North Carolina Coastal Flood Analysis System Hurricane Parameter Development

TR-08-06

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Hurricane Parameter Development

Submittal Number 1, Section 5

A Draft Report for the State of North Carolina Floodplain Mapping Project

Technical Report TR-08-06
Date: 12 September 2008

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The simulation system for the North Carolina floodplain-mapping project uses a suite of state-of-the-art numerical wind, wave, and surge models to compute stillwater and wave setup elevations along the North Carolina coast. This technical report describes the development of the tropical storm statistical representation. This constitutes Section 5 of Submittal Number One, which the State of North Carolina, Division of Emergency Management has tendered for review to the Federal Emergency Management Agency.

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Table of Contents

3 Hurricane Parameter Selection/Development

The Joint Probability Method (JPM) for simulating hurricane risk has been used in some form or another since the late 1960's. The original JPM application, while not called JPM, was developed by Larry Russell (Russell, 1968), for predicting wave loads on offshore structures in the Gulf of Mexico. The JPM approach used by Russell was a full Monte-Carlo simulation where model hurricanes were modeled using straight-line segments with wind and wave fields computed using hurricane wind and wave models. The methodology was first introduced because the number of historical events (hurricanes) at any one location is insufficient to enable standard statistical techniques (such as extreme value analyses) to estimate flood risk, wave height risk, wind speed risk, etc. For coastal risk assessment, the introduction of long duration tracks that mimic the behavior of hurricanes while they are offshore (and generating a wave field) was first introduced by Resio, et al, (2007). Modeling the full storm track from a wind-only point of view was introduced by Vickery, et al (2000). The simulation methodologies employed by Resio, et al (2007), and Vickery, et al (2000) both attempt to properly model the correlations between storm intensity (central pressure) and radius to maximum winds (RMW). Vickery, et al, (2000) also modeled a relationship between *RMW* and the Holland *B* (Holland, 1980) parameter.

The JPM approach is a simulation methodology that relies on the development of statistical distributions of key hurricane input variables (central pressure, radius of maximum winds, translation speed, and heading) and sampling from these distributions to develop model hurricanes. The simulation results in a family of modeled storms that preserve the relationships between the various input model components, but provides a means to model the effects and probabilities of storms that have not yet occurred. For this study, a method known as JPM-OS (Joint Probability Method - Optimum Sampling) will be used which reduces the number of required simulated storms.

The key model inputs and data sources for deriving the inputs for the meteorological modeling of the hurricanes include:

Central pressure (from HURDAT and/or Blake et al., 2007)
Minimum distance to site (HURDAT)
Translation speed (HURDAT)
Storm heading (HURDAT)
Holland *B* parameter (NOAA flight level data)
Radius to maximum winds (Ho et al.(1987), post storm analyses)

The following sections of the report discuss the selection of storms used in the modeling process, the modeling of the statistical distributions of the key parameters and the selection of the final model storms, statistical weights and storm tracks used in the storm surge and wave modeling.

Hurricane Data Base and Probabilistic Models

3.1.1 Storm Data Base

Following the methodology used by the USACE in the 2007 Louisiana Coastal Protection and Restoration (LACPR) project and in the coastal Mississippi Flood Insurance Study (FEMA, 2007), only hurricanes affecting the North Carolina coastline between 1940 and the present were used to develop the statistical distributions for storm central pressure, heading, translation speed, radius to maximum winds, and the Holland-B parameter. It is know that historic storm data collected earlier than approximately 1940 is inconsistent and suffers in accuracy. For the North Carolina area there is a sufficient number of storm events after 1940 to fill out the statistical sample space and to develop distributions for the key hurricane parameters. To develop the statistical distributions for the key hurricane parameters, the storms were divided into two classes, with the statistical distributions for some parameters (e.g. storm heading and occurrence rate) within each class developed separately. The first class consists of all hurricanes making landfall along a coastal segment extending from near Charleston South Carolina through to near Cape Lookout, North Carolina. This line segment has a length of 440 km. The second class consists of bypassing hurricanes that include all storms that do not make landfall along the landfall line segment, but cross a line extending from Cape Lookout 76.2 W, 35.6 N eastward to 73.6 W, 35.2 N a distance of 300 km. See Figure 3.1.

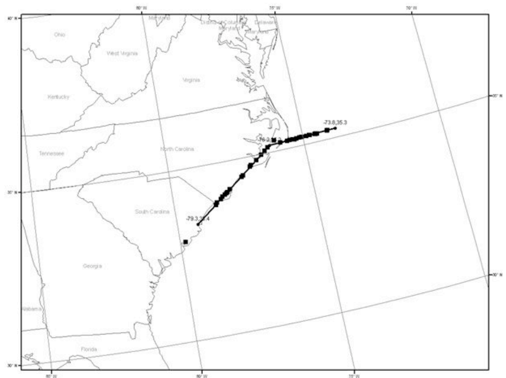

Figure 3.1 Locations of landfall and bypassing storms used to define North Carolina hurricane parameter distributions. The line segments used to define landfalling and bypassing storms are also shown.

Table 3.1 presents the list of landfalling and bypassing storms affecting North Carolina since 1940. The table presents the storm name and year, the central pressure (p_c) at landfall (or by-pass location), storm heading and translation speed and the latitude-longitude of the landfall or by-pass location. Figure 3.1 shows the landfall/bypass locations of the hurricanes given in Table 3.1. As indicated in Table 3.1, a total of only 38hurricanes have affected the North Carolina coast during the period 1940 through 2007.

3.1.2 Model Hurricane Probability Distributions

In order to model hurricane induced coastal flood risk for return periods of the order of 10 years and longer, a reduced sample consisting of only hurricanes with central pressures less than 980 mbar was used to derive probability distributions for central pressure, heading, translation speed, radius to maximum winds, Holland (1980) *B* parameter, landfall location and occurrence rate, (need to include all here). The pressure data, when expressed as a central pressure difference, Δp (defined as the far field pressure, taken here as 1013 mbar, minus the central pressure, p_c) is well characterized by a Fischer-Tippet Type I extreme value distribution. The translation speed is adequately modeled using a log-normal distribution, but the storm heading at landfall cannot be modeled with any typical two-parameter distributions.

Table 3.1 Parameters of hurricanes affecting North Carolina during the period 1940 to 2007

Hurricane Name	Central Pressure (mbar)	Heading (Degrees CW from North)	Translation Speed (m/sec)	HURDAT Wind Speed (kts)
1940 NOT NAMED 04	960[(1)]	35	3.6	80
1944 NOT NAMED 03	990	-4	8.0	90
1944 NOT NAMED 07	942[(1)]	20	8.5	105
1949 NOT NAMED 01	977	10	8.5	110
1953 BARBARA	987	20	5.4	105
1954 CAROL	960[(1)]	7	6.3	100
1954 EDNA	951[(1)]	25	7.6	120
1954 HAZEL	937	7	13.9	125
1955 CONNIE	962	14	2.7	80
1955 DIANE	987	-32	4.0	85
1955 IONE	960	-6	5.4	105
1958 HELENE	946	65	8.0	125
1959 CINDY (SC)	983	-35		
1960 DONNA	958	30	10.7	110
1962 ALMA	986	40	7.2	75
1968 GLADYS	985	55	9.4	80
1969 GERDA	991	40	9.4	80
1971 GINGER	990	-79	1.8	70
1976 BELLE	963	10	9.8	110
1981 DENNIS	998	60	9.4	65
1984 DIANA	979	-76	1.8	90
1985 GLORIA	942	12	8.9	105
1986 CHARLEY	992	22	3.6	75
1989 HUGO (SC)	934	-35	8.9	140
1991 BOB	957	20	8.5	110

1993 EMILY	960	15	4.5	115
1996 BERTHA	974	20	7.2	105
1996 FRAN	954	-25	7.2	115
1998 BONNIE	964	45	2.2	100
1999 FLOYD	956	31	8.5	105
1999 IRENE	964	55	11.2	110
2002 GUSTAV	985	50	5.8	65
2003 ISABEL	957	-41	7.2	105
2004 ALEX	974	48	7.2	100
2004 CHARLEY	992	36	11.6	75
2004 GASTON	985	-5		
2005 OPHELIA	979	63	0.9	65
2006 ERNESTO	985	17	7.2	70

(1) Pressure Estimated

3.1.3 Central Pressure

Central pressure data for landfalling and bypassing storms were separated into two data sets and compared to determine if the pressure data should be modeled as separate populations. The mean and standard deviation of Δp for the landfall data are 55 mbar and 13 mbar respectively. The corresponding values for the bypassing hurricanes are 53 mbar and 13 mbar respectively. Standard t and F tests for equivalence of mean and variance reveal that the null hypotheses (that the means and variances of the two distributions are the same) cannot be rejected at the 95% confidence level. Figure 3.2 presents the cumulative distribution of Δp plotted in Type I space (Δp vs. $-\ln(-\ln(\text{CDF}))$ for both the landfall and bypass Δp data where it is seen that the distributions of the two data are similar. The form of the Type I distribution used here is given as:

(1)

where U is the mode of the distribution, and $1/\alpha$ is a measure of the dispersion of the data.

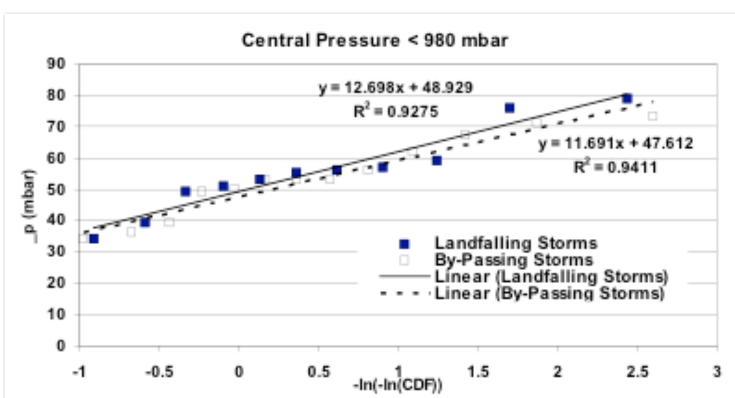

Figure 3.2. Modeled and observed distributions of Δp for North Carolina area bypassing and

landfalling hurricanes separately (central pressure < 980 mbar).

Since there does not appear to be any statistically significant difference between the Δp characteristics of the landfalling and bypassing hurricanes (for Δp<980 mbar), we combined the data into one group to estimate the parameters of the extreme value distribution. The ability to group the data into one set is further verified considering that there is no statistically significant correlation between storm heading and central pressure (P-value=0.6). Figure 3.3 presents the cumulative distribution of Δp plotted in Type I space for the combined data set.

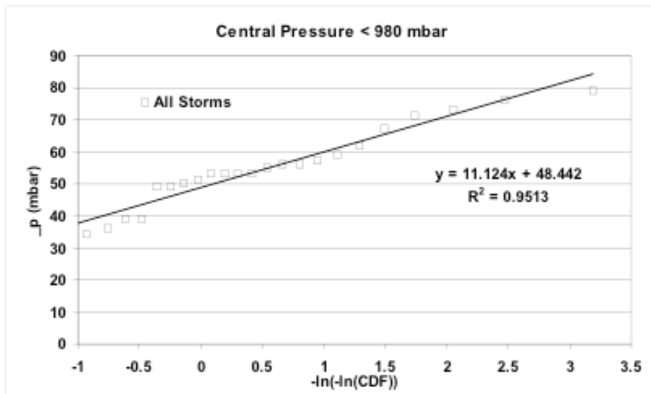

Figure 3.3. Modeled and observed distributions of Δp for North Carolina area bypassing and landfalling hurricanes combined (central pressure < 980 mbar).

The full distribution for Δp was modeled using four discrete values of Δp of 36, 51, 64 and 82 mbar. The statistical distribution for Δp using the discrete values is defined by:

$$f(\Delta p) = w(\Delta p)$$

where $w(\Delta p)$ are statistical weights (Table 3.2) chosen such that the mean and variance of the discrete distribution match those of the full distribution of Δp. Figure 3.4 presents the CDF for Δp showing the discrete distribution, the Type I fit to the data (defined with U=48.4 mbar and α=11.1 mbar) and the data.

Note that for the limited data set containing hurricanes affecting coastal North Carolina, there is no statistically significant correlation between central pressure and any of latitude, storm heading or translation speed. The P-values for the Δp-latitude, Δp-heading, and Δp-translation speed correlations are 0.70, 0.60 and 0.12 which are all greater than the standard test value of 0.05.

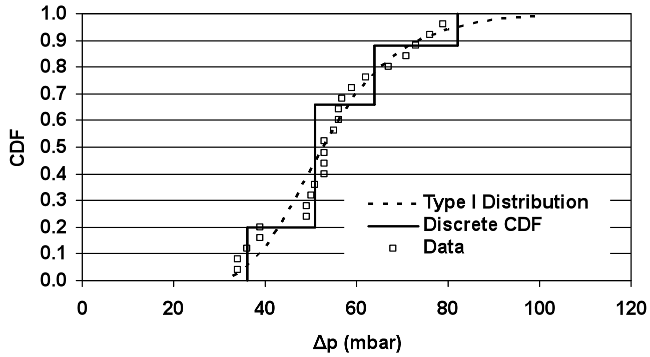

Figure 3.4. Modeled and observed distributions of Δp for North Carolina area bypassing and landfalling hurricanes (central pressure < 980 mbar).

The selection of representative parameters for the distributions, and the weights of the selected parameters, is reported in Tables 3.2, 3.3, and 3.4 for landfalling, stalling-landfalling, and bypassing storm distributions, respectively. The statistical weight of each storm is the product of the weights for the selected parameters for that storm. The resulting statistical weight for each of the 675 modeled storm tracks are given in Tables 3.6, 3.7, and 3.8 in the Appendix.

As an example of a distribution and weighting scheme, consider a normal distribution with a mean of 0.0, and standard deviation of 1.0. The CDF and PDF of this distribution are shown in Figure 3.4.1. To model this distribution with a three samples that preserve its mean and variance, the sampled values are (-1.22, 0.00, 1.22), and the weights are (0.333, 0.333, 0.333).

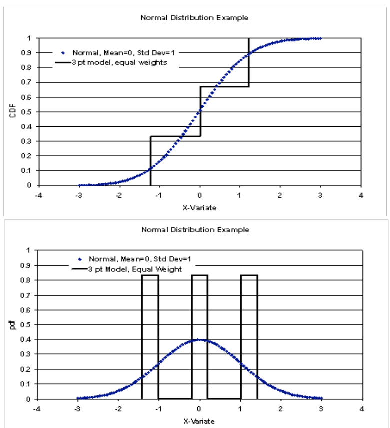

Figure 3.4.1. Example of a normal distribution and weighting scheme. The mean is 0.0 and the variance is 1.0. The sampled values preserve the distribution mean, variance, and skewness.

Table 3.2. Numerical values and statistical weights of hurricane parameters used to model landfalling hurricanes.

Parameter	**Number of Values**	**Values**	**Weights**
RMW (km)	3	Model Mean ±1.22σ	0.33,0.34,0.33
B	3	Model Mean ±1.22σ	0.33,0.34,0.33
Δp (mbar) at landfall	4	36, 51, 64, 82	See Table 3.3
Translation Speed (m/sec) at time of landfall	3	2.9, 7.2, 10.5 (3.6,4.0,4.4for stalled hurricanes)	0.33,0.34,0.33
Heading at landfall (degrees CW from N)	4	-78, -35, 10, 35	,0.10,0.25,0.33,0.32
Total	**351**		

Table 3.3. Numerical values and statistical weights of hurricane parameters used to model stalling landfalling hurricanes.

Heading	Heading Weight	Central Pressure Difference Weights			
		Δp=36 mbar	Δp=51 mbar	Δp=64 mbar	Δp=82 mbar
-78	.1	0.2	0	0	0
-35	.25	0.2	0.511	0.244	0.133
10	.33	0.2	0.511	0.244	0.133
36	.32	0.2	0.511	0.244	0.133

Table 3.4. Numerical values and statistical weights of hurricane parameters used to model bypassing hurricanes.

Parameter	Number of Values	Values	Weights (conditional on a by-passing hurricane)
RMW (km)	3	Model Mean ±1.22σ	0.33,0.34,0.33
B	3	Model Mean ±1.22σ	0.33,0.34,0.33
Δp (mbar)	4	36, 51, 64, 82	0.20,0.48,0.24,0.08
Translation Speed (m/sec)	3	2.9, 7.2, 10.5	0.33,0.34,0.33
Heading at landfall (degrees CW from N)	3	11, 30, 61	0.38,0.39,0.23
Total	324		

3.1.4 Translation Speed

No statistically significant correlation between translation speed and either heading or hurricane intensity (as defined by central pressure) is evident for hurricanes affecting coastal North Carolina. Using the Wilkes-Shapiro tests for normality, it is found that the translation speed for the hurricanes affecting North Carolina is normally distributed, and the logarithm of the translation speed is not. The mean and standard deviation of the translation speed at the time of landfall, or at the time the bypassing track crosses the bypass segment (Figure 3.1) are 6.8 and 3.1 m/sec respectively. The discrete distribution for translation speed was modeled using translation speed values of 2.9 m/sec, 7.2 m/sec, and 10.5 m/sec. The associated statistical weights are 0.33, 0.34 and 0.33, which result in a mean and variance of the discrete distribution for the translation speed that matches the mean and variance of the data, but makes no assumption as to the normality of the underlying data. Figure 3.5 presents the CDF of the modeled and observed translation speeds as well as both normal and lognormal fits to the data, where it is clear that the lognormal distribution is a poor fit to the data.

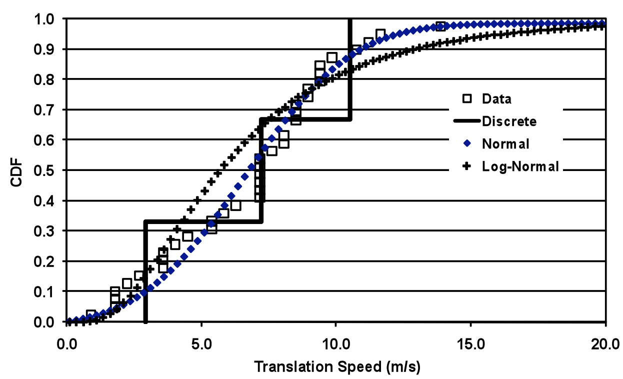

Figure 3.5. Modeled and observed distributions of translation speed for North Carolina area bypassing and landfall hurricanes.

3.1.5 Radius to Maximum Winds and Holland B Parameter

As indicated in Table 3.1, only 24 hurricanes with central pressure less than 980 mbar affected the North Carolina coastline. Of these 24 hurricanes, estimates of *RMW* are available for 14 hurricanes, and estimates of *B* are available for 11 hurricanes. Table 3.5 presents the *B* and *RMW* values for each hurricane, along with the central pressure and latitude associated with the data. Instead of developing statistical models for *B* and *RMW* using the limited NC data set, we use previously developed "global" statistical models developed using a much larger database of hurricanes that correlate *B* and *RMW* to other parameters. The database of hurricanes used to develop these statistical models is described in detail in Vickery and Wadhera, 2008, and includes an analysisof upper level aircraft pressure and wind data collected by NOAA aircraft during the period 1977 through 2001. The data set used to develop a database of *B* and *RMW* is available at ftp://ftp.aoml.noaa.gov/hrd/pub/data/flightlevel/.The validity of these statistical models for modeling the characteristics of *B* and *RMW* in the NC area is tested by comparing the model estimates of *B* and *RMW* for the 11 and 14 cases noted earlier to the observed values and performing statistical tests on the resulting distributions (observed and modeled).

Table 3.5. *B* and *RMW* for North Carolina Hurricanes

Hurricane	Landfall or Bypass	Central Pressure (mbar)	RMW (km)	Holland B Parameter
1954 HAZEL	LF	937	46	
1960 DONNA	LF	958	48	
1984 DIANA	LF	979	30	1.40
1985 GLORIA	BP	942	64	0.73
1989 HUGO (SC)	LF	934	40	1.15
1991 BOB	BP	957	33	1.16
1993 EMILY	BP	960	35	1.50
1996 BERTHA	LF	974	65	1.34
1996 FRAN	LF	954	80	0.98
1998 BONNIE	LF	964	60	1.00
1999 FLOYD	LF	956	85	1.00
2003 ISABEL	LF	957	90	0.95
2004 ALEX	BP	970	30	
2005 OPHELIA	BP	979	65	1.40

The statistical model used for the radius of maximum winds (*RMW*) is described in Vickery and Wadhera, 2008, where for hurricanes in the Atlantic Ocean, the *RMW* is modeled as a function of Δp^2 and latitude, ψ, and is given as:

$$; r^2=0.297, \sigma_{\ln RMW}= 0.441 \quad (2)$$

The error, $\sigma_{\ln RMW}$, is modeled in the form:

$\sigma_{\ln RMW} = 0.448$	$\Delta p \leq 87$ mbar	(3a)
$\sigma_{\ln RMW} = 1.137 - 0.00792\Delta p$	87 mbar $\leq \Delta p \leq$ 120 mbar	(3b)
$\sigma_{\ln RMW} = 0.186$	Δp>120 mbar	(3c)

The modeled and observed values of *RMW* are plotted vs. Δp in Figure 3.6. The model results are presented as the median values and the 90% confidence range. If the statistical model for *RMW* described above were a valid model it would be expected that, on average, for every 10 samples of *RMW* data taken in the North Carolina coastal region, no more than one sample would fall outside of the confidence bounds shown in Figure 3.6. As indicated in Figure 3.6, of the 13 samples, all fall within the 90% confidence bounds. The hypothesis that the means and standard deviations of the modeled and observed data are equivalent cannot be rejected at the 95% confidence level. These three equivalence tests indicate that the *RMW* associated with the North Carolina hurricanes are from the same population as those used in the development of the regional *RMW* model for Atlantic hurricanes.

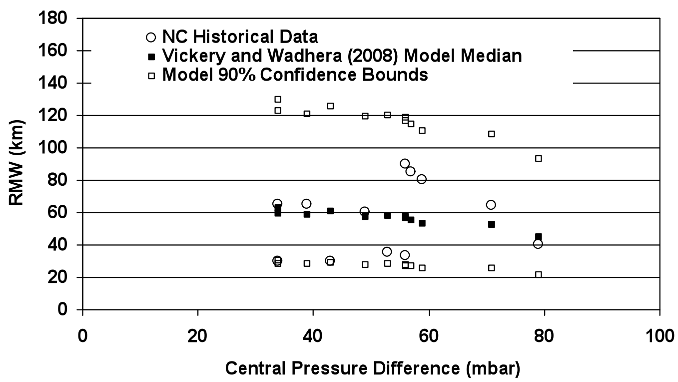

Figure 3.6. Modeled and observed values of *RMW* for North Carolina area landfall and bypassing hurricanes.

The statistical model used to model the Holland *B* parameter employs the model described in Vickery and Wadhera, 2008, where *B* is described by

$$B = 1.881 - 0.00557RMW - 0.01295\,\psi; \qquad r^2=0.356,\ \sigma_B = 0.221 \qquad (4)$$

The error term σ_B is taken as being normally distributed, and *B* is constrained to lie within the range 0.5 to 2.5. The data used to derive the statistical model for *B* indicate that the likelihood of a storm with a central pressure less than ~930 mbar, and a *RMW* greater than 40 km, combined with a *B* value greater than about 1.1 is remote. For these large and intense hurricanes, *B* is constrained such that *B* is the lesser of that computed using Equation 4 (including the sample error value) or the value of *B* sampled from a normal distribution with a mean of 1.01 and a standard deviation of 0.082. As will be shown later, this large storm limit is reached for some of the JPM-OS model hurricanes, and when the limit is reached, the values of *B* in the simulated storms are reduced (i.e. the storm weakens and expands).

The modeled and observed values of *B* are plotted vs. *RMW* in Figure 3.7. The model results are presented as the mean values and the 90% confidence range.

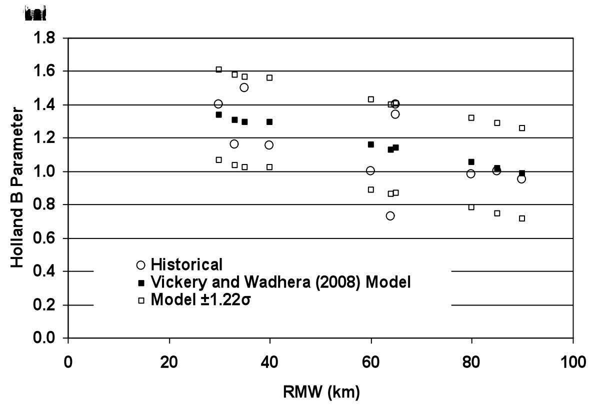

Figure 3.7. Modeled and observed values of *B* for North Carolina area landfalling and bypassing hurricanes.

If the statistical model for *B* described above were a valid model it would be expected that, on average, for every 10 samples of *B* data taken in the NC coastal region, no more than one sample would fall outside of the confidence bounds shown in Figure 3.7. As indicated in Figure 3.7, of the 11 samples, 10 fall within the 90% confidence bounds. The data point that falls outside the 90% confidence range is associated with bypassing Hurricane Gloria. In testing for equivalence of means and variances of *B*, the hypothesis that the means and standard deviations of the modeled and observed data are equivalent cannot be rejected at the 95% confidence level. These three statistical tests indicate that the *B* values associated with the NC hurricanes are from the same population as those used in the development of the regional model for *B*.

In the JPM-OS modeling, the full statistical distribution of the errors (or variability) in *B* and *RMW* is obtained by using three estimates of *B* and *RMW*, one being the mean estimate and the other two representing the mean ±1.22 standard deviations. Modeling the variation of *B* and *RMW* using this approach preserves the mean observed relationship between *B* and *RMW* and the other hurricane parameters, as well as preserving the variance. Figure 3.8 presents the modeled range of *B* plotted vs. *RMW* and the modeled range of *RMW* plotted vs. Δp along with the historical data.

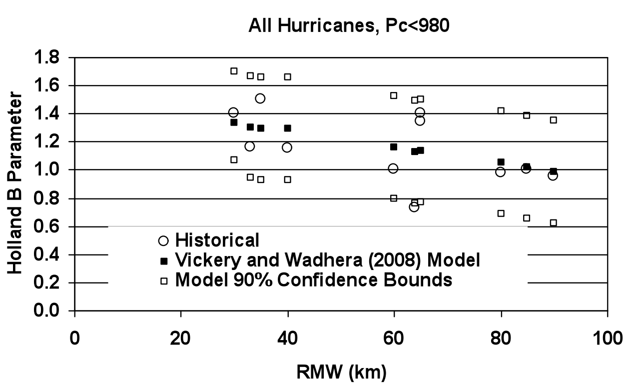

Figure 3.8. Variation of *RMW* and *B* used in weighted hurricane modeling showing comparison to recent historical values.

3.1.6 Storm Heading

In the case of storm heading, we separated the historical database into two categories, one corresponding to landfall hurricanes and the other corresponding to bypassing hurricanes. The following sub-sections present, separately, the analyses of the hurricane headings for the bypassing and landfalling hurricanes.

3.1.6.1 Landfalling Hurricanes

Within the landfalling hurricane category, the trajectory of the landfalling hurricanes can be further divided into two sub-categories, one comprising hurricanes that move northward from the Atlantic, Caribbean or Florida areas without stalling, and the other comprising hurricanes that stall in the Atlantic Ocean east of the NC coast, and then make landfall approaching from a near due east direction. There is only one of the 11 landfalling hurricanes (Hurricane Diana, in 1985) having a central pressure less than 980 mbar at the time of landfall that is representative of a hurricane that has stalled and then subsequently moves west and impacts the coast. Two (out of 20) such cases exist in the all-hurricane category. The other hurricane stalling off the coast was Hurricane Dennis in 1999, which finally re-curved and made landfall but as a tropical storm.

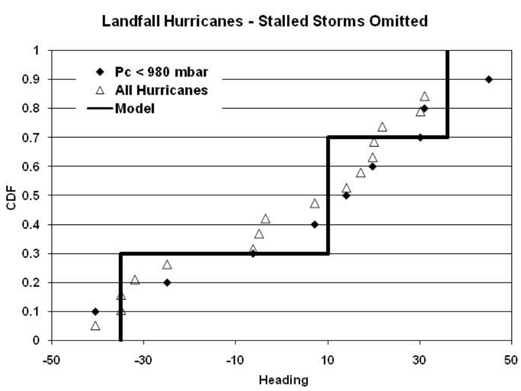

Figure 3.9. Modeled and observed hurricane heading at landfall (without Hugo).

In the case where stalled storms are omitted from the storm set, hurricane heading at the time of landfall is modeled using 3 discrete values of hurricane heading as shown in Figure 3.9 through a comparison of the CDF of the data to the CDF of the discrete probability distribution. The data are given for both the all hurricane data set and the subset including only hurricanes with central pressures less than 980 mbar. The discrete values of heading are -35 degrees, 10 degrees and 35 degrees, and have weights of 0.3, 0.4 and 0.3 respectively. Figure 3.9 presents the modeled (discrete) and observed CDF's of landfalling hurricane headings. As indicated in Figure 3.9, the distributions for storm heading associated with the all hurricanes and the hurricanes < 980 mbar, are nearly identical. Note that although Hurricane Hugo was originally treated as being from the NC population of hurricanes, it was later dropped from the analysis, as it did not make landfall along the simulation coastline segment noted earlier in Figure 3.1.

Figure 3.10 presents the modeled (discrete) and observed CDF's of landfalling hurricane headings including those hurricanes that stalled off the NC coast and then moved west making landfall along the coast. The discrete values of heading are -78, -35 degrees, 10 degrees and 36degrees, and have weights of 0.1, 0.25, 0.33and 0.32respectively. As indicated in Figure 3.10, and as seen in the case of the distribution of heading for hurricanes that did not stall off the NC coastline, the distributions for storm heading associated with the all hurricanes and the hurricanes with central pressures less then 980 mbar, are nearly identical.

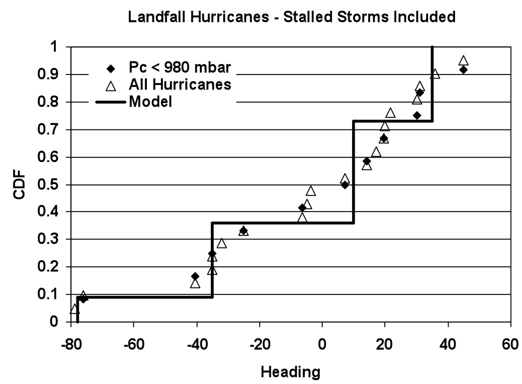

Figure 3.10 Modeled and observed storm heading at landfall (including hurricanes that stall off the NC coast (without Hugo).

3.1.6.2 Bypassing Hurricanes

In the bypassing storms category, the data set consists of a total of 18 hurricanes, 13 of which had central pressures of less than 980 mbar when they passed the by-pass line segment shown in Figure 3.1. Figure 3.11 presents the modeled (discrete) and observed CDF's of bypassing hurricane headings including only those hurricanes that passed the North Carolina coast with central pressures of less than 980 mbar. The discrete values of heading are 11 degrees, 30degrees and 61degrees, and have weights of 0.38, 0.39, and 0.23 respectively. The parameter weights are reported in Table 3.4, and the storm weights are reported in Table 3.8 in the Appendix.

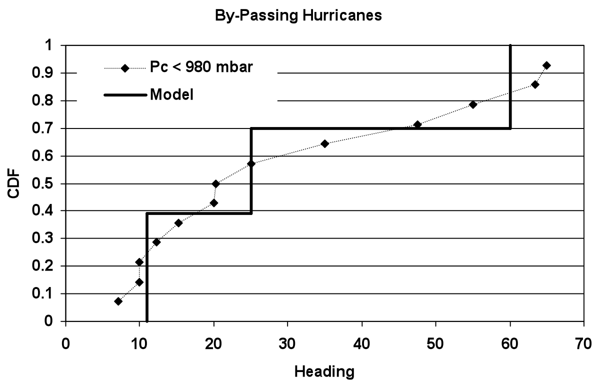

Figure 3.11. Modeled and observed storm heading for bypassing hurricanes (central pressure < 980 mbar).

Development of Model Storm Tracks

The wind-wave models used for the North Carolina coastal risk assessment require the modeling of a sufficiently long length and history of the hurricane track to allow for the development of a background wave field that reflects the history of the hurricane. The modeling process used here involved two steps, the first being the selection of representative storms, landfall parameters and associated statistical weights, and the second being the modeling of the variation of storm parameters along the length of the modeled track. The following two sections discuss the selection of the storm tracks and then the modeling of the hurricane parameter variations along the length of the model track.

3.1.7 Modeling of Hurricanes

Figure 3.12 presents the historical tracks of all landfalling hurricanes having central pressures < 980 mbar at the time of landfall, and Figure 3.13 presents the three representative hurricane tracks, making landfall at four different locations along the model coastline segment, yielding a total of twelve different example tracks. Figure 3.14 presents the historical tracks of all bypassing hurricanes and Figure 3.15 presents three representative hurricane tracks crossing the bypass line segments at three different locations resulting in nine example tracks.

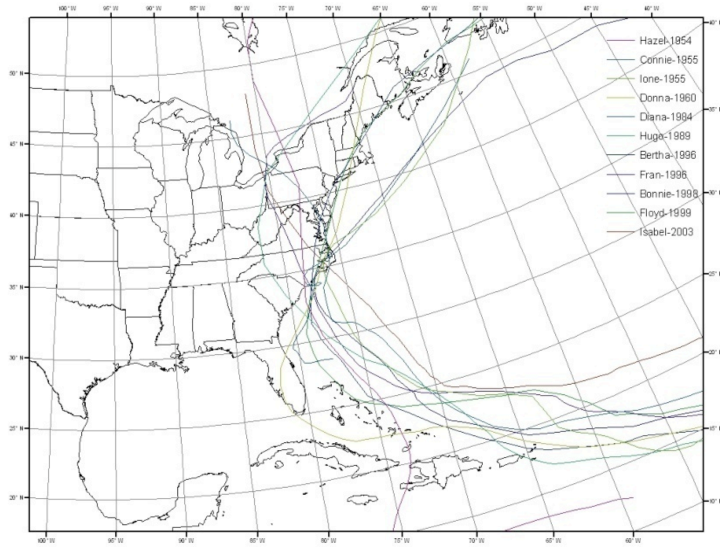

Figure 3.12. Tracks of all historical landfalling hurricanes (central pressure < 980 mbar) during the period 1940-2007.

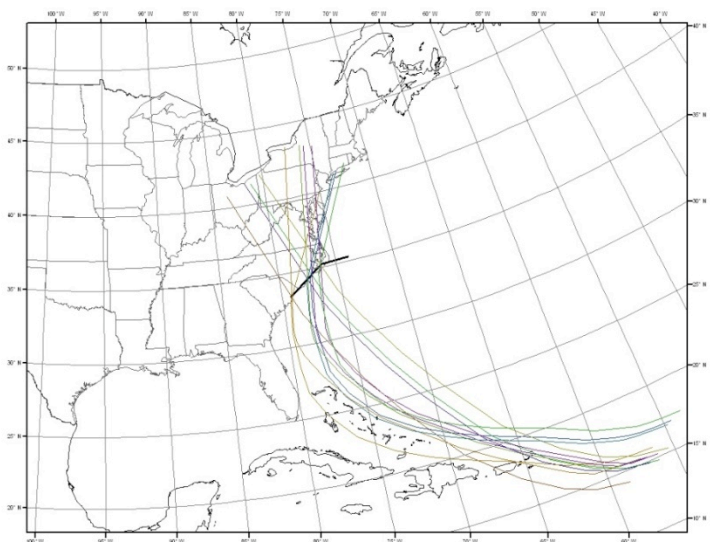

Figure 3.13.Tracks of model landfalling hurricanes.

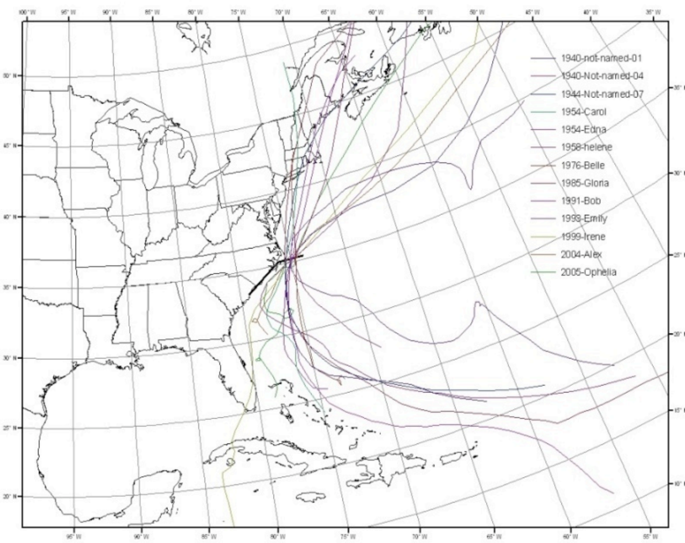

Figure 3.14. Tracks of all historical bypassing hurricanes (central pressure < 980 mbar) during the period 1940-2007.

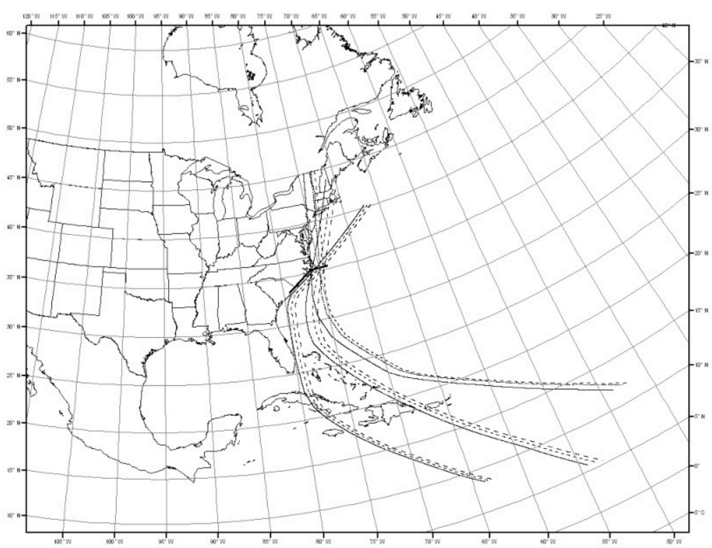

Figure 3.15.Tracks of model bypassing hurricanes.

As discussed in the previous section, the statistical distributions of the key hurricane parameters (storm heading, central pressure, translation speed, *RMW*, and *B)* were modeled using 3 or 4 discrete values. Tables 3.2-3.4 summarize the number of discrete values used for each of the parameters varied in the simulation, and the values of those parameters, for landfalling, stalling-landfalling, and bypassing storms, respectively. In the case of *B* and *RMW*, which are modeled using equations rather than discrete values, Figure 3.16 presents the actual values of *B* plotted vs. *RMW* and *RMW* plotted vs. Δp as used in the simulated storms. The discontinuity evident in the *B* vs. *RMW* plot is a result of the *B* limit placed on large but intense (as defined by central pressure) hurricanes. A total of 351 different combinations of *RMW*, *B*, Δp, translation speed and heading are possible for landfalling hurricanes. Note that only one value of central pressure is modeled for the case where hurricanes stall off the North Carolina coast and then subsequently move westward and make landfall.

For simulating the coastal flood hazard, the landfall location of each model hurricane track was randomly selected so that the distribution of landfall points along the coastal segment is uniform. The average spacing along the landfall coastal segment is ~1 km. The average spacing of the smallest model hurricanes (those modeled as the mean *RMW* minus 1.22 standard deviations) is ~3 km, and the average *RMW* of the smallest hurricanes is about 30 km, indicating that there is a sufficient number of simulated storms making landfall along a 348 km long coastal segment extending from near Cape Lookout, North Carolina through to near Myrtle Beach South Carolina (Figure 3.1). All simulated tracks are shown in Figure 3.19.

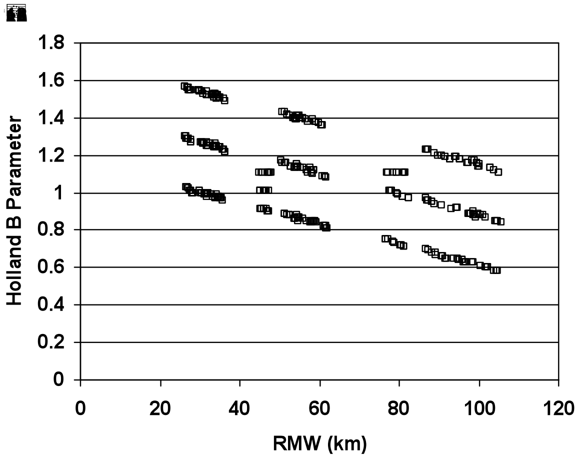

Figure 3.16. Modeled values of *B* and *RMW* for all hurricanes (values of *B* equal to 1.11 for *RMW* near 80 kmhave reached the critical limit for *B*).

3.1.8 Variation of Storm Intensity along Track

Landfalling Hurricanes Given the landfall parameters of each simulated hurricane, the variation of the storm parameters along the length of the modeled track is required for ocean response modeling. The hurricane parameters, *B* and *RMW* are modeled using Equations 2 and 4, and are dependent only on latitude and Δp. Translation speed is dependent primarily on latitude, increasing with increasing latitude. The along track variation of central pressure varies from storm to storm, typically increasing from tropical depression strength through to a maximum and then decreasing as a hurricane moves north towards the Carolinas. A generic Δp scaling model was developed using the Δp history of the four most recent strong hurricanes to affect the North Carolina coast (Fran, Floyd, Isabel and Bonnie). Figure 3.17 shows the idealized modeled representation of the time history of Δp, where the idealized version of the normalized central pressure follows reasonably closely to three of the four historical cases. Once a model hurricane makes landfall it is filled following the filling model for hurricanes given in Vickery, (2005). As described in Vickery (2005), the magnitude of $\Delta p(\mathrm{t})$, where *t* is the time since landfall, is given as

$$\Delta p(\mathrm{t})=\Delta p_o \exp\text{-}at$$

where *a* is a decay constant that defines the rate of a weakening hurricane after making landfall. The parameter *a* is a function of Δp*c/RMW, where c is the translation speed in m/sec. In general faster smaller hurricanes fill (weaken) more rapidly than larger weaker slow moving hurricanes.

Bypassing Hurricanes The normalized along track variation of Δp for all historical hurricanes as well as the idealized function used herein is given in Figure 3.18. Note that in Figure 3.18, for some of the older hurricanes, if central pressure data is not given in HURDAT, the values have been estimated using the HURDAT wind speeds.

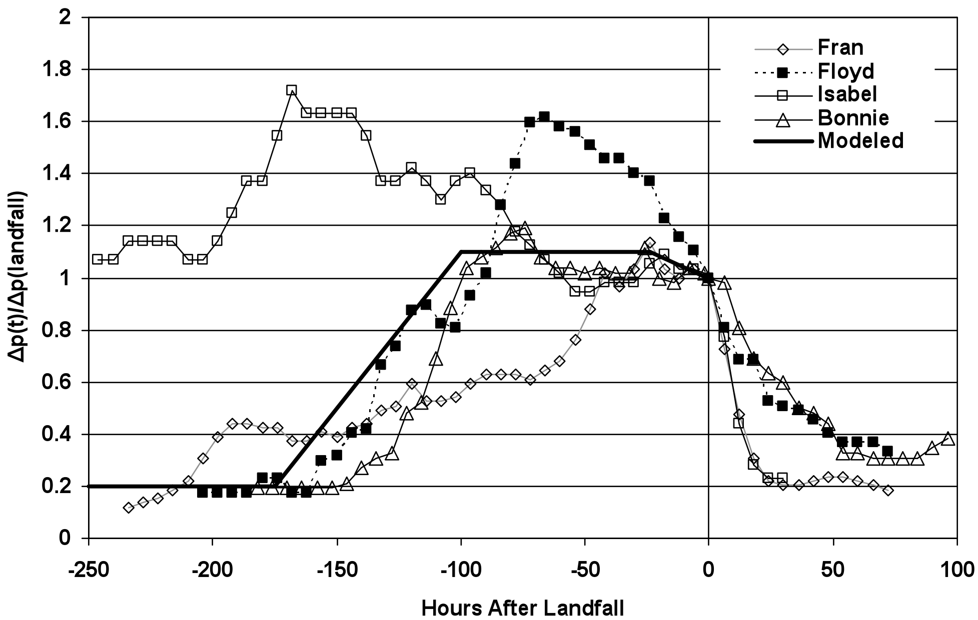

Figure 3.17. Historical and idealized normalized Δ*p* vs. time – landfalling hurricanes

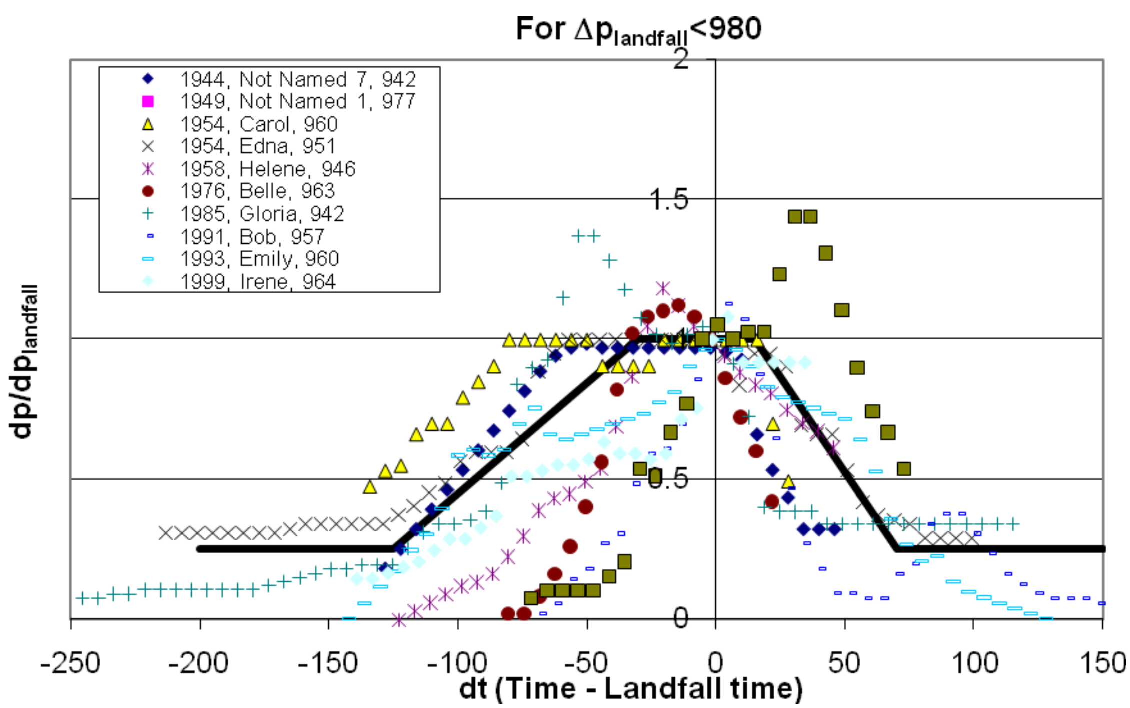

Figure 3.18. Historical and idealized normalized Δ*p* vs. time – bypassing hurricanes.

Development of Hazard Curves from Simulated Hurricanes

In order to develop the flood hazard curves associated with hurricanes, water elevations are computed with the hydrodynamic models (ADCIRC, SWAN, etc) at each of the ADCIRC grid points for each of the 675 combinations of *RMW*, Δp, etc, given in Tables 3.6 through 3.8 in the Appendix. Each hurricane has a probability of occurrence (conditional on a hurricane affecting the North Carolina coast) equal to the product of the individual parameter weights and as given in Tables 3.6 through 3.8. The sum of the weights (over all three storm types (landfalling, stalling-landfalling, bypassing) is equal to unity.

The probability that a hurricane induced water elevation is exceeded during time period t is

$$P_t(\eta > \eta_0) = 1 - \sum_{x=0}^{\infty} P(\eta < \eta_0 \mid x)\, p_t(x) \qquad (1)$$

where is the probability that the water elevation η is less than η_0 given that x storms occur, and $p_t(x)$ is the probability of x storms occurring during time period t. From Equation 1, with $p_t(x)$ defined as Poisson and defining t as one year, the annual probability of exceeding a storm surge elevation is,

$$P_a(\eta > \eta_0) = 1 - \exp[-\lambda P(\eta_0 > \eta_0)] \qquad (2)$$

Where λ represents the average annual number of storms cross the modeled coastline segment and is the probability that the water elevation, η is greater than η_0 given the occurrence of any one storm. In the development of the cumulative distribution for water elevation, , each simulated hurricane used to develop the distribution has a probability of occurrence of w_i, where w_i is the product of the individual storm weights given in Table 3.6. The annual occurrence rate, λ, is 0.343. All of the model hurricane tracks are given in Figure 3.19.

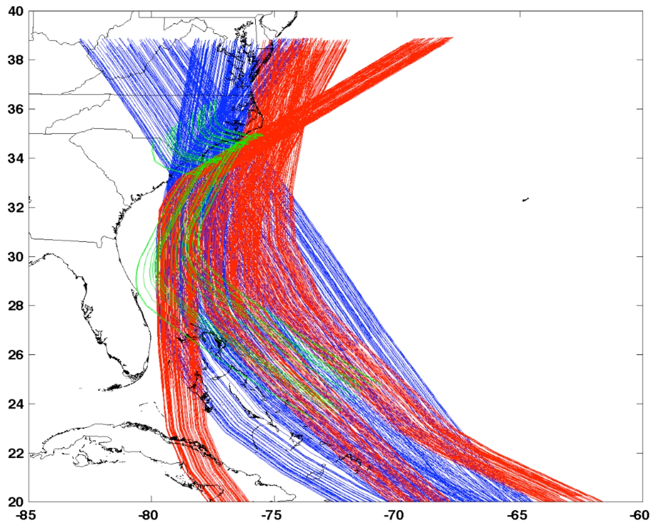

Figure 3.19. Tracks of 675 Model Hurricanes used in Full JPM Simulations for landfalling (blue), bypassing (red), and landfalling-stalling (green) storms.

3.1.9 Comparison of Wind Hazard Curves Derived Using the JPM Approach to those Derived from a Full Stochastic Simulation

In order to verify that the weighted simulation methodology yields reasonable results, and to determine the return period range over which the results can be considered valid, we compare the estimates of the predicted hurricane induced wind speeds at five mileposts along the North Carolina coast (Figure 3.20) derived using the 675 model hurricanes to those predicted using the 100,000 year simulation of hurricanes described in Vickery et al, 2008b. The purpose of this comparison (Figure 3.21) is to see how the simulation (for wind speeds) performed using the 675 model hurricanes, to a full Monte-Carlo simulation employing tens of thousands of model hurricanes. These comparisons lend some insight into the accuracy of the simulation in terms of the range of return periods over which the JPM results are likely valid. The comparisons of the predicted wind speeds should not be expected to yield identical results because:

(i) the stochastic model described in Vickery, et al (2008a) was developed using the period 1900 through 2007 rather than 1940 through 2007;

(ii) the JPM method assumes a uniform hurricane climate for landfalling hurricanes whereas the simulation methodology in Vickery, et al (2008b) does not.

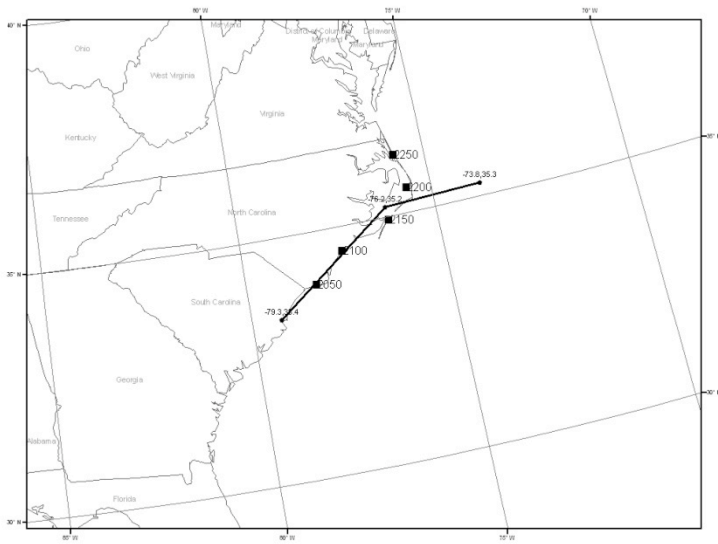

Figure 3.20. Coastline segments used for JPM landfall and bypassing hurricane simulations, and the five milepost locations.

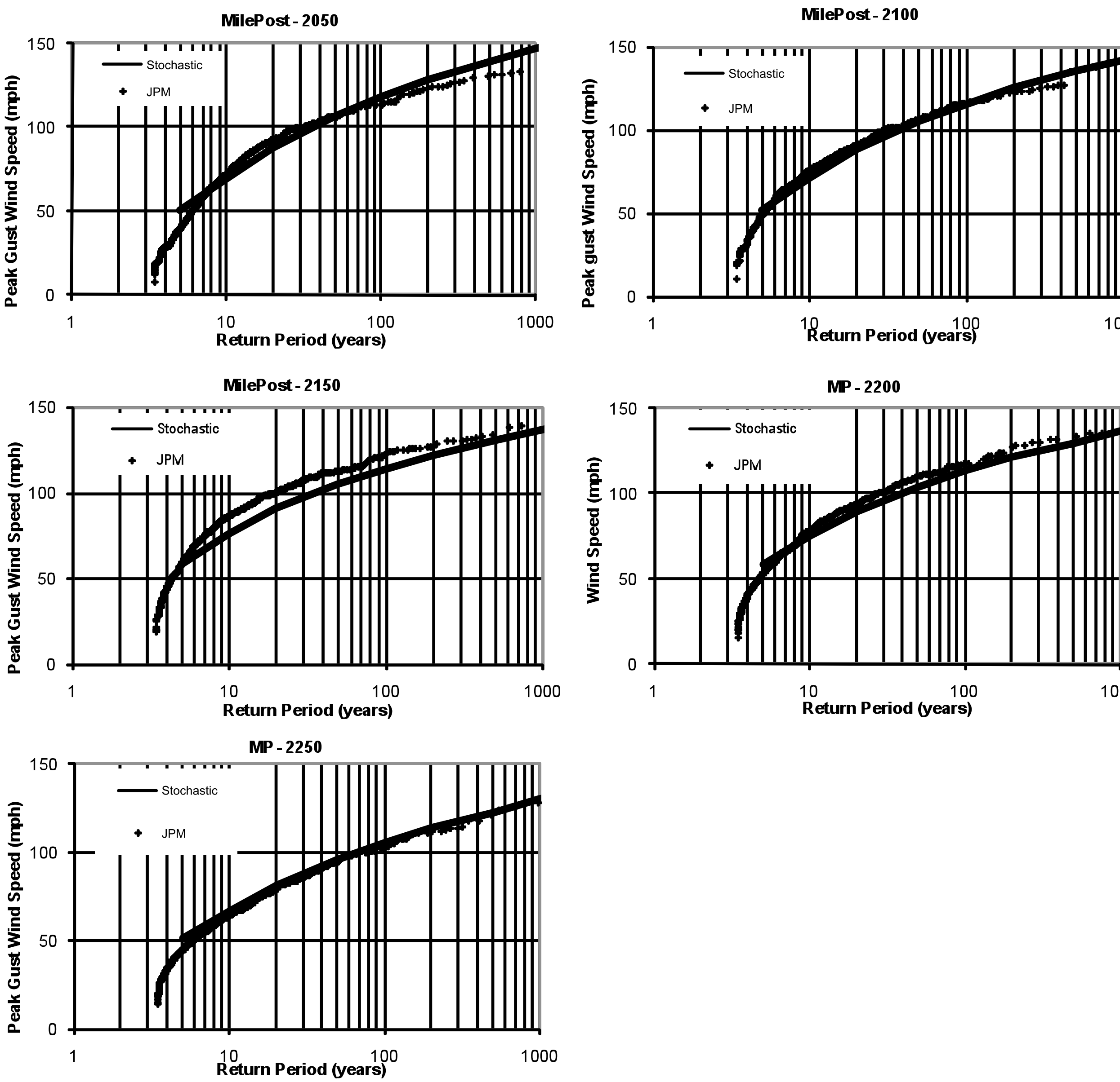

Figure 3.21 Comparison of Predicted wind speeds vs. return period at five mileposts derived from JPM landfalling hurricanes and a full stochastic simulation from Vickery et al (2008b). Wind speeds represent peak gust values at a height of 10 m in open terrain.

The effect of (i) is an expected increase in the values of the predicted wind speeds for a given return period since the North Carolina coast experienced a higher hurricane landfall rate during the period 1940 through 2007 than during the period 1900 through 2007. In the case of landfalling hurricanes, the effect of (ii) is a relative decrease in the JPM wind speeds associated with land falling hurricanes in the Wilmington area, and a relative increase in the JPM wind speeds (compared to the stochastic track model wind speeds) associated with landfalling hurricanes moving north. Figure 3.22 presents the mean and standard deviation of the modeled pressures plotted along the length of the simulation coastline segment, from both the model JPM hurricanes and the stochastic hurricanes as produced by the Vickery, et al (2008) model.

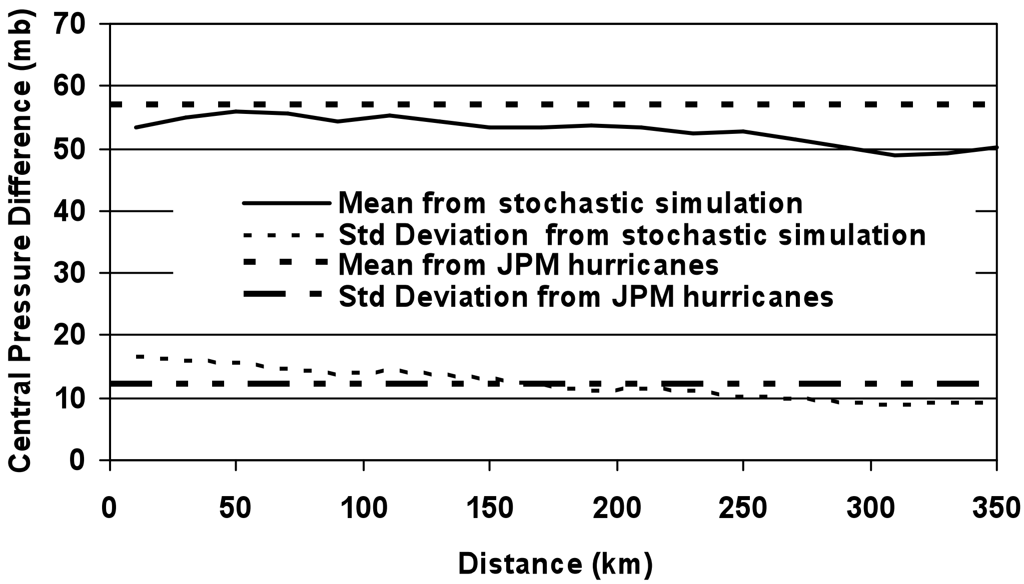

Figure 3.22.Comparison of JPM and stochastic model mean and standard deviation of dP at landfall as a function of distance along the modeled coastline segment.

The comparisons indicate the distribution of the central pressures derived from the stochastic model has a longer tail (higher standard deviation) near the southern portion of the coastline segment and a short tail at the northern end of the segment. The longer tail associated with the stochastic model hurricanes will result in higher rare event (i.e. long return period wind speeds).

The overall agreement between the two methods of simulating hurricanes is within the typical uncertainty range associated with modeling hurricanes. The comparison of the wind speed vs. return period curves indicate that the JPM approach used here can be used for coastal flooding risk (associated with storm surge and waves) for return periods ranging from 10 years up to about 1000 years.

2 References

Blake, E.S., E.N. Rappaport, J.D. Jarrell, and C.W. Landsea, 2007, "The Deadliest, Costliest and Most Intense United States Hurricanes from 1851 to 2006 (and Other Frequently Requested Hurricane Facts)", *Technical Memorandum NWS-TPC-5*, NOAA, 43 pp.

Ho, F.P. et al., 1987, Hurricane Climatology for the Atlantic and Gulf Coasts of the United States, NOAA Technical Report NWS38, Federal Emergency Management Agency, Washington, DC.

Holland, G.J.,1980, An analytic model of the wind and pressure profiles in hurricanes, *Monthly Weather Review*, 108, 1212-1218.

Resio, D. T, S. J. Boc, L. Borgman ,V. J. Cardone, A. Cox, W. R. Dally, R. G. Dean, D. Divoky, E. Hirsh, J. L. Irish, D. Levinson, A. Niederoda, M. D. Powell, J.J. Ratcliff, V. Stutts, J. Suhada , G. R. Toro and P. J. Vickery, 2007, White Paper on Estimating Hurricane Inundation Probabilities.

Russell, L.R.,1968, Probability distribution for Texas gulf coast hurricane effects of engineering interest, Ph.D. Thesis, Stanford University.

Vickery, P.J., D. Wadhera, M.D. Powell and Y. Chen, 2008a, A Hurricane Boundary Layer and Wind Field Model for Use in Engineering Applications, *Journal of Applied Meteorology and Climatology*, accepted for publication.

Vickery, P.J.; D.Wadhera, L.A. Twisdale Jr. andF. M. Lavelle, 2008b. "United States Hurricane Wind Speed Risk and Uncertainty", *Journal of Structural Engineering*. Accepted for publication

Vickery, P.J. and D. Wadhera, 2008, Statistical Models of Holland Pressure Profile Parameter and Radius to Maximum Winds of Hurricanes from Flight Level Pressure and H*Wind Data, *Journal of Applied Meteorology and Climatology*, in press

Vickery, P.J., 2005, "Simple empirical models for estimating the increase in the central pressure of tropical cyclones after landfall along the coastline of the United States", *Journal of Applied Meteorology,* Vol. 44.

Vickery, P.J., P.F. Skerlj and L.A. Twisdale Jr., 2000, Simulation of hurricane risk in the U.S. using an empirical track model, *Journal of Structural Engineering*, 126, 10.

Westerink, J., R. Luettich, J. Feyen, J. Atkinson, C. Dawson, H. Roberts, M. Powell, J. Dunion, E. Kubatko, and H. Pourtaheri, 2008, A basin- to channel-scale unstructured grid hurricane storm surge model applied to Southern Louisiana, *Monthly Weather Review*, Vol. 136, 833-864.