ELSEVIER

Reliability Engineering and System Safety 74 (2001) 239–249

RELIABILITY
ENGINEERING
&
SYSTEM
SAFETY

www.elsevier.com/locate/ress

Long-term hurricane risk assessment and expected damage to residential structures

Zhigang Huang[a], David V. Rosowsky[b,*], Peter R. Sparks[c]

[a]Applied Research Associates, Raleigh, NC, USA
[b]Departments of Forest Products and Civil Engineering, Oregon State University, Corvallis, OR 97331-5751, USA
[c]Department of Civil Engineering, Clemson University, Clemson, SC 29634-0911, USA

Accepted 11 August 2000

Abstract

This paper presents results from a study to evaluate long-term hurricane risks in the Southeastern United States using event-based simulation procedures. These risks are defined by (1) the statistical extreme wind climate, and (2) the expected insured losses from damage to residential structures. A probabilistic hurricane event model developed by the authors is used to evaluate long-term risks. The event model parameters were derived from a statistical analysis of storms affecting the Southeastern United States and include radius of maximum winds, central pressure difference, landfall location, storm track, and decay rate. The 50-year mean recurrence interval (MRI) gradient-level and surface gust wind speeds are evaluated for the region investigated using results from the simulation analysis. When coupled with a damage model, also developed by the authors, the results from the event-based simulation analysis are used to provide estimates of the expected losses. The states of North Carolina, South Carolina, and Florida are used to demonstrate the applicability of this procedure for evaluating expected losses. Implications for setting design wind speeds as well as risk-consistent insurance rates are discussed. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Damage model; Hurricane; Insured losses; Probability; Risk assessment; Simulation; Statistics; Wind speeds

1. Introduction

Hurricanes are among the greatest natural hazards affecting communities in the United States. In recent years, windstorm catastrophes have caused enormous economic losses and placed tremendous burdens on the insurance industry. Despite significant improvements in predicting, tracking and warning the public about hurricanes, there has been relatively little progress in our ability to estimate expected hurricane losses. These losses can be in the form of structural damage, damage to utilities or lifelines, or business interruptions. A number of models have been developed to predict losses due to hurricanes, however, these models are largely proprietary and are not available to the public. As such, they are of little value to individuals or organizations other than those for whom the models were developed (i.e. insurance companies).

Short-term hurricane risk can be defined either in terms related to the intensity of the storm or in terms of the economic damage (losses) caused by the storm. In this paper, risk is defined using the second definition as it incorporates both the extreme wind climate and the vulnerability (susceptibility) of residential buildings (e.g.) to hurricanes. Therefore, consideration of uncertainty in the risk assessment includes both uncertainties associated with the storm model and the economic loss model. Long-term hurricane risk is defined herein through a statistical characterization of the extreme wind climate and the associated expected insurance losses to residential structures.

In order to estimate the hurricane risks in the Southeastern United States and provide timely and easily interpreted guidance to insurers, emergency managers and the public, a GIS-based hurricane hazard assessment system was developed to predict expected wind conditions and associated damages [1]. This paper reports on the application of the wind field model and event-based simulation procedure developed in that study to the evaluation of design wind speeds and expected hurricane damage to residential structures. Specifically, event-based Monte Carlo simulation techniques are used to statistically characterize the wind climate and expected insurance losses in the Southeastern

---

* Corresponding author. Address: Department of Forest Products, Oregon State University, 104 Richardson Hall, Corvallis, OR 97331-5751, USA. Tel.: +1-541-737-8422; fax: +1-541-737-3385.
E-mail address: david.rosowsky@orst.edu (D.V. Rosowsky).

PII: S0951-8320(01)00086-2

United States. The occurrence of a hurricane is modeled as a Poisson process while the change in translational speed of a hurricane over land is modeled as a Markov process. The results from the analysis are used to determine 50-year mean recurrence interval (MRI) gradient-level wind speeds for the region being investigated. The surface wind speeds can then be determined using appropriate gradient-to-surface conversion factors. Using a damage model, also developed by the authors, the expected loss, defined as a percentage of the total insured portfolio, can then be estimated. This damage model was developed using actual insurance loss (claim) data from Hurricanes Hugo and Andrew. When coupled with the damage model, the results from the event-based simulation analysis are used to provide estimates of the expected losses. These can be presented on a 50-year basis or on an annualized basis. While the former corresponds to a typical building design life, the latter may be of greater interest to the insurance industry. The states of North Carolina, South Carolina, and Florida are used to demonstrate the applicability of this procedure for evaluating expected losses.

2. Wind field model and Monte Carlo simulation

A number of models have been used for hurricane wind speed simulation and risk analysis studies [2–9]. The starting point for most of these models has been the gradient level wind field. Huang [10] evaluated and compared a number of these models using data from Hurricanes Hugo, Fran, Bonnie, Earl, and Georges. In general, Batts' model was found to overestimate the surface wind speeds, while Georgiou's model was found to predict the surface wind speeds quite well at inland sites and at sites close to the ocean when the wind was blowing from the ocean. However, Georgiou's model overpredicted the wind speeds at sites near the coast and underpredicted the gradient wind speeds in the region of most intense winds, i.e. the eye wall. To overcome these problems, Georgiou's model was modified by Huang [10] to be able to better predict wind speeds. Specifically, a modification factor was applied to model's estimate of the gradient wind speed. The modification factor is a function of the central pressure difference (ΔP), the radius of maximum wind speed (R_m), and the translation wind speed (V_t), as well as the relative distance to the hurricane center (r/R_m). Surface wind speeds were then obtained by reducing the gradient wind speed in a manner appropriate for the terrain. The modified Georgiou's model was used in the event-based simulation analysis in this study. Further details of this model may be found elsewhere [1,10].

Once a hurricane makes landfall, the energy balance between the heat source and frictional dissipation is disturbed due to the reduced availability of heat and increased frictional dissipation. This results in a rise in atmospheric pressure in the storm's center, and consequently, the hurricane weakens and the wind speeds decrease. The rise in the central pressure is most often used to model the weakening of a landfalling hurricane. Based on an analysis of historical hurricanes (see Ref. [10]), a decay model having the following form was assumed

$$\Delta p(t) = \Delta p_0 \exp(-at) \tag{1}$$

where $\Delta p(t)$ is the difference between the central pressure and the atmopheric pressure at a distance beyond the effect of the hurricane at time t; Δp_0, the pressure difference when the hurricane crossed the coast; a is the filling constant modeled as a normally distributed random variable. The mean and standard deviation of the filling constant a for the three states investigated (North Carolina, South Carolina, and Florida) are shown in Table 1. This decay model is similar to that used by Vickery and Twisdale [9], however their model generally suggests a more rapid decay rate. In this study, the correlation between the filling rate and the intensity of the storm was not found to be statistically significant. Further information on the decay model may be found elsewhere [10].

Table 1
Statistics of hurricane model parameters (from: Ref. [10])

Parameter	Distribution	Distribution parameters			
		North Carolina	South Carolina	Florida (Atlantic Coast)	Florida (Gulf Coast)
Annual occurrence rate, λ	Poisson	$\lambda = 0.277$	$\lambda = 0.306$	$\lambda = 0.252$	$\lambda = 0.379$
Approach angle, θ (degrees)	Normal	$\mu = 2.19$	$\mu = -20.88$	$\mu = -60.05$	$\mu = 34.42$
		$\sigma = 42.77$	$\sigma = 44.41$	$\sigma = 24.79$	$\sigma = 29.78$
Central pressure difference ΔP (mb)	Weibull	$u = 51.120$	$u = 50.094$	$u = 64.831$	$u = 42.751$
		$k = 3.155$	$k = 2.304$	$k = 3.465$	$k = 3.929$
Radius of maximum wind speed, $R_{\max}$ (km)	Lognormal	$\lambda = 3.995$	$\lambda = \ln(260/\sqrt{\Delta p})$	$\lambda = 4.045 - 0.0083\Delta p$	$\lambda = 3.984 - 0.012\Delta p$
		$\zeta = 0.275$	$\zeta = 0.461$	$\zeta = 0.451$	$\zeta = 0.350$
Translation velocity, V_t (m/s)	Lognormal	$\lambda = 1.787$	$\lambda = 1.805$	$\lambda = 1.616$	$\lambda = 1.734$
		$\zeta = 0.513$	$\zeta = 0.456$	$\zeta = 0.365$	$\zeta = 0.418$
Filling constant, a	Normal	$\mu = 0.032$	$\mu = 0.042$	$\zeta = 0.021$	$\zeta = 0.024$
		$\sigma = 0.025$	$\sigma = 0.016$	$\sigma = 0.014$	$\sigma = 0.033$

Probabilistic process models were used in the event-based Monte Carlo simulations in this study. Specifically, the occurrence of hurricanes was modeled as a Poisson Process while a Markov chain was used to describe the evolution of the hurricane. Monte Carlo simulation involves the direct sampling from the distributions of all the random variables in the performance function being evaluated. Since the generation of random variables is a relatively simple task, Monte Carlo techniques can be used efficiently to simulate both discrete and continuous random processes. Simulation therefore provides a framework for considering spatial uncertainty and temporal uncertainty simultaneously, i.e. in a time-dependent analysis. Using event-based hurricane simulation as an example, the realizations in the time domain are generated first (i.e. hurricanes are generated according to an arrival model). Then, realizations of the random variables defining the gradient wind field are generated in the space domain. Using appropriate gradient-to-surface conversion factors, the surface wind speeds can also be determined. The hurricane is then moved to the next location and the wind field is re-generated taking into account spatial changes such as decay. After the hurricane has degraded to the point that wind speeds are no longer significant, the simulation proceeds to the next randomly generated hurricane event. These steps are repeated a specified number of times, and the distributions of maximum wind speeds (e.g.) are determined. These can then be used in the analysis of extreme wind climate and hurricane risks. Further discussion about Monte Carlo simulation and its application to hurricane simulation can be found in Ref. [10].

Five basic variables were used to characterize the wind field in this study: central pressure difference (ΔP), radius of maximum winds ($R_{\max}$), approach angle (θ), translation velocity (V_t) and annual occurrence rate (λ). These event model parameters were determined from an analysis of historical landfalling hurricanes in the region of interest [1]. Hurricane data covering 112 years (1887–1998) were used to determine the distribution and statistical moments (including possible correlations) of the five basic variables. Three states (North Carolina, South Carolina, and Florida) in the Southeastern United States were investigated, and site-specific statistical information was determined for each (see Table 1). Since the hurricanes can approach the Florida peninsula either from the Atlantic Ocean or the Gulf of Mexico, two different sets of statistics were developed to model the characteristics of hurricanes approaching from each of these directions. The transition matrix for the Markov analysis was developed using historical hurricane track information which reported the storm's position every six hours [11]. The translational wind speed states in the transition matrix therefore corresponded to the ratios of current states to the translational wind speed at landfall at each six-hour interval. The simulation results were shown to agree well with actual data [10]. Further details can be found elsewhere [1,10].

3. Damage model

Loss information from Hugo and Andrew was obtained from a large insurer. For uniformity, only data from standard homeowners policies for single-family dwellings were used. The total insured value of a property was assumed to be 150% of the value of the structure. The insurer provided information on the number of policies, number of claims, total insured value and the total amount paid in claims in each zip (postal) code area. Zip codes with fewer than 20 policies were eliminated since the sample size was considered too small to be reliable. The information from Hurricane Hugo covered 81,161 policies in South Carolina with insured values totaling about $10.42 billion. The total number of claims was 44,448 and the total claim amount reached $247.4 million (2.4% of the total insured value). Information was collected from 118 zip codes in South Carolina (31% of the state's 381 zip codes). Following Hurricane Andrew, information was collected from 71 zip codes in Florida, covering 72,796 policies and with insured values totaling about $12.36 billion. The total number of claims was 59,523 and the total claim amount reached $2.64 billion (21.3% of the total insured value).

The damage model was developed by relating the mean surface wind speed to the claim ratio and damage ratio in each zip code. The claim ratio is defined as the total number of claims in a zip code divided by the total number of insurance policies in that zip code. The damage ratio is defined as the amount paid out by the insurer divided by the total insured value. The reference wind speed was assumed to be the maximum mean surface wind speed, averaged over 10 min, which would be measured at a height of 10 m in the middle of an imaginary airport, located at the geographical centroid of the zip code area. These speeds were determined by multiplying the maximum gradient wind speed at the zip-code centroid by the following factors: 0.60 for very exposed coastal islands with wind from the sea, 0.50 for the same locations with the wind blowing from the mainland, 0.50 for zip-codes with centroids within 10 km of the coast for winds approaching over the sea, 0.45 for these locations with winds approaching over the land, and 0.45 for all other zip code areas. The gradient wind speeds for these two events (Hugo and Andrew) were obtained using a wind field model developed by the authors [12].

Most insurance losses occurred in suburban and wooded areas. However, in a few areas affected by Andrew, the houses were scattered in flat, treeless terrain. In these areas, the over-land boundary layer would develop very slowly as the wind passed from the sea to the land. Using the fetch factor in Ref. [13], it can be shown that in such terrain, even 20 km inland, the mean wind speed could still be 60% of the gradient speed. This value was adopted for all such areas in South Florida. Thus, the *effective* mean wind speed is defined as the reference wind speed at the notional airport taking into account the local exposure.

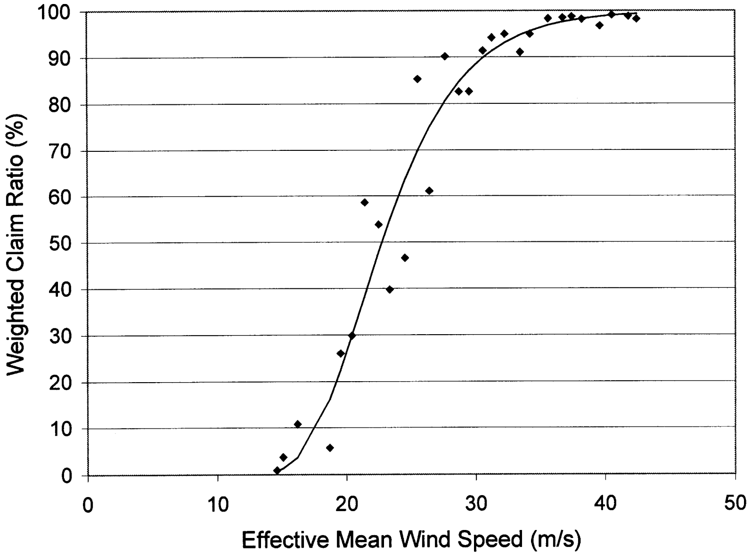

Fig. 1. Claim ratio vs. effective mean surface wind speed.

Data from zip codes having similar wind conditions were weighted according to the total number of policies in each zip code (i.e. the wind speeds, claim ratios, and damage ratios were weighted averages). The relationship between the weighted claim ratio and effective surface wind speed is shown in Fig. 1. The relationship between weighted damage ratio and effective surface wind speed is shown in Fig. 2. It is interesting to note that these figures are essentially a quantification of the old Beaufort Scale, which suggested that structural damage was likely to begin when the mean wind speed reached 20 m/s, and became widespread by about 30 m/s. Fig. 1 suggests that a few people will file insurance claims in locations with mean wind speeds less than 20 m/s, but that nearly everyone will file a claim by the time the speed reaches 30 m/s. Fig. 2 shows that above 35 m/s, the amount of damage increases rapidly, likely the result of large amounts of rain entering buildings through breaches in the building envelopes. Considering the loss data shown in Figs. 1 and 2, the relationship between claim ratio and effective mean surface wind speed follows a double exponential form, while the relationship between the damage ratio and effective mean surface wind speed follows an exponential form. Using regression techniques, the claim ratio and damage ratio corresponding to a given surface mean wind speed x can therefore be obtained as [10]

$$F_C(x) = \exp(-\exp(-0.239(x - 21.21)))^* 100 \tag{2}$$

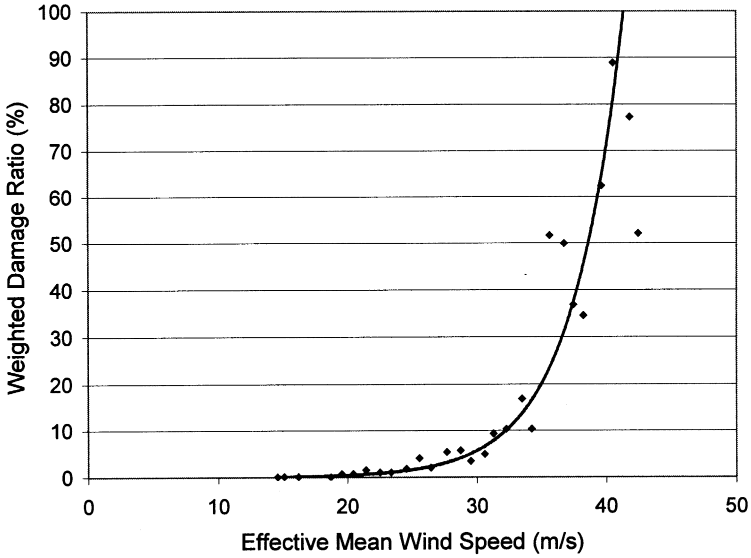

Fig. 2. Damage ratio vs. effective mean surface wind speed.

and

$$\begin{cases} F_{\mathrm{D}}(x) = \exp(0.252x - 5.823) & x \leq 41.4\ \mathrm{m/s} \\ F_{\mathrm{D}}(x) = 100 & x > 41.4\ \mathrm{m/s} \end{cases} \tag{3}$$

where $F_{\mathrm{C}}(x)$ is the expected claim ratio in percent and $F_{\mathrm{D}}(x)$ is the expected damage ratio in percent. Once the maximum mean surface wind speed at the centroid of each zip code is known (or has been estimated), the damage ratio and claim ratio in each zip code are obtained from Eqs. (2) and (3), respectively.

4. Evaluation of *N*-year MRI wind speeds

The basic design wind speed for buildings in the United States is the 3-second gust wind speed having a 2% annual exceedance probability, i.e. a 50-year MRI (ASCE 7-95). Assuming independent annual maximum wind speeds, the probability of exceeding the *N*-year MRI wind speed in *m* years is $1 - (1 - (1/N))^m$. Thus, the knowledge of the *m*-year maximum wind speed distribution can be used to evaluate the design wind speeds. In this paper, a value of $m = 50$ was assumed since 50 years is the typical design life for a building in the United States. Huang et al. [14] have also shown that the problem of overestimating the extreme wind climate in hurricane-prone regions by using equivalent annual maximum wind speeds may be overcome by using 50-year maximum wind speeds. It is proposed herein that the gradient wind speed is an appropriate basis for characterizing the wind climate in hurricane-prone regions. Since the gradient-level wind speed is unaffected by surface friction, the uncertainties associated with modeling the surface exposure, and thus the gradient-to-surface conversion factors, do not influence the *N*-year MRI gradient wind speed. The maximum wind speed values from 1000 simulated 50-year exposure periods were used as the basis for the estimating 50-year MRI gradient wind speeds for the Southeastern United States in this study. For each 50-year period, hurricanes were simulated using the long-term risk model described previously and the maximum gradient and surface wind speeds at the centroid of each zip code were recorded. The claim ratios and damage ratios associated with each hurricane during the 50-year period were also determined (using the damage model given by Eqs. (2) and (3)), summed, and divided by 50 at the end of each 50-year period to obtain the annual claim ratio and annual damage ratio for each zip code. The presumption of independent hurricane events serves as justification for this method.

The 50-year MRI gradient wind speeds for the Southeastern United States determined using this procedure are shown in Fig. 3. The gradient wind speeds are seen to drop gradually with distance from the coast, except in Florida where the gradient wind speeds increase moving down the peninsula. Most of the coastal areas in North Carolina and South Carolina have a 50-year MRI gradient wind speed of 60 m/s while the southern part of Florida has a 50-year MRI gradient wind speed of 68 m/s. However, in order to determine design wind speeds at the surface, appropriate conversion factors that properly take into account site characteristics must be applied to the 50-year MRI gradient wind speeds. Note that the 50-year MRI gradient wind speed contours are almost equally spaced with distance from the coast. However, due to the relatively quick transition from an over-water gust structure to an over-land gust structure once a hurricane makes landfall [15], the surface gust wind speed contours will not be equally spaced.

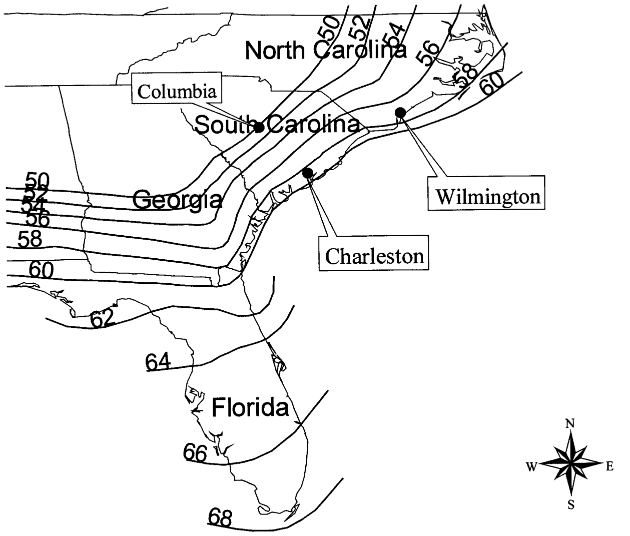

Fig. 3. 50-year MRI gradient wind speed contours (m/s) for the Southeastern United States.

Surface wind speeds for open terrain at a standard height of 10 m can be obtained directly from the gradient wind speeds using appropriate gradient-to-surface conversion factors. In the present study, gradient-to-gust conversion factors of 0.90 and 0.80 are used for sites located directly on the beach and within 10 km of the coast, respectively, when the wind is blowing from the water to the land. When the wind is blowing from the land to the water (with increased surface roughness), the conversion factors change to 0.80 and 0.72, respectively. For inland sites, the gust-to-gradient conversion factor is 0.72 regardless of wind directions. Similarly, the ratios of mean wind speed to gradient wind speed are 0.65 and 0.50 for sites located directly on the beach and open sites, respectively, at initial landfall with wind blowing from the water; 0.50 and 0.45, respectively, with wind blowing from the land; and 0.45 for open sites located far inland regardless of wind directions. The land exposure effects on the wind profile are assumed to change abruptly with change in wind direction, i.e. the gradient-to-surface conversion factor changes immediately once the wind changes from blowing from the water to blowing from the land, or vise versa. Fig. 4 shows the cumulative distribution functions for the 50-year maximum gust wind speeds for several sites considered in this study. The

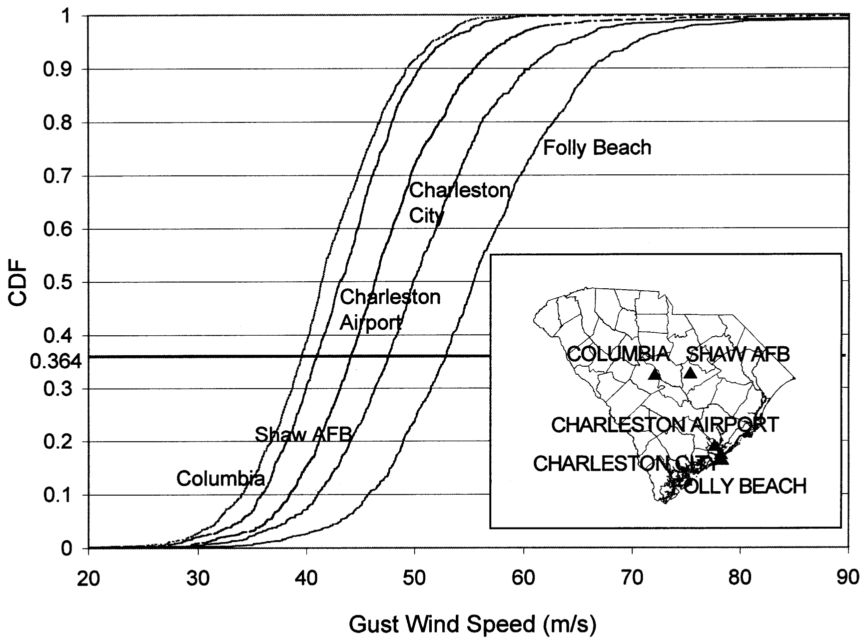

Fig. 4. 50-year maximum gust wind speed CDFs.

non-exceedance probability for the 50-year MRI (0.364) is indicated by the horizontal line. The figure indicates that wind speeds initially drop very rapidly with distance from the coast. The 50-year MRI gust wind speed is 52.9 m/s at Folly Beach (located directly on the coast), 47.7 m/s at Charleston City (10 km from the coast), and 43.2 m/s at Charleston Airport (25 km from the coast). Thereafter, the decrease is much more gradual, dropping to 41.0 m/s at Shaw Air Force Base (150 km inland). A Lognormal distribution was found (rather than an Extreme Type I or Type II distribution as had been found in other studies) to provide the best fit to the simulated 50-year maximum wind speeds for all sites considered in the Southeastern United States [10].

Wind speeds reported using different averaging times must be converted to a standard averaging time before they can be compared. However, studies by Batts et al. and Vickery and Twisdale [5,9] reported fastest-mile wind speeds and insufficient information was provided about their assumed gust structures and mean wind profiles to permit accurate conversions to 3-second gusts or 10-minute mean speeds. Therefore, the results from the present study are compared only with the results by Georgiou [7]. Since the reported hourly mean wind speeds at different mileposts in Georgiou's study are values over water, a gradient-to-surface conversion factor of 0.65 [15] was used to estimate the 50-year MRI mean wind speed at various coastal locations. This resulted in very close agreement with Georgiou's results. In the present study, the 50-year MRI mean wind speed over water near Charleston, SC was $(60)(0.65) = 39$ m/s, while Georgiou [7] found a value of 36 m/s. The 50-year MRI mean wind speed over water near Wilmington, NC was $(58)(0.65) = 37.7$ m/s, while Georgiou [7] reported a value of 37 m/s. Similarly, for the southern tip of Florida, the 50-year MRI value was $(68)(0.65) = 44.2$ m/s, very close to the value (44 m/s) found by Georgiou [7]. For inland areas, a gradient-to-surface conversion factor of 0.45 was assumed [15]. The 50-year MRI mean wind speed for Columbia, SC, located about 180 km inland, was $(50)(0.45) = 22.5$ m/s, which compares well with 22.7 m/s obtained using Georgiou's model. To be compatible with the design wind speed definition (open terrain) in ASCE 7-95 [16], a uniform gradient-to-surface conversion factor of 0.72 was used to obtain the surface gust wind speeds from the gradient wind contour map Fig. 3. The design wind speeds in ASCE 7-95 are considerably higher for coastal areas than those obtained in this study. For example, the value for Charleston in ASCE 7-95 is 53 m/s (note that the hurricane importance factor of 1.05 has been taken out), while a value of $(60)(0.72) = 43.2$ m/s was found in this study. One possible explanation for this difference is the assumption in ASCE 7-95 of a very slow exposure transition from over-water to over-land after a hurricane makes landfall. The basic design wind speed map given in ASCE 7-95 was based on the simulation results from Refs. [5,7,9], all of which assumed a very gradual transition from over-water to over-land exposure. For example, Georgiou assumed the over-water to over-land transition zone extended 50 km inland. In fact, this transition has been shown to occur relatively quickly in an actual hurricane environment [15]. Moreover, in deriving the 3-second design gust wind speeds in ASCE 7-95, the gust factors developed by Krayer and Marshall [17] were applied to the simulated wind speeds. However, these gust factors were intended to be representative values over land. Applying the over-land gust factors to over-water mean

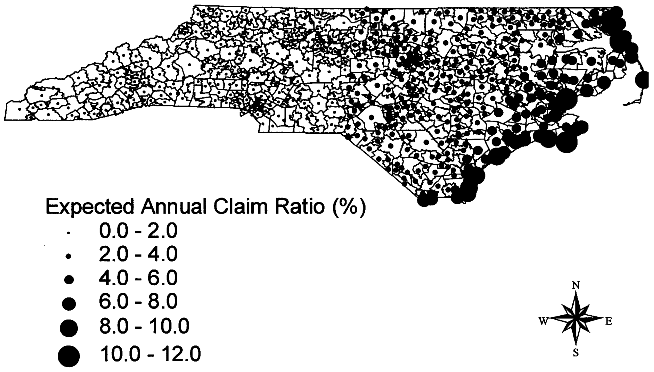

Fig. 5. Expected annual claim ratio for each zip code in North Carolina.

wind speeds results in higher gust wind speeds. Therefore, the coastal region design wind speeds in ASCE 7-95 are higher than would be predicted in this study. Finally, ASCE 7-95 presents design wind speeds on the coast corresponding to exposure C (open terrain) over land. However, the wind speeds given by Batts et al., Georgiou and Vickery and Twisdale [5,7,9] for locations along the coast were representative values over water. This may help to further explain the higher wind speeds in ASCE 7-95 than those obtained herein.

Studies of recent hurricanes, including Hugo (1989), Andrew (1992), Bertha (1996), Fran (1996), Bonnie (1998), Earl (1998), and Georges (1998), have shown that the transition from an open water exposure to an open country exposure in an actual hurricane environment occurs much faster than previously assumed [15]. Within 10–20 km after landfall, the gust structure and gradient-to-surface ratios are almost the same as those for hurricanes well inland. Studies of historical wind records, including sites for which more than 100 years of annual maximum wind speed data are available, found that for a typical coastal location such as Charleston, located about 25 km inland from the open sea, the 50-year MRI gust speed was approximately 44 m/s [18]. This is similar to the value (43.2 m/s) obtained in the present study. An analysis of annual maximum gust wind speeds in Wilmington from 1891 to 1998 by Sparks and Huang [15] found the 50-year MRI gust wind speed to be 43.9 m/s, very close to the value of $(58)(0.72) = 41.8$ m/s obtained in the present study. Using annual maximum wind speed records, the 50-year MRI gust wind speed for the regions not affected by hurricanes in South Carolina and North Carolina was found to be approximately 37 m/s and was independent of distance from the coast. The 50-year MRI gust wind speed for Columbia based on the hurricane simulation analysis in this study was found to be $(50)(0.72) = 36$ m/s. This suggests that both hurricanes and thunderstorms contribute to the extreme wind climate in Columbia. This ‘transition zone’ concept is further described in the paper by Huang et al. [14].

5. Prediction of expected insured losses

The damage model described previously can be used to determine the expected loss ratio at each zip code for a single event (see Ref. [12]) or for a period of time, i.e. using the long-term risk model developed herein. The states of North Carolina, South Carolina, and Florida are used to demonstrate the applicability of the wind field model and the damage model to the expected loss analysis. For each 50-year period, hurricanes were simulated and the

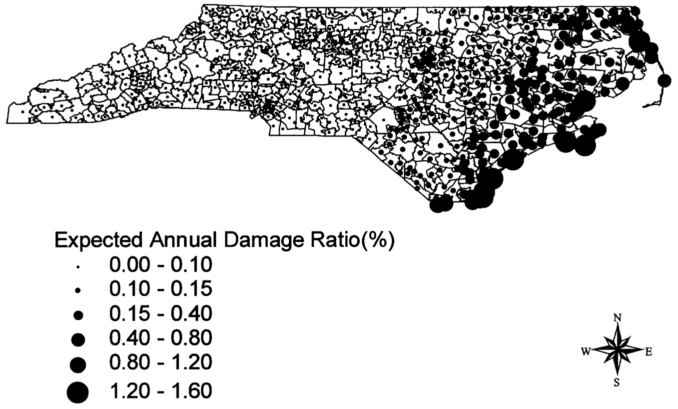

Fig. 6. Expected annual damage ratio for each zip code in North Carolina.

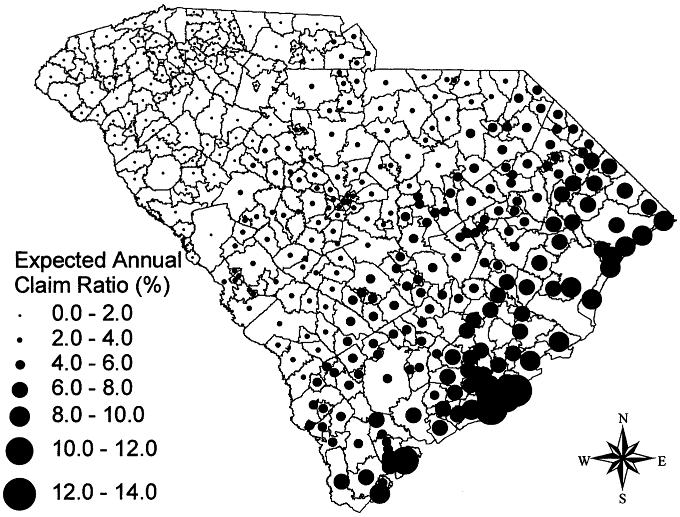

Fig. 7. Expected annual claim ratio for each zip code in South Carolina.

maximum gradient and surface wind speeds at the centroid of each zip code were recorded. The claim ratios and damage ratios associated with each hurricane during the 50-year period were also calculated, summed, and divided by 50 at the end of each 50-year period to obtain the annual claim ratio and annual damage ratio for each zip code. After a specified number of simulations, the expected values and distributions for the annual claim ratio and annual damage ratio were determined. Figs. 5–10 show the simulated expected annual claim ratio and damage ratio for each zip code in North Carolina, South Carolina, and Florida, respectively. These values have also been presented in tabular form [10]. As seen in Fig. 11, the expected annual claim ratio and damage ratio drop very quickly with distance from the coast. For those zip codes on barrier islands in South Carolina with open terrain (such as Isle of Palms, Sullivans Island, St. Helena Island, and Hilton Head Island), the expected annual damage ratio is about 2%. This implies

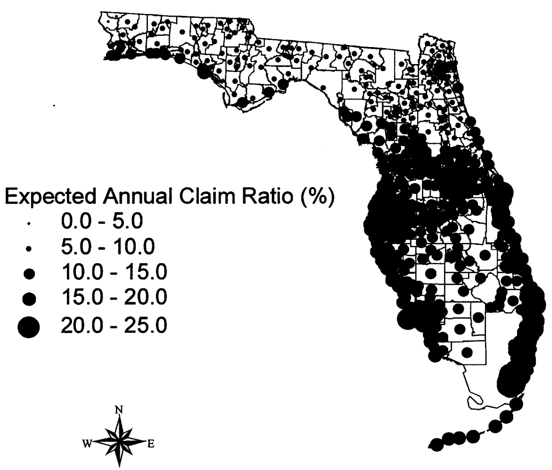

Fig. 9. Expected annual claim ratio for each zip code in Florida.

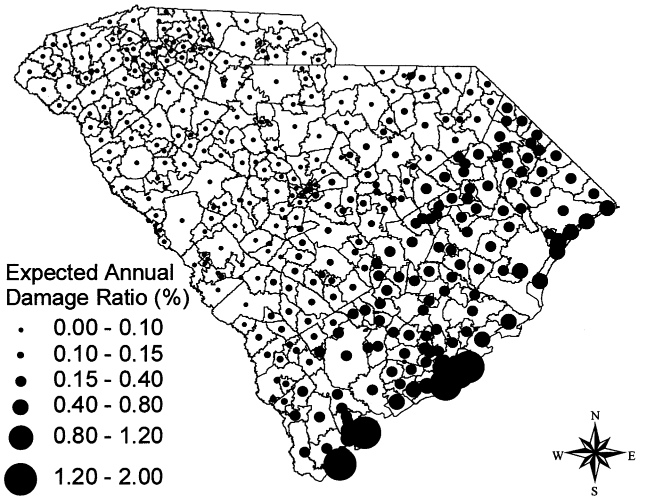

Fig. 8. Expected annual damage ratio for each zip code in South Carolina.

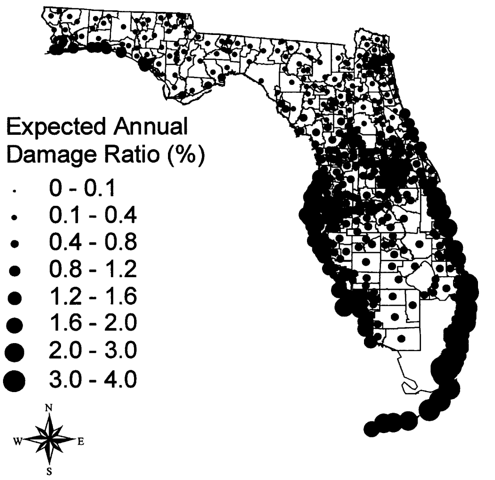

Fig. 10. Expected annual damage ratio for each zip code in Florida.

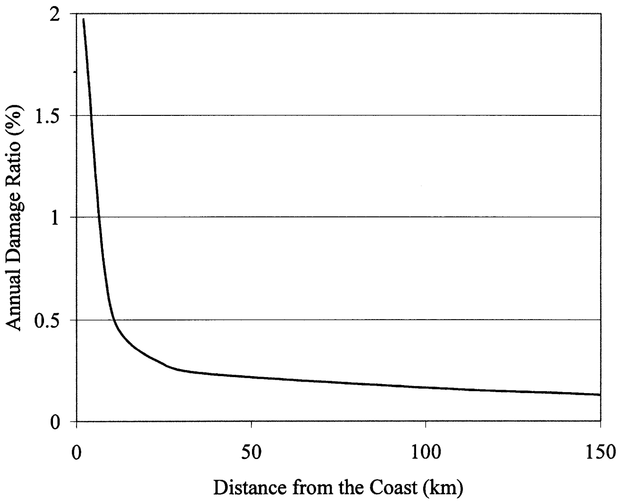

Fig. 11. Expected annual damage ratio vs. distance from coast.

that houses on these barrier islands will experience losses totaling 100% of the insured value, on average, every 50 years. However, only about 20 km inland, the expected annual damage ratio drops to 0.2–0.3%, or about one tenth of the value for the barrier islands. Further inland, the expected annual damage ratio drops to less than 0.1%. The quick drop in the expected annual damage ratio in the first 20 km from the coast is largely due to the fast transition from over-water winds to over-land winds when a hurricane makes landfall. Beyond that, the effects of hurricane decay contribute most to the gradual drop in the expected annual damage ratio. Similar trends can be seen in North Carolina and Florida. Note that only hurricane risks (losses) were considered in this research; losses caused by extratropical cyclones and thunderstorms were not taken into account. These non-hurricane losses may be significant (from a percentage standpoint) for inland regions in which these events contribute to the extreme wind climate.

Figs. 3 and 5–10 also suggest that South Carolina and North Carolina have similar hurricane risks (considering both the extreme wind climate and expected annual claim and damage ratios), while those in Florida are much higher. The maximum expected annual claim and damage ratios for coastal areas in Florida are more than twice those in South Carolina and North Carolina.

Figs. 12 and 13 show the cumulative distribution functions for the annual claim ratio and annual damage ratio for several sites in South Carolina. The drop in these ratios with distance from the coast is quite obvious from these figures. Since significant landfalling hurricanes are relatively rare events, variabilities in the annual claim ratio and damage ratio are relatively large for the sites investigated; coefficients of variation (COVs) averaged about 0.40 and 0.80 for the annual claim ratio and damage ratio (in South Carolina), respectively. Claim ratio COVs were about 10% lower for coastal areas and about 20% higher for areas located well inland. Damage ratio COVs were about 10% lower and about 10% higher for coastal and inland areas, respectively.

Even though limited information is presently available to validate the long-term damage assessment procedure, these results still provide meaningful information for insurance regulators, particularly on a relative risk basis. Such information could be used, for example, when setting appropriate insurance rates.

6. Conclusions

Event-based simulation techniques were used to statistically characterize the long-term hurricane risks in the

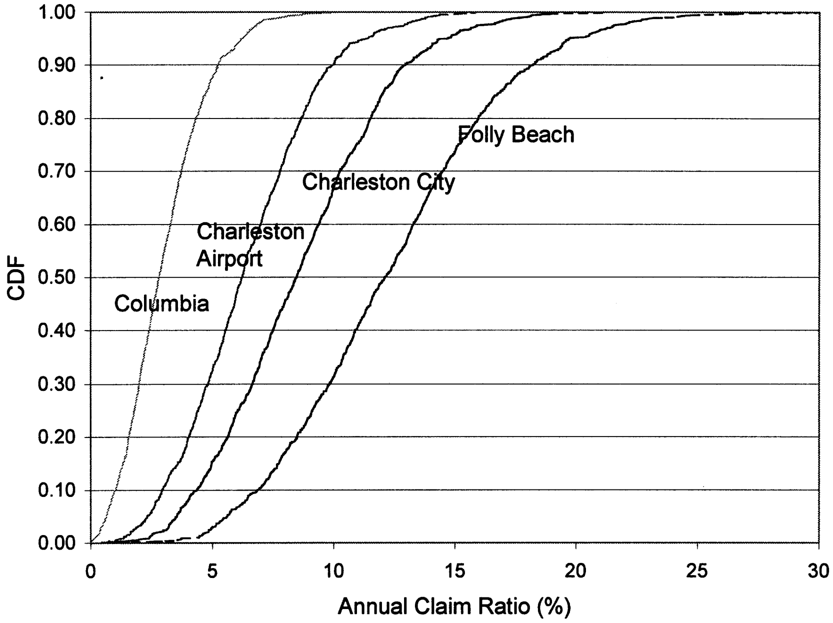

Fig. 12. Annual claim ratio CDFs.

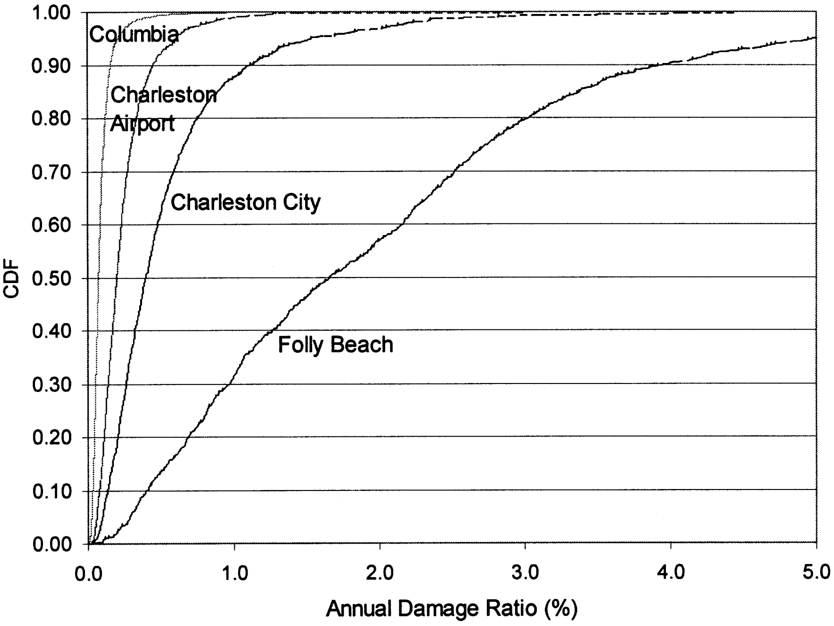

Fig. 13. Annual damage ratio CDFs.

Southeastern United States. These risks were defined to include both the statistical extreme wind climate and the expected insured losses for residential structures. The latter were expressed as expected claim ratios and damage ratios. Historical hurricane events were used to calibrate the proposed wind field model and long-term station wind speed records were used to validate the simulation results. The states of North Carolina, South Carolina, and Florida were used to demonstrate the applicability of the proposed methodology for expected loss analysis. The major findings from this study were as follows:

1. The 50-year MRI surface gust wind speeds over-water obtained in the present study agree well with Ref. [7]. However, other studies, including those used as the basis for design wind speeds in ASCE 7-95, may overestimate the 50-year MRI surface wind speeds over land near the coast.
2. Due to the rapid reduction in wind speeds, the expected annual losses from hurricanes at sites just 20 km inland are about an order of magnitude less than those on the most highly exposed islands.
3. Considering both extreme wind climate and expected insurance losses, Florida has a much greater hurricane risk than North Carolina or South Carolina, which have similar risks.

Acknowledgements

Funding for this work has been provided by the South Carolina Sea Grant Consortium. The authors gratefully acknowledge this support.

References

[1] Huang Z, Rosowsky DV, Sparks PR. Event-based hurricane simulation for the evaluation of wind speeds and expected insurance losses, Proceedings of the 10th International Conference on Wind Engineering 1999, Copenhagen, Denmark.
[2] Russell LR. Probability distributions for Texas Gulf Coast hurricanes effects of engineering interest. PhD Dissertation, Stanford University, Stanford, CA, 1968.
[3] Russell LR. Probability distributions for hurricane effects. ASCE J Waterways, Harbors, Coastal Engng 1971;97(1):139–54.
[4] Tryggvason BV, Surry D, Davenport AG. Predicting wind-induced response in hurricane zones. ASCE J Struct Div 1976;102(12):2333–50.
[5] Batts ME, Cordes MR, Russell LR, Shaver JR, Simiu E. Hurricane wind speeds in the United States, NBS Building Science Series 124. Washington, DC: US Department of Commerce, National Bureau of Standards, 1980.
[6] Tuleya RE, Bender MA, Kurihara Y. A simulation study of the landfall of tropical cyclones using a movable nested-mesh model. Mon Weath Rev 1984;112(1):124–36.
[7] Georgiou PN. Design wind speeds in tropical cyclone-prone regions. PhD Dissertation. Department of Civil Engineering, University of Western Ontario, Canada, 1985.
[8] Sanchez-Sesma J, Aguirre J, Sen M. Simple modeling procedure for estimation of cyclonic wind speeds. ASCE J Struct Engng 1988;114(2):352–70.
[9] Vickery PJ, Twisdale LA. Prediction of hurricane wind speeds in the United States. ASCE J Struct Engng 1995;121(11):1691–9.
[10] Huang Z. Stochastic models for hurricane hazard analysis. PhD Dissertation. Department of Civil Engineering, Clemson University, Clemson, SC, 1999.
[11] Neuman CJ, Jarvinen BR, McAdie CJ, Elms JD. Tropical cyclones of the North Atlantic Ocean, 1871–1992. US Department of Commerce-NOAA, 1997.
[12] Huang Z, Rosowsky DV, Sparks PR. Hurricane hazard assessment system for damage to residential structures in South Carolina. Envir Geosci 2000;7(1):57–65.
[13] Cook NJ. The Designer's guide to wind loading of building structures, part I. Garston: Building Research Establishment, 1985.

[14] Huang Z, Rosowsky DV, Sparks PR. Statistical modeling of mixed wind climate using event-based simulation and analysis of wind records, Proceedings of the Eighth International Conference on Applications of Statistics and Probability 1999, Sydney, Australia.

[15] Sparks PR, Huang Z. Wind speed characteristics in tropical cyclones, Proceedings of the 10th International Conference on Wind Engineering 1999, Copenhagen, Denmark.

[16] ASCE. Minimum design loads for buildings and other structures ASCE 7-95. New York: American Society of Civil Engineers, 1995.

[17] Krayer WR, Marshall WR. Gust factors applied to hurricane winds. Bull Am Met Soc 1992;73:613–7.

[18] Sparks PR, Saripalli P. The use of historical records to put modern wind storms into perspective, Proceedings of the Seventh US National Conference on Wind Engineering 1993, UCLA, Los Angeles, CA.