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Joint distribution model for prediction of hurricane wind speed and size

Yue Wang [a,1], David V. Rosowsky [a,b,*]

[a] Department of Civil and Environmental Engineering, Rensselaer Polytechnic Institute, 110 8th St., Troy, NY 12180, United States
[b] Department of Engineering, Rensselaer Polytechnic Institute, 110 8th St., Troy, NY 12180, United States

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ABSTRACT

This paper suggests a methodology for characterizing the joint distribution of hurricane intensity (maximum wind speed) and size (radius of maximum winds). Such a model represents an extension of traditional wind hazard models by including joint information on the critical spatial dimension. Typically, the hurricane hazard is described in terms of maximum wind speed V_{max} (at the eye-wall), since damage descriptors associated with intensity scales (e.g., the Saffir–Simpson Hurricane Scale) and collateral hazards (e.g., hurricane surge) are related most often to maximum wind speed. However, recent studies have shed light on the importance of storm size (i.e., radius of maximum wind, R_{max}) in describing the hurricane wind field and thus the spatial extent of potential damage. The large losses from several recent hurricanes underscore the need for better understanding the impact of storm size on damage. To that end, we seek to develop event parameter combinations (e.g., V_{max} and R_{max}) that define "characteristic" risk-consistent hurricanes in one particular geographic region. A simulation framework is developed to generate 10,000 years of simulated hurricane events and a synthetic hurricane wind speed database for the state of Texas, using state-of-the-art hurricane modeling techniques and information extracted from historical hurricane data. The resulting 10,000 years database, which includes information developed for every zip-code in Texas, includes time of hurricane passage, maximum gradient wind speed and surface wind speed. Using this simulation framework, selected parameters (i.e., intensity and size parameters) are recorded for each hurricane at the time of landfall along the Texas coast. Using a hurricane decay model specifically calibrated for this location, parameters V_{max} and R_{max} at inland locations also are recorded. The critical values of V_{max} and R_{max} are then selected to jointly describe the intensity and spatial extent of hurricanes and the joint histogram is developed. Finally, these variables are statistically characterized and a suite of the characteristic V_{max} and R_{max} combinations corresponding to certain hazard levels are identified. The proposed methodology can be used to develop characteristic hurricane hazard definitions (and event parameter combinations corresponding to specific hazard levels) for use in performance-based engineering applications.

1. Introduction

Hurricanes (tropical storms) are among the most deadly hazards threatening the Gulf Coast of the United States and Mexico. Significant improvements have been made in hurricane forecasting, warning and evacuation. Recent studies (e.g., [9,5,13,20,26,7]) have focused on hurricane loss estimation and mitigation. Despite significant progress in hurricane hazard mitigation, the losses associated with recent events have been very large, demonstrating the vulnerability (both physical and economic) that exists in these coastal areas. More accurate hurricane models are needed to validate and define structural design criteria in load standards, better anticipate future events, and prepare for the storm's impact and for post-event recovery.

Typically, the hurricane hazard is described in terms of maximum wind speed V_{max} (at the eye-wall), since damage descriptors associated with intensity scales (e.g., the Saffir–Simpson Hurricane Scale) and collateral hazards (e.g., hurricane surge) are related most often to maximum wind speed. However, the hurricane storm size (i.e., radius of maximum winds, R_{max}) also plays an important role in describing the hurricane wind field intensity and thus the spatial extent of damage. Prior to hurricane Katrina in 2005, few studies addressed storm size when evaluating hurricane damage. Irish et al. [11] investigated the influence of storm size on hurricane surge for the coastal area around Corpus Christi, TX and showed that both maximum hurricane wind speed and storm size are important factors influencing hurricane surge and hence the damage impact on coastal infrastructure. For a given wind speed intensity, they found that storm surge (which caused

* Corresponding author.
E-mail addresses: wangy20@rpi.edu (Y. Wang), rosowd@rpi.edu (D.V. Rosowsky).
[1] Formerly at: Zachry Department of Civil Engineering, Texas A&M University, College Station, TX, United States.

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the most damage in Katrina) varied by as much as 30% over a range of storm sizes. In order to more fully define future (predicted) events for purposes of design, assessment, disaster management, or loss estimation, joint distribution information on storm intensity (e.g., V_{max}) and storm size (e.g., R_{max}) is required.

Powell and Reinhold [18] proposed the using integrated kinetic energy (IKE) to define the intensity of a specific hurricane event by integrating the energy under the volume of the complete wind field, thereby explicitly considering storm size. However statistical (predictive) models cannot be developed based on the IKE concept that could result in design-basis event characterization for performance-based applications.

For performance-based engineering applications, it would further be useful to develop parameter combinations (e.g., V_{max} and R_{max}) that define (and therefore predict) "characteristic" risk-consistent hurricanes. Some recent studies have focused on risk-consistent hurricane hazard characterization and these are described below.

Legg et al. [15] suggested one way to identify a set of hurricanes to develop hazard-consistent probabilistic scenarios for the state of North Carolina. A set of hurricanes with different return periods was first selected by running HAZUS-MH [5] for each county in North Carolina and recording the maximum gust wind speed for each county. An optimization program was used to select a reduced set of hurricanes and determine the corresponding annual exceedance probabilities for a set of defined hazard levels. Once the data pairs of annual exceedance probability (or return period) and the maximum gust wind speed for each county were generated, the hazard curve (wind speed vs. annual exceedance probability or return period) for a given county was constructed. Although this approach successfully characterized the hurricane hazard in a consistent probabilistic manner, the maximum wind speed (i.e., a point-measure of intensity with no spatial descriptor included) was the only hazard metric considered.

Phan and Simiu [16] proposed a multi-hazard risk assessment approach to develop design criteria for structures subjected to hurricane wind and storm surge. The joint distribution of (correlated) wind speed/storm surge height was developed for the area around Tampa Bay, FL. This general approach to fitting the joint distribution of two hazard (intensity) variables (i.e., wind speed and surge height) could also be used to determine the joint distribution of two hurricane (event) variables (e.g., V_{max} and R_{max}). However, the maximum storm surge was generated by the SLOSH model [12] and often did not occur at the same time as maximum hurricane wind speed occurred. In the approach suggested by Phan and Simiu, the maximum storm surge and the maximum hurricane wind speed for one event were assumed to occur simultaneously and therefore any design criteria developed using their approach would be conservative, which is generally favorable from an engineering design viewpoint. An alternative method for estimating the joint exceedance probability, in load effects space, was proposed by Phan et al. [17]. This approach did not result in overestimation of the joint wind speed and storm surge effects.

State-of-the-art hurricane prediction models are introduced to simulate hurricane events in this paper. Using the models developed by Vickery et al. [23], Vickery et al. [24], Lee and Rosowsky [14] developed a framework for the simulation of hurricane events. The availability of historical hurricane records [10] has enabled such event-based simulation procedures to be developed in the public sector. Previously, such models were largely proprietary. This paper uses the simulation framework developed by Lee and Rosowsky to develop a hurricane wind speed database for the state of Texas. Key components for the framework are the gradient wind-field model [6] and the tracking and central pressure models [23,24]. Decay model parameters specifically for Texas were developed as part of this study. These models and their various parameters are described in the following sections. Using the Texas coastline as an example, all of the information (intensity, size and direction) needed to describe 10,000 years of hurricane events is completely developed in the synthetic wind speed database. Using this information, the dominant variables (e.g., V_{max}, R_{max}) can be jointly characterized statistically and the characteristic hurricane hazard (considering both wind speed and size) can be defined.

2. Proposed methodology

The approach developed in this study to generating a synthetic hurricane wind speed database and defining risk-consistent characteristic hurricanes (through the development of the joint distribution of hurricane wind speed and size) is described in the following four steps. First, a 10,000 year synthetic hurricane wind speed database for the state of Texas is developed using state-of-the-art hurricane wind field and tracking models [6,23,24], event-based simulation techniques and information extracted from historical hurricane data [10]. In the analysis, after a simulated hurricane makes landfall, the hurricane intensity decays as a function of distance travelled inland using a decay model developed specifically for Texas. The resulting 10,000-year database, which includes information developed for every zip-code in Texas, includes time of hurricane passage, maximum gradient wind speed and surface wind speed (developed using appropriate gradient-to-surface wind speed conversion factors described in a later section).

Second, once the synthetic hurricane wind speed database is developed, the critical event parameters are extracted. State-of-the-art parametric hurricane wind field models such as the one used to create the 10,000 year synthetic hurricane wind speed database include multiple parameters (e.g., maximum wind speed V_{max}, radius of maximum winds R_{max}, Holland pressure profile parameter B, etc.) describing the vortex shape of the gradient wind-field. Among these, two critical parameters, the maximum wind speed V_{max} (i.e., at the eye-wall) and the radius of maximum winds, R_{max}, are selected in the present study to describe the wind speed intensity and the size of the hurricane, respectively. These parameters will be further discussed in a later section.

The focus in the present study is on characterizing (probabilistically) the hurricane at the time of landfall. Therefore, the key parameters (i.e., V_{max} and R_{max}) for each hurricane at the time of landfall along the Texas coast is extracted from the 10,000 year simulated hurricane wind speed time histories. Hurricane information (descriptors) from the closest time (data are generated/stored at 6-h intervals) prior to landfall are used. In addition to statistically characterizing hurricane events at the time of landfall, the parameters for attenuated inland hurricane events also were extracted.

Third, the joint histogram of selected variables is constructed. Specifically, the histogram of V_{max} and R_{max} is generated for hurricane events which were simulated to make landfall along the Texas coast. Note that each data pair of V_{max} and R_{max} is presumed simultaneous herein. Once the joint histogram is generated, the joint exceedance probability "surface" of V_{max} and R_{max} at the time of landfall can be developed. The joint annual exceedance probability of V_{max} and R_{max} at the time of landfall can then be determined knowing the mean annual occurrence rate. Using the hurricane decay model developed for Texas and the translational hurricane wind speed at the time of landfall, V_{max} and R_{max} data pairs at inland locations (i.e., at certain distance inland or time since landfall) can be determined.

Fourth and finally, characteristic hurricane parameter combinations corresponding to specific hazard levels (e.g., annual exceedance probabilities or mean recurrence intervals) are selected/identified. Once the joint annual exceedance probability of V_{max}

and R_{max} is known, the corresponding mean recurrence interval (MRI) and hazard curve (contour loop) for a given annual exceedance probability m in Y years (e.g., 2%/50 years) can be generated. Risk-consistent design-basis events corresponding to *high* (2%/50 years), *medium* (10%/50 years) and low (50%/50 years) hazard levels can then be defined by selecting the appropriate V_{max} and R_{max} combinations.

3. Georgiou's gradient wind field model

Using information obtained by aircraft reconnaissance observations, well-formed hurricane gradient wind fields can be represented as a vortex with translational movement. Therefore, the gradient wind speed V_g can be decomposed into a rotational component V_R and a translational component V_T (Fig. 1). The rotational component V_R can be described as a function of distance from the hurricane eye (Fig. 2). The gradient rotational wind speed vortex is assumed herein to be symmetrical about the hurricane eye, a somewhat simplified assumption but one that is generally assumed to be reasonable for well developed storms. Therefore, the hurricane can be viewed simply as a rotational vortex moving along its track with some translational speed. Georgiou's model [6] describes the rotational vortex shape through the following expression:

$$V_g^2(r,\alpha) = \frac{r}{\rho}\cdot\frac{\partial P}{\partial r} + V_g(r,\alpha)\cdot(V_T\sin\alpha - fr) \tag{1}$$

where V_g = gradient wind speed, r = distance from hurricane eye, α = angle from hurricane heading direction (counter-clockwise +), ρ = air density, V_T = translational wind speed, f = coriolis parameter and P = horizontal air pressure. Information needed to statistically characterize these parameters (central pressure, storm track and translational speed) can be obtained from the HURDAT database of historical hurricane records [10]. The horizontal air pressure $P(r)$ at a distance r from the hurricane eye is given by [24]:

$$P(r) = P_c + \Delta p\exp\left[-\left(\frac{R_{max}}{r}\right)^B\right] \tag{2}$$

where P_c = air pressure at the hurricane eye, Δp = the central pressure deficit (mb) = 1013 − P_c (mb), R_{max} = radius of maximum winds, and B = pressure profile parameter. As suggested by Vickery et al. [24], R_{max} and B are functions of the hurricane eye latitude ψ and central pressure deficit Δp. The best single equation estimates of R_{max} and B can be written as [24]:

$$\ln R_{max} = 2.636 - 0.0005086\Delta p^2 + 0.0394899\psi + \varepsilon \tag{3}$$

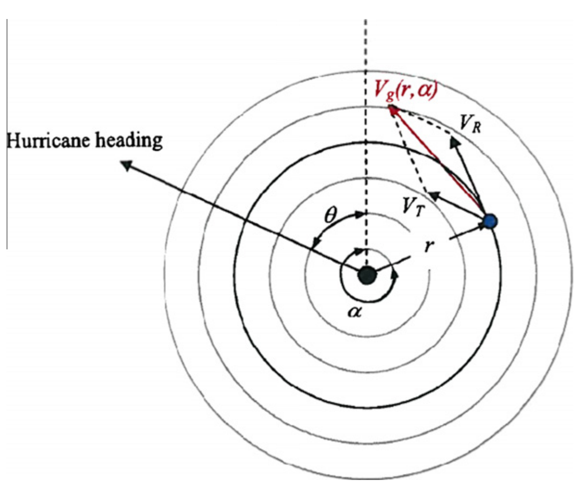

Fig. 1. Hurricane gradient wind speed components.

$$B = 1.38 + 0.00184\Delta p - 0.00309R_{max} \tag{4}$$

where the error term ε (in km) is assumed Normal (0, 0.4164) south of 30°N and Normal (0, 0.3778) north of 30°N [24]. Lee and Rosowsky [14] suggested the error term can be modeled as Normal (0, 0.40) at all latitudes; this model is adopted herein.

Once the horizontal air pressure is calculated using Eqs. (2)–(4), the gradient horizontal air pressure $\frac{\partial P}{\partial r}$ is easily obtained. By substituting Eq. (2) into Eq. (1), the gradient wind speed V_g is calculated as [24]:

$$V_g = \frac{1}{2}(V_T\sin\alpha - fr) + \sqrt{\frac{1}{4}(V_T\sin\alpha - fr)^2 + \frac{B\Delta p}{\rho}\left(\frac{R_{max}}{r}\right)^2\exp\left[-\left(\frac{R_{max}}{r}\right)^2\right]} \tag{5}$$

4. Vickery's empirical storm tracking and central pressure model

Vickery et al. [24] developed an empirical tracking model to describe the hurricane translational wind speed and heading angle. The entire Atlantic basin is divided into a 5° × 5° grid (Fig. 3). Each grid block has its own grid-based parameters which are used to determine the translational wind speed and heading angle at the next time-step:

$$\begin{cases} \Delta\ln c = a_1 + a_2\psi + a_3\lambda + a_4\ln c_i + a_5\theta_i + \varepsilon \\ \Delta\theta = b_1 + b_2\psi + b_3\lambda + b_4c_i + b_5\theta_i + b_6\theta_{i-1} + \varepsilon \end{cases} \tag{6}$$

where c = translational velocity (translational wind speed), θ = heading angle, $a_i(i = 1, 2, \ldots)$ = coefficient for translational velocity, $b_i(i = 1, 2, \ldots)$ = coefficient for heading angle, ψ and λ = storm latitude and longitude, c_i = translational velocity at previous time-step i, θ_i = heading angle at previous time-step i, θ_{i-1} = heading angle at previous time-step $i-1$, and ε = random error term. The HURDAT database contains data at 6-h intervals describing hurricane eye position, translational velocity, heading angle and central pressure for all hurricanes that have occurred in the Atlantic basin since 1851. Therefore, the coefficients a_i and b_i for each grid location can be determined through regression analysis of HURDAT data at each grid location. For those grid locations with little or no hurricane data, the coefficients are assigned the corresponding values from the nearest grid location.

The hurricane central pressure model suggested by Vickery et al. [24] was developed based on the relative intensity concept [4]. The hurricane eye central pressure P_c can be expressed in terms of relative intensity I, and vice versa. The details of the relationship between hurricane eye central pressure and the relative intensity I can be found in the appendix of Darling's paper [4]. Of interest in this paper, the hurricane eye central pressure is described by Darling [4] as a function of sea surface temperature as:

$$\ln(I_{i+1}) = c_0 + c_1\ln(I_i) + c_2\ln(I_{i-1}) + c_3\ln(I_{i-2}) + c_4T_s + c_5\Delta T_s + \varepsilon \tag{7}$$

where I_{i+1} = relative intensity at the next time-step $i+1$, I_i, I_{i-1}, I_{i-2} = relative intensity at the previous time-steps i, $i-1$ and $i-2$, c_i = the grid-based coefficient for relative intensity, T_s = sea surface temperature (K), ΔT_s = difference in sea surface temperatures at time-steps i and $i+1$ (K), and ε = random error term. Similar to the tracking model coefficients, the coefficient parameters c_i for each grid location can be determined by regression analysis, using the relative intensity values calculated from the HURDAT central pressure data at each grid location. For those grid locations with little or no hurricane data, the coefficients are assigned the corresponding value

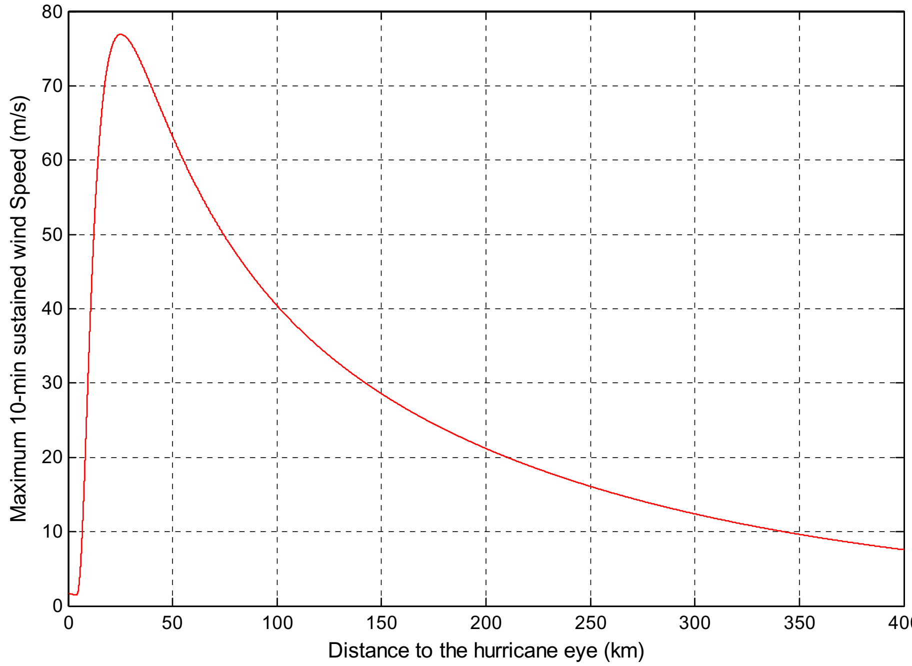

Fig. 2. Example of vortex shape of hurricane gradient wind field (Hurricane Katrina, 2005).

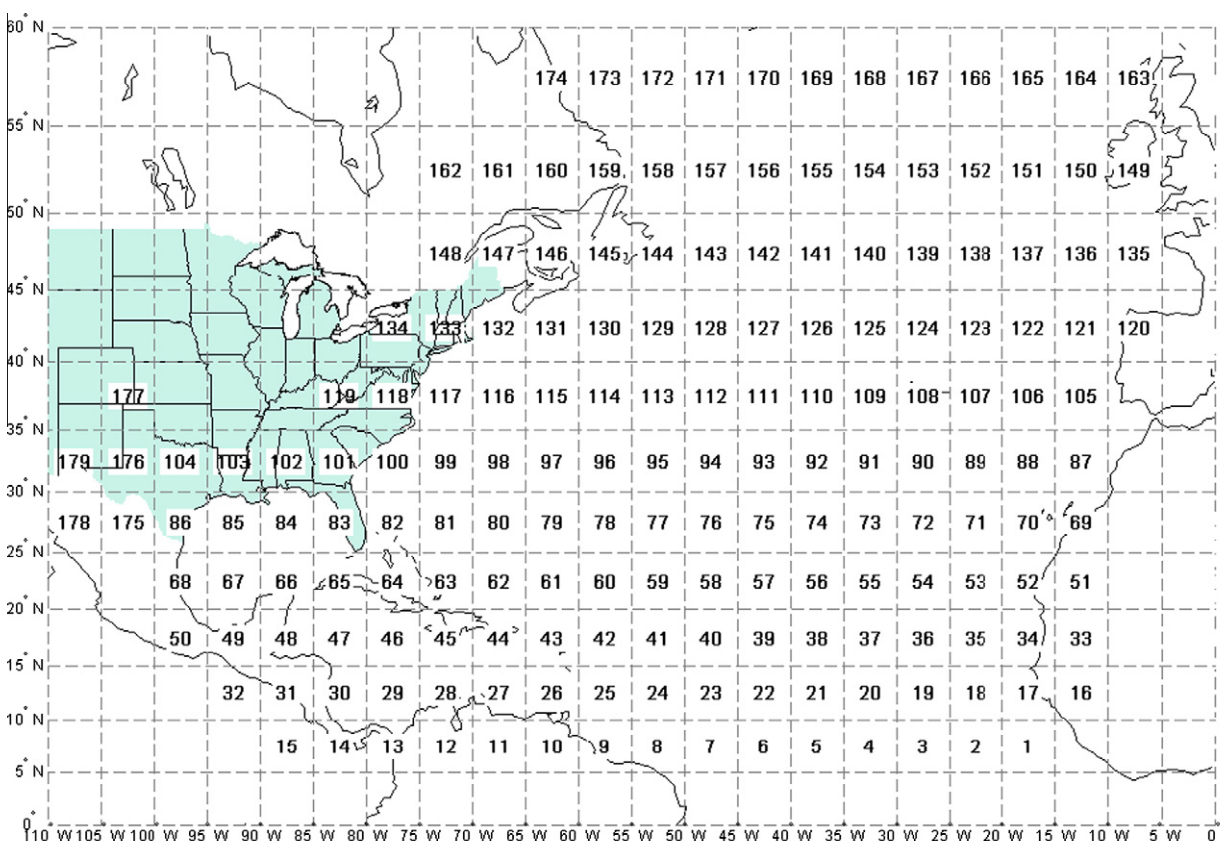

Fig. 3. Division of Atlantic basin into 5° × 5° grid locations.

from the nearest grid location. After the hurricane makes landfall, the central pressure decays and the relative intensity approach is no longer applicable. Once the storm makes landfall, the hurricane decay (filling) model proposed by Vickery and Twisdale (1995) is used to describe the central pressure at the hurricane eye. The hurricane decay model is described in the following section.

5. Decay model

Once a hurricane makes landfall, its energy decreases due to increased surface friction and the lack of a heat source from the sea. Consequently, both the central pressure difference and the rotational wind speed decrease. A number of decay models have been proposed (e.g., [6,2,8,22]. The Vickery and Twisdale model, adopted herein, takes the form of an exponential decay function:

$$\Delta p(t) = \Delta p_0 \exp(-at) \tag{8}$$

where $\Delta p(t)$ = the central pressure deficit (mb) at time t after landfall, Δp_0 = the central pressure deficit (mb) at landfall, a = site-specific decay parameter (constant), and t = time after landfall. The key decay parameter a for each hurricane can be obtained through analysis of the historical hurricane central pressure data [10]. Statistical analyses of decay constants for North Carolina, South Carolina and the Florida were performed by Rosowsky et al. [19]. The same procedure was used for Texas as part of this study using eleven hurricane events that made landfall along the Texas coast between 1980 and 2004. The storm tracks are shown in Fig. 4 while Fig. 5 shows the time history of normalized central pressure deficit of the eleven sample storms after landfall. The mean and standard deviation of the decay constant a for Texas were determined to be 0.04 and 0.032, respectively. The best-fit distribution was determined to be Lognormal with parameters $\lambda = -3.464$ and $\xi = 0.703$.

6. Gradient-to-surface wind speed conversion

The surface wind speed at 10 m height above the ground at an assumed open terrain location can be estimated using conversion factors applied to the wind speed at the gradient level, generally taken as between 500 m and 2000 m. Gradient-to-surface wind speed conversion factors were proposed by Caton [3] and later modified by Sparks and Huang [21]. A summary of the gradient-to-surface conversion factors assumed herein for both 10-min sustained wind speeds and 5-s gust wind speeds are summarized in Table 1 [14].

7. Simulation procedure

This section describes the simulation procedure used to develop the 10,000 years of record in the synthetic hurricane wind speed database. The occurrence of hurricane events follows a Poisson process with an annual occurrence rate in the Atlantic basin of λ = 8.4/year [14]. The locations for each hurricane formation in the HURDAT database are shown in Fig. 6. A simulated hurricane starts in the Atlantic basin with parameters based on historical data (i.e. initial location, angle and translational speed). The hurricane then moves along a track defined by the tracking and central pressure model. The hurricane's position at each subsequent 6-h interval can be determined using Eq. (6) using the parameters derived from information in the HURDAT database. Similarly, the next interval's central pressure can be obtained using Eq. (7). Once the hurricane makes landfall, the central pressure decays according to Eq. (8). Finally the gradient wind speed can be obtained from Eq. (5) and converted to a surface wind speed using the gradient-to-surface wind speed conversion factors in Table 1. If the maximum 10-min surface wind speed at any site is greater than 15 m/s (the threshold specified in this study), this value is recorded in the time series for that location. Following this procedure, 10,000 years of simulated hurricane events are generated and the synthetic hurricane wind speed records are developed for each zip-code in Texas. Critical parameters for each hurricane at the time of landfall on the Texas coast are extracted from the

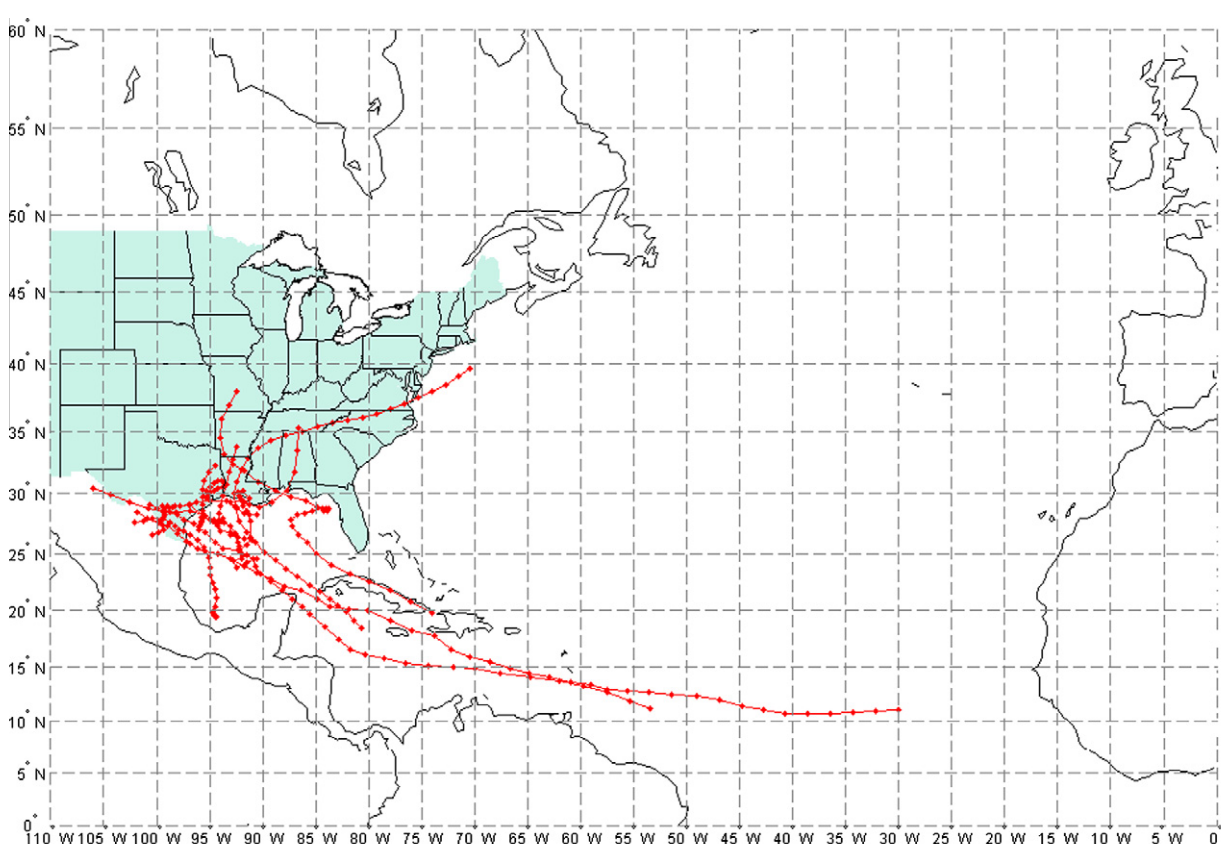

Fig. 4. Map showing the tracks of eleven landfalling hurricanes along the Texas coast (1980–2004).

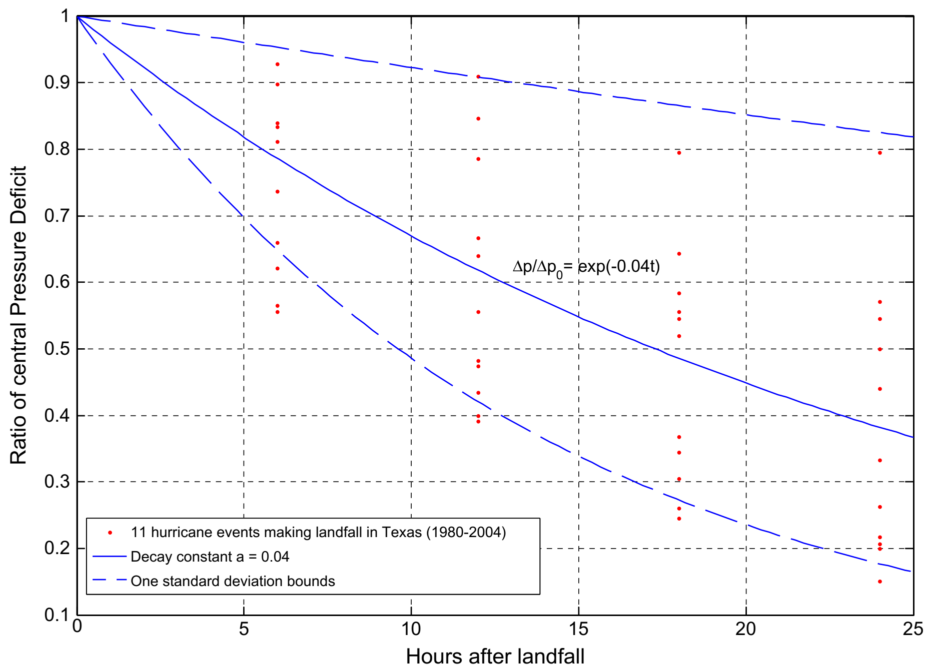

Fig. 5. Decay rate model based on historical hurricanes in Texas (1980–2004).

Table 1
Gradient-to-surface wind speed conversion factors (from [14]).

Location	Wind from ocean		Wind from land	
	Gradient-to-mean	Gradient-to-gust	Gradient-to-mean	Gradient-to-gust
Zone 1[a]	0.45	0.72	0.45	0.72
Zone 2[b]	0.50	0.80	0.45	0.72
Zone 3[c]	0.65	0.90	0.50	0.80
Zone 4[d]	0.65	0.90	0.65	0.90

[a] Zone 1 = inland open terrain (airports) more than 10 km from the coast.
[b] Zone 2 = airport within 10 km of the coast.
[c] Zone 3 = sites adjacent to the sea.
[d] Zone 4 = off-shore sites.

10,000 year simulated hurricane wind speed database and parameters describing the attenuated inland hurricane events are developed thereafter. The simulation procedure is shown in Fig. 7.

The synthetic hurricane database also can be used to develop the *N*-year MRI wind speed map for Texas, and this can be compared with the design wind speeds in ASCE 7 (for example). This comparison was made by Wang [25], and the results were shown to compare very well with both the ASCE 7 [1] wind speed map and those obtained by Vickery et al. [24] which formed the basis for the ASCE 7 map. The predicted surface wind speed time-histories (using the modeling approach used in the present study) were also shown to agree very well with actual surface wind speed data recorded at selected coastal, as presented by Lee and Rosowsky [14]. These two comparisons [25,14] serve to validate the simulation model used herein.

8. Probabilistic description of bivariate hurricane event

Relevant information for each hurricane at the time of landfall is extracted from the 10,000 year simulated hurricane wind speed time histories. Specifically, the key descriptors (V_{max} and R_{max}) from the closest 6-h time interval prior to landfall are considered. The joint histogram and estimates of the probability of exceedance and mean recurrence intervals of the joint simulated events can then be determined. A suite of risk-consistent hurricanes can be defined by selecting the appropriate combinations of V_{max} and R_{max}.

In total, 4776 landfalling hurricanes were simulated to occur in 10,000 years with landfall position assumed to occur with more or less equal probability along the length of the Texas coastline. The equiprobably assumption is validated by looking at the landfalling positions for the simulated hurricane events. These are shown in Fig. 8a–c for simulation periods of 100, 1000 and 10,000 years, respectively. Data pairs of V_{max} and R_{max} at the time of landfall for each simulated hurricane were recorded. Paired values of V_{max} and R_{max} are assumed to occur simultaneously. The 4776 data pairs were used to construct a joint histogram, as shown in Fig. 9. The figure suggests that the Texas coast would be most frequently struck by events with V_{max} of 50–100 mph (22.3–44.7 m/s) and R_{max} of 20–40 miles (32–64 km) at the time of landfall.

The joint exceedance probability of V_{max} and R_{max}, denoted $P(V_{max} > v,\ R_{max} > r)$, can be determined from the histogram in Fig. 9 (or its frequency-normalized joint PDF). Using the joint histogram (Fig. 9), the number of data pairs having maximum wind speeds greater than v and radius of maximum wind speed greater than r would be divided by the total number n of data pairs (4776 here). Multiplying the joint exceedance probability by the mean annual hurricane rate of occurrence λ (=4776/10,000 = 0.4776 per

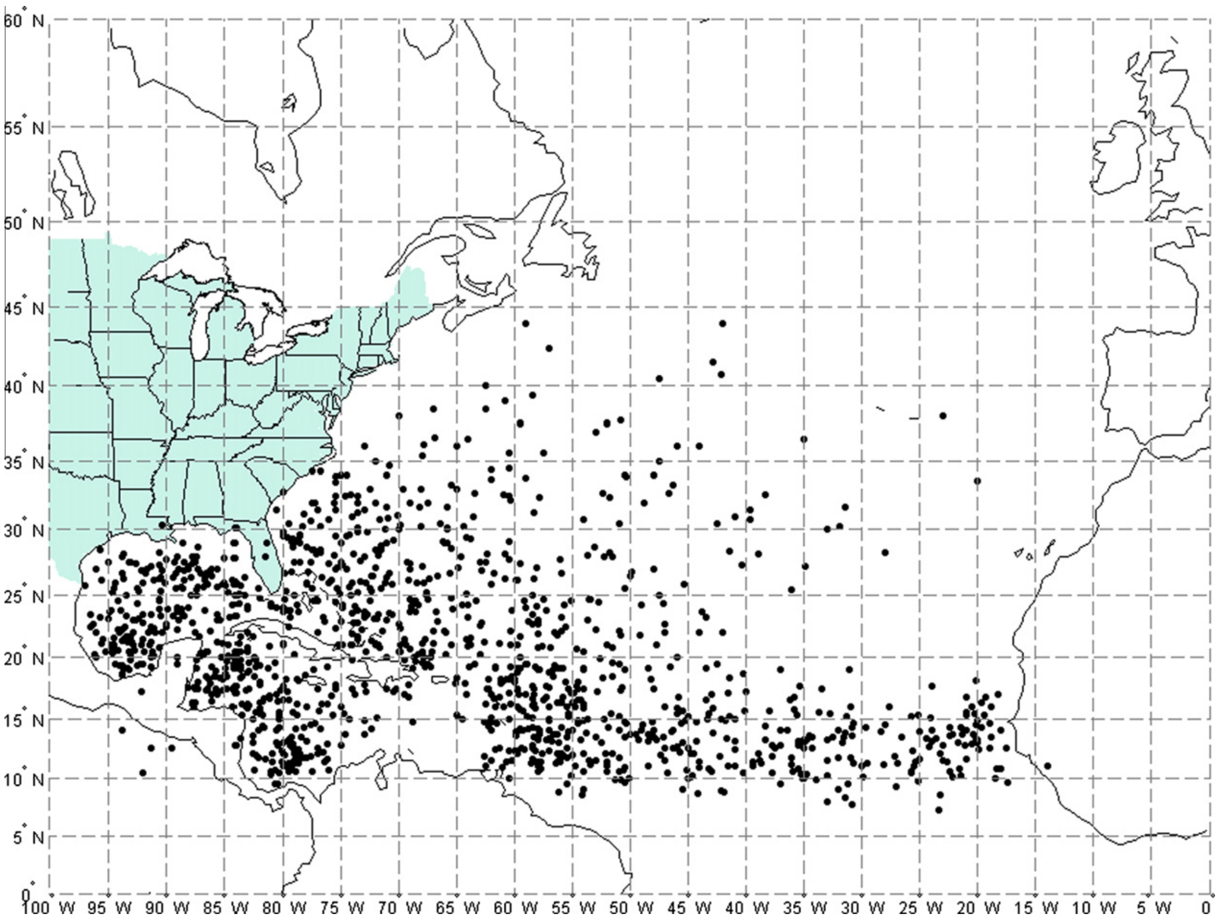

Fig. 6. Initial positions of hurricanes in the HURDAT database (2005).

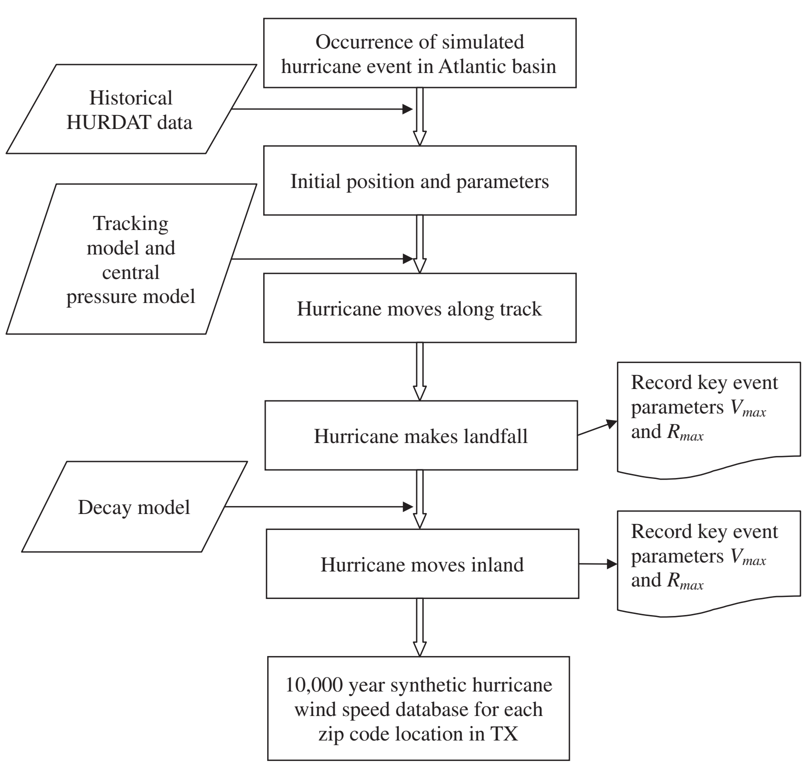

Fig. 7. Simulation procedure flow chart.

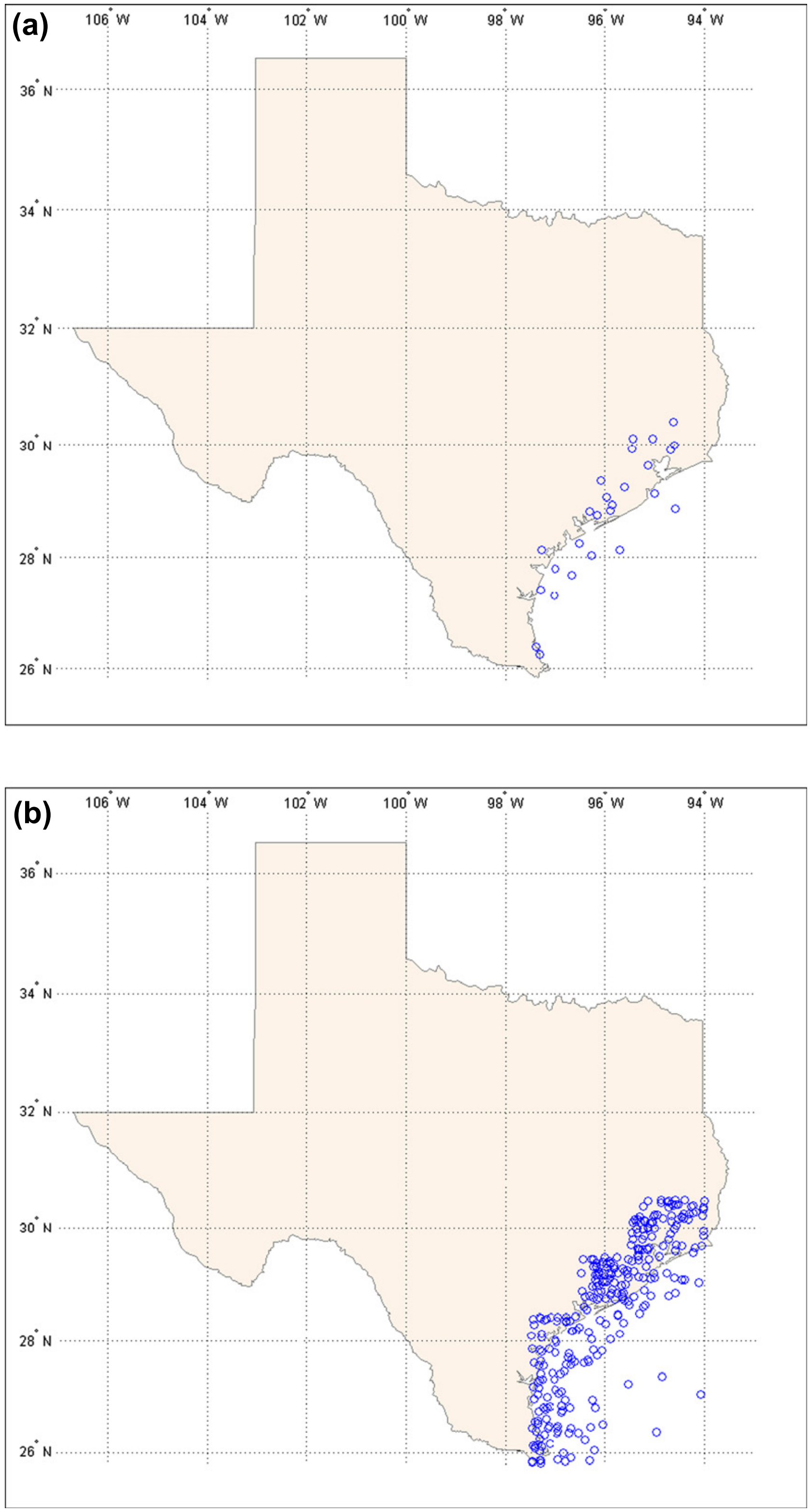

Fig. 8. Landfalling positions (closest 6-h recorded data) during 100 years, 1000 years and 10,000 years period, respectively. (a) Landfalling positions in 100 years of simulated events. (b) Landfalling positions in 1000 years of simulated events. (c) Landfalling positions in 10,000 years of simulated events.

year), one obtains an estimate of the joint annual exceedance probability of V_{max} and R_{max} (see Fig. 10).

Once the joint annual exceedance probability of V_{max} and R_{max} is developed, as shown in Fig. 10, equiprobability contours describing hazard levels with different annual exceedance probabilities can be generated. Hurricanes described by V_{max} and R_{max} data pairs on (or near) the same contour have the same joint annual exceedance probability. The contours of bivariate annual exceedance probabilities corresponding to 0.04%, 0.2%, 1%, 1.4%, 2%, 5% and 10% are shown in Fig. 11. The simulated V_{max} and R_{max} data points also

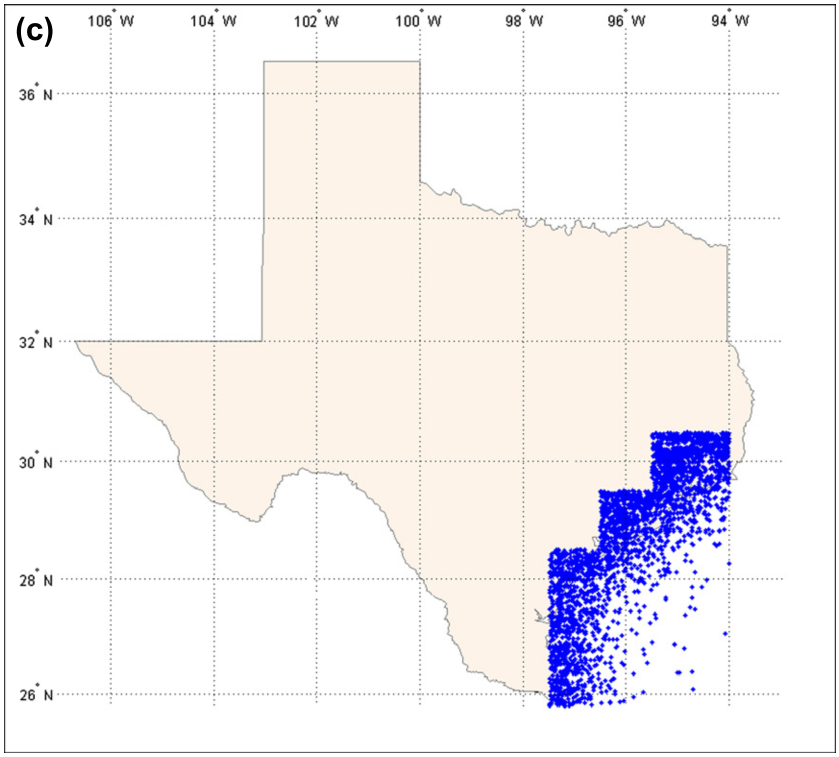

Fig. 8 (*continued*)

are shown on this figure, indicating the density of data pairs (from simulated landfalling hurricane events) in bivariate space. Fig. 11 further shows the data pairs of actual historical hurricanes, tropical depressions and tropical storms (dating back to 1851) that made landfall along the Texas coast. This allows one to estimate the approximate hazard level corresponding to historical events. For performance-based design purposes, the hazard level is normally described as an exceedance probability in Y years (e.g., 2%/50 years). Table 2 presents hazard levels and corresponding values of annual exceedance probability and MRI (in years), where annual exceedance probability = 1/MRI and probability of exceedance (i.e., m% in Y years) given by MRI = $1 - \exp\left(-\frac{Y}{MRI}\right)$. The MRI values for corresponding values of V_{max} and R_{max} are listed in Table 3. Note that this is simply another way to present the contours in Fig. 11.

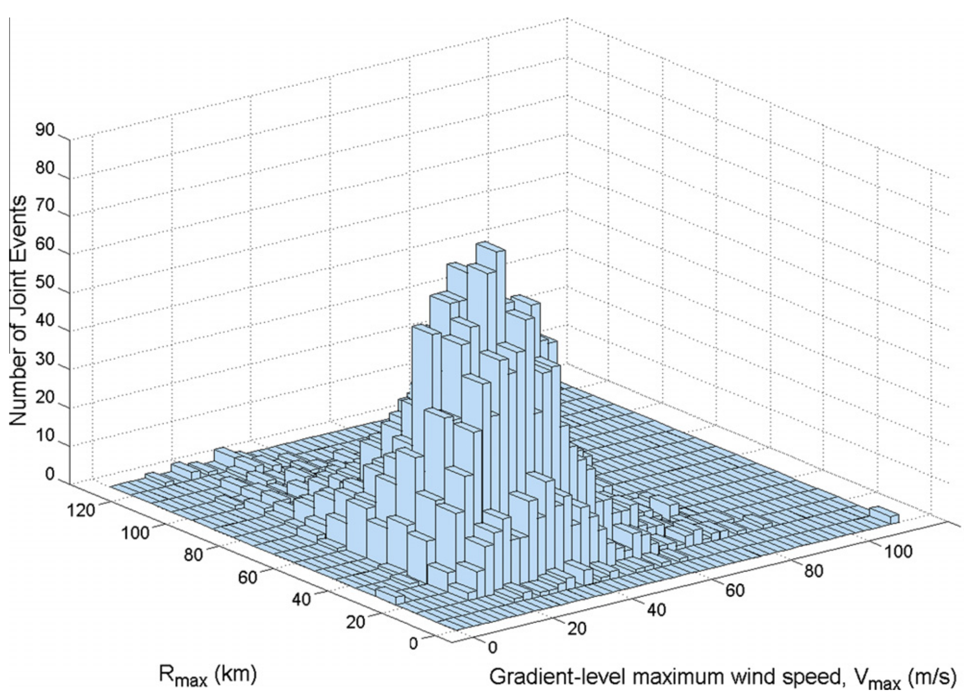

Fig. 9. Joint histogram of V_{max} and R_{max}.

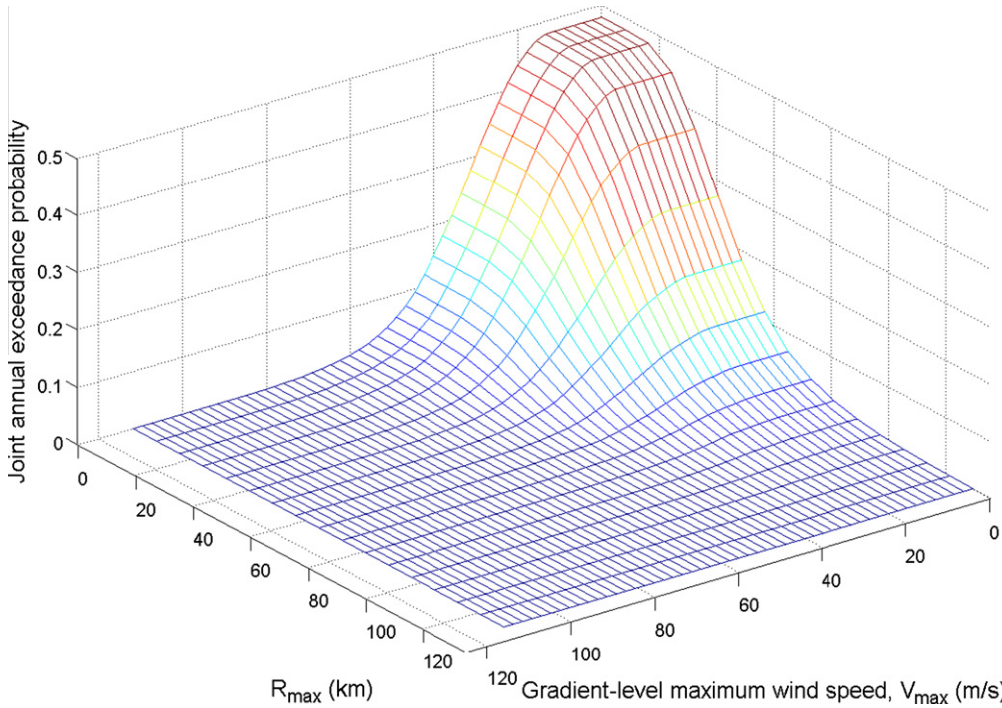

Fig. 10. Joint annual exceedance probability of V_{max} and R_{max}.

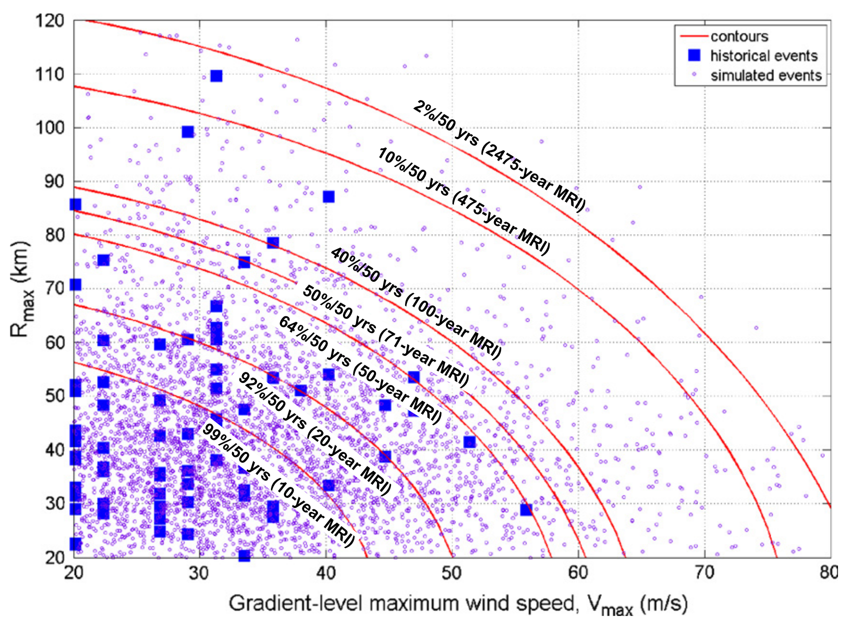

Fig. 11. Hazard level contours showing both historical and simulated events at landfall.

Table 2
Hazard levels and corresponding annual exceedance probabilities and MRI values.

Hazard level	Annual probability of exceedance (%)	MRI (years)
99%/50 years	10	10
92%/50 years	5	20
64%/50 years	2	50
50%/50 years	1.4	71
40%/50 years	1	100
10%/50 years	0.2	475
2%/50 years	0.04	2475

The information in Fig. 11 or Table 3 can be used to define characteristic (risk-consistent) hurricanes for use in performance-based engineering applications. Specifically, the contours in Fig. 11 can be used to select the desired combination of V_{max} and R_{max} corresponding to a given hazard level. For example, for the 10%/50 years hazard level, four characteristic event combinations of V_{max} and R_{max} could be selected: (80, 63), (100, 55), (120, 45) and (140, 34). Similarly, risk-consistent candidate hurricanes can be selected from Table 3 on the basis of MRI values rather than hazard levels. With the selected combinations and an assumed translational wind speed V_T of each candidate hurricane, a suite of candidate hurricanes can be generated using Eqs. (3)–(5). Such

Table 3
Mean recurrence intervals for combinations of V_{max} and R_{max}. (Note: Inf = greater than 10,000 years) (*Note*: 1 mile = 1.6 km, 1 mph = 0.447 m/s).

V_{max} (mph)	R_{max} (mile)												
	20	25	30	35	40	45	50	55	60	65	70	75	80
75	5	8	12	20	36	59	105	182	333	625	1428	9996	Inf
80	6	9	13	23	43	71	132	227	416	714	1666	9996	Inf
85	7	11	16	28	53	88	167	286	500	909	2499	9996	Inf
90	9	13	20	35	68	112	208	400	625	1249	3332	Inf	Inf
95	11	16	25	46	93	156	256	526	909	2499	4998	Inf	Inf
100	14	21	33	61	123	208	345	625	1249	4998	4998	Inf	Inf
105	18	26	43	80	154	270	400	714	1666	4998	4998	Inf	Inf
110	23	32	53	104	192	333	526	833	2499	Inf	Inf	Inf	Inf
120	30	44	72	132	227	400	625	1111	4998	Inf	Inf	Inf	Inf
125	40	57	99	185	286	526	909	1428	4998	Inf	Inf	Inf	Inf
130	54	77	128	256	384	769	1249	1999	4998	Inf	Inf	Inf	Inf
135	69	105	175	322	476	1000	1666	2499	9996	Inf	Inf	Inf	Inf
140	90	139	250	500	714	1249	1999	3332	Inf	Inf	Inf	Inf	Inf
145	115	182	357	714	1000	2499	3332	9996	Inf	Inf	Inf	Inf	Inf
150	149	232	454	1000	1249	3332	4998	9996	Inf	Inf	Inf	Inf	Inf
155	208	357	769	2499	3332	9996	Inf	Inf	Inf	Inf	Inf	Inf	Inf
160	278	476	833	2499	3332	9996	Inf	Inf	Inf	Inf	Inf	Inf	Inf
165	555	1249	4998	9996	9996	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
170	714	1428	9996	9996	9996	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
175	833	1666	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
180	1999	2499	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf

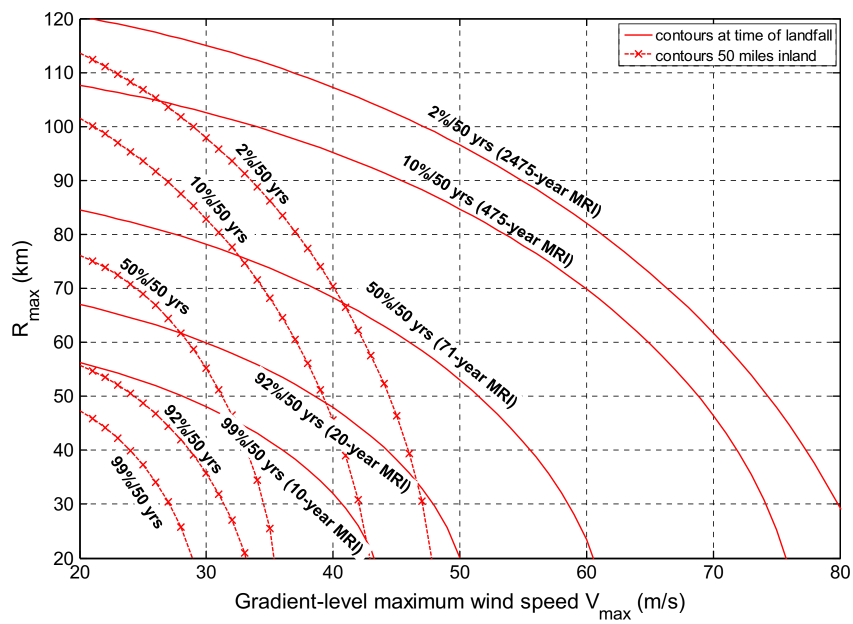

Fig. 12. Hazard level contours for hurricane events both at landfall and 50 miles (80 km) inland.

design-basis events could, for example, be coupled with appropriate surge models and damage (loss) models to develop estimates of the total damage (economic loss). This enables a risk-based (hazard-level specific) distribution of losses to be determined for each location of interest, e.g., the hurricane hazard-prone areas along the Texas coast. Such application to hurricane loss projection modeling (or comparisons to existing models such as the Florida Public Model, HAZUS, and ARA) is beyond the scope of this paper.

One possible limitation is that hazard level contours in Fig. 11 were derived considering all simulated hurricane events along the entire Texas coast, without consideration of particular strike (landfall) location. To further consider the relative position of a particular position to the hurricane landfall location, Wang [25] proposed the term ROD, defined as the ratio of the distance from a given location of interest to the hurricane eye (R) to the radius of maximum wind speed (R_{max}). An additional axis for ROD could be added to Fig. 11 and the 3D surface describing the joint distribution of V_{max}, R_{max} and ROD could be generated for any given location. This could be used to select a suite of risk-consistent candidate hurricanes with additional information on the relative position of a particular location to the hurricane landfall location. While beyond the scope of this paper, this is the subject of continued work by the authors.

Similarly, the hazard level contours at inland locations, i.e., for attenuated inland hurricane events, also can be developed. Using the decay model described earlier and the translational hurricane wind speed at the time of landfall, V_{max} and R_{max} data pairs for each simulated hurricane event at a certain distance inland or time since landfall can be determined. With the information on the attenuated inland hurricane events, the joint histogram and joint annual exceedance probability of V_{max} and R_{max} can be similarly determined. Once the joint annual exceedance probability of V_{max} and R_{max} is developed, contours describing inland hazard levels with different annual exceedance probabilities can be constructed and a suite of risk-consistent inland hurricanes (i.e., a certain distance inland or at a certain time since landfall), can once again be defined by selecting appropriate combinations of V_{max} and R_{max}. As an example, Fig. 12 shows the hurricane hazard level contours both at the time of landfall and a distance 50 miles (80 km) inland.

9. Summary

A methodology to develop the joint distribution of hurricane wind speed and size was presented. This enables the hurricane hazard to be defined as a spatial event rather than just a point-variable (wind speed only). Specifically, a database of hurricane events is generated (using numerical simulation) and future hurricanes are statistically characterized in terms of maximum wind speed and radius of maximum winds. This bivariate hurricane hazard definition thus explicitly takes into account both wind speed intensity and spatial extent.

A total of 10,000 years of synthetic hurricane wind speed records (for every zip-code in Texas) was generated using event-based simulation techniques. The resulting database includes information on time of hurricane passage, maximum gradient wind speed and maximum surface wind speed (both sustained and gust wind speeds). The database can be used to statistically characterize the *N*-year maximum wind speed distribution for a given zip-code location. This information has been used to independently validate the design wind speed maps for Texas [25], at least close to the coast where the extreme wind climate is controlled by the hurricane (tropical storm) hazard.

The objective of this study was to use the synthetic hurricane wind speed database to develop a suite of risk-consistent characteristic hurricanes corresponding to certain hazard levels, for use in performance-based engineering applications. Data pairs of V_{max} and R_{max} at the time of landfall were extracted from the 10,000 year database of simulated hurricanes events. The joint histogram was then constructed, enabling the joint statistical characterization of V_{max} and R_{max} and identification of characteristic hurricanes corresponding to designated hazard levels (i.e., combinations of V_{max} and R_{max}). Using a hurricane decay model and the translational hurricane wind speed at the time of landfall, data pairs of V_{max} and R_{max} at inland locations, e.g., at a certain distance inland or time since landfall, also can be determined. Finally, it was shown how the proposed methodology can be used to develop characteristic hurricane hazard definitions for use in performance-based engineering applications.

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