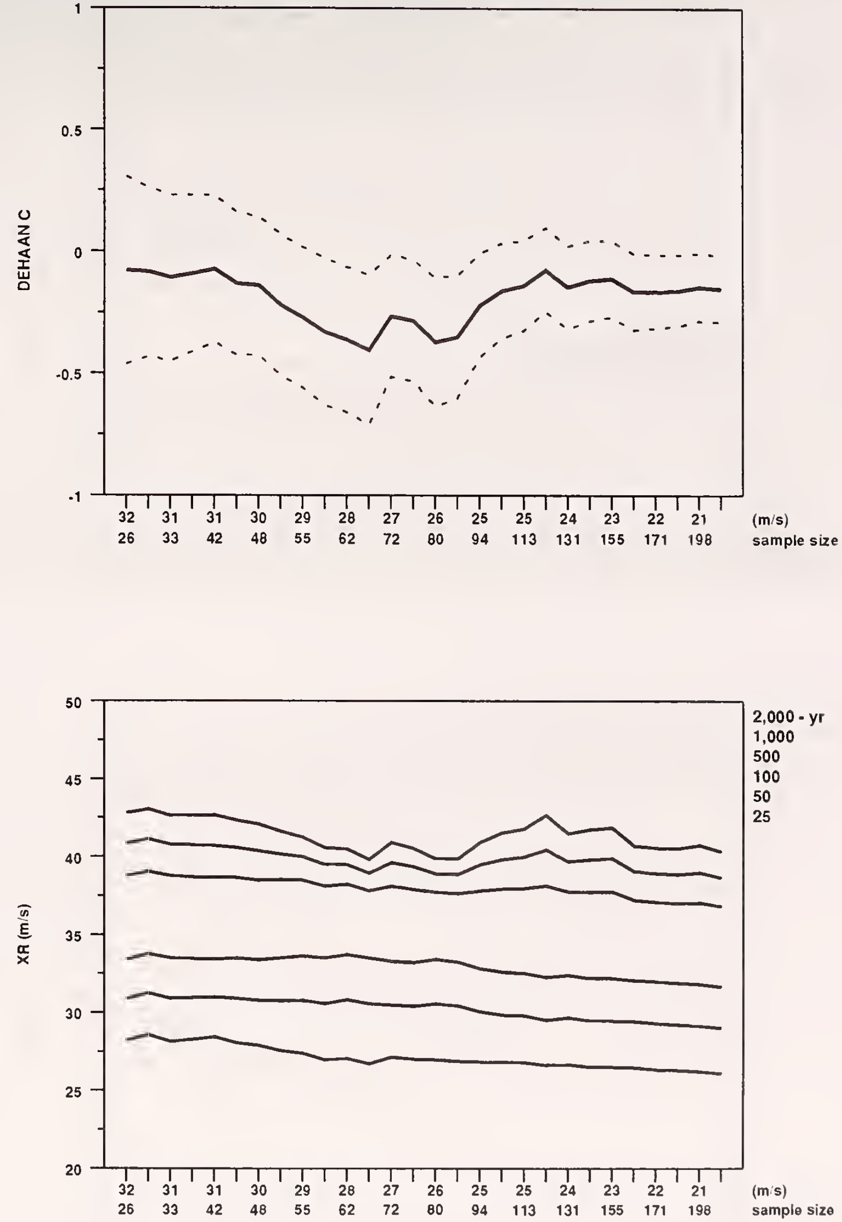

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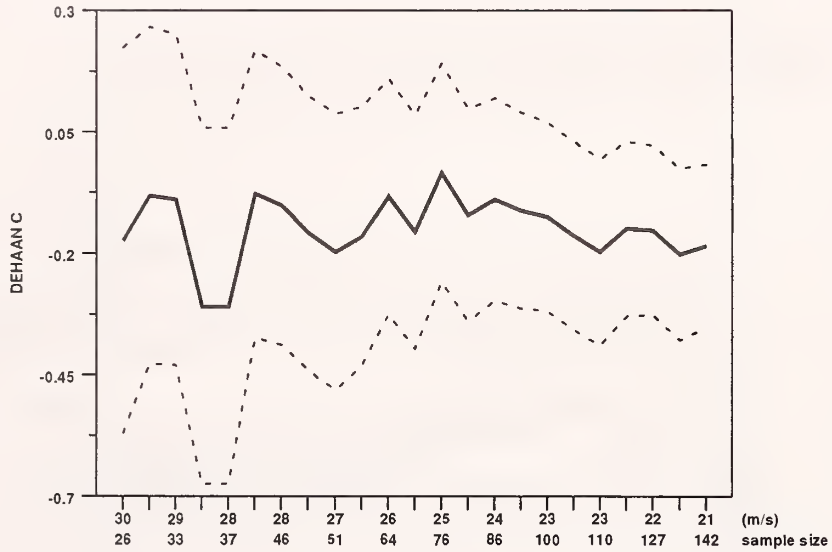

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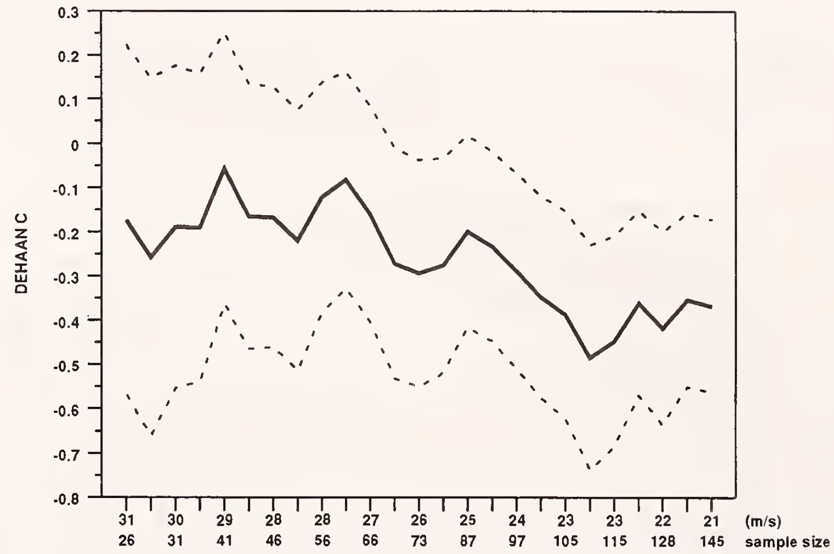

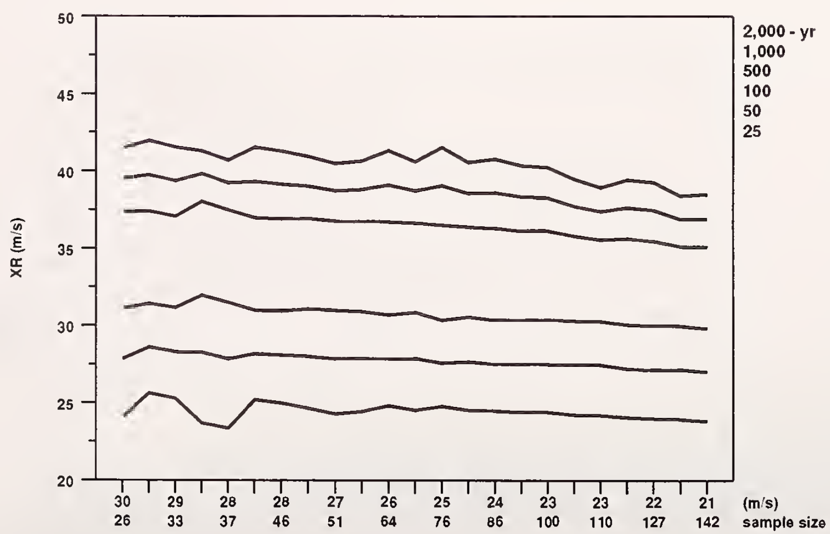

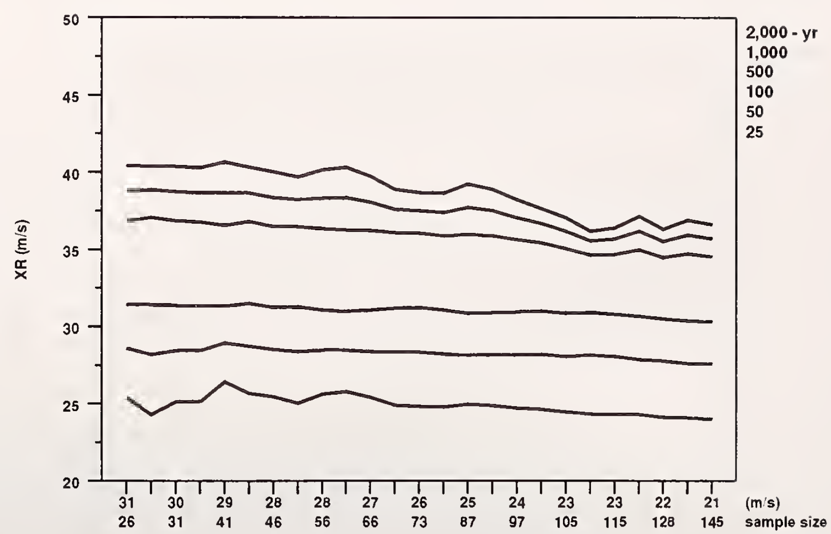

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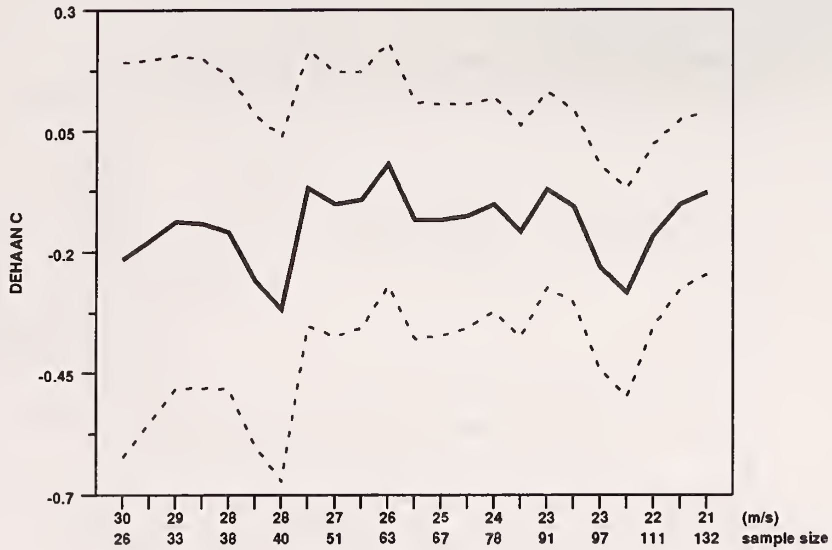

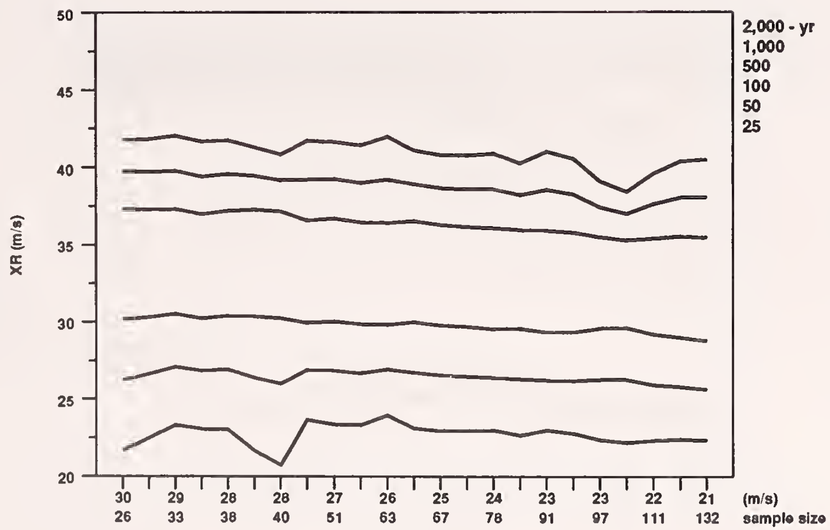

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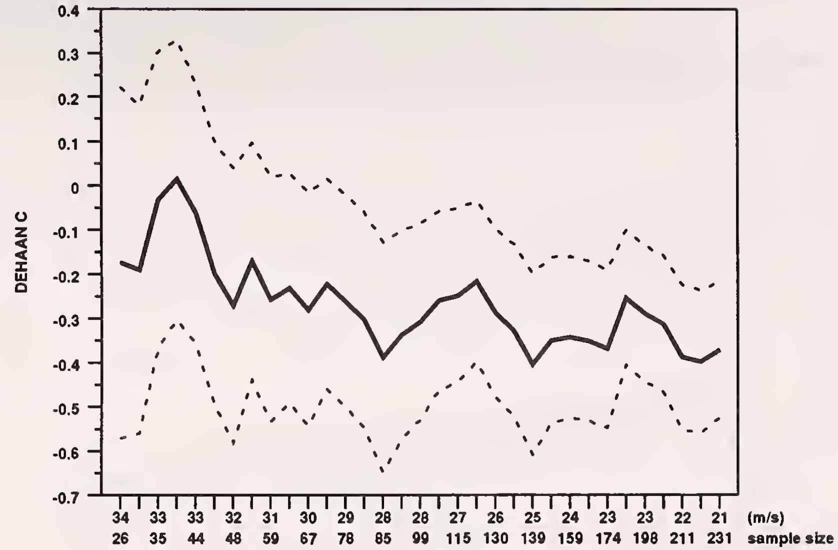

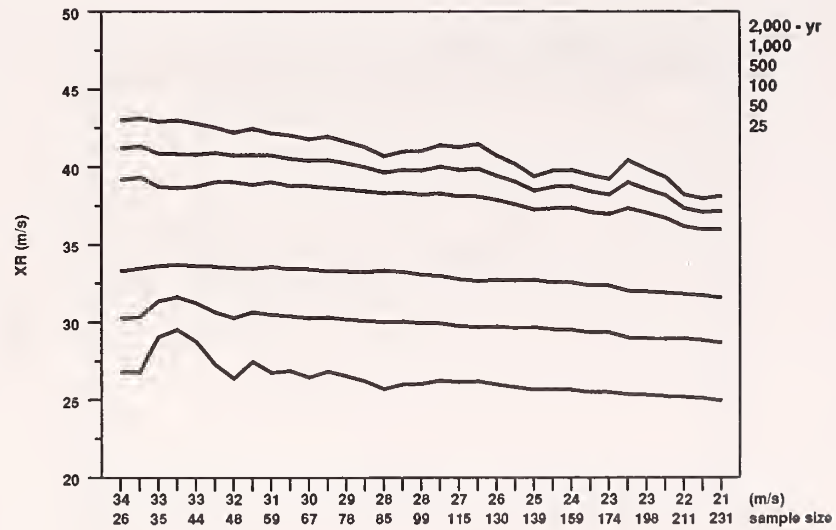

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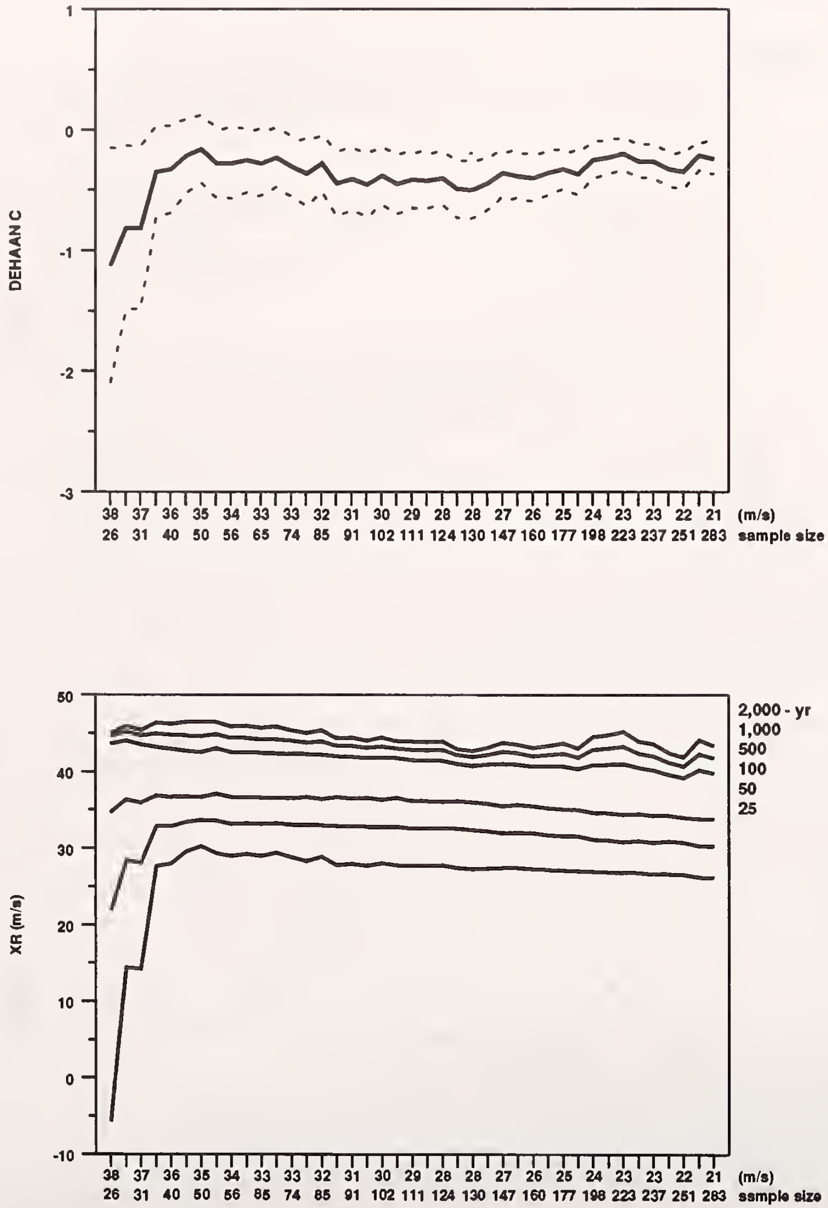

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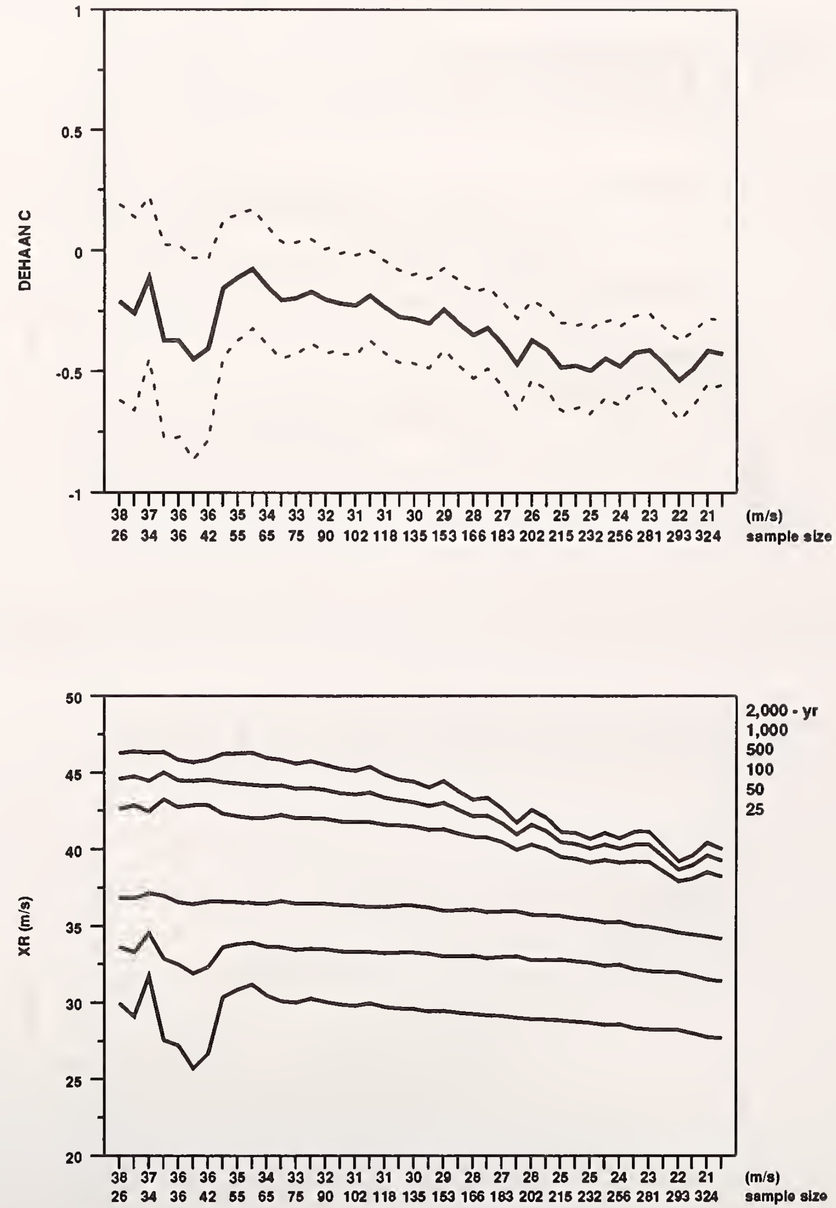

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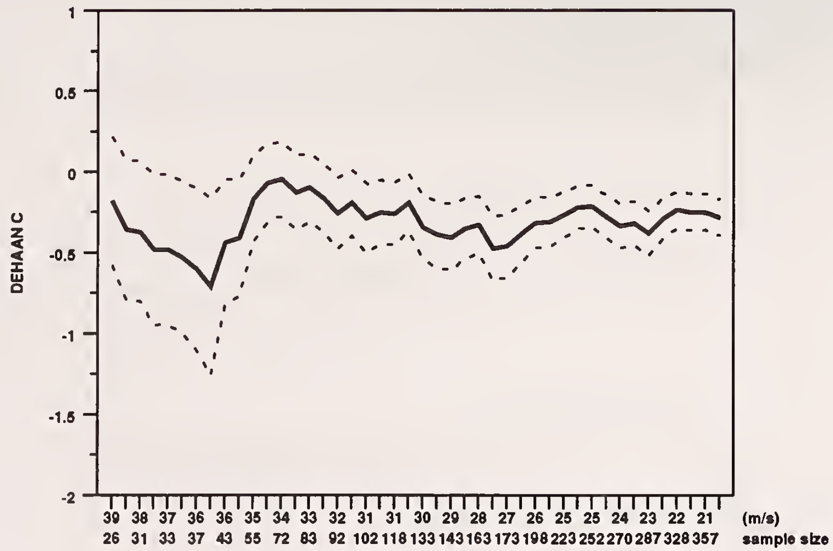

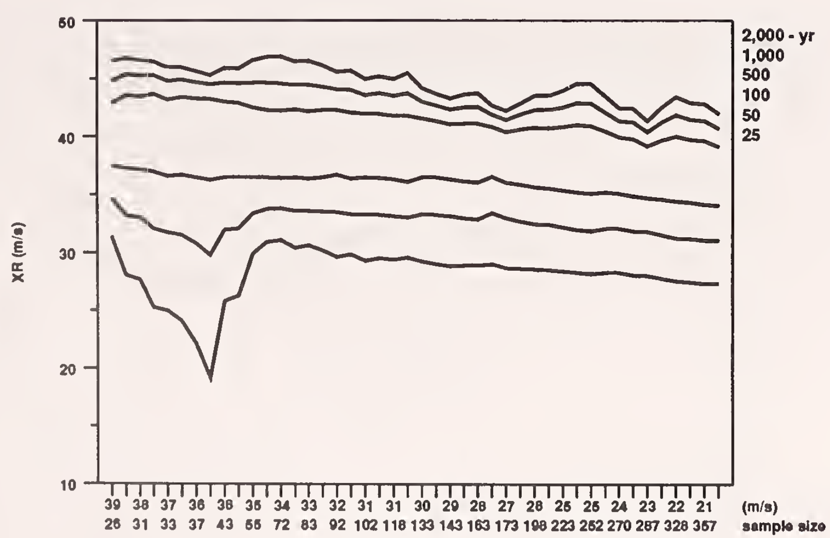

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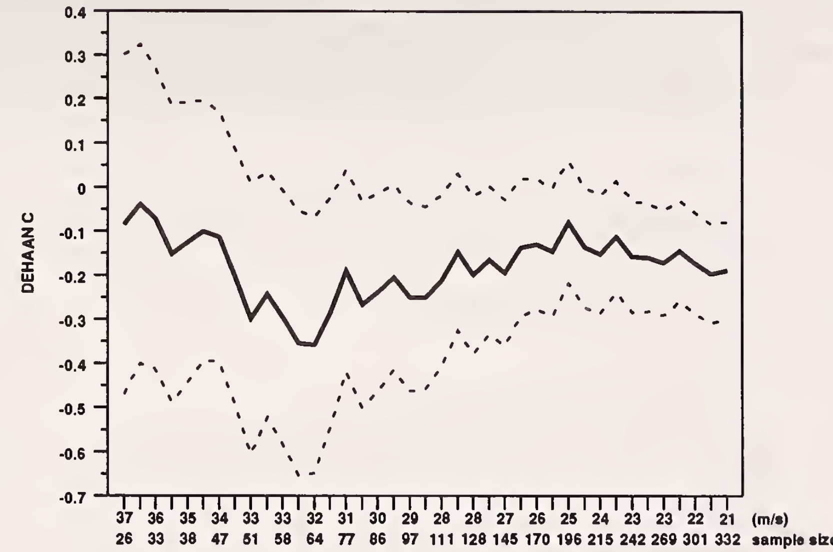

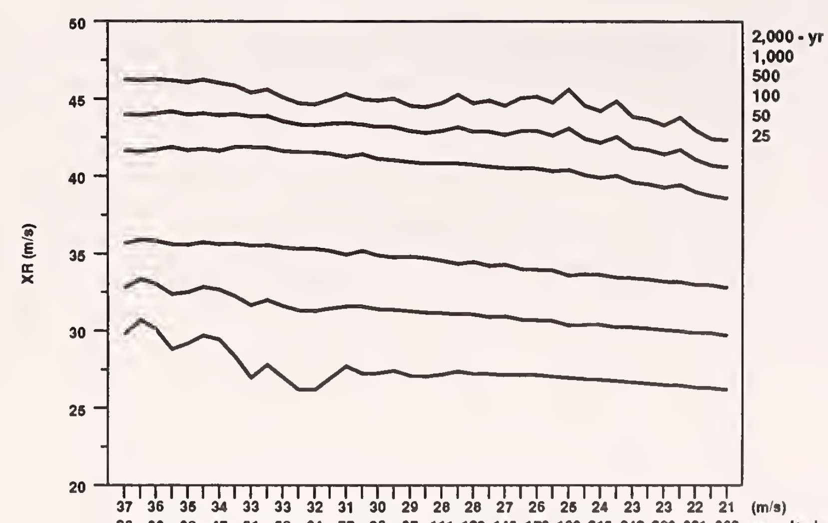

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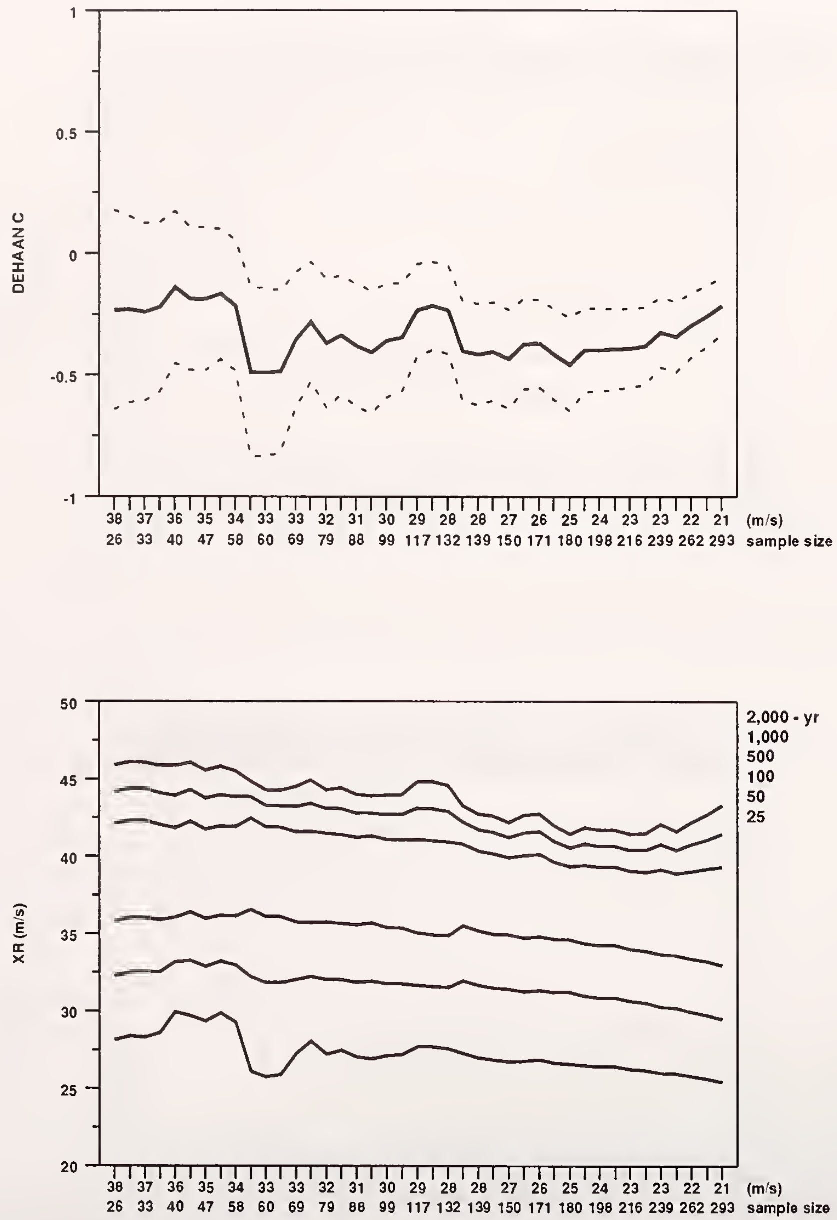

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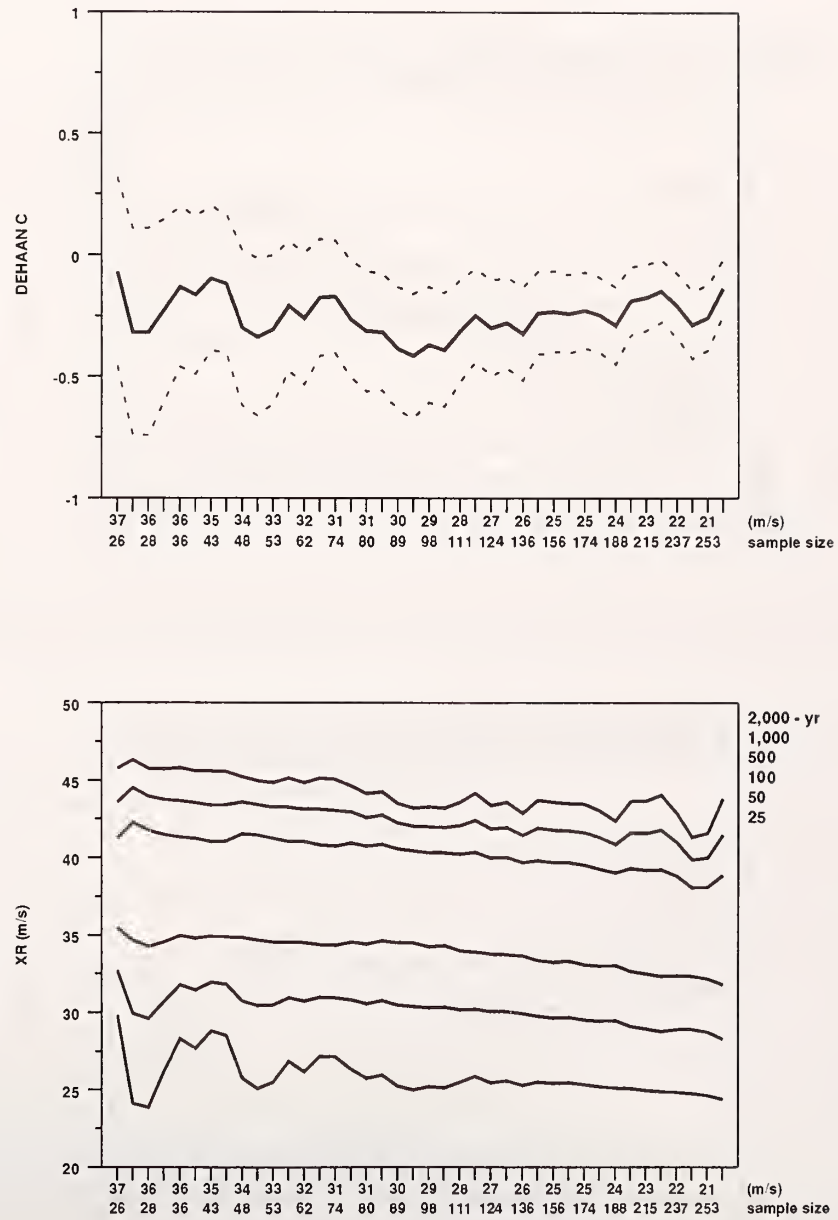

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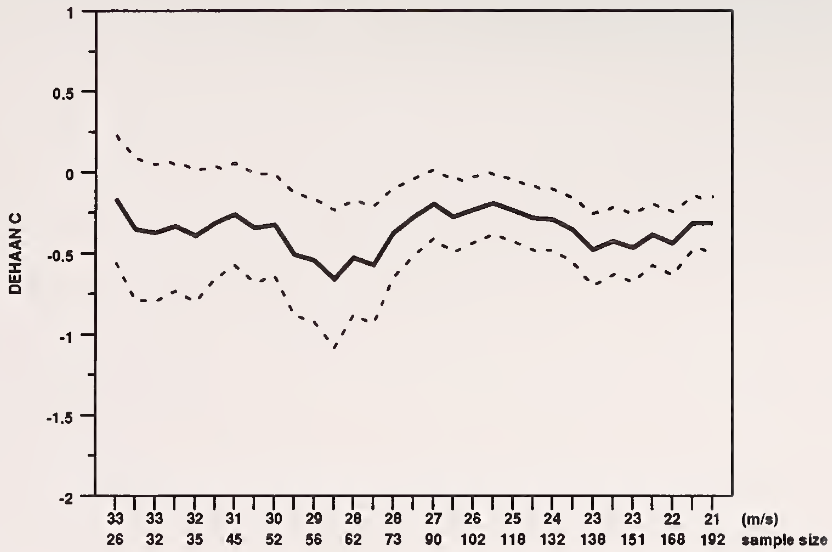

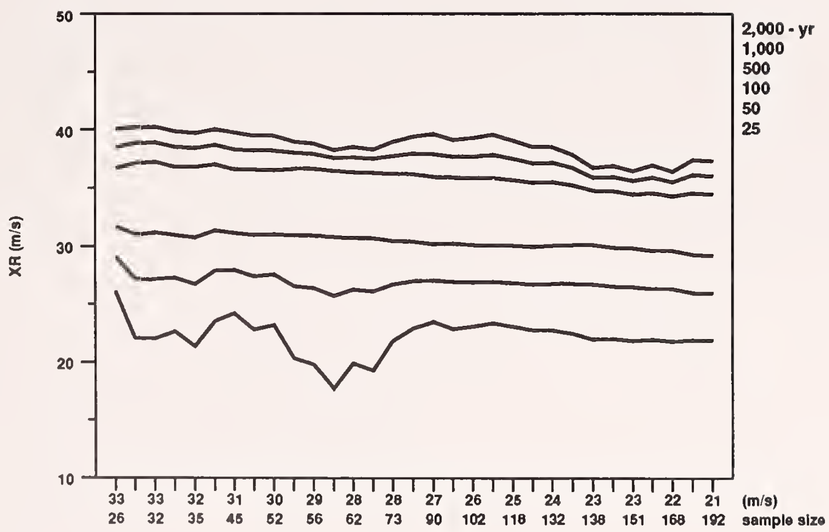

APPENDIX II

Instructions for accessing data sets and computer programs

```
ftp enh.nist.gov (or ftp 129.6.16.1)
>user anonymous
enter password >guest
>cd emil/hurricane/datasets (to access data)
>prompt off
>dir (this lists available files)
>mget * (this copies all the data files)
>cd../../..
>cd emil/hurricane/programs (to access programs)
>dir (this lists all available files)
>mget * (this copies all the files)
get <enh.name> <local name> (this copies a specific file; example:get
milepost.350 milepost.350)
>quit
```

Note. The directory emil/hurricane contains a README file with details on the programs and datasets.

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