PREDICTION OF HURRICANE WIND SPEEDS IN THE UNITED STATES

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ABSTRACT: Prediction of hurricane wind speeds using a simulation approach is the most universally accepted methodology for estimating design wind speeds in hurricane-prone regions of the world. An updated hurricane simulation methodology incorporating newly developed wind-field and filling models is used to obtain hurricane wind speeds associated with various return periods along the hurricane-prone coastline of the United States. Simulation results using the new hurricane simulation methodology indicate that design wind speeds given in ASCE-7-88 for the inland portion of the hurricane-prone coastline are excessive, and that the long-return-period wind speeds given in 1980 by Batts et al. are low. The simulation approach is extended to illustrate areawide hurricane area risk versus single-point risk by comparing hurricane risk for Dade County, Fla., to a single-point risk of a building in Miami, Fla.

INTRODUCTION

The use of mathematical simulation methods to estimate hurricane wind speeds was first implemented by Russell (1968, 1971) for the Texas coast. Others have used this approach for portions of the United States coastline (Russell and Schueller 1974; Tryggvason et al. 1976; Batts et al. 1980; Georgiou et al. 1983; Twisdale and Dunn 1983; Georgiou 1985). The study by Batts et al. (1980) was a milestone, being the first study to examine the entire United States coastline, and it provided a rational means to determine design wind speeds associated with the Gulf and Atlantic coasts of the United States. At the time the Batts study was being carried out, there was relatively little good quality, full-scale data available with which to evaluate the physical models used in the simulation. Although the Monte Carlo simulation methods used by Batts et al. (1980) and other investigators are similar, there are significant differences in the physical models, methods of analysis, and critical hurricane wind-field modeling details. This paper summarizes results from a recent National Science Foundation project funded to develop an improved prediction methodology for hurricane wind speeds (Twisdale and Vickery 1992) with an emphasis placed on the importance of the hurricane wind-field models and filling models used in the methodology. The wind-field model, based on the work of Shapiro (1983), and the filling models are described in detail in Vickery and Twisdale (1995).

Simulation results indicate that hurricane wind speeds at inland locations are significantly overestimated in the study performed by Batts et al. (1980) and consequently, the design wind speeds given in ASCE-7-88 ("Minimum" 1990) for most inland stations (less than 200 km from the hurricane coastline) are excessive.

SIMULATION METHODOLOGY

At any given location on the hurricane-prone coastline of the United States, there are insufficient direct wind-speed measurements to enable estimates of hurricane wind speeds as a function of return period to be determined using traditional methods. To overcome this limitation, an indirect method first developed by Russell (1968) is used. With this approach, statistical distributions are developed of the central pressure difference (Δp), translation speed (c), size of the hurricane ($R_{\max}$), and storm track and occurrence rate for a circular subregion centered on the site. The circular subregion approach was also used by Georgiou (1985) and Neumann (1991). Russell (1968), Russell and Schueller (1974), Tryggravson et al. (1976), Batts et al. (1980), and Twisdale and Dunn (1983) used a coast-crossing technique to derive the basic statistical distributions for Δp, c, θ, etc. Using the coast-crossing technique, straight-line segments radiating from the site are used, where storms crossing a given line segment are used to derive the basic input statistics. Neither approach (coast crossing or circular subregion) has an advantage over the other, and both are subject to the limitation that the selection of the subregion size or coastline segment length is arbitrary and requires subjective judgement. The effect of the subregion size selection on predicted hurricane wind speeds is discussed later.

The minimum basic parameters required to estimate wind speeds within a hurricane are the central pressure difference, Δp; the translation speed of the hurricane, c; and the size of the hurricane as defined by the radius to maximum winds, $R_{\max}$. These data are then used in a hurricane wind-field model to estimate wind speeds within the hurricane. Information on the direction of storm travel θ (defined as the direction of motion measured clockwise from true north), and the minimum distance from the site of interest, $d_{\min}$ (defined as positive if the site is located to the right of the storm), are also used to simulate the effects of the hurricane. In the study described here, the site-specific statistical distribution of central pressure difference, storm speed, etc., are obtained for storms passing within a prescribed distance of the site under examination.

The statistical distributions of the central pressure difference, the translation velocity of the hurricane, the angle of approach of the hurricane, and the distance from the center of the hurricane to site are derived from data given on the HURDAT diskettes obtained from the National Climatic Data Center in Asheville, N.C. The statistics of Δp, c, θ, and $d_{\min}$ are determined from information on all tropical storms passing within a certain distance of the site of interest (sample circle), between the years 1886 and 1991. These statistics are site-specific and vary significantly with location along the Gulf and Atlantic coastlines.

Using the site-specific probability distributions of Δp, c, θ, and $d_{\min}$ in conjunction with a hurricane wind-field model, thousands of hurricanes are simulated. Each simulated storm travels along a straight line path, defined using the sampled values of $d_{\min}$ and θ, through the simulation subregion. The sampled value of Δp is held constant until landfall, after which time the storm is decayed using the filling models described in Vickery and Twisdale (1995). The storm translation speed is held constant for each simulated storm. The maximum

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Note. Associate Editor: Ahsan Kareem. Discussion open until April 1, 1996. Separate discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on December 3, 1993. This paper is part of the ***Journal of Structural Engineering***, Vol. 121, No. 11, November, 1995. ©ASCE, ISSN 0733-9445/95/0011-1691–1699/\$2.00 + \$.25 per page. Paper No. 7006.

fastest-mile wind speeds at the site under investigation produced by each synthesized storm independent of direction and in each of 16 compass directions are recorded. The probability that the tropical storm wind speed (independent of direction) is exceeded during the time period, t, is

$$P(v > V) = \sum_{x=0}^{\infty} P(v > V|x)p_t(x) \tag{1}$$

where $P(v > V|x)$ = probability of the velocity, v, exceeding V given the occurrence of x storms; and $p_t(x)$ = probability of x tropical cyclones occurring during the time periods t. A uniform Poisson distribution is used to model the arrival rate statistics.

The probability that the tropical storm wind speed is exceeded during the time period, t, within the directional sector $\theta \pm \Delta\theta/2$ is

$$P(v > V, \theta) = [n(\theta)/N] \sum_{x=0}^{\infty} P_\theta(v > V|x)p_t(x) \tag{2}$$

where $P_\theta(v > V|x)$ = probability of the velocity v exceeding V given that x storms occur and produce a wind speed with a direction $\theta \pm \Delta\theta/2$; $n(\theta)$ = number of simulated storms producing a wind speed within the direction $\theta \pm \Delta\theta/2$; and N = total number of storms simulated.

The simulation methodology uses site-specific statistical models defining Δp, c, θ, $d_{\min}$, and $R_{\max}$, a physical model defining the hurricane wind field, and region-specific statistical models for the rate of decay of hurricanes after reaching land. The site-specific models for statistical models described in the following sections, and the filling rate models and wind-field models are described in Vickery and Twisdale (1994).

STATISTICAL MODELS

Translation Velocity

The translation velocity of the tropical storm, c, is modeled using a lognormal distribution. The translation velocity is determined using the 6-h position data given in the HURDAT database. Along the Gulf Coast and South Atlantic coasts, a positive correlation between the translation velocity and the storm direction, θ, is observed. This correlation exists because storms that have recurved toward the north, on average, travel faster than those that have not yet recurved. Along the North Atlantic coast, virtually all storms have recurved and no correlation between heading and speed was observed. To take into account the correlation between the translation velocity, c, and heading, θ, the logarithmic mean of the translation velocity is modeled in the following form:

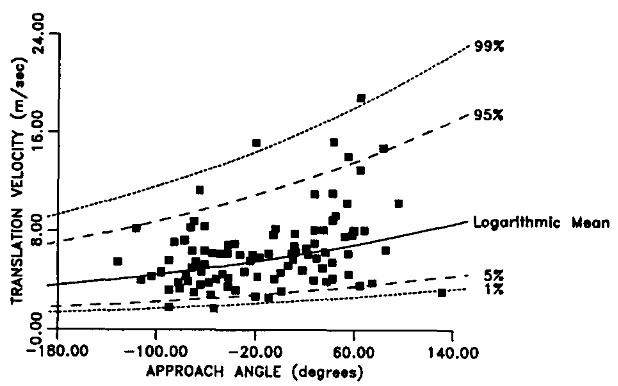
$$m_{\ln c} = a_0 + a_1\theta \tag{3}$$

where $m_{\ln c}$ = logarithmic mean of the translation speed; and a_0 and a_1 = constants determined using the method of maximum likelihood. The logarithmic standard deviation, $\sigma_{\ln c}$, is treated as a constant. Fig. 1 shows the modeled and observed relationship between heading and translation speed for storms in the Miami region and in the Galveston, Tex., region.

Approach Angle

The characteristics of the approach angle θ vary significantly along the coastline. We examined the von Mises distribution and a normal distribution, and with few exceptions, these distributions were rejected. The approach angle at all locations examined was found to be best modeled using a binormal distribution. Fig. 2 shows the fitted and observed distribution of the approach angle at Key West, Fla., and Wilmington, N.C. Note that for Key West, the bimodal char-

(a) MIAMI, FL



(b) Galveston, TX

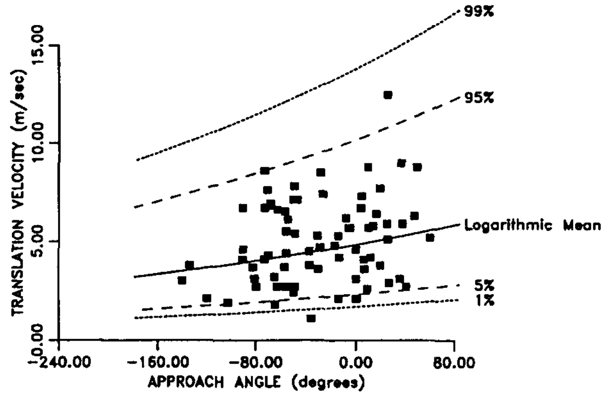


FIG. 1. Modeled and Observed Relationships between Storm Translation Speed and Approach Angle: (a) Miami; (b) Galveston, Tex.

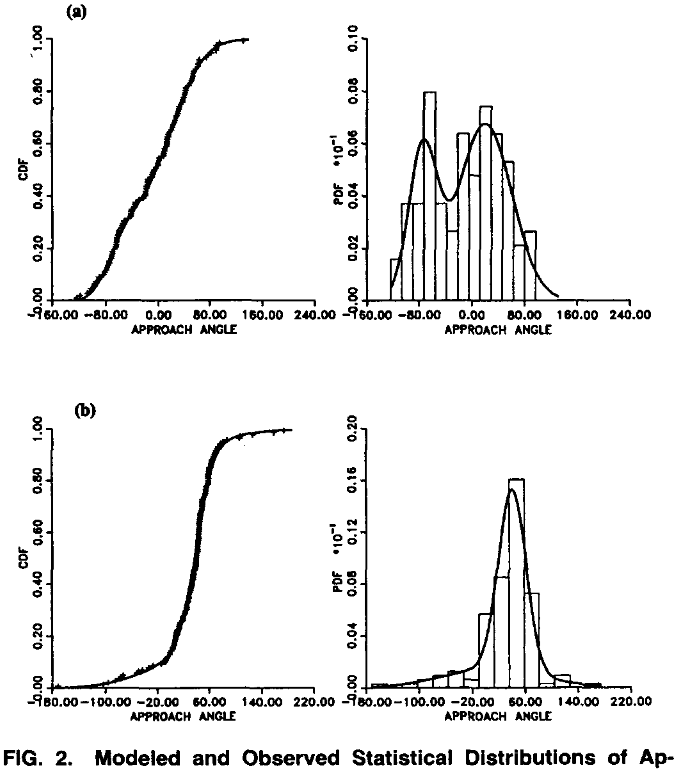


FIG. 2. Modeled and Observed Statistical Distributions of Approach Angle: (a) Key West, Fla.; (b) Wilmington, N.C.

acteristics of approaching hurricanes is clearly evident. This bimodal characteristic in the Key West region is produced by separate tropical cyclone populations, the first of which originate in the Atlantic and approach from easterly directions ($\theta = -90°$), and the second of which originate in the Gulf of Mexico and approach from westerly directions. This distinct bimodal approach angle characteristic is evident at all locations in South Florida and is noted in Ho et al. (1987).

Distance of Closest Approach

The distance of closest approach $d_{\min}$ is modeled at all stations examined using either a uniform or trapezoidal distribution.

Central Pressure Difference

The central pressure difference, Δp, is modeled using a Weibull distribution. To convert the central pressure data given in the HURDAT diskettes to a central pressure difference, a periphery pressure of 1,013 millibar (mbar) is used. The choice of a Weibull distribution was first suggested by Georgiou (1985) and was validated in this investigation. The lognormal distribution used by others (Russell 1968; Tryggvason et al. 1976; Batts et al. 1980; Twisdale and Dunn 1983) was found to be a poor model for the central pressure difference for all tropical cyclones; however, the lognormal distribution is suitable if only hurricanes ($\Delta p > 28$ mbar) are used in the simulation procedure. At some of the locations examined (South Florida, New York City area, South Carolina), there is a statistically significant correlation between Δp and the approach angle. In the South Florida region this correlation is attributed to the fact that storms generated in the Atlantic Ocean, which approach from the east, are usually more intense than those generated in the Gulf of Mexico, which approach from westerly directions. In the New York and South Carolina regions, the correlation between Δp and θ is attributed to the fact that storms with northeasterly direction components have, in general, during their history, passed over land and have weakened. The effect of the correlation between Δp and θ was included by modeling the scale parameter in the Weibull distribution as a linear function of the storm heading. The parameters describing the linear relationship between Δp and θ are determined using the maximum likelihood technique.

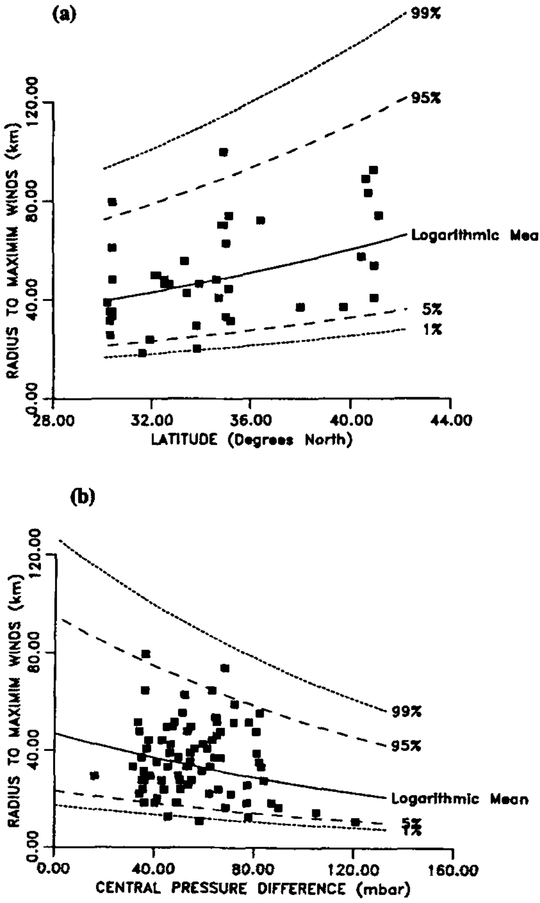


FIG. 3. Statistical Distributions for $R_{\max}$ Used in Simulation Methodology: (a) North of 30°N; (b) Between 22°N and 30°N

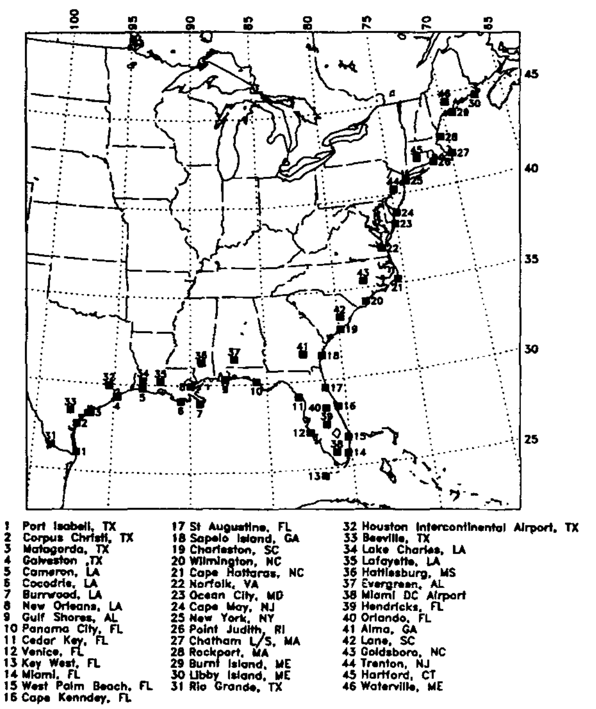


FIG. 4. Locations of Sites Examined for Predictions of Hurricane Wind Speeds

Radius to Maximum Winds

Using the $R_{\max}$ and Δp data given in Ho et al. (1987), relationships between $R_{\max}$ and Δp and $R_{\max}$ and latitude, ψ, were developed. Using all the $R_{\max}$ and Δp data yields a correlation coefficient of -0.23 between $R_{\max}$ and Δp, and a positive correlation coefficient of 0.47 between $R_{\max}$ and latitude. Both correlation coefficients are significant at the 5% level of confidence. The $R_{\max}$-Δp information was separated into two groups, one for storms located between 22°N and 30°N (Florida and Gulf Coast region) and the other for storms north of 30°N (Atlantic Coast). Within the first latitude group, a correlation coefficient -0.18 exists between Δp and $R_{\max}$ (significant at the 10% level); and a smaller correlation of 0.14 between $R_{\max}$ and latitude is not significant. Within the second latitude group a correlation coefficient of 0.4 (significant at the 1% level) exists between Δp and latitude, and the negative correlation between $R_{\max}$ and Δp is not statistically significant.

In the simulation procedure, for locations south of 30°N, $R_{\max}$ is modeled using a lognormal distribution with the lognormal parameters given as

$$m_{\ln R_{\max}} = 3.853 - 0.0061\Delta p; \quad \sigma_{\ln R_{\max}} = 0.427 \qquad (4a,b)$$

For storms north of 30°N the lognormal parameters are modeled using

$$m_{\ln R_{\max}} = 2.395 + 0.0426\psi; \quad \sigma_{\ln R_{\max}} = 0.369 \qquad (5a,b)$$

where ψ = latitude of the site.

The observed and modeled relationships between $R_{\max}$ and Δp, and $R_{\max}$ and ψ are shown in Fig. 3.

SIMULATIONS FOR COASTAL AND INLAND STATIONS

Coastal Stations

Simulations were performed at the 30 coastal and 16 inland stations shown in Fig. 4. Predicted 50- and 100-yr return period wind speeds are given in Tables 1 and 2 for coastal stations. All simulations were performed for site subregions that had a diameter of 500 km, with 10,000 storms simulated at each site. Results are given for the Shapiro-based (Vickery and Twisdale 1995) wind-field model coupled with the new filling-rate model, and with the Batts wind-field model coupled with both the new filling-rate model and the filling-rate model used by Batts et al. (1980). Comparing the results obtained using the different wind-field/filling models shows the effect of these components on the final predictions. Comparisons to the results obtained from Batts et al. (1980) are given for both the 50-yr and 100-yr return period wind speeds. Comparison of the predicted 100-yr return period wind speeds with those obtained by Georgiou (1985) are also presented. Table 1 also presents the recommended design wind speeds given in ASCE-7-88 ("Minimum" 1990), which are based principally on the results given in Batts et al. (1980). Fig. 5 compares the 50-, 100-, and 2,000-yr return period wind speeds versus the milepost obtained using the Shapiro-based wind-field model, new filling-rate models, and site-specific statistical distributions for Δp, c, $d_{\min}$, and θ (here referred to as HURSIM), to the results given in Batts et al. (1980). The results clearly indicate that for rarer events (direct strikes by the eyewall), the Shapiro-based results exceed those given in Batts et al. (1980) and are more consistent with the maximum wind speeds in severe hurricanes.

The predicted 50- and 100-yr return period wind speeds derived in this study (using either wind-field/filling model combination) vary more rapidly with changes in position along the coastline than do those presented in Batts et al. (1980). This more rapid change with location is attributed to a combination of the modeling of the central pressure (using all tropical cyclones and a Weibull distribution) and the size of the sample subregion. In the study performed by Batts et al. (1980) all hurricanes making landfall 470 km to the left of the site (downcoast) and 370 km to the right of the site (upcoast) were used to derive statistics for Δp, etc. This large sample region smears any local climatological features that may exist at a particular site, decreasing wind speeds in regions subject to high hurricane activity, which are near those regions having relatively low hurricane activity, and conversely increasing wind speeds in adjacent regions experiencing reduced hurricane activity.

The most notable differences between the results obtained in this study and the results presented in Batts et al. (1980) are the lower predicted wind speeds (50- and 100-yr return period) obtained here along the Texas coast between Corpus Christi and Galveston, and the increase in predicted wind speeds along the New Orleans, Alabama, Mississippi, and Florida panhandle coastlines. We were unable to resolve differences in the wind speeds given in Batts et al. (1980) along the Texas coast between Corpus Christi and Galveston, which are much higher than the wind speeds obtained in this investigation using the HURSIM models. It is noted that these lower wind speeds are also evident in investigations per-

TABLE 1. 50-yr Return Period Fastest-Mile Wind Speeds at Coastal Locations

		PREDICTED FASTEST-MILE WIND SPEEDS									
		Vickery and Twisdale (1995)		Batts Wind New Filling		Batts Wind Batts Filling		Batts et al. (1980)		ASCE-7-88	
Location (1)	Milepost (2)	m/s (3)	mi/hr (4)	m/s (5)	mi/hr (6)	m/s (7)	mi/hr (8)	m/s (9)	mi/hr (10)	m/s (11)	mi/hr (12)
Port Isabell, Tex.	150	44	98	42	94	42	93	44	98	45	100
Corpus Christie, Tex.	250	39	87	36	81	36	80	43	96	42	95
Matagorda, Tex.	320	40	90	38	85	38	85	42	93	42	95
Galveston, Tex.	400	43	96	40	90	39	87	41	92	44	98
Cameron, La.	480	41	93	37	82	37	83	41	91	43	97
Cocodrie, La.	620	47	105	42	93	42	94	41	91	47	105
Burrwood, La.	700	49	109	45	101	45	100	41	92	47	105
New Orleans, La.	720	45	101	40	90	42	93	41	92	45	100
Gulf Shores, Ala.	820	48	107	43	96	43	96	41	91	45	100
Panama City, Fla.	920	45	102	40	90	40	90	39	87	44	99
Cedar Key, Fla.	1,120	43	96	37	83	38	85	40	89	43	97
Venice, Fla.	1,280	44	98	40	90	42	95	46	102	45	100
Key West, Fla.	—	50	111	45	101	45	100	—	—	51	115
Miami, Fla.	1,460	51	114	47	105	47	105	48	107	49	115
West Palm Beach, Fla.	1,510	50	112	44	99	45	100	46	104	46	102
Cape Canaveral, Fla.	1,610	43	95	38	85	40	89	44	99	43	97
St. Augustine, Fla.	1,700	43	96	38	85	42	95	41	92	42	95
Sapelo Island, Ga.	1,800	40	89	35	79	38	84	38	86	41	92
Charleston, S.C.	1,920	45	101	41	92	39	88	42	95	43	97
Wilmington, N.C.	2,050	48	107	41	92	42	94	43	96	45	100
Cape Hatteras, N.C.	2,180	46	103	42	94	44	98	44	98	49	110
Norfolk, Va.	2,280	40	90	35	79	41	92	42	93	40	90
Ocean City, Md.	2,380	41	93	38	85	41	92	36	81	40	90
Cape May, N.J.	2,450	41	92	38	86	42	93	37	81	37	83
New York, N.Y.	2,530	40	89	36	81	37	83	41	91	37	82
Port Judith, R.I.	2,650	42	94	36	81	38	85	43	96	39	88
Chatham L/S, Mass.	2,720	44	98	37	83	39	86	42	93	42	95
Rockport, Mass.	2,800	41	92	35	85	38	86	38	85	38	85
Burnt Island, Me.	2,910	39	87	32	72	33	75	33	74	34	88
Libby Island, Me.	3,050	39	87	32	72	32	72	—	—	—	—

TABLE 2. 100-yr Return Period Fastest-Mile Wind Speeds at Coastal Locations

		PREDICTED FASTEST-MILE WIND SPEEDS									
		Vickery and Twisdale (1995)		Batts Wind New Filling		Batts Wind Batts Filling		Batts et al. (1980)		Georgiou (1985)	
Location (1)	Milepost (2)	m/s (3)	mi/hr (4)	m/s (5)	mi/hr (6)	m/s (7)	mi/hr (8)	m/s (9)	mi/hr (10)	m/s (11)	mi/hr (12)
Port Isabell, Tex.	150	50	112	45	101	46	102	48	107	58	129
Corpus Christie, Tex.	250	45	100	40	90	40	90	48	107	55	122
Matagorda, Tex.	320	45	101	41	91	41	93	47	105	55	122
Galveston, Tex.	400	48	108	42	94	42	95	46	102	57	126
Cameron, La.	480	46	102	40	90	40	90	45	101	59	132
Cocodrie, La.	620	52	116	47	105	45	102	45	101	61	136
Burrwood, La.	700	54	121	47	106	47	106	45	100	61	137
New Orleans, La.	720	50	112	43	96	45	100	45	101	61	137
Gulf Shores, Ala.	820	53	119	46	102	46	104	45	101	60	135
Panama City, Fla.	920	50	111	43	96	43	96	43	96	58	129
Cedar Key, Fla.	1,120	47	106	41	92	41	92	42	95	53	118
Venice, Fla.	1,280	49	110	43	96	47	106	50	111	59	131
Key West, Fla.	—	55	124	51	114	49	109	—	—	—	—
Miami, Fla.	1,460	57	127	52	116	52	116	51	114	66	148
West Palm Beach, Fla.	1,510	56	125	48	107	49	110	51	113	66	148
Cape Canaveral, Fla.	1,610	48	108	42	94	46	103	48	108	63	140
St. Augustine, Fla.	1,700	48	107	42	94	48	107	44	99	56	125
Sapelo Island, Ga.	1,800	45	102	38	85	42	95	42	93	53	118
Charleston, S.C.	1,920	52	116	45	101	44	99	47	105	56	125
Wilmington, N.C.	2,050	53	119	48	107	45	100	47	105	56	126
Cape Hatteras, N.C.	2,180	52	116	48	107	49	110	48	107	55	122
Norfolk, Va.	2,280	44	99	38	85	45	101	44	99	51	114
Ocean City, Md.	2,380	46	104	40	89	47	105	41	92	46	102
Cape May, N.J.	2,450	46	104	42	94	46	102	42	93	50	112
New York, N.Y.	2,530	45	102	41	92	42	94	45	101	53	119
Port Judith, R.I.	2,650	46	103	39	87	41	91	47	105	54	120
Chatham L/S, Mass.	2,720	48	108	40	89	42	94	46	103	54	121
Rockport, Mass.	2,800	46	103	39	87	42	94	43	96	49	110
Burnt Island, Me.	2,910	43	96	35	78	37	83	38	86	44	99
Libby Island, Me.	3,050	43	96	34	76	35	79	—	—	—	—

formed by Georgiou et al. (1983) and Sanchez-Sezma et al. (1988), suggesting that the predicted wind speeds given in Batts et al. (1980) are excessive in this region. A reduction in predicted wind speeds on the west coast of the Florida peninsula is attributed to the new filling-rate model reducing the intensity of hurricanes approaching from the Atlantic Ocean and crossing the Florida peninsula. The predicted wind speeds on the west coast of Florida presented here are considered to be conservative because in this region the most intense hurricanes approach from an easterly direction, thus the strongest winds also approach from approximately easterly directions and will be reduced because of frictional effects, not included in the study for coastal locations (Vickery and Twisdale 1995) because the wind field treats coastal locations for onshore winds. At most other coastal locations examined here, the dominant wind direction associated with the simulated storms approaches from over water, indicating that the coastal exposure (onshore winds) assumption used in the wind-field model is appropriate. For locations along the Atlantic Coast, north of the South Carolina–North Carolina border, differences between results obtained in this study and those given in Batts et al. (1980) are not significantly different, and both results are believed to be conservative as a result of the wind-field model limitations associated with water temperature discussed in Vickery and Twisdale (1995).

Table 2 compares the 100-yr return period fastest-mile wind speeds obtained here to those given in Georgiou (1985) and Batts et al. (1980). The fastest-mile wind speeds, given in Georgiou (1985) as mean hourly values, were converted to fastest-mile wind speeds using the gust factor curve derived by Krayer and Marshall (1992). The Georgiou (1985) results appear high in comparison to the results of this investigation and other studies. The wind speeds given in Georgiou et al. (1983) agree reasonably well with those obtained here.

Inland Stations

Predicted 50- and 100-yr return period fastest-mile winds at the 16 inland stations examined are given in Tables 3 and 4. Simulations were performed using the HURSIM models, the Batts wind-field model coupled with both the HURSIM filling models, and the filling rate model used by Batts et al. (1980). The distance from the coastline for the stations examined varies between 40 and 100 km. The wind speeds obtained using the Shapiro-based models are significantly lower than those predicted using the Batts wind-field model coupled with the Batts filling model. The majority of the reduction in wind speeds is associated with the new wind-field model, rather than the new filling model. The relative contribution to the reduction in wind speed associated with the wind-field model and the filling model varies from site to site, and is a function of the local geography and the heading of the tropical cyclones. The results obtained using HURSIM models, which are shown in Vickery and Twisdale (1995) to be significant improvements over the models used in Batts et al. (1980), suggest that with the exception of the Florida peninsula, for locations 100 km or farther from the coast, the influence of hurricanes on the 50- and 100-yr return period wind speeds can be ignored. For locations less than 100 km from the coast, the combined influence of both hurricanes and nonhurricane winds needs to be considered, and for return periods of longer than approximately 100 yr, the influence of hurricanes may need to be considered. Comparisons of the 50-, 100-, and 2,000-yr predicted wind speeds derived using HURSIM models and those given in Batts et al. (1980) for the 16 inland stations

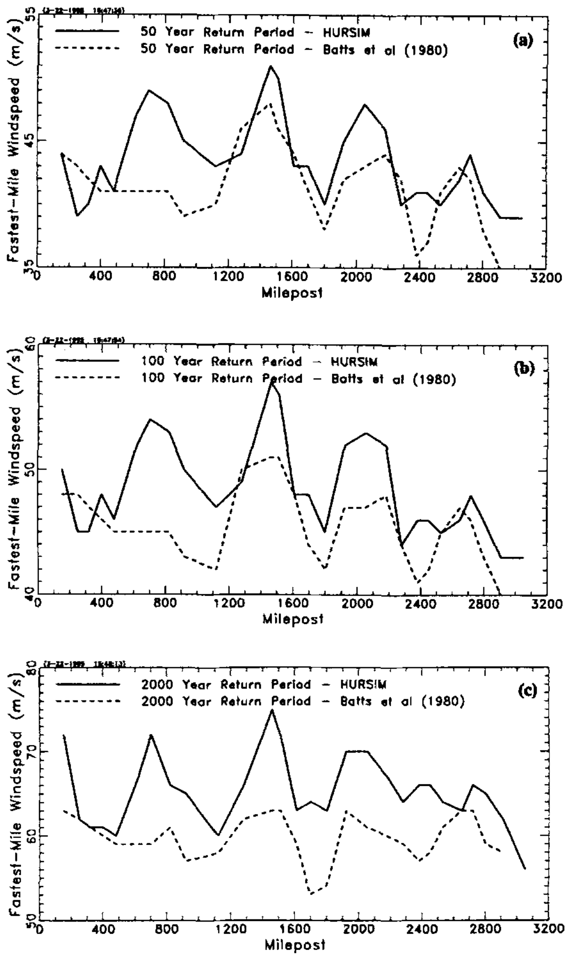


FIG. 5. Comparisons of Predicted Wind Speeds Obtained Using HURSIM Models and those Derived by Batts et al. (1980) for Coastal Stations

are plotted versus approximate milepost in Fig. 6. The HURSIM wind speeds are consistently lower than those of Batts et al. (1980) for all locations and all return periods. It is noteworthy that the results given in Batts et al. (1980) indicate that the 100-yr return period wind speeds 200 km inland from the coast at mileposts 500–600 and milepost 1,450 are identical to those wind speeds at the coast, raising questions as to the validity of the results of Batts et al. (1980) for inland locations.

SENSITIVITY STUDIES FOR MIAMI AND NEW YORK

Miami

Statistical distributions of the location dependent parameters ($d_{\min}$, Δp, θ, and c) for storms centered around Miami were derived for sample circles having diameters ranging between 200 and 1,000 km. Sensitivity studies examining the effects of parameter correlation, storm decay models, etc., were performed for a 500-km diameter sample subregion. Table 5 presents the values of each of the input statistical distribution parameters used in the Miami simulation for the 500-km diameter subregion.

Correlation

Table 6 shows the results of a correlation analysis of the four variables (Δp, c, $d_{\min}$, and θ) and the year of observation. As eluded to earlier, the correlation between Δp and θ is consistent with the observation that storms approaching from the east (generated off the African coast) are generally more intense than those generated in the Gulf of Mexico; and the correlation between the translation velocity, c, and the heading of the storm is consistent with the observation that storms that have recurved towards the north move faster than the easterly storms that have not recurved.

The negative correlation between Δp and year was observed at most stations examined. This negative correlation is primarily attributed to the fact that prior to the 1960s, there is a significant bias in recorded central pressures, where data are available only for the more significant storms. During the 1970s and later, central pressure data is given for all storms at each of the 6-h position on the HURDAT diskettes. This bias in the central pressure records suggests that there may be some conservatism in the statistical distributions of Δp.

Using statistics derived from the 500-km-diameter sample subregion and the Batts wind-field model, sensitivity studies examining the effect of correlated sampling and distribution censoring showed that including the correlation between Δp and θ, and θ and c produced changes in the 50- and 100-yr return period wind speeds of less than 2%. If the correlation between Δp and $R_{\max}$ is ignored, the predicted wind speeds are increased by 10% to 20%, depending on the return period. The effects of censoring the sampled values of the cen-

TABLE 3. 50-yr Return Period Fastest-Mile Wind Speeds at Inland Locations

Location (1)	Distance inland (2)	PREDICTED FASTEST-MILE WIND SPEEDS							
		Vickery and Twisdale		Batts Wind New Filling		Batts Wind Batts Filling		ASCE-7-88	
		m/s (3)	mi/hr (4)	m/s (5)	mi/hr (6)	m/s (7)	mi/hr (8)	m/s (9)	mi/hr (10)
Rio Grande, Tex.	100	22	49	30	67	31	69	36	80
Houston IAH, Tex.	60	33	74	37	83	37	83	38	85
Beeville, Tex.	60	27	60	31	70	32	72	37	92
Lake Charles, La.	50	34	77	47	83	37	83	41	92
Lafayette, La.	40	34	76	36	81	36	81	42	95
Hattiesburg, Miss.	100	32	72	40	90	42	93	39	87
Evergreen, Ala.	100	28	63	34	75	36	80	37	83
Miami DC Airport, Fla.	70	40	90	44	99	44	98	47	105
Hendricks, Fla.	90	32	72	37	83	41	92	43	97
Orlando, Fla.	60	35	78	34	77	39	87	42	95
Alma, Ga.	100	25	57	29	65	33	74	34	75
Lane, S.C.	60	35	77	37	83	41	92	39	88
Goldsboro, N.C.	100	29	64	32	72	39	87	35	78
Trenton, N.J.	60	36	80	36	81	39	87	34	75
Hartford, Conn.	60	34	77	35	78	37	83	34	75
Waterville, Me.	70	32	72	30	68	31	70	38	85

TABLE 4. 100-yr Return Period Fastest-Mile Wind Speeds at Inland Locations

		PREDICTED FASTEST-MILE WIND SPEEDS					
		Vickery and Twisdale		Batts Wind New Filling		Batts Wind Batts Filling	
Location (1)	Distance inland (2)	m/s (3)	mi/hr (4)	m/s (5)	mi/hr (6)	m/s (7)	mi/hr (8)
Rio Grande, Tex.	100	25	57	33	74	35	79
Houston IAH, Tex.	60	37	82	35	78	39	88
Beeville, Tex.	60	32	71	34	77	36	81
Lake Charles, La.	50	39	87	39	87	40	90
Lafayette, La.	40	38	85	39	88	39	87
Hattiesburg, Miss.	100	36	81	43	96	46	103
Evergreen, Ala.	100	31	70	37	83	39	87
Miami DC Airport, Fla.	70	45	100	47	105	48	108
Hendricks, Fla.	90	36	80	42	94	45	101
Orlando, Fla.	60	39	87	38	85	41	92
Alma, Ga.	100	29	65	32	72	36	80
Lane, S.C.	60	38	86	40	90	45	100
Goldsboro, N.C.	100	33	73	37	83	43	96
Trenton, N.J.	60	40	90	39	87	44	99
Hartford, Conn.	60	38	85	37	83	41	92
Waterville, Me.	70	35	79	33	74	35	78

tral pressure difference to be less than 150 mbar and forcing R_{max} to be greater than 5 km and less than 150 km were both negligible, changing predicted wind speeds by less than 1/2%.

Subregion Size

The effect of diameter of the subregion circle was examined using the Shapiro-based representation of the hurricane wind field. Ten thousand storms were simulated for subregions of 300 km in diameter through to 1,000 km in diameter. The investigation showed that the predicted 50-yr return period wind speed ranged between a maximum of 55 m/s (124 mi/hr) for a sample subregion diameter of 300 km to a minimum of only 47 m/s (106 mi/hr) for a sample subregion diameter of 1,000 km. This 15% reduction in wind speed is reflected in predictions for other return periods as well. Most of the difference in the predicted wind speeds is caused by changes in the central pressure statistics with increasing circle diameter.

Return Period and Direction

Fig. 7 shows the resulting predicted wind speeds as a function of return period and direction for Miami obtained using both the Batts windfield model and the Shapiro-based windfield model. It is particularly noteworthy that the predicted wind speeds for long return periods are much greater when the Shapiro-based wind-field model is used to model the hurricane wind field. These larger wind speeds arise because the model more accurately represents the radial distribution of wind speed within the storm, where it does not underestimate the wind speeds within the eyewall region at the coastline. The directional characteristics of the predicted wind speeds obtained using the two different wind-field models exhibit some differences. The major difference is evident for westerly winds, where the Batts wind-field model yields higher wind speeds than the Shapiro-based wind-field model. The higher westerly winds predicted using the Batts model are caused by an overestimate in the magnitude of wind speeds modeled on the left side of the hurricane, and not because of the modeling of the wind direction itself.

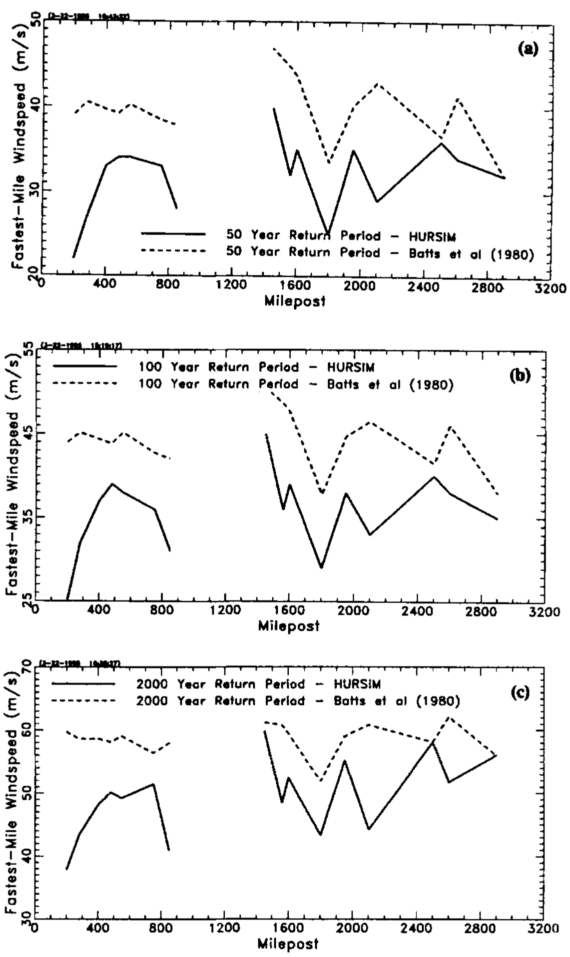


FIG. 6. Comparisons of Predicted Wind Speeds Obtained Using HURSIM Models and those Derived by Batts et al. (1980) for Inland Stations

Area versus Point Windspeed Exceedance Events

In addition to the point simulation for Miami used in this investigation and most others, a simulation was performed in which the maximum wind speeds produced by each storm at Miami were recorded, as were the maximum wind speeds at any point on the Dade County coastline. Fig. 8 shows a comparison of the predicted wind speeds for both a single-point location (of a few kilometers in length) in Miami and at any location on the Dade County coastline. The results indicate that the 100-yr return period fastest-mile wind speed at a single location in the Miami area is about 57 m/s (127 mi/hr), however the 100-yr return period fastest-mile wind speed for any location along the Dade County coastline is about 66 m/s (147 mi/hr). The wind speed predictions for the Dade County area indicate that on average, somewhere in Dade County, a fastest-mile wind speed of 45 m/s (100 mi/hr) will be exceeded once every 15 yrs. Although this result is not important for specifying the design wind speed for any single structure, it provides a better means to estimate the expected annual losses associated with hurricanes in a particular region. Clearly, if the heavily populated Broward County coastline had been included in this simulation, the predicted wind speeds for a given return period for this longer coastline segment would be higher, or conversely, the return period associated with a 45 m/s (100 mi/hr) fastest-mile wind speed would be lower. Examining hurricane wind speeds with a regional approach enables the frequency of intense storms that make landfall in the United States to be examined in a more rational manner. For example, in the case of Hurricane Andrew in

TABLE 5. Distributions and Distribution Parameters Used for Simulation of Hurricanes in Miami Region

Parameter (1)	Distribution (2)	Probability-density function $f_x(x)$ (3)	Distribution parameters (4)
$d_{\min}$ (km)	Uniform	a_2	$a_2 = 0.002;\ -R \le x \le R$
θ	Bi-Normal	$\frac{a_1}{\sqrt{2\pi}\sigma_{x1}} \exp\left[-\frac{1}{2}\left(\frac{x - m_{x1}}{\sigma_{x1}}\right)^2\right] + \frac{(1 - a_1)}{\sqrt{2\pi}\sigma_{x2}} \exp\left[-\frac{1}{2}\left(\frac{x - m_{x2}}{\sigma_{x2}}\right)^2\right]$	$m_{x1} = -51.6;\ \sigma_{x1} = 38.1;\ m_{x2} = 37.3$ $\sigma_{x2} = 33.0;\ a_1 = 0.55$
c (m/s)	Lognormal	$\frac{1}{x\sqrt{2\pi}\sigma_{\ln x}} \exp\left[-\frac{1}{2}\left(\frac{\ln x - m_{\ln x}}{\sigma_{\ln x}}\right)^2\right]$	$m_{\ln x} = 1.768 - 0.002750\theta;\ \sigma_{\ln x} = 0.413$
Δp (mbar)	Weibull	$\frac{k}{C}\left(\frac{x}{C}\right)^{k-1} \exp\left[-\left(\frac{x}{C}\right)^k\right]$	$C = 33.68 - 0.1334\theta;\ k = 1.15$
$R_{\max}$ (km)	Lognormal	$\frac{1}{x\sqrt{2\pi}\sigma_{\ln x}} \exp\left[-\frac{1}{2}\left(\frac{\ln x - m_{\ln x}}{\sigma_{\ln x}}\right)^2\right]$	$m_{\ln x} = 3.85 - 0.00607\Delta p;\ \sigma_{\ln x} = 0.427$
λ	Poisson	$\frac{\lambda^x e^{-\lambda}}{x!}$	$\lambda = 1.22$

Note: m_x = mean of x; σ_x = standard deviation of x; $m_{\ln x}$ = mean of the logarithm of x; $\sigma_{\ln x}$ = standard deviation of the logarithm of x; and R = radius of the simulation subregion.

TABLE 6. Results of Correlation Analysis for Miami

	Year	$d_{\min}$	θ	c (m/s)	Δp (mbar)
Year	1	0	0	0	−0.71
$d_{\min}$		1	0	0	0
θ			1	0.33	−0.29
c				1	0
Δp (mbar)					1

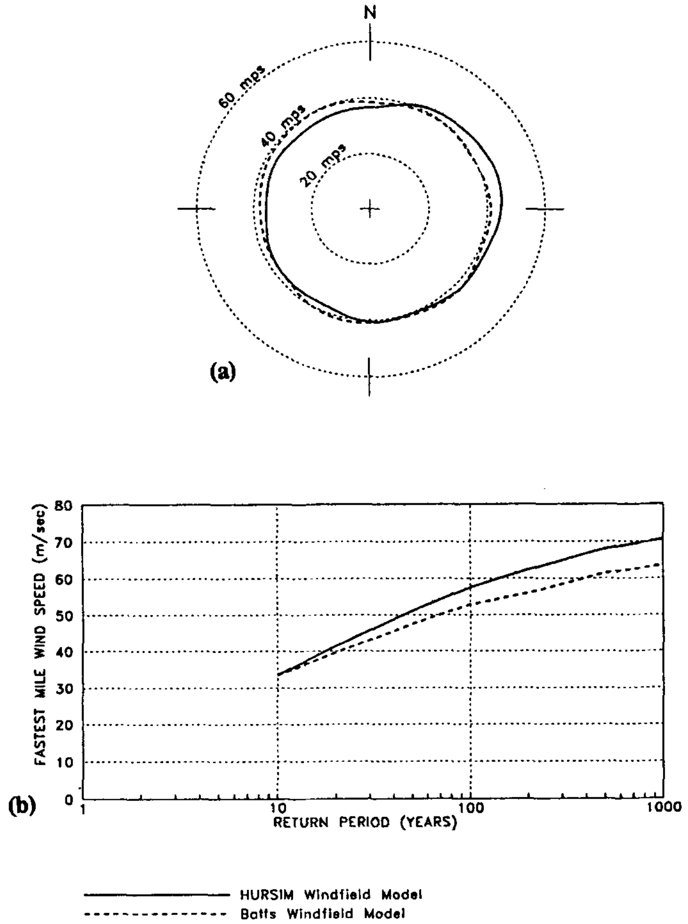


FIG. 7. Comparisons of Predicted Wind Speeds for Miami Showing Effect of Wind-Field Model on Predicted Wind Speeds

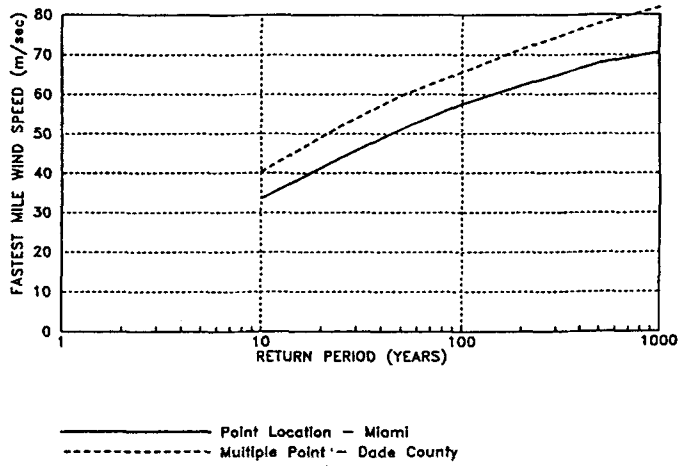


FIG. 8. Comparison of Predicted Wind Speeds for Miami (Point Location) and Dade County, Fla.

1992, the maximum fastest-mile wind speeds were on the order of 65 m/s (145 mi/hr) (Reinhold et al. 1993), and when considering a single point in the Miami region, this wind speed is associated with a return period of about 300 yr; however, the return period of this wind speed anywhere in Dade County, Florida is only about 100 yr. Using the results of Batts et al. (1980), the 65 m/s (145 mi/h) fastest-mile wind speed produced by Hurricane Andrew corresponds to a return period well in excess of 2,000 yr.

New York

Statistical distributions of the location-dependent parameters ($d_{\min}$, Δp, θ, and c) for storms centered on New York City were derived for subregion diameters ranging from 200 to 800 km. The distribution defining $d_{\min}$, Δp, θ, and c were all markedly influenced by changes in the sample subregion size (unlike Miami, where only the probability distribution of the central pressure difference was markedly influenced by the subregion size). Correlations between variables were found to change significantly with subregion size.

The predicted wind speeds given in Fig. 9 present results obtained using both the Batts and the Shapiro-based wind-field models combined with the HURSIM filling model for a 500-km-diameter subregion, so that the differences in results are the effect of different wind-field models only. Using the Batts wind-field model, the strongest winds are predicted to

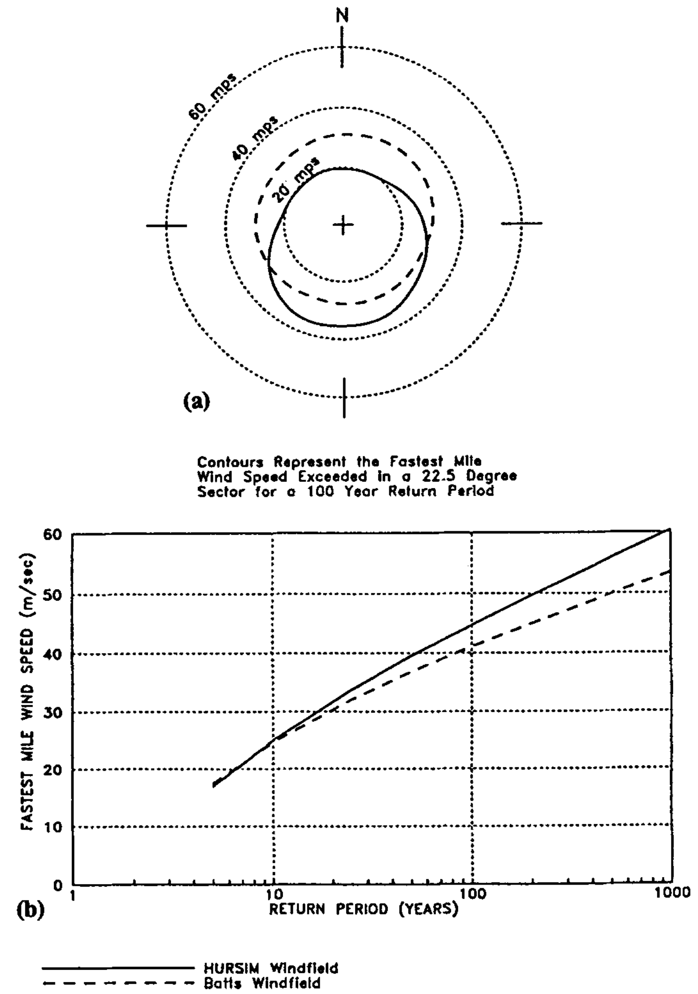


FIG. 9. Predicted Wind Speeds versus Return Period for New York Showing Effect of Wind-Field Model on Predicted Wind Speeds

approach from the north; whereas those predicted using the Shapiro-based wind-field model are easterly though southerly. The difference in directionality is again produced by the manner in which the translation speed of the storm is modeled. The empirical Batts wind-field model adds (subtracts) one-half of the translation speed to the right (left) side of the storm. The Shapiro-based wind-field model properly includes the full value of the storm motion, resulting in a more asymmetric storm. Along the northeast Atlantic coast, where hurricanes translate much faster than they do in the south Atlantic and Gulf regions, the impact of the translation speed on the wind-field is more pronounced than it is in the lower latitudes.

SUMMARY AND CONCLUSIONS

The Shapiro-based methodology incorporates significant improvements in filling models and wind-field models, and improved modeling of the correlations between key parameters used in the simulation procedure. The comparison of predicted wind speeds for return periods of 50, 100, and 2,000 yr shown in Fig. 5 reflects wind-field model differences where for rare events, wind speeds predicted using a Shapiro-based method are significantly higher than those given in Batts et al. (1980).

These new results suggest that for locations 100 km or farther from the coast, hurricanes contribute little to the design wind speeds for return periods of 100 yr or less. Hurricane winds may need to be considered when designing for less frequent events, and in such cases a site-specific study is recommended.

The results indicate that subregion identification is an important part of the simulation process. At this time a subregion diameter on the order of 500 km is recommended; however, improvements in the simulation methodology that will eliminate the subregion difficulties need to be examined in future research efforts.

The choice of the wind-field model has a significant impact on predicted wind speeds. This impact is particularly noteworthy where estimates of wind speed as a function of direction are required and it is felt that the directional data given in Batts et al. (1980) should not be used. Further comparisons between simulated and measured wind speeds in hurricanes are essential for improving the reliability of predicted windspeeds. These comparisons are particularly important for hurricanes along the North Atlantic coast, where not only is the colder water expected to influence results, but many of the hurricanes move at much higher speeds than those used to evaluate the wind-field models.

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