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Wind direction and hurricane-induced ultimate wind loads

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Abstract

A consensus on the wind directionality issue is needed for the validation by building officials of the wind-tunnel procedure allowed by the ASCE 7-95 Standard, and for the development of provisions for wind loads that use large aerodynamic and climatological databases. As a contribution to the debate needed to achieve such a consensus, we describe an updated method for estimating wind loads that takes into account the directional dependence of the aerodynamic coefficients and the extreme wind climate, and uses the 'peaks over threshold' approach for the estimation of extremes. For hurricane-prone regions, assuming epistemic uncertainties are negligible, we estimate mean recurrence intervals (MRIs) of wind loads inducing the design strength, obtained from 50 yr loads via multiplication by a factor specified by the ASCE 7-95 Standard. For typical aerodynamic coefficients with strong directional preference, depending upon location and building orientation those estimated MRIs varied between less than 1000 to more than 10 000 yr. If epistemic uncertainties were taken into account the estimated MRIs would be shorter. We also found that for loads with very large MRIs the common practice of disregarding direction effects is not necessarily conservative from a structural engineering viewpoint. © 1998 Elsevier Science Ltd. All rights reserved.

1. Introduction

The ASCE 7-95 Standard [1] (henceforth referred to as the Standard) specifies two procedures for estimating design wind loads: a *conventional procedure* and the *wind-tunnel procedure*.

In the *conventional procedure*, design wind loads are based on aerodynamic and climatological information provided primarily in reductive tables and graphs. This information does not reflect the dependence of the aerodynamics and the wind climate

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on wind direction. For this reason the conventional procedure for calculating wind loads is referred to as *non-directional.*

The Standard provides aerodynamic information consisting of one aerodynamic coefficient – the largest of the aerodynamic coefficients measured for all wind directions – and climatological information consisting essentially of two parts. The first part is the basic wind speed at 10 m above ground in open terrain, estimated from the time series of the largest wind speeds regardless of direction. For most applications the nominal mean recurrence interval (MRI) of the basic wind speed is 50 yr. (The nominal MRI is estimated without accounting for wind direction effects. An estimate of the mean recurrence interval that does account for wind direction effects is referred to in this paper as MRI, as opposed to nominal MRI.) The second part is a wind speed safety factor. For structures for which the wind loading is dominant the design strength is induced by a wind speed equal to the basic wind speed times the wind speed safety factor. Implicit in the Standard are specified wind speed safety factors $(\phi_w)^{1/2}$ for non-hurricane winds and $(1.05)(\phi_w)^{1/2}$ for hurricane winds, where $\phi_w = 1.3$ is commonly referred to as the wind load factor, and 1.05 is a hurricane importance factor. The hurricane importance factor is justified by the fact that "the probability distributions of hurricane winds and extratropical winds are different" (see Ref. [1], p. 152). For brevity, in this paper we denote by *ultimate wind load* the wind load induced by a speed equal to the 50 yr speed times the wind speed safety factor.

The purposes of the wind speed safety factor are (1) to make allowance for epistemic uncertainties (i.e., uncertainties in the estimation of the terrain roughness, aerodynamic coefficients, and extreme wind speeds) and (2) to ensure that the MRIs of wind speeds inducing the ultimate wind loads are much larger than 50 or 100 yr. To the extent that the latter objective is achieved, the probability of attaining the design strength will be acceptably small. In this paper, we assume that the design is governed by the wind loading. We also assume that epistemic uncertainties are negligible. Thus, the MRIs and nominal MRIs we estimate are upper bounds for the respective actual mean recurrence intervals. We note that, according to recent studies, upper bounds for nominal MRIs of speeds inducing the ultimate wind loads are of the order of 10 000–100 000 yr or more for non-hurricane regions, but only of the order of 500 yr for hurricane-prone regions near the coastline [2].

For the *wind-tunnel procedure* the Standard limits itself to specifying performance criteria for the turbulent flow simulation in the wind tunnel. It is implicitly assumed that if those criteria are met the wind tunnel tests will yield acceptable aerodynamic data, which are routinely obtained in the laboratory as functions of wind direction. These directional aerodynamic data should be used in conjunction with directional information on the extreme wind climate. However, the Standard contains no such information. Nor does it include a directional estimation method (or, for short, a *directional method*); i.e. a method for estimating wind loads that takes into account the directional dependence of both the aerodynamic coefficients and the extreme wind speeds. By default, the tasks of acquiring or assembling directional data and developing a directional method are left by the ASCE Standard to the discretion of the structural engineer or his/her wind engineering consultant.

Since efforts are under way to develop standards utilizing large aerodynamic and climatological databases [3], we anticipate that this state of affairs will change. Standard provisions for wind loads utilizing large databases are essentially an application of the wind-tunnel procedure, with the difference that (1) the aerodynamic and climatological data are publicly available in databases attached to the provisions, and (2) the directional method being used is based on professional consensus, rather than on the individual preferences of wind engineering consultants. The advantage of provisions utilizing large databases over the conventional procedure is that they use the full information needed for design, rather than the few reductive tables or graphs included in the Standard. This advantage results in more realistic representations of the loads, improved risk consistency, and more economical designs.

A wide-ranging debate on the directional estimation issue is needed to achieve professional consensus. As a contribution to this debate we present the directional method originally proposed in Ref. [4], updated by the use of the 'peaks over threshold' approach to the estimation of extremes. In this paper we restrict the application of our directional method to the case of hurricane-induced wind loads near the coastline. Our main objective is to compare estimates of MRIs and estimates of nominal MRIs for given hurricane wind loads (recall that our estimates represent upper bounds, i.e., they are conditional on the epistemic uncertainties being negligible). Alternatively, for MRIs equal to nominal MRIs, we wish to compare the respective directional and non-directional estimates of the corresponding wind loads.

It is known that, in general, estimated loads with 50 yr nominal MRI are considerably larger than their 50 yr MRI counterparts [5]. We show, however, that a similar statement does not necessarily hold for large MRIs. For example, loads with 100 000 yr nominal MRI are on average comparable to their 100 000 yr MRI counterparts. It thus appears that non-directional estimates of wind loads with very large nominal MRIs are not necessarily conservative. In addition, we are seeking estimates of MRIs for ultimate wind loads in hurricane-prone regions near the coastline. As noted earlier, the nominal MRIs for those loads are only of the order of 500 yr. According to our results, their MRIs are larger than the nominal MRIs by a factor that, depending upon geographical location and building orientation, varies in most cases between about 3 and 15, with an average of roughly 8. Thus, assuming epistemic uncertainties to be negligible, estimated MRIs of ultimate hurricane-induced wind loads are, on average, of the order of a few thousand years. However, if epistemic uncertainties are significant, the estimated MRLs may be considerably less.

In the next sections we review the directional and non-directional estimation procedures, summarize results of our analyses, interpret our results, and present our conclusions.

2. Description of estimation methods

2.1. Directional method

In this subsection we review briefly the directional estimation method proposed in Ref. [4]. The method is applicable provided that the wind effects depend on wind speed and direction in the form

$$p(\theta) = (\rho/2)C(\theta)x(\theta)^2, \tag{1}$$

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

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

where $i = 1, 2, \ldots, N$ denotes the direction, $j = 1, 2, \ldots, M$, M is the number of years or, for hurricane-prone regions, of hurricane events, $\max_i[C(\theta_i)]$ is the largest of the values $C(\theta_i)$, and $\max_i$ denotes the maximum over all i. For hurricane-prone regions, $N = 16$. From these time series we form the single time series

$$P_j = \max_i\{[P_j(\theta_i)]\}. \tag{3a}$$

To within a constant factor, P_j is the largest wind effect in year (or hurricane) j. Rather than analyzing the time series P_j, we analyze the time series of *equivalent wind speeds*

$$x_{\mathrm{eq}\,j} = (P_j)^{1/2}. \tag{3b}$$

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

$$p_R = (\rho/2)\{\max_i[C(\theta_i)]\}(x_{R\mathrm{eq}})^2. \tag{4}$$

2.2. Non-directional method

We now describe the non-directional method, used in the vast majority of codes and standards, including the ASCE 7-95 Standard. First form the time series

$$x_j^{\max} = \max_i[x_j(\theta_i)] \tag{5}$$

of the largest wind speed in year (or hurricane) j, regardless of its direction. Next, from the analysis of this time series, obtain the estimate x_R, that is, the non-directional estimate of the R yr speed, where R now denotes the nominal MRI. The corresponding non-directional estimate of the wind effect with an R-yr nominal MRI is

$$p_{R,\mathrm{nom}} = (\rho/2)\max_i[C(\theta_i)]x_R^2. \tag{6}$$

In other words, $p_{R,\mathrm{nom}}$ is obtained by following exactly the same steps used in the preceding subsection to estimate p_R, except that in Eq. (2) the factor $C(\theta_i)$ is replaced by the factor $\max_i[C(\theta_i)]$. Each of the terms of the time series $x_j^{\max}$ is equal to or larger than its counterpart in the time series $x_{\mathrm{eq}\,j}$. Therefore, if the MRI and the nominal MRI have the same value, one might expect $p_R < p_{R,\mathrm{nom}}$; if the MRI is larger than the nominal MRI one might expect $p_R = p_{R,\mathrm{nom}}$. This explains the common belief that non-directional estimates of wind effects are conservative from a design viewpoint. However, as is shown in the next section, this belief is not necessarily borne out by extreme value analyses of hurricane wind speeds.

3. Analyses and results

3.1. Extreme value estimation method, hurricane wind speed data, and aerodynamic coefficients

Our analyses are based on De Haan's 'peaks over threshold' estimation method, whose application to both extratropical and hurricane wind speeds is described in some detail in Ref. [5] (Appendix 1), and Refs. [6,7]. We note that, on account of the form of Eqs. (4) and (6), it is sufficient to compare the estimated values of $x_{R\ \mathrm{eq}}$ and x_R, rather than the respective wind effects. (In this paper, we omit the circumflex used in the statistical literature to denote estimated values.) The estimation method we use is the same as in Ref. [6], except that for purposes of comparison it is applied to both directional and nondirectional simulated data.

The directional hurricane wind speed data were obtained by simulation [8], are available in electronic files for 55 mileposts along the Gulf and Atlantic coasts (for milepost definition see Ref. [5], Ch.3), and may be accessed as indicated in the appendix. (The appendix also contains programs and wind speed data for non-hurricane regions.) The wind effect coefficients were assumed to have the values shown below:

θ_i	N	NNE	NE	ENE	E	ESE	SE	SSE
$C(\theta_i)$	1.1	1.0	0.5	0.6	0.7	0.6	0.5	0.9
θ_i	S	SSW	SW	WSW	W	WNW	NW	NNW
$C(\theta_i)$	1.8	3.3	1.1	0.6	0.1	0.2	0.2	0.8

(these values are close to values of suction coefficients with negative signs omitted, measured in the wind tunnel for a point near the corner of a tall building roof). Note that, as is commonly the case for corner pressures, for one of the directions (in this case for the SSW direction) the coefficient is much larger than for the others.

3.2. Comparisons of estimates by the directional and non-directional methods for various MRIs

We compare directional estimates $x_{R\ \mathrm{eq}}$ for MRIs of 50, 2000, 10 000 and 100 000 yr on the one hand, with, respectively, non-directional estimates x_R for nominal MRIs of 50, 2000, 10 000 and 100 000 yr, on the other. As an example, for milepost 600, located on the Lousiana coastline, Fig. 1 shows the mean and the maximum wind speeds for each of the sixteen azimuths (minima are in many instances zero for certain directions and were not accounted for in calculating means). Fig. 2a and 2b show estimates x_R and $x_{R\ \mathrm{eq}}$, based on mean hourly wind speeds, as functions of threshold. Fig. 2c and d show the estimated tail length parameters c of the extreme value distribution and their 95% confidence bounds corresponding to Fig. 2a and 2b, respectively. (The larger the parameter c, the longer the distribution tail is – see Ref. [9].) As the threshold increases the sample size decreases. For the type of graphs of Fig. 2 a roughly horizontal portion is judged to correspond to a reasonable approximate

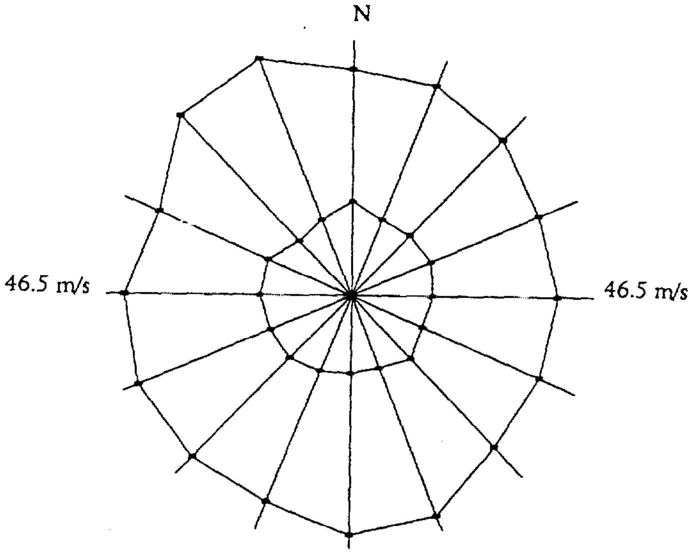


Fig. 1. Directional mean and maximum hurricane mean hourly wind speeds, milepost 600.

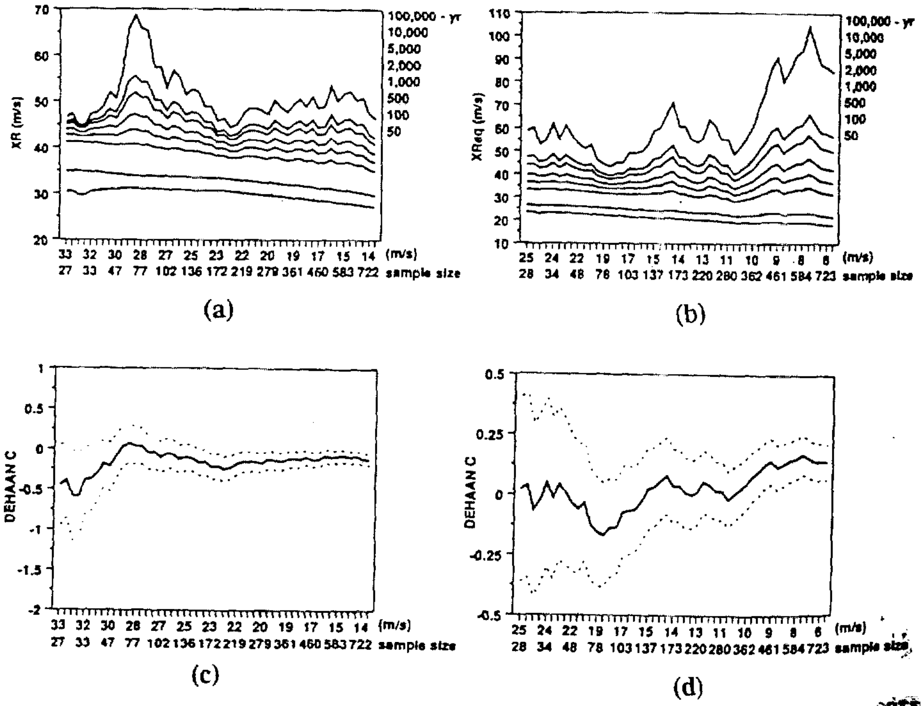


Fig. 2. Estimates of: (a) speeds x_R with 50 yr (bottom curve) to 100 000 yr (top curve) nominal MRIs; (b) speeds $x_{R_{eq}}$ with 50 to 100 000 yr MRIs, for largest pressure coefficient $C(\theta_i) = 3.3$ in SSW direction; (c), (d) tail length parameter c and 95% confidence bands corresponding to (a) and (b), respectively.

estimate of the variate of concern (for a discussion of this issue, see Ref. [6]). From Fig. 2a and 2b we estimate, roughly, $x_{50} \approx 30$ m/s, $x_{50\ \mathrm{eq}} \approx 23$ m/s and $x_{100\,000} \approx 50$ m/s, $x_{100\,000\ \mathrm{eq}} = 55$ m/s. Note that, for the milepost being considered, while the estimates of the 50 yr speeds vary slowly as a function of threshold, for the 100 000 yr speeds the variability is very large. In fact, owing to this variability there are stations for which the plots are not useful for estimating speeds with very large mean recurrence intervals. For this reason some of our estimates are more qualitative than quantitative, though the fact that in this paper estimates are made for a large number of different cases helps to provide useful indications of trends.

Note that the 50 yr estimates are significantly smaller for $x_{R\ \mathrm{eq}}$ than for x_R. However, this does not appear to be true for the estimates with large MRIs. We list below sample statistics of the 55 milepost estimates of $r_R = x_{R\ \mathrm{eq}}/x_R$:

	r_{50}	r_{2000}	$r_{10\,000}$	$r_{100\,000}$
Mean	0.71	0.85	0.90	0.96
Standard deviation	0.12	0.11	0.12	0.18

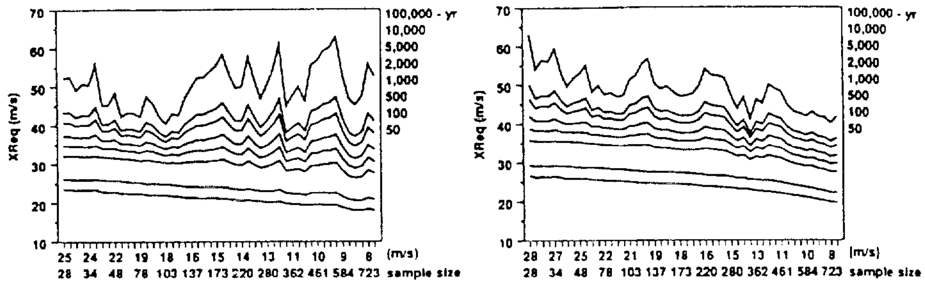
We stress again that these values are based on the very approximate estimates made possible by plots similar to the plots of Fig. 2a and b, especially for large R. We note, however, that the relatively large number of plots we used leads to results for which the errors are, on average, considerably smaller than the sampling errors for any individual time series.

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 Eqs. (3a) and (3b), the time series of the equivalent wind speeds $x_{\mathrm{eq}\ j}$ is then 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, using Eq. (5), we obtain the time series $x_j^{\max} = \{52,46,47\}$, with mean and standard deviation $48.33 > 44.33$ and $3.21 < 4.33$, respectively. Since the mean is larger and the standard deviation is smaller for the time series $x_j^{\max}$ than for the time series $x_{\mathrm{eq}\ j}$, it can be expected that, for very short MRIs, $x_R > x_{R\ \mathrm{eq}}$, while for very long MRIs $x_R < x_{R\ \mathrm{eq}}$. If, for example, the extreme value distribution was assumed to be Type I, from the method of moments (wherein $x_R \approx M + 0.78(\ln R - 0.5772)\,s$, where M and s denote sample mean and sample standard deviation, respectively [5]), it would follow $x_{25\mathrm{eq}} = 53$, $x_{100\,000\mathrm{eq}} = 81$, and $x_{25} = 55 > 53$, $x_{100\,000} = 76 < 81$.

Designs are governed by the wind loads with long recurrence intervals, rather than by the 50 yr loads. Therefore, our results appear to indicate that the loads obtained by the non-directional method (i.e., from the time series $x_j^{\max}$) are not necessarily conservative, as has been commonly believed to be the case.

3.3. *MRIs of ultimate wind loads*

According to Ref. [2], for hurricane-prone regions near the coastline estimated nominal MRIs of ultimate wind loads (i.e., 50 yr loads multiplied by the square of the wind speed safety factor) are quite low, i.e., of the order of 500 yr. For Fig. 2 (milepost



(a) (b)

Fig. 3. Estimates of speeds $x_{R_{eq}}$, for largest pressure coefficient $C(\theta_i) = 3.3$ in: (a) NNW direction; (b) SSE direction.

600), the nominal MRI and the MRI of the ultimate wind load are estimated as follows. The speed inducing the ultimate wind load is $(1.05)(1.3)^{1/2}x_{50} \approx 1.2x_{50} \approx 36$ m/s. From Fig. 2a it can be seen that the nominal MRI of that speed is about 300 yr. From Fig. 2b, the MRI of the 36 m/s speed (and, therefore, the MRI of the ultimate wind load) is roughly 1500 yr. This is still an insufficient MRI from a safety viewpoint. Fig. 3a and 3b show plots of $x_{R_{eq}}$ obtained for milepost 600 by assuming that the building for which the aerodynamic coefficients were tabulated earlier is rotated clockwise by 135° and 315°, respectively. It can be seen from Fig. 3a and 3b that for these cases the MRIs of the ultimate wind load (i.e., the load induced by a 36 m/s speed) would be, respectively, about 1500–2000 and 500–1000 yr, say.

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 55×8 situations is 3500 yr, say. However, as was the case for milepost 600, MRIs considerably smaller than 3500 yr can occur in some cases. Moreover, all our estimates are based on the assumption that epistemic uncertainties are negligible. If, as is normally the case, the errors are not negligible, then the actual MRIs could in some cases be significantly less than 1000 yr, say. Such small MRIs may explain, at least in part, the large losses caused by hurricane winds. In light of these results it appears that the Standard specification of wind load factors needs to be reassessed.

4. Summary and conclusions

In this paper we presented estimates of hurricane wind loads near the coastline, which take into account the dependence on direction of both the aerodynamic coefficients and the extreme wind climate. The estimates were based on time series of the square root of the largest wind loads in successive simulated hurricane events, and on the application to those time series of the 'peaks over threshold' approach to estimating extremes. Following the ASCE 7-95 Standard, we defined loads inducing the design strength as the 50 yr loads times $(1.05)^2(\phi_w)$, where $\phi_w = 1.3$ is the wind load factor specified in the Standard for all regions and 1.05 is a hurricane importance factor specified in the Standard to account for probability distribution shapes. For any given load, the nominal mean recurrence interval (nominal MRI) was estimated for that load by ignoring the variation of the aerodynamic coefficients and the extreme wind climate with direction. The mean recurrence interval (MRI, without the qualifier "nominal") was estimated for that same load by accounting for that variation.

According to our results, loads with a relatively short MRI (50 yr, say) are generally smaller than loads whose nominal MRI is equal to that MRI. However, this is not necessarily true for large MRIs. This means that the method for estimating extreme wind loads used in the ASCE Standard and most other standards is not necessarily conservative from a structural engineering point of view.

We also found that MRIs of ultimate wind loads induced by hurricanes near the coastline, conditional on epistemic uncertainties being negligible, vary between less than 1000 yr to more than 10 000 yr, the average being, roughly, 3500 yr. The actual MRIs could be considerably smaller if, as is the case in practice, epistemic uncertainties are significant. This suggests that the ultimate wind loads specified by the ASCE Standard may result in unsafe designs, and that the Standard provisions defining ultimate wind loads for hurricane-prone regions need to be reassessed.

The estimates presented in this paper do not cover all possible dependences on site, building orientation, and aerodynamic properties and are therefore largely illustrative. However, the directional method for estimating wind loads presented in this paper can serve as a tool for assessing the adequacy of the specified wind load inducing the design strength, or any other design load, for any given site, orientation, or aerodynamics. Although results are affected by relatively large sampling errors and uncertainties in the simulation of hurricane wind speeds, in our opinion this tool can be useful for design and standard development purposes.

Acknowledgements

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Appendix A. Instructions for accessing datasets 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

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