NORTH CAROLINA Turnpike Authority

CDG

Mid-Currituck Bridge

Coastal Engineering

Design Criteria Report

CURRITUCK COUNTY, NORTH CAROLINA • JULY 31, 2009

moffatt & nichol

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July 31, 2009

Prepared for:

North Carolina Turnpike Authority

CDG Currituck Development Group

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1 Introduction

This report provides a costal engineering study in support of the planning and design of the Mid-Currituck Bridge in north-eastern North Carolina. The main objective of this investigation is to support the development of design criterion for the proposed bridge.

This investigation includes a literature review of the potential sea level rise in the study area, and the possibility of barrier island breaches in the surroundings of the proposed bridge. The study also contains the review and analysis of the Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS) for the Currituck County from which initial storm surge elevations and flood levels were extracted. A numerical modeling program to determine the design criteria for storm surge, wave height, and maximum wave crest elevation was undertaken as well.

Taking into account the investigations stated above, the study establishes a preliminary recommended low chord elevation for the proposed bridge.

The analysis and recommendation of this low chord elevation is based on AASHTO's recently published "Guide Specifications for Bridges Vulnerable to Coastal Storms." These specifications state that "Wherever practical, the vertical clearance of highway bridges should be sufficient to provide at least 1 ft of clearance over the 100-year design wave crest elevation, which includes the design storm water elevation." Thus, this study is focused on determining the design surge and maximum wave parameters for the 100-year event at the proposed bridge location in order to establish the recommended low chord elevation.

2 Sea Level Rise

Ice ages have come and gone in regular cycles for nearly the past three million years and there is strong evidence that these cycles are linked to regular variations in the earth's orbit around the sun; however, it is clear that the current rate of global climate change is much more rapid and very unusual in the context of past changes (IPCC, 2007). The observed warming of the atmosphere and ocean are very likely a result of depletion of stratospheric ozone and increasing levels of greenhouse gasses, which have been increasing at unprecedented levels since the industrial era (IPCC, 2007a). The primary anthropogenic greenhouse gas emissions that contribute to global climate change include carbon dioxide from the burning of fossil fuels and deforestation, and methane resulting from agriculture activities (IPCC, 2007a). There is no single thermometer measuring global temperature; therefore, confirmation of global climate change comes from evidence of ocean warming, rising sea levels, glaciers melting, sea ice retreating in the Arctic, and diminished snow cover in the Northern Hemisphere (IPCC, 2007a).

The changes in the global climate have resulted in an increased global sea level. The two primary causes of global sea level rise are thermal expansion of the oceans (water expands as it warms) and the melting loss of land-based ice resulting from increased temperatures (IPCC, 2007a). The elevation of global sea level is determined by the mass of ice on land in glaciers and ice sheets and the mass of water in ocean basins. Both of these factors are highly influenced by the earth's atmospheric temperature (EPA, 2009). Though there is some uncertainty in the estimates, it is believed that thermal expansion and melting of land-based ice contribute equally to the observed rise in global sea level (IPCC, 2007a).

Global sea level has increased about 120 m (394 ft) since the end of the last glacial maximum or ice age, but the increases have been highly variable across the globe (EPA, 2009). There is strong evidence that after a period of little change between 0 AD and 1900 AD (change did not exceed ±0.25 m [0.8 ft]) global sea level rose gradually in the 20th century at an estimated rate of 1.7 mm (0.07 in) per year. Since 1993, sea level has been rising at an increased rate of approximately 3 mm (0.12 in) per year, which is significantly higher than the previous half century (IPCC, 2007a). Figure 2.1 depicts the trend of increasing global mean sea level since 1870.

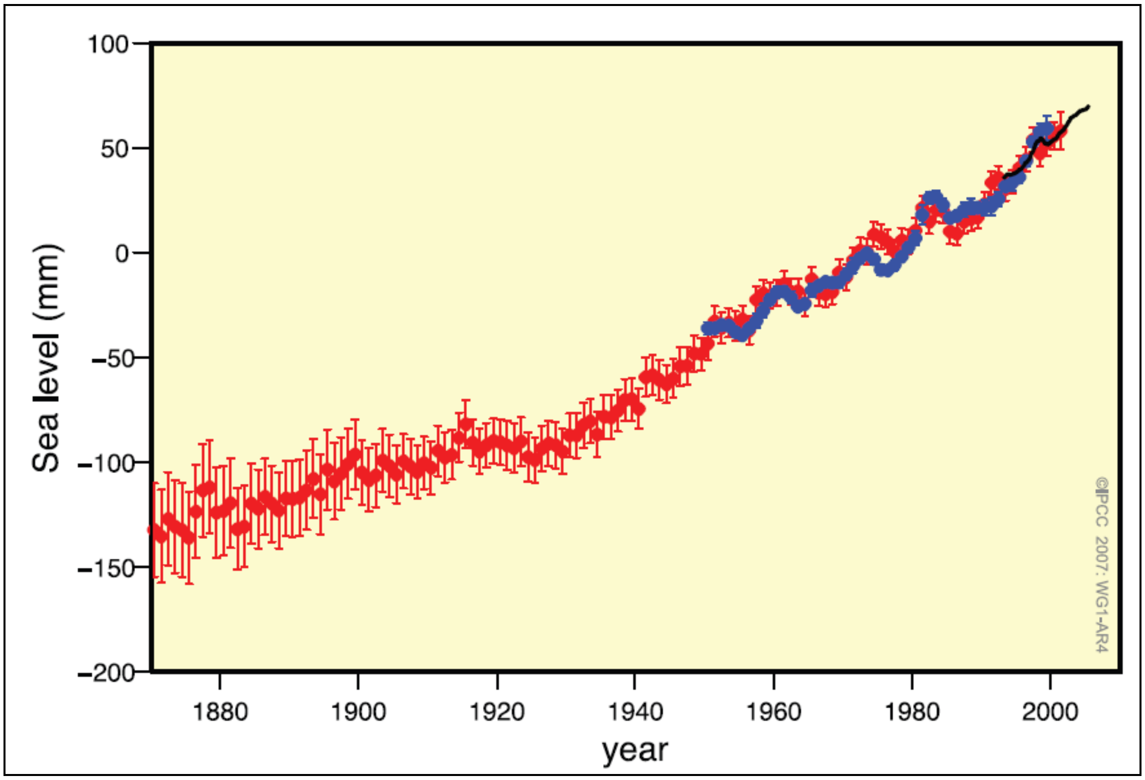

Figure 2.1: Global Mean Sea Level

Annual averages of the global mean sea level based on reconstructed sea level fields since 1870 (red), tide gauge measurements since 1950 (blue) and satellite altimetry since 1992 (black). Units are in mm relative to the average for 1961 to 1990. Error bars are 90% confidence intervals. Figure excerpted from IPCC (2007a).

Sea level is projected to rise at an even greater rate in the 21st century than was observed between 1961 and 2003. Figure 2.2 depicts a time series of global mean sea level in the past and as projected for the future.

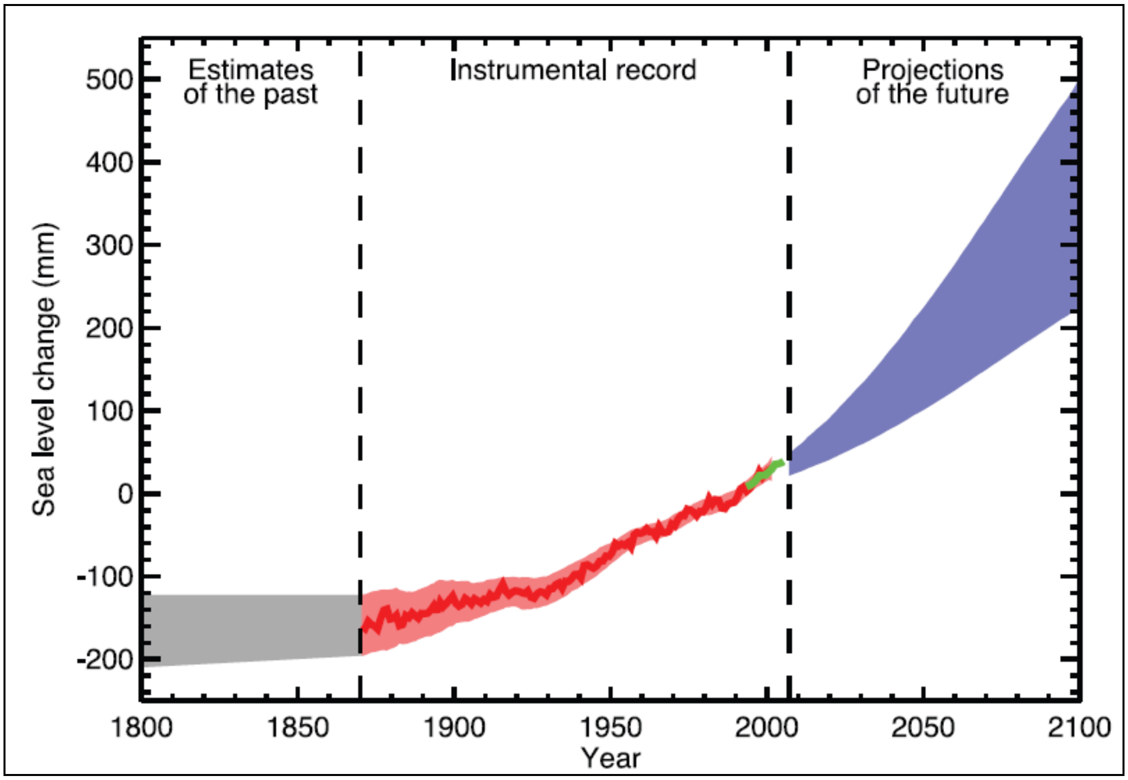

Figure 2.2: Projection of Future Global Mean Sea Level

For the period before 1870, global measurements of sea level are not available and the grey shading shows the uncertainty. The red line is a reconstruction of mean sea level based on tide gauges. The green line depicts sea level based on satellite altimetry. The blue shading represents the range of model projections for the SRES A1B scenario for the 21st century relative to the 1980 to 1999 mean. Figure excerpted from IPCC (2007a).

The IPCC Special Report on Emission Scenarios (SRES) developed a series of scenarios that are grouped into four families intended to explore alternative global development pathways covering a wide range of demographic, economic, and technological driving forces and their resulting greenhouse gas emissions (IPCC, 2007b). No likelihood has been attached to any of the scenarios or a "preferred alternative" identified. Table 2.1 depicts the sea level rise in meters for each scenario. The range of scenarios suggest that global sea level will rise to a level between 0.18 m (0.6 ft) and 0.59 m (1.94 ft) above the 1990 level by the mid 2090's with a regional variation of ±0.15 m (0.6 ft) or about 2 to 6 mm (0.1 to 0.2 in) rise per year (IPCC, 2007b). Evidence suggests that this will vary significantly on a regional scale.

Table 2.1:
Sea Level Rise Projections

Case	Temperature Change (°C at 2090-2099 relative to 1980-1999) [a]		Sea Level Rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	*Likely* range	Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations [b]	0.6	0.3 – 0.9	NA
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Recent observations suggest that the sea level rise rates may already be approaching the higher end of the IPCC estimates due to a potentially important factor, meltwater contributions from Greenland and Antarctica, having been excluded as a result of limited data and an inability to adequately model ice flow processes at the time of analysis (EPA, 2009). While acknowledging the longer term trend is unclear, the U.S. Climate Change Science Program (2009) reports that extrapolating recent discharges from polar ice sheet melt would imply adding up to 0.20m to the IPCC estimates. Other potential impacts discussed are the possibility of increased coastal storm surges due to more intense hurricanes but agreement and quantification of these remain uncertain.

REGIONAL ISSUES

Sea level rise is not occurring uniformly around the globe. In some regions rates are several times the global mean rise and in other areas the sea level is falling. Spatial variability of the rates of rise and fall result primarily from the non-uniform changes in temperature, salinity of ocean water, and changes in ocean circulation (IPCC, 2007a). A recent study presented by the National Science Foundation (Hu et.al. 2009) suggests that the ice melt and the resulting fresh water runoff from Greenland may significantly shift ocean circulation by the year 2100. Taking into consideration the weakened circulation, sea level could potentially rise near the northeast North American coastline greater than other locations on the globe.

One way to evaluate the relative rate of sea level rise or fall is the change in mean sea level as measured by the National Oceanic and Atmospheric Administration (NOAA) tide gauges from one tidal epoch to the next. For example, the relative change in mean sea level over the two last tidal epochs (1960 to 1978, and 1983 to 2001) was +0.25 ft (0.07 m)) at a gauge located near Charleston, South Carolina. In contrast, the sea level fell -0.03 ft (0.01 m) at a gauge located near Juneau, Alaska. This can be explained by glacial retreat, which makes the land mass near the coast rebound or emerge (Zervas, 2004).

The majority of the Atlantic Coast experiences higher rates of relative sea level rise (2 to 4 mm [0.1 to 0.2 in] per year) than that of the global average (1.7 mm [0.1 mm] per year) (EPA, 2009). The highest rates of sea level rise in the Atlantic Coast occur between northern New Jersey and southern Virginia (EPA, 2009). This is due to localized sinking of the land surface, which has been attributed to on-going adjustment of the earth's crust due to the melting of former ice sheets, sediment compaction and consolidation, and withdrawal of hydrocarbons from underground (EPA, 2009).

The NOAA Center of Operational Oceanographic Products and Services (CO-OPS) has collected North Carolina water level data for many decades. The stations located at Southport and Wilmington have over 70 years of data, and eight other stations have data that spans at least 20 years, which is adequate to determine the mean sea level trends with reasonable confidence intervals. Mean sea level trends for eight stations within North Carolina show an increase in sea level that appears to have a regional gradient with the lowest levels of rise in the southern portion of the state to the highest levels in the northern portion of the state. The trends range from an increase of 2.04 mm (0.1 in) per year in the southern-most station at Southport to 4.27 mm (0.2 in) per year at the northern-most station in Duck (Zervas, 2004). This implies that the land is sinking more rapidly along the northern portion of the North Carolina coastline. Figure 2.3 depicts the mean sea level trends for eight North Carolina water level stations.

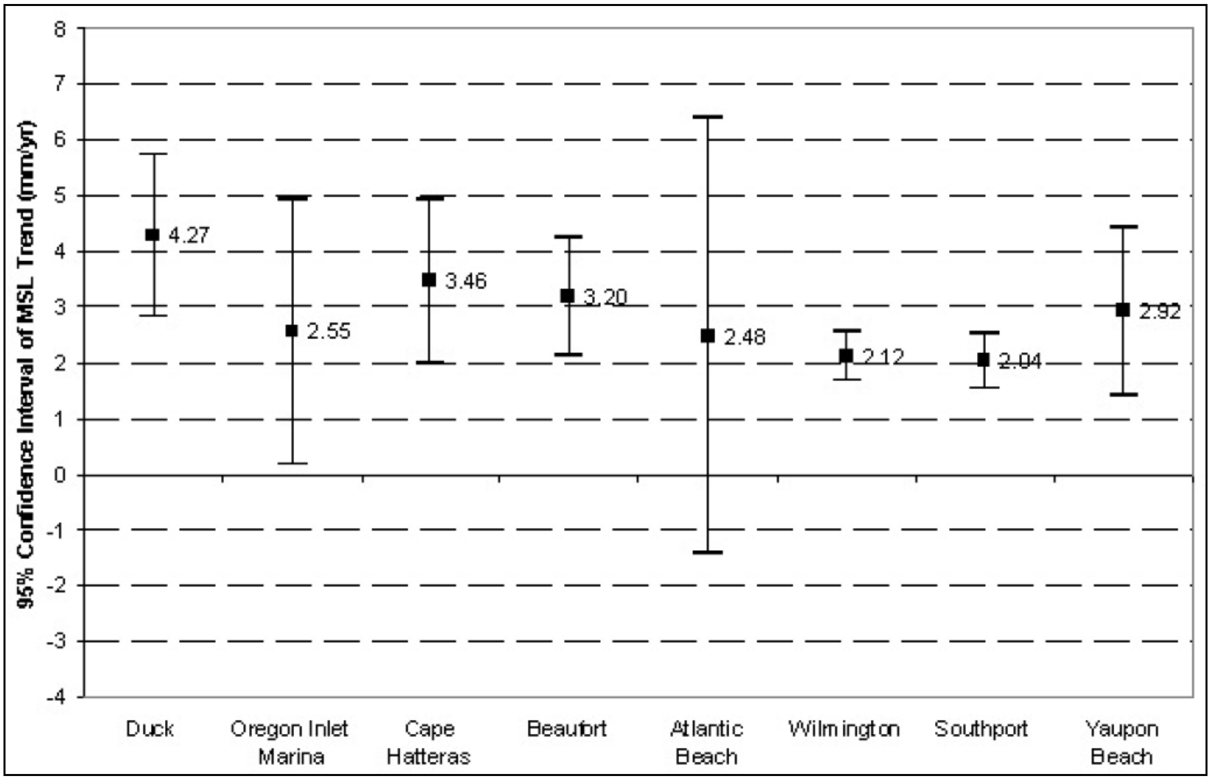

Figure 2.3: Mean Sea Level Trends in North Carolina

Mean sea level trends and 95% confidence intervals for North Carolina water level stations from north (Duck) to south (Yaupon Beach). Figure excerpted from Zervas (2004).

Another source (Riggs et al, 2008) demonstrates with tidal gauges and historical data that the relative mean sea level rose in northeastern North Carolina at a rate of about 0.4 m (16 – 18 in) in the last century. In the 19th century this rate was 0.18 m (7 in) per 100 years, and 200 hundred years ago it was 0.08 m (3 in).

In evaluating sea level rise, the average seasonal cycle is also an important consideration. Sea level fluctuates throughout the year, but the average seasonal cycle is very similar throughout the eight stations analyzed in North Carolina. The highest monthly water levels typically occur in September and October and the lowest monthly water levels occur in January and February (Zervas, 2004). Figure 2.4 depicts the average seasonal water level cycle in Duck, North Carolina, which is the sampling site closest to the project site.

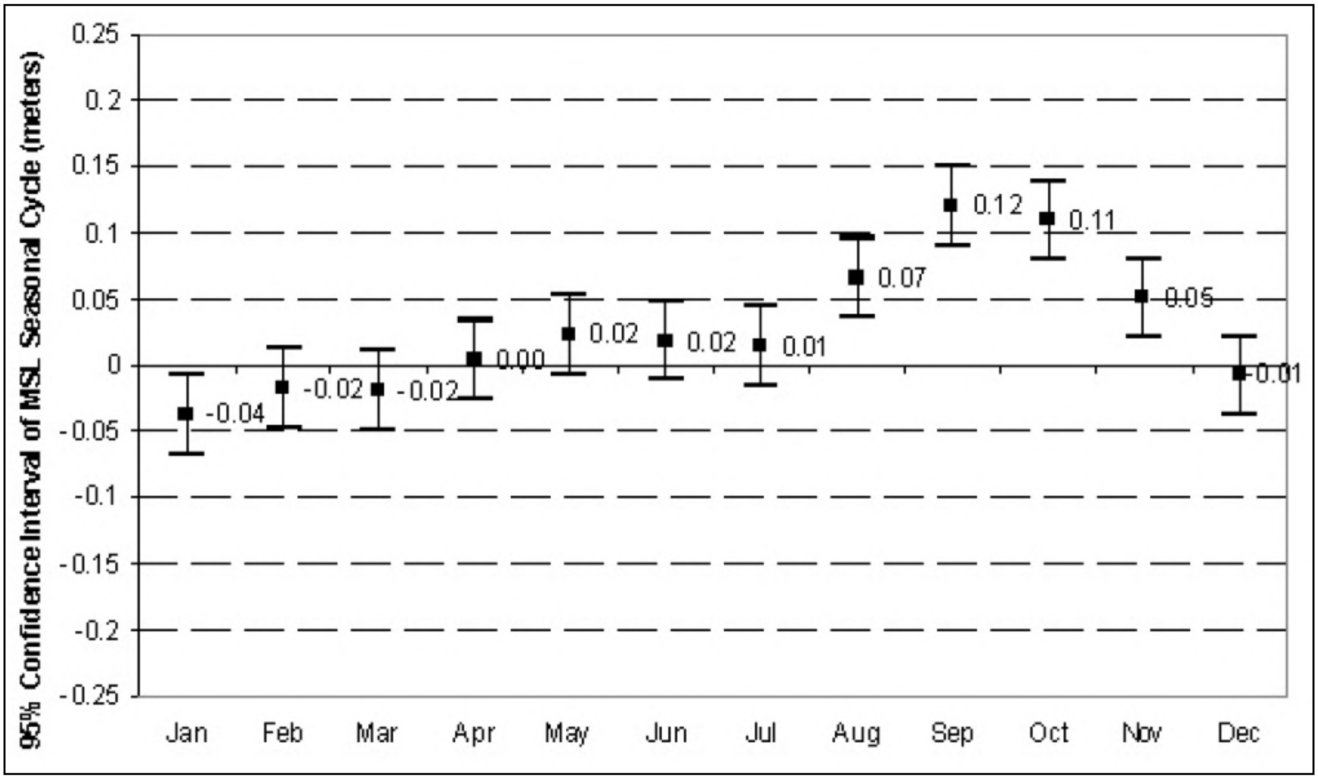

Figure 2.4: Average Seasonal Water Level Cycle in Duck, North Carolina

Average seasonal cycle of mean sea level for Duck in meters. Figure excerpted from Zervas (2004).

One often overlooked impact of sea level rise is the decreased clearance under existing bridges (EPA, 2009). This will be an important consideration in the design of new structures such as the proposed Mid Currituck Bridge. The bridge will have a designed life span of 75 years and is planned to be fully functional around the year 2013; therefore, the design life will last until about the year 2088. Utilizing the most conservative estimate of the IPCC SRES scenarios, a rise of 6 mm (0.2 in) per year for the approximately 80 years between now and the year 2088, would equate to an approximate rise of about 480 mm or 19 in above the 1980-1999 tidal epoch levels.

3 Breaching

The North Carolina coastal system is in constant change. This transformation can occur at a gradual pace in response to climate change (sea level rise) and low energy wave-induced processes over a extended period of time, or during a short period of time in response to the high energy storm or hurricane events (Zhang et al, 2002 and Riggs et al, 2008). Barrier islands and inlets are built and modified by these events, and depend on storms to maintain their short-term health and long-term evolution (Riggs et al, 2008).

During the 20th century, 105 tropical storms and hurricanes impacted the coast of North Carolina. Also, up to 35 extra-tropical storms (known in the area as nor'easters) attack the coast of North Carolina every year. These events are not as strong as a tropical storm but can build a sea state that strikes the coast over several tidal cycles (Stick, 1987). The consequences of any given storm are not predictable, and depend on the type, size, strength, duration, path, rainfall amount, surge elevation and bathymetry (Riggs et al, 2008).

Storm surges are critical on low and narrow barrier islands like the ones present on the northeast coast of North Carolina. Some of the storm events may open inlets and build back-barrier flow-tide deltas which are vital to the health of the barrier islands and the inlet migration as the sea level rises (Riggs et al, 2008). In fact, several breaches have dissected the barrier islands north of Cape Lookout since 1585 (Stick, 1958 and Fisher 1962), and recent research suggests that around 50 to 70% of the coastline between Oregon Inlet and Cape Hatteras has had inlets in the last several hundreds years (Smith et al, 2006). Inlets are high energy, self adjusting safety valves along the barrier islands that allow water flow into the sounds due to a high storm surge, or that let water volume flow out to the ocean caused by an increased river flow due to a heavy rainfall or storm surge generated within a sound system such as North Carolina's. When the storm surges and rainfall cease, these new inlets close back to a hydrodynamicly equilibrium point dictated by the coastal-estuarine system.

A study developed by Fisher (1962) recognized paleo-inlets along the Outer Banks. This was complemented by Smith (2006) using modern geophysical techniques. Figure 3.1 presents the results of this research providing the position and dates of known historic inlets. In Figure 3.1 it can be observed that in the barrier islands of Currituck County there were four openings that connected the ocean with the Currituck Sound in the past: Old Currituck, New Currituck, Musketo and Caffeys.

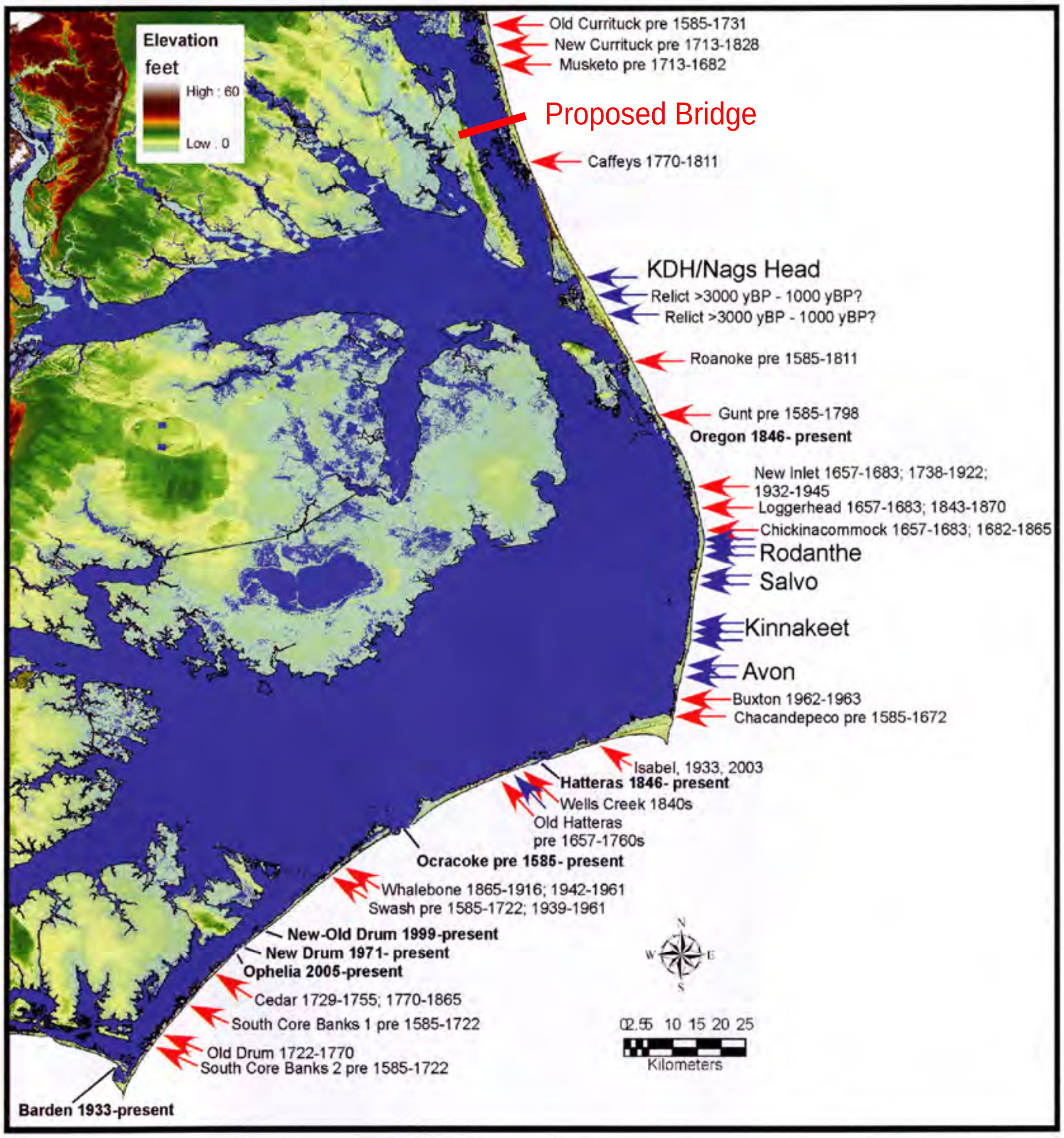

Figure 3.1: Approximate Locations and Dates of Existence of Documented Historic Inlets (Smith, 2006)

Using LiDAR elevation information, the barrier island's cross sectional volume was quantified to establish the risk of forming a new inlet. Figure 3.2 shows the result of this study. With this study, now it can be understood that areas with high breaching risk also have the potential to erode significantly below the sea level. The investigation does not include the Mid Currituck proposed bridge area, but gives an idea of the potential barrier islands openings elsewhere along the Outer Banks.

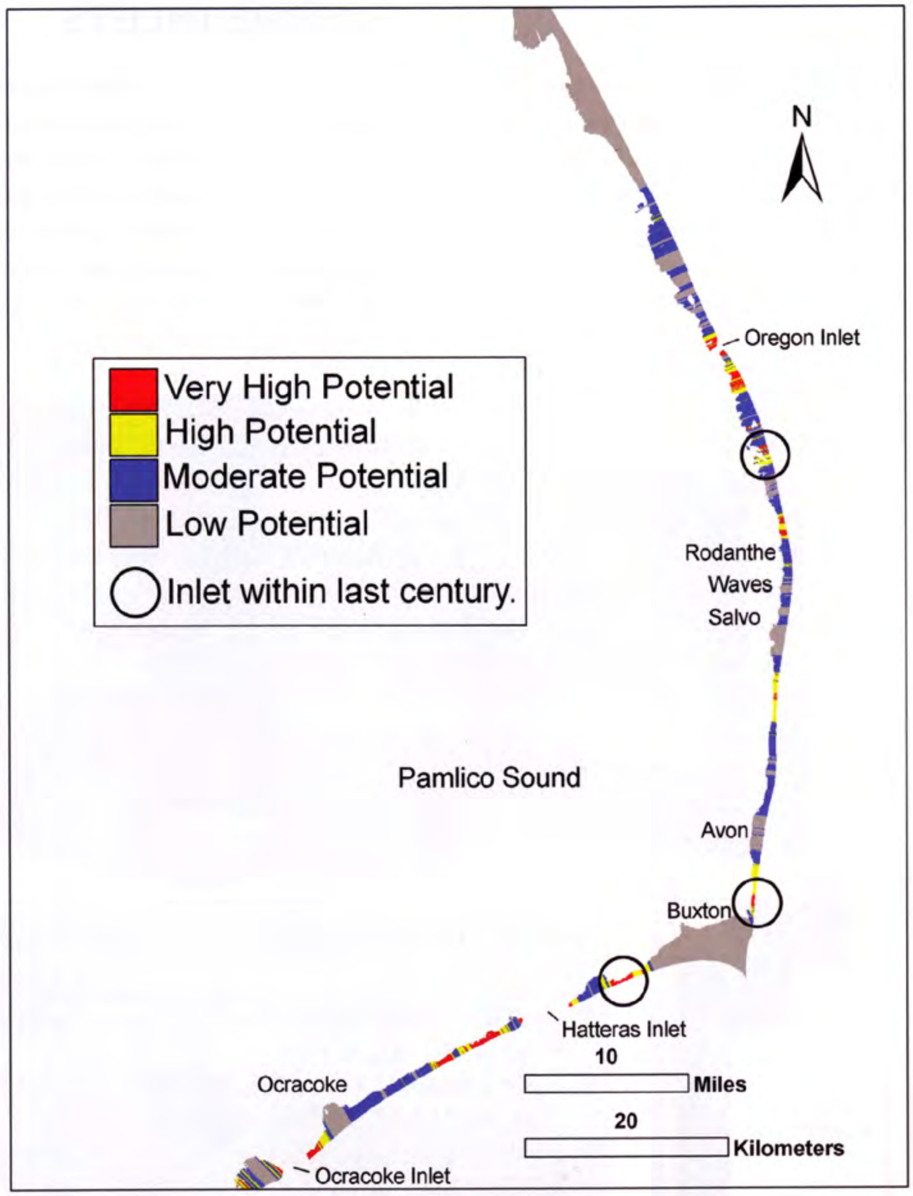

Figure 3.2: Inlet Opening Potential along the Outer Banks
(http://coastal.geology.ecu.edu/NCCOHAZ/maps/inlet_potential.html)

Topographic surveys of the proposed bridge region show that the barrier island has an average elevation of 12 to 15 feet, and the width ranges from 1,600 to 3,300 feet wide. The topography combined with the extrapolation of the results of Figure 3.2 to the north, leads to the conclusion that the location of the project has a low potential of inlet opening. This can be corroborated with Figure 3.1 which shows no active or historic inlets present in the area except for one which remained open for 41 years (Caffeys inlet, which is south of the proposed bridge location).

Furthermore, a North Carolina coastal highway vulnerability study, developed by the North Carolina Department of Transportation (NCDOT, 2005), investigated the impacts of storms and long-term shoreline erosion on the coastal highway system. The study states that there are no areas where NC 12 is vulnerable to erosion between 2003 and 2023 in Currituck County due to the large distance between the highway and the shoreline as well as low long-term erosion rates.

4 FEMA and North Carolina Flood Mapping

The Federal Emergency Management Agency (FEMA) developed a Flood Insurance Study (FIS) for Currituck County, North Carolina (2005). Flood elevations for various return periods were established for the project study area.

A potential source of flooding in Currituck Sound is storm surge generated in the Atlantic Ocean by tropical storms and hurricanes. The wind induced by the storms can produce large waves. This wave action associated with the storm surge can be much more damaging than the higher water level.

The FEMA standard coastal surge model was used to simulate the coastal surge elevation generated by any chosen storm (several storms were utilized). Each storm is described by five parameters that influence the surge height. These parameters are: central pressure depression, radius to maximum winds, forward speed of the storm, shoreline crossing point, and crossing angle. Simulating a large number of storms that have passed near the coast of North Carolina permits the establishment of the frequency distribution of the still water elevations as a function of location. This is a large scale model and does not include the finer scale phenomenon such as wave height, set up, or run up. Then, the astronomic tide of the region is combined with the computed storm surge to obtain recurrence intervals of total water level.

Nor'easters (winter storms) are less intense storms than hurricanes, but they occur with more frequency covering larger areas. After analyzing the nor'easter's effects two significant conclusions were determined. The effects of these storms are significant only on the ocean side of the Outer Banks areas north of Cape Hatteras; and they are not especially significant in Currituck County, contributing less than half a foot of the total surge to the 1% annual chance surge elevations. The contribution refers to the added effects of the winter storms above surge computations of hurricanes and tropical storms.

The methodology followed to analyze the wave heights associated with coastal storms surge elevations is described in the National Academy of Sciences Report (1977), which is based on three major concepts:

- Depth-limited waves in shallow water reach a maximum breaking height of 78% of the still water depth; and the wave crest elevation is 70% of the total wave height above still water level.
- The wave height may be reduced by dissipation of energy due to the presence of dunes, dikes and seawalls, buildings and vegetation.
- The wave height can be regenerated in open fetch areas (transfer of wind energy to the water).

The wave heights were computed along transects. These transects are perpendicular to the shoreline and extend inland to a point where the wave action ceased. Along each transect, wave heights and elevations were computed. The 100-year return period surge elevations were used as starting elevations for the computations.

Flood Insurance Rate Maps (FIRM) provide the 100-year return period flood elevations, and also designate flood insurance rate zones. In the study area, two different types of zone designations were encountered:

- AE: Flood insurance rate zone that corresponds to the 1% annual chance flood that is determined in the FIS Report by detailed methods. Whole foot base flood elevations derived from the detailed hydraulic analyses are shown at selected intervals within this zone.
- VE: Flood insurance rate zone that corresponds to the 1% annual chance flood that has additional hazards associated with storm waves. Whole foot base flood elevations derived from the detailed hydraulic analyses are shown at selected intervals within this zone.

Figure 4.1 shows the proposed alignment of the bridge, and the colors define the designated flood insurance rate zones along the bridge. Table 4.1 provides the floodplain elevation for each zone defined in the Figure.

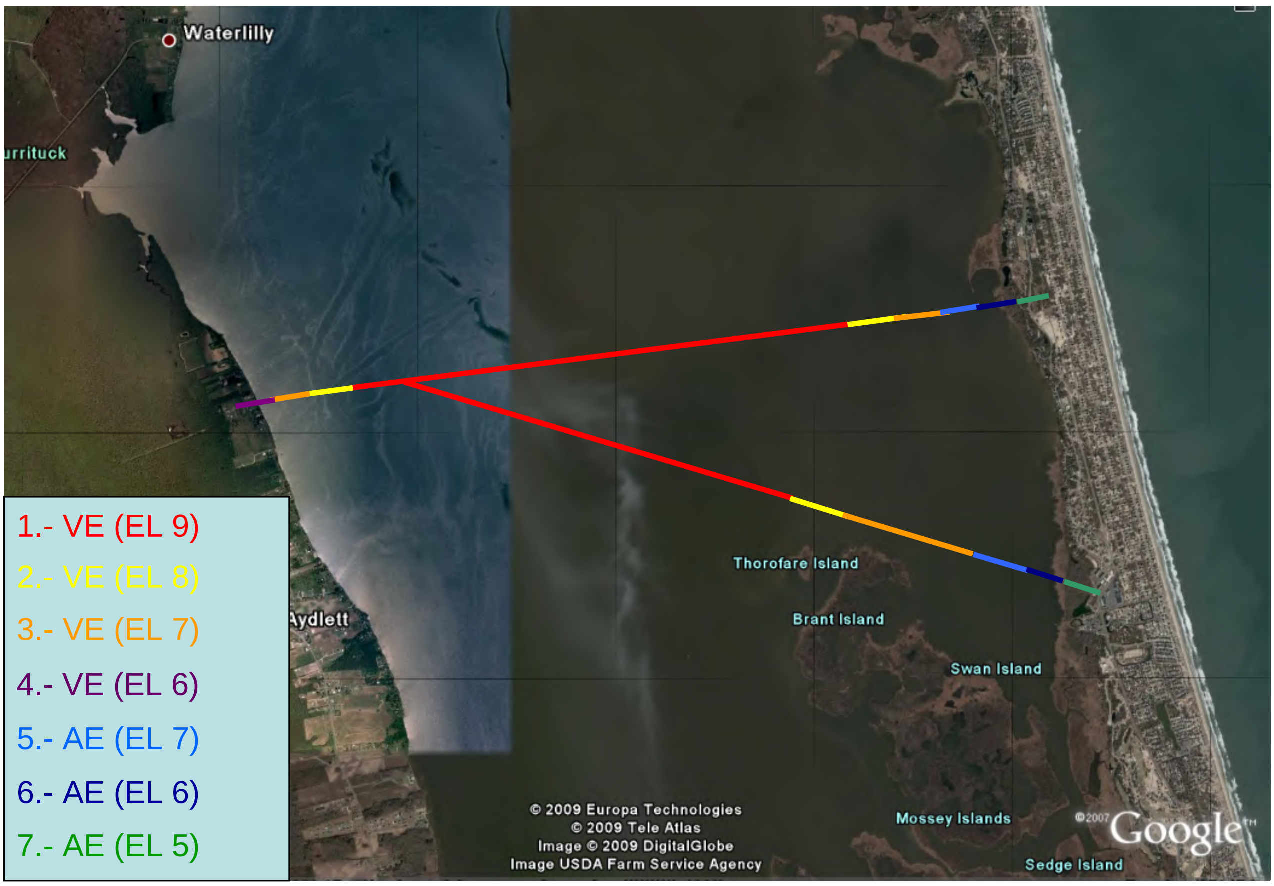

Figure 4.1: Flood Zone Designations

Table 4.1:
Flood Zone Designation and Elevation

Zone	Flood Designation	Elevation [ft NAVD]
1	VE	9
2	VE	8
3	VE	7
4	VE	6
5	AE	7
6	AE	6
7	AE	5

Looking at the results it can be seen that the predicted 100 year flood elevation is lower at the shore of the sound and higher in the middle of the sound. This matches the methodology used to predict the flood elevations; the waves decrease across the barrier island and are regenerated in the Currituck Sound due to the wind stress.

The VE flood zones include storm waves in the flood elevation. Hence, the flood elevation for these zones is the wave crest elevation. The FIS study does include the still water (no wave effect) storm surge elevations along transects perpendicular to the Currituck barrier islands and Currituck sound. For the zones with VE from 7 to 9 ft NAVD, the still water elevation is 5.0 ft NAVD; for the zones with VE equal to 6 ft NAVD, the still water elevation is 4.2 ft NAVD. Therefore, the wave crest height above the still water elevation can be calculated.

The FEMA study assumes that the wave crest is 70% of the total significant wave height above the still water level in shallow water. With this assumption, the significant wave height can be calculated by dividing the wave crest height by 70% percent of the significant wave height. Table 4.2 presents the wave crest elevations, the still water surge elevations and the significant wave heights for the different zone designations.

Table 4.2:
Wave Crest Elevation, Surge Elevation and Significant Wave Height

Zone	Flood Designation	Wave Crest Elevation [ft NAVD]	Surge Elevation [ft NAVD]	Significant Wave Height [ft]
1	VE	9	5.0	5.7
2	VE	8	5.0	4.3
3	VE	7	5.0	2.9
4	VE	6	4.2	2.6
5	AE	N/A	7.0	N/A
6	AE	N/A	6.0	N/A
7	AE	N/A	5.0	N/A

The maximum possible wave height, H_{max}, can be calculated using the significant wave height, H_S. The Coastal Engineering Manual suggests a relation developed by Abramowitz and Stegun (1965), in which the maximum wave height is 1.86 times the significant wave height. Table 4.3 presents the maximum wave heights for the different zone designations.

Table 4.3:
Surge Elevation and Maximum Wave Height

Zone	Flood Designation	Surge Elevation [ft NAVD]	Maximum Wave Height [ft]
1	VE	5.0	10.6
2	VE	5.0	8.0
3	VE	5.0	5.3
4	VE	4.2	4.8
5	AE	7.0	N/A
6	AE	6.0	N/A
7	AE	5.0	N/A

Using the same methodology, the wave crest height above the still water level of the maximum wave height is 70% of the total wave height as well. Hence, the maximum wave height was multiplied by 0.7 to obtain the maximum wave crest elevation above the still water level. This value was added to the still water storm surge elevation to obtain the maximum wave crest elevation. Table 4.4 presents the maximum wave crest elevations, the still water surge elevations and the maximum wave heights for the different zone designations.

Table 4.4:
Maximum Wave Crest Elevation, Surge Elevation and Maximum Wave Height

Zone	Flood Designation	Max. Wave Crest Elev. [ft NAVD]	Surge Elevation [ft NAVD]	Maximum Wave Height [ft]
1	VE	12.4	5.0	10.6
2	VE	10.6	5.0	8.0
3	VE	8.7	5.0	5.3
4	VE	7.5	4.2	4.8
5	AE	N/A	7.0	N/A
6	AE	N/A	6.0	N/A
7	AE	N/A	5.0	N/A

5 Numerical Wave Hindcast Modeling

The Currituck County FEMA FIS report modeled waves originating in the Atlantic Ocean, crossing the shoreline of the barrier island, and then being regenerated across Currituck Sound. However, hurricanes traversing inland and across the sounds of North Carolina can also generate significant wave activity within the sounds. Thus, additional wave hindcast numerical modeling, which is discussed in this chapter, was performed to simulate waves propagating within Currituck Sound.

MODEL DESCRIPTION

The numerical model used for this purpose was DHI's Nearshore Spectral Wind-Wave Model, MIKE 21 NSW. MIKE 21 NSW is a wind-wave model that describes the propagation, growth and decay of short period and short crested waves in nearshore areas. The model takes into account the effects of refraction and shoaling due to varying depth, local wind generation and energy dissipation due to bottom friction and wave breaking.

The basic equations are solved using an Eulerian finite difference technique. The zeroth and the second moment of the action spectrum are calculated on a rectangular grid for a number of discrete directions. A once through marching numerical solution procedure is applied in the predominant direction of wave propagation.

SIMULATION SETUP

Upon review of hurricane parameters presented in the FEMA FIS in the region near the proposed bridge, four different hurricane tracks were modeled, which are shown in Figure 5.1. Multiple simulations were performed by varying the forward speed of the hurricane and the radius to the maximum wind. The central pressure depression though, was kept as a constant in the simulations.

Table 5.1 shows the parameters of the storms passing by the study area. These storm characteristics (extracted from the FEMA FIS for Currituck County) were described statistically based on an analysis of storms that have passed near the coast of North Carolina.

Table 5.2 provides the parameters of the different simulated storms in this study. These characteristics were chosen based on the probability of occurrence and the likelihood to generate the maximum waves at the proposed bridge site.

Table 5.1:
Parameter Values for Hurricanes – Atlantic Ocean North of Hatteras Inlet (FIS, 2005)

<table>
<tr><td rowspan="4">Central Pressure (millibars)</td><td>Parameter Value</td><td></td><td>5</td><td>15</td><td>25</td><td>35</td><td>45</td><td>55</td><td>65</td><td>75</td><td>85</td></tr>
<tr><td rowspan="3">Probabilities</td><td>I:</td><td>0.144</td><td>0.137</td><td>0.138</td><td>0.121</td><td>0.161</td><td>0.139</td><td>0.061</td><td>0.088</td><td>0.011</td></tr>
<tr><td>II:</td><td>0.144</td><td>0.136</td><td>0.139</td><td>0.119</td><td>0.159</td><td>0.143</td><td>0.060</td><td>0.089</td><td>0.011</td></tr>
<tr><td>III:</td><td>0.247</td><td>0.240</td><td>0.246</td><td>0.086</td><td>0.063</td><td>0.055</td><td>0.023</td><td>0.033</td><td>0.007</td></tr>
<tr><td rowspan="2">Storm Radius to Maximum Winds (nm)</td><td>Parameter Value</td><td colspan="5">20</td><td colspan="5">35</td></tr>
<tr><td>Probabilities</td><td colspan="5">0.51</td><td colspan="5">0.49</td></tr>
<tr><td rowspan="4">Maximum Forward Speed (knots)</td><td>Parameter Value</td><td></td><td colspan="3">10</td><td colspan="3">20</td><td colspan="3">30</td></tr>
<tr><td rowspan="3">Probabilities</td><td>I:</td><td colspan="3">0.647</td><td colspan="3">0.235</td><td colspan="3">0.118</td></tr>
<tr><td>II:</td><td colspan="3">0.396</td><td colspan="3">0.377</td><td colspan="3">0.226</td></tr>
<tr><td>III:</td><td colspan="3">0.448</td><td colspan="3">0.431</td><td colspan="3">0.121</td></tr>
<tr><td rowspan="3">Direction of Storm Path (deg. from True North)</td><td>Parameter Value</td><td colspan="2">276</td><td colspan="2">312</td><td colspan="2">348</td><td colspan="2">24</td><td colspan="2">60</td></tr>
<tr><td>Probabilities</td><td colspan="2">0.016</td><td colspan="2">0.016</td><td colspan="2">0.102</td><td colspan="2">0.414</td><td colspan="2">0.453</td></tr>
<tr><td>Rate (Storm/nm/year)</td><td colspan="2">0.09</td><td colspan="2">0.076</td><td colspan="2">0.49</td><td colspan="2">2.32</td><td colspan="2">2.06</td></tr>
</table>

Table 5.2:
Storm Tracks, Forward Speed and Radius

Hurricane (Scenario)	Storm Path	Forward Speed [knots]	Radius to Max Wind [nm]
1	Track 1	10	20
2	Track 2	10	35
3	Track 3	10	20
4	Track 1	20	20
5	Track 2	20	35
6	Track 1	30	20
7	Track 2	30	35
8	Track 4	30	20

As seen in Figure 5.1 the selected storm paths were:

- Track 1 runs south to north, parallel to the center of the Currituck Sound, with the center of the hurricane located 20 nautical miles from the center of the sound towards the west.
- Track 2 runs south to north, parallel to the center of the Currituck Sound, with the center of the hurricane located 35 nautical miles from the center of the sound towards the west.
- Track 3 follows the trajectory of the hurricane Charley (1986). It runs from south to north and the center of the storm passes over the location of the proposed bridge.
- Track 4 runs north to south parallel to the center of the Currituck Sound, with the center of the hurricane located 20 nautical miles from the center of the sound towards the east (this clearly was not a likely scenario, but was modeled to confirm waves propagating from the north end of Currituck Sound would not control the design).

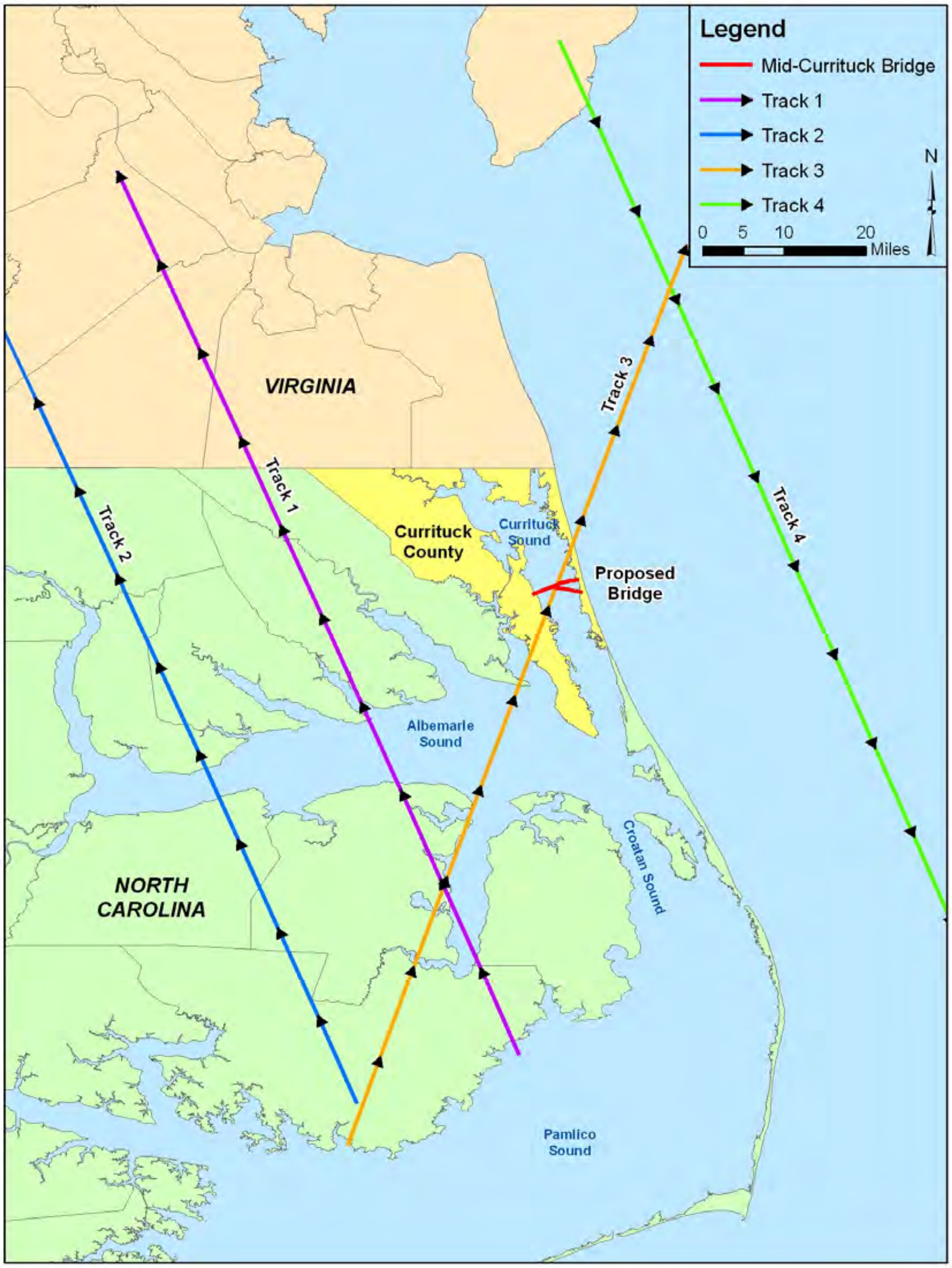

Figure 5.1: Modeled Hurricane Tracks

The maximum wind speed of the proposed storms was taken from the ASCE 7-05 "Minimum Design Loads for Buildings and Other Structures". The chosen wind is a constant for the eight storm simulations and corresponds to the 100-year wind speed at the project location. Figure 5.2 provides the 3-second gust wind speed values for the Mid and Northern Atlantic Hurricane Coastline for a 50-year return period event. At the location of this project, the gust speeds are approximately 120 mph. Table 5.3 provides a table of the conversion factors for different return period winds.

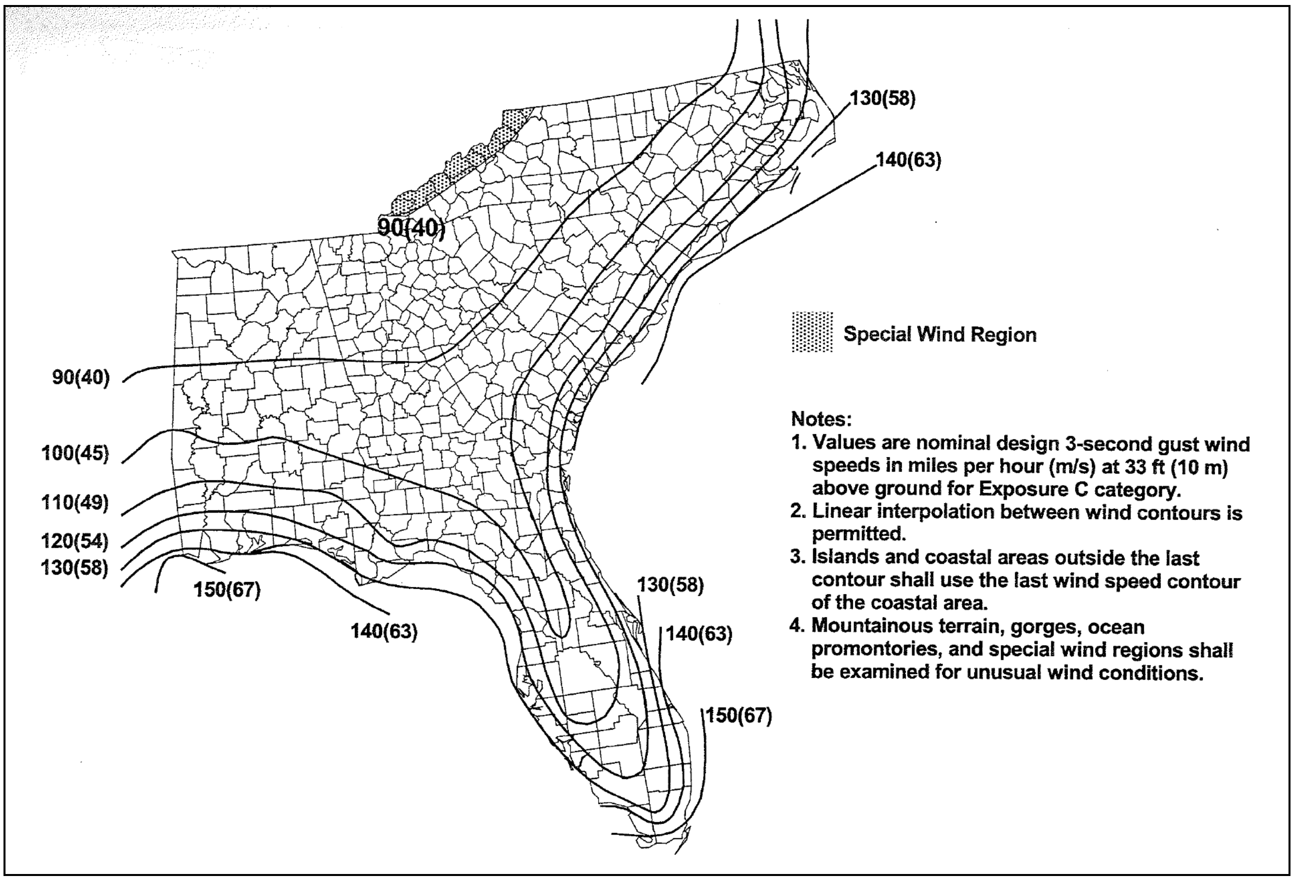

Figure 5.2: Basic Wind Speed – Eastern Gulf of Mexico and South-eastern US Hurricane Coastline (ASCE 7-05)

Table 5.3:
Conversion Factors for Varying Recurrence Intervals (ASCE 7-05)

MRI (years)	Peak gust wind speed, V (mph) (m/s)		
	Continental U.S.		Alaska
	V = 85-100 (38-45 m/s)	V > 100 (hurricane) (44.7 m/s)	
500	1.23	1.23	1.18
200	1.14	1.14	1.12
100	1.07	1.07	1.06
50	1.00	1.00	1.00
25	0.93	0.88	0.94
10	0.84	0.74 (76 mph min) (33.9 m/s)	0.87
5	0.78	0.66 (70 mph min) (31.3 m/s)	0.81

To obtain the wind condition for the 100-year return period event, the value from Figure 5.2 was factored by the value stipulated in Table 5.3 for the 100-year return period event. The 3-second gust wind for the 100-year event is 129 mph, and the corresponding 1-minute sustained wind is 106 mph.

The storms were simulated for 9 hours (to account for the slowest moving hurricane), with a central pressure depression of 45 millibars. Hence, the central pressure of the hurricanes is 968.25 millibars, which corresponds to the most probable central pressure of a storm that passes through the study area.

The simulations include a storm surge still water level of 7 ft NAVD, which corresponds to the largest 100-year storm surge for the Currituck Sound in the vicinity of the proposed bridge location (FEMA FIS for the Currituck County, North Carolina). This is a conservative assumption as the 100-year still water storm surge in the FEMA FIS varies from 4.2 feet NAVD to 7 feet NAVD across the length of the proposed bridge.

The grid used to simulate the waves generated by the hurricanes extends from Croatan Sound to past the North Carolina / Virginia border. The grid is 65.8 miles (105.9 kilometers) in the direction of wave propagation, which is south to north (north to south for hurricane track 4), and 37.3 miles (60 kilometers) wide. Figure 5.3 shows the extents of the model domain.

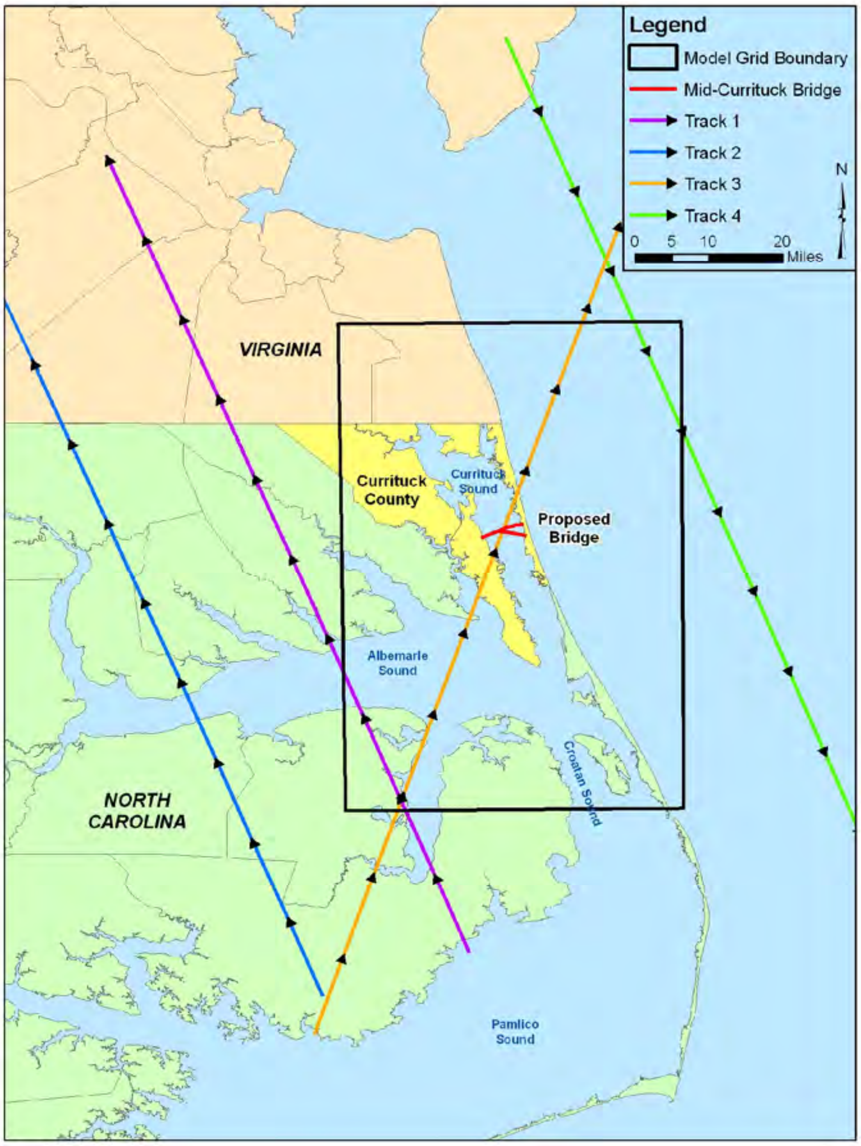

Figure 5.3: Model Domain

The grid cells are 10 meters x 40 meters (33 feet x 131 feet). The cells along the wave propagation direction are finer (10 meters) in order to have a better resolution along the wave length. This criterion is also used to enhance the stability of the wave model.

The bathymetry information was taken from the National Oceanic and Atmospheric Administration (NOAA) navigational charts (charts number 12204 and 12207). Figure 5.4 shows the bathymetry used in the simulations.

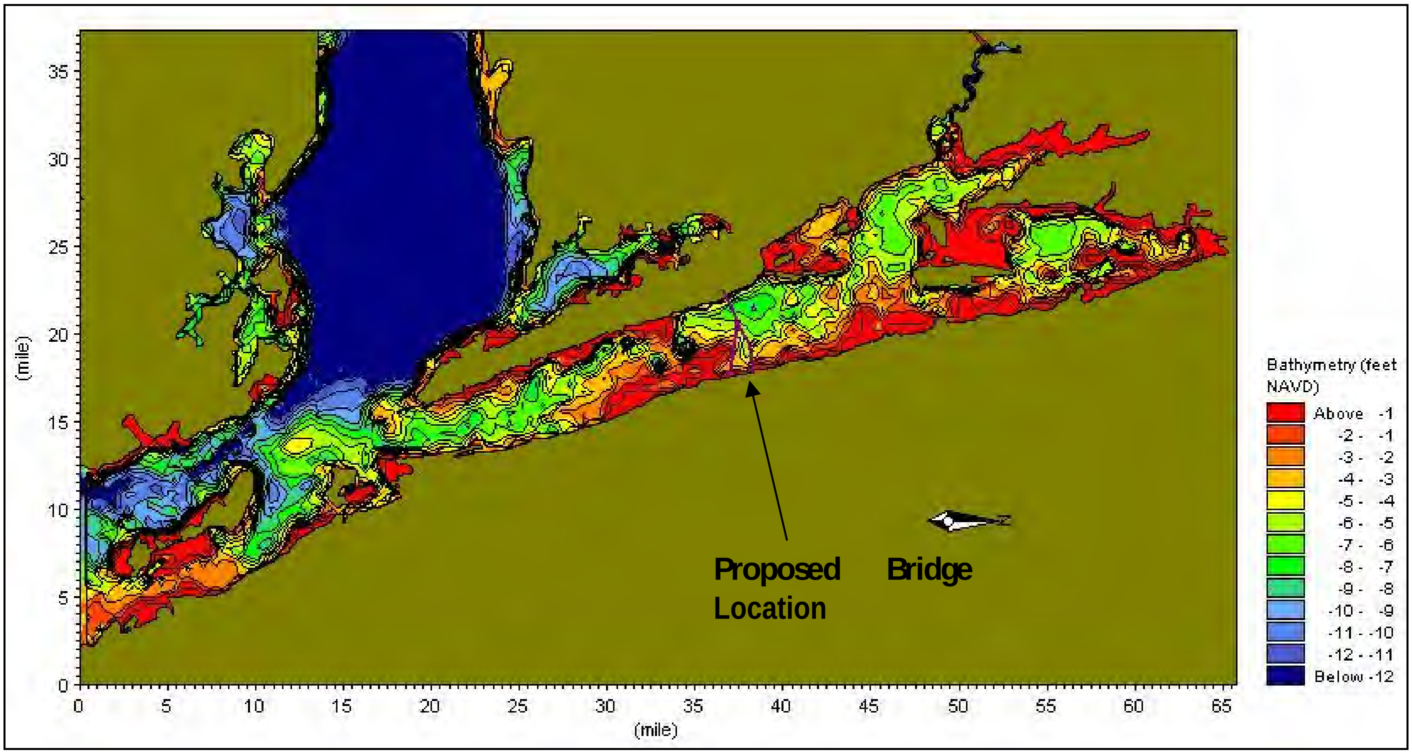

Figure 5.4: Bathymetry of the Model Domain

RESULTS

The MIKE 21 NSW simulations provide results for significant wave height, wave peak period, and mean wave direction. Figures 5.5 to 5.12 show the maximum significant wave height around the proposed bridge area. In other words, the figures show the envelope of the maximum significant wave heights of all time steps for each of the simulations. In the figures, the waves propagate from left to right, with the exception of Figure 5.12 where the waves propagate in the opposite direction (Hurricane 8).

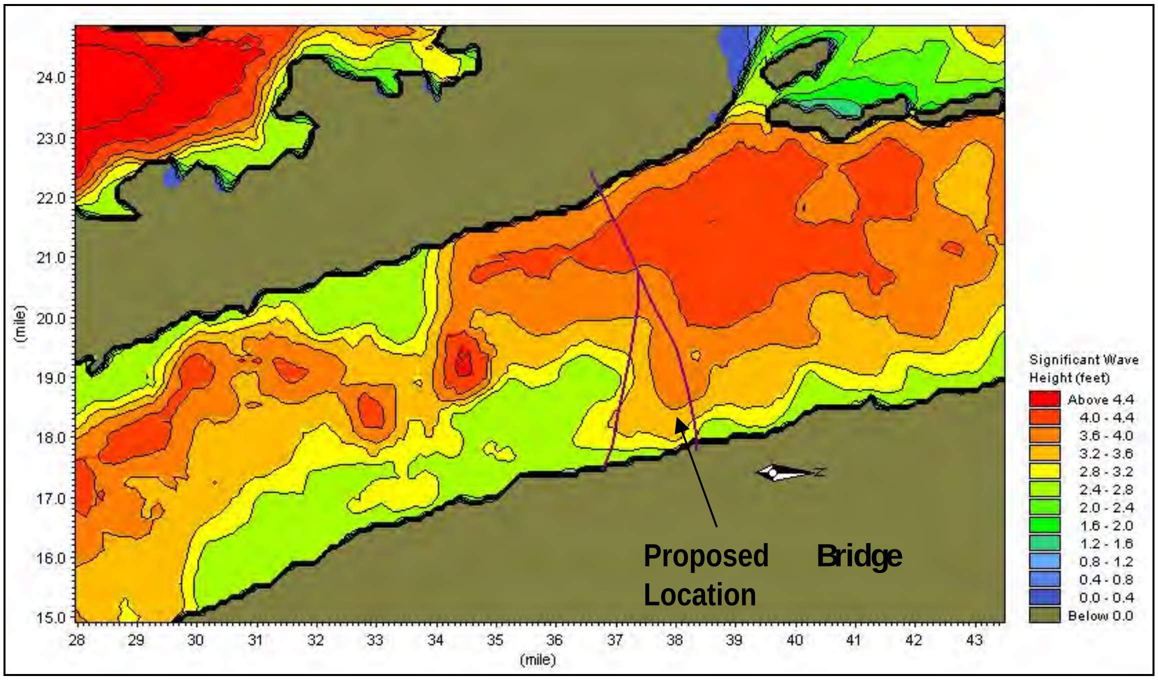

Figure 5.5: Maximum Significant Wave Height – Hurricane Scenario #1

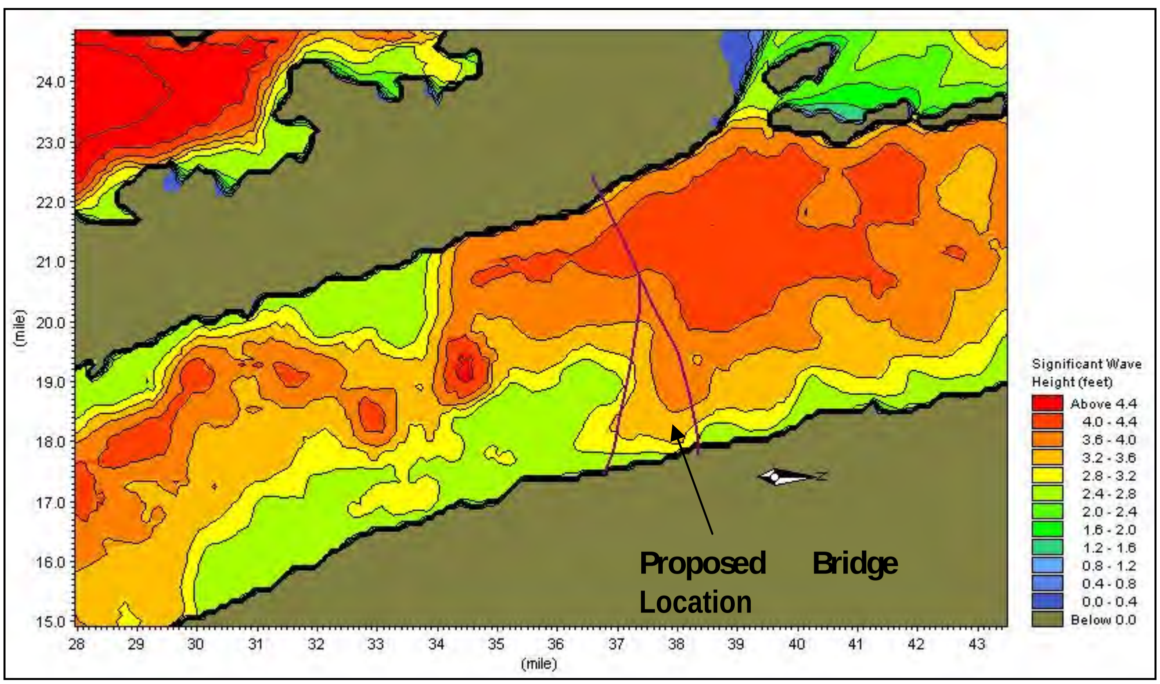

Figure 5.6: Maximum Significant Wave Height – Hurricane Scenario #2

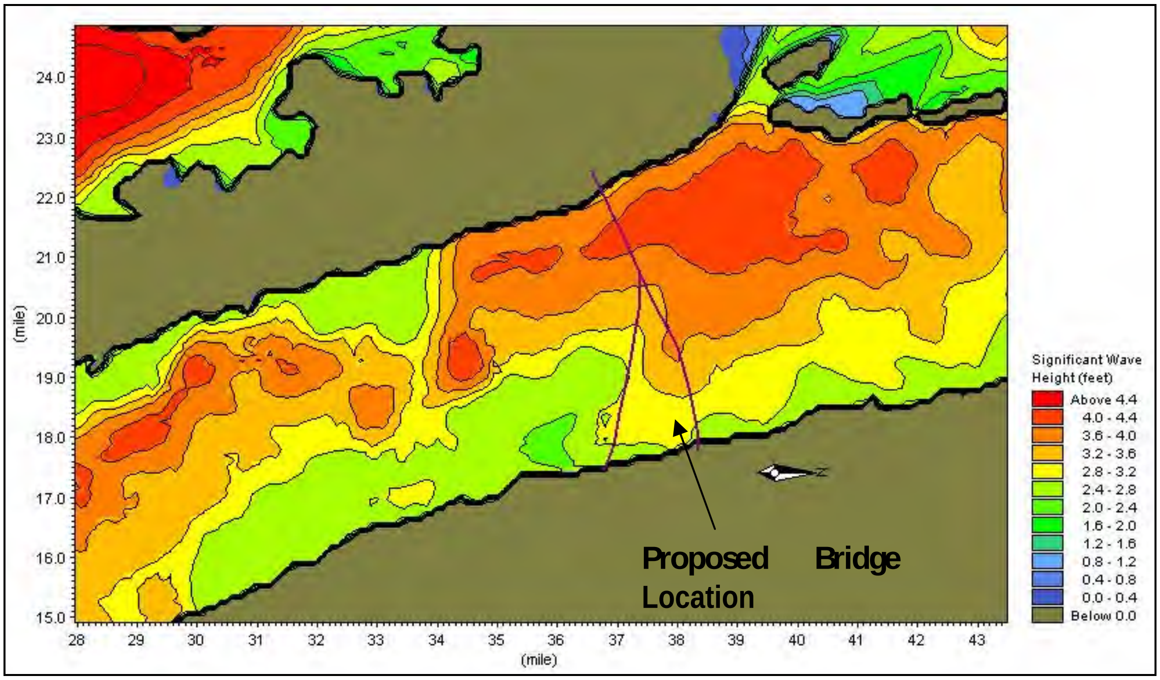

Figure 5.7: Maximum Significant Wave Height – Hurricane Scenario #3

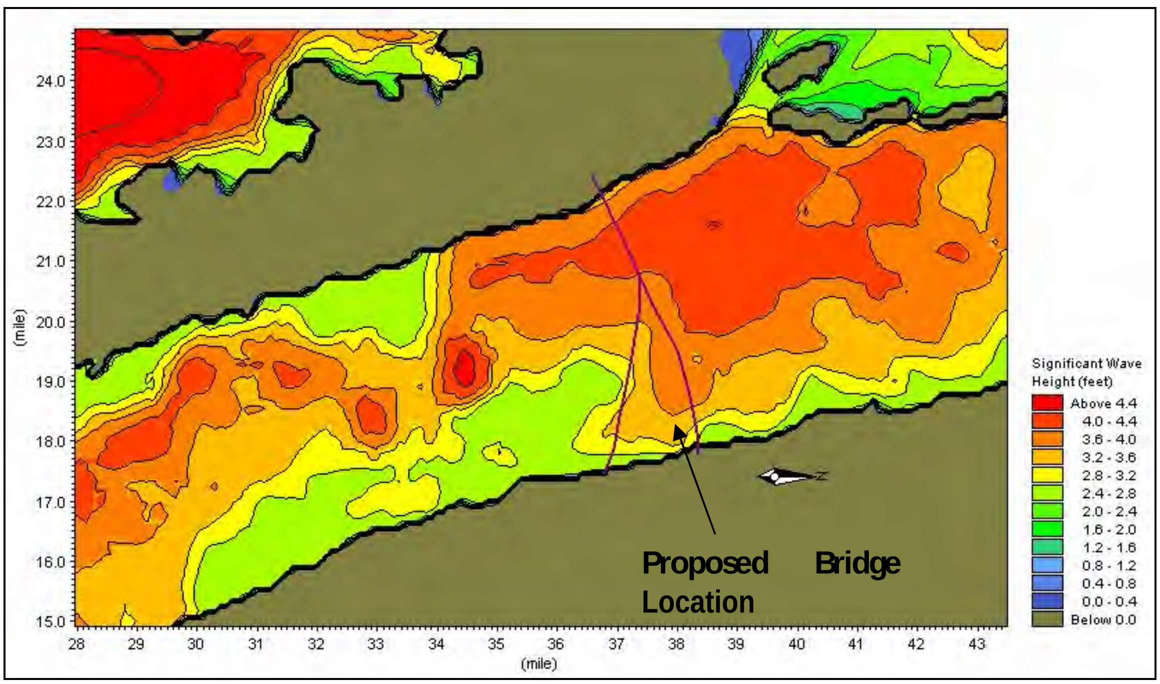

Figure 5.8: Maximum Significant Wave Height – Hurricane Scenario #4

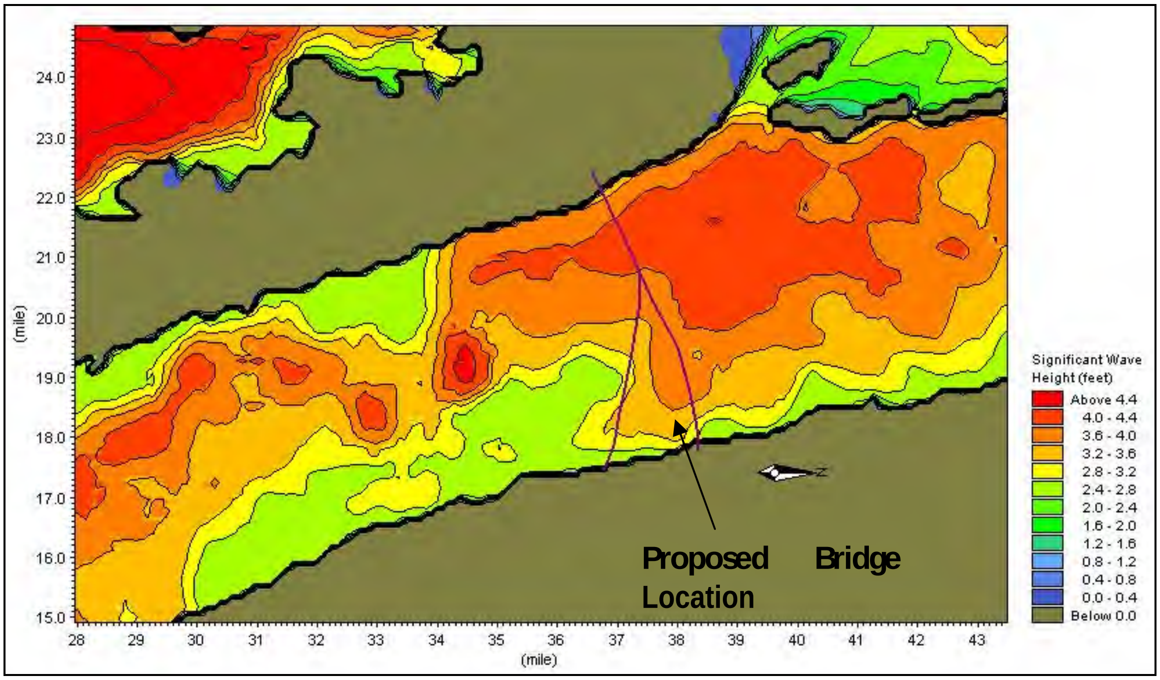

Figure 5.9: Maximum Significant Wave Height – Hurricane Scenario #5

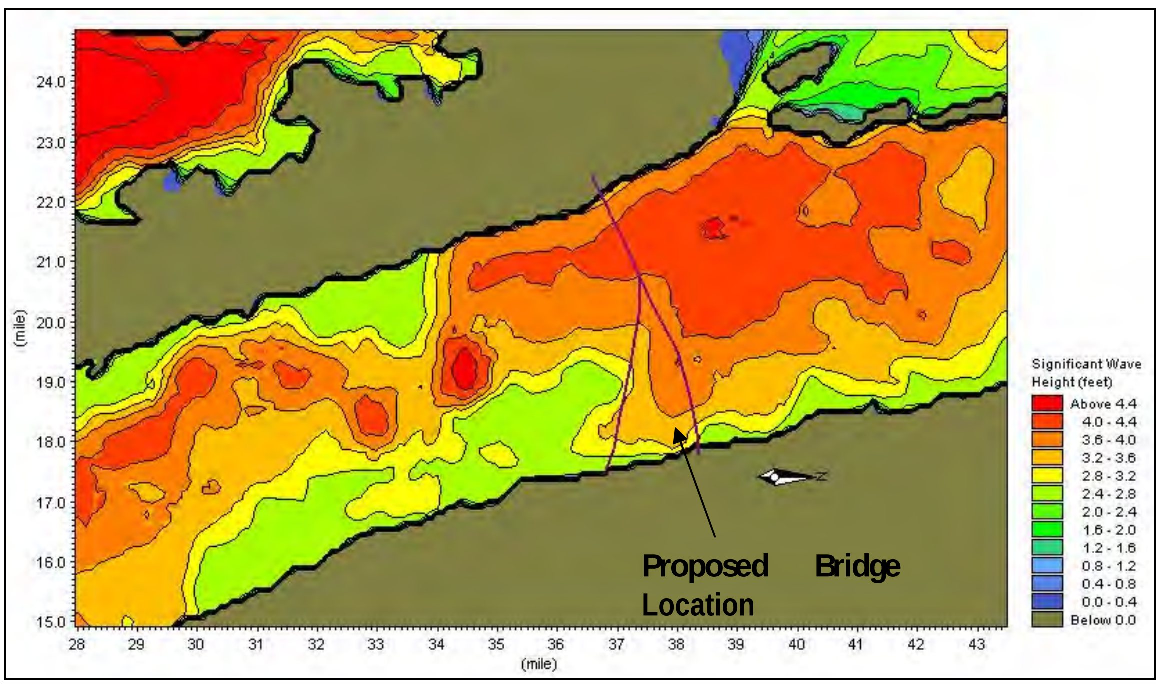

Figure 5.10: Maximum Significant Wave Height – Hurricane Scenario #6

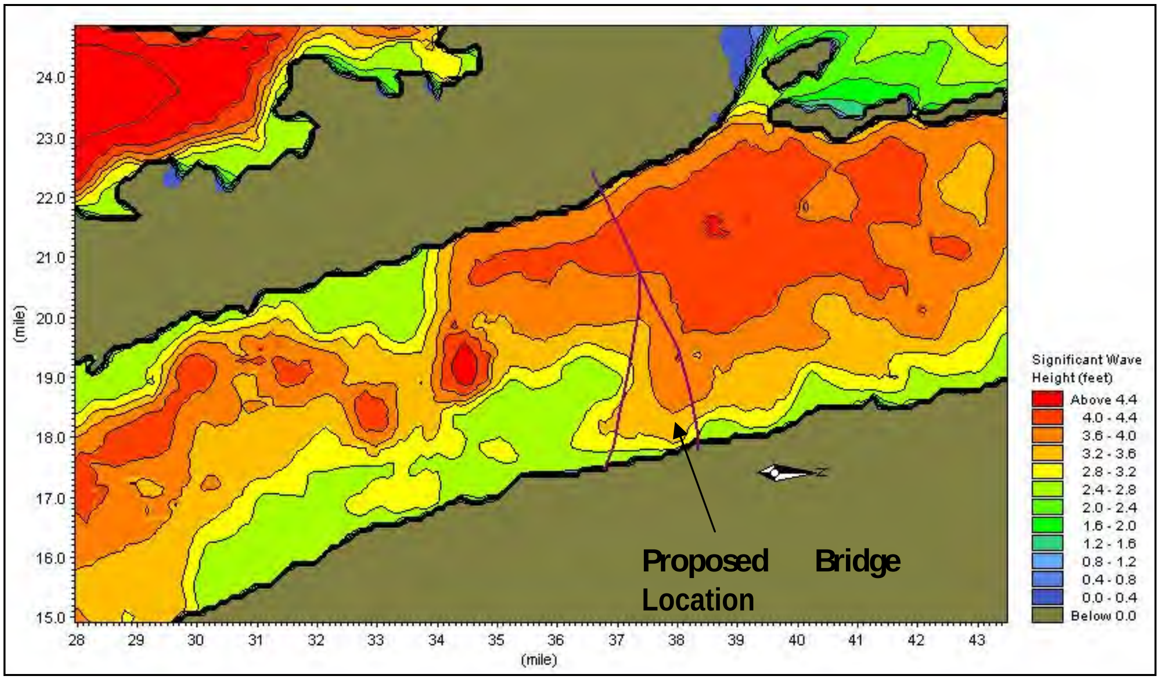

Figure 5.11: Maximum Significant Wave Height – Hurricane Scenario #7

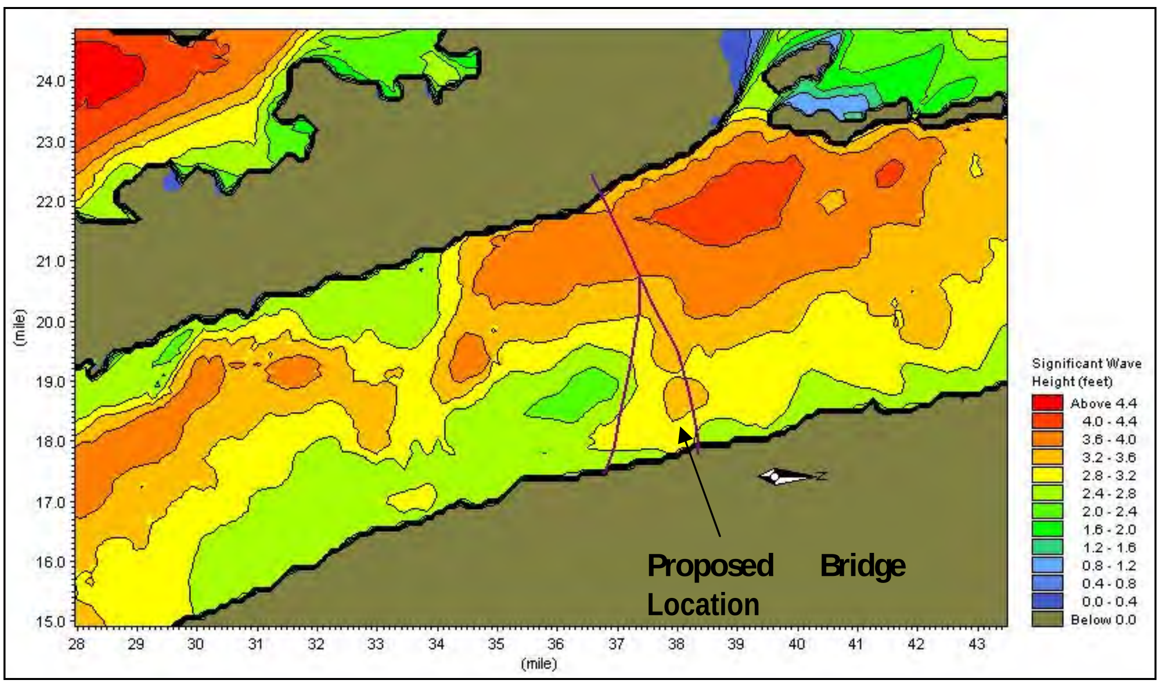

Figure 5.12: Maximum Significant Wave Height – Hurricane Scenario #8

To analyze in detail the maximum significant wave height at the bridge location, the results were extracted from each model run along the length of the bridge. Figure 5.13 shows the maximum significant wave height along the location of the proposed bridge. Figure 5.14 provides the maximum wave peak period along the location of the proposed bridge for each model run as well. The starting point is on the west side of the sound.

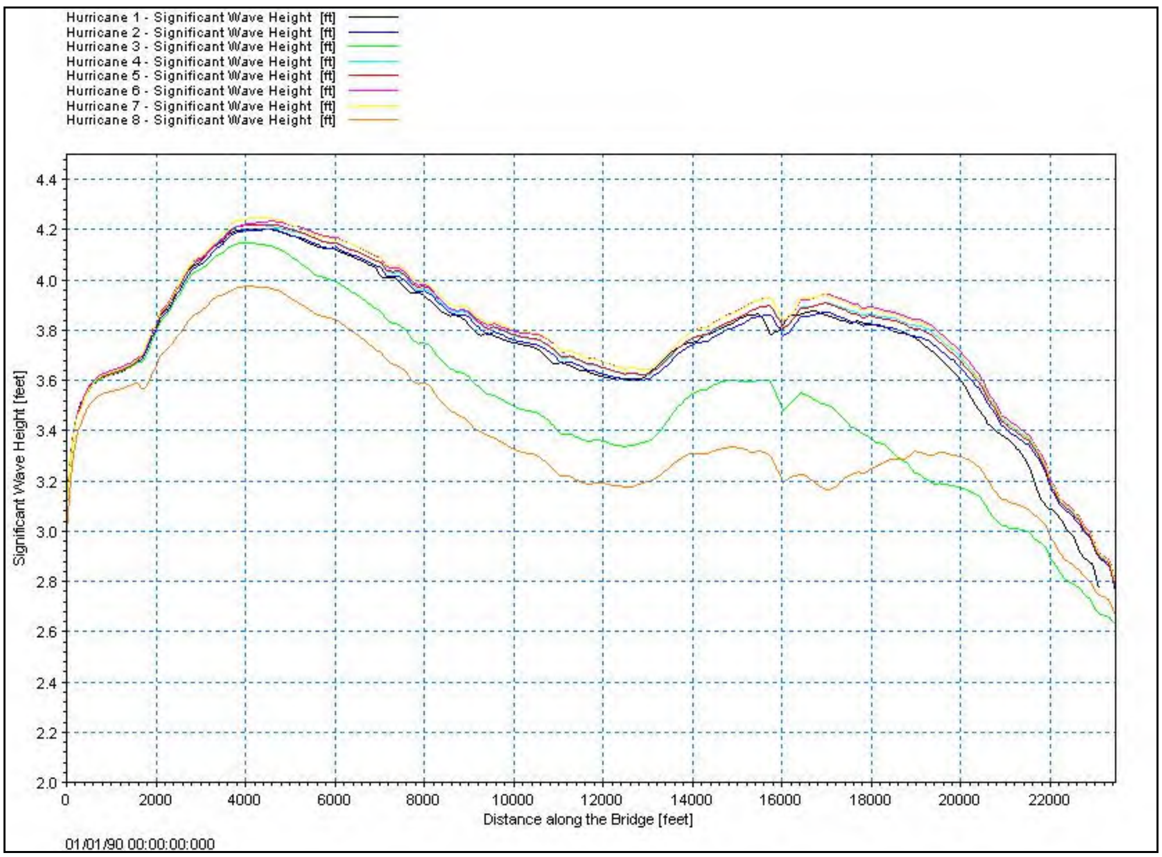

Figure 5.13: Maximum Significant Wave Height along the Proposed Bridge Location

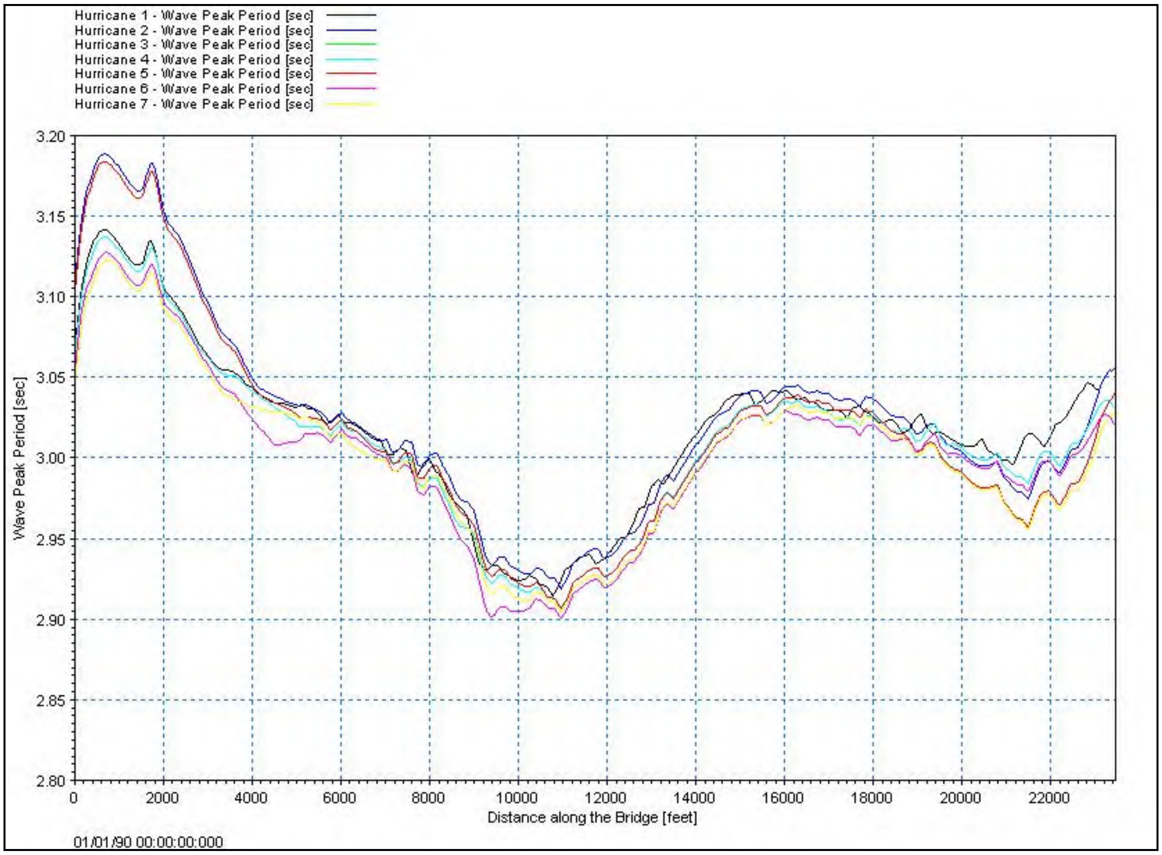

Figure 5.14: Maximum Wave Peak Period along the Proposed Bridge Location

Using the Coastal Engineering Manual (USACE CEM) relation developed by Abramowitz and Stegun (1965), in which the maximum wave height is 1.86 times the significant wave height, the maximum probable wave height along the proposed bridge location was calculated. Figure 5.15 shows the maximum wave height along the location of the proposed bridge.

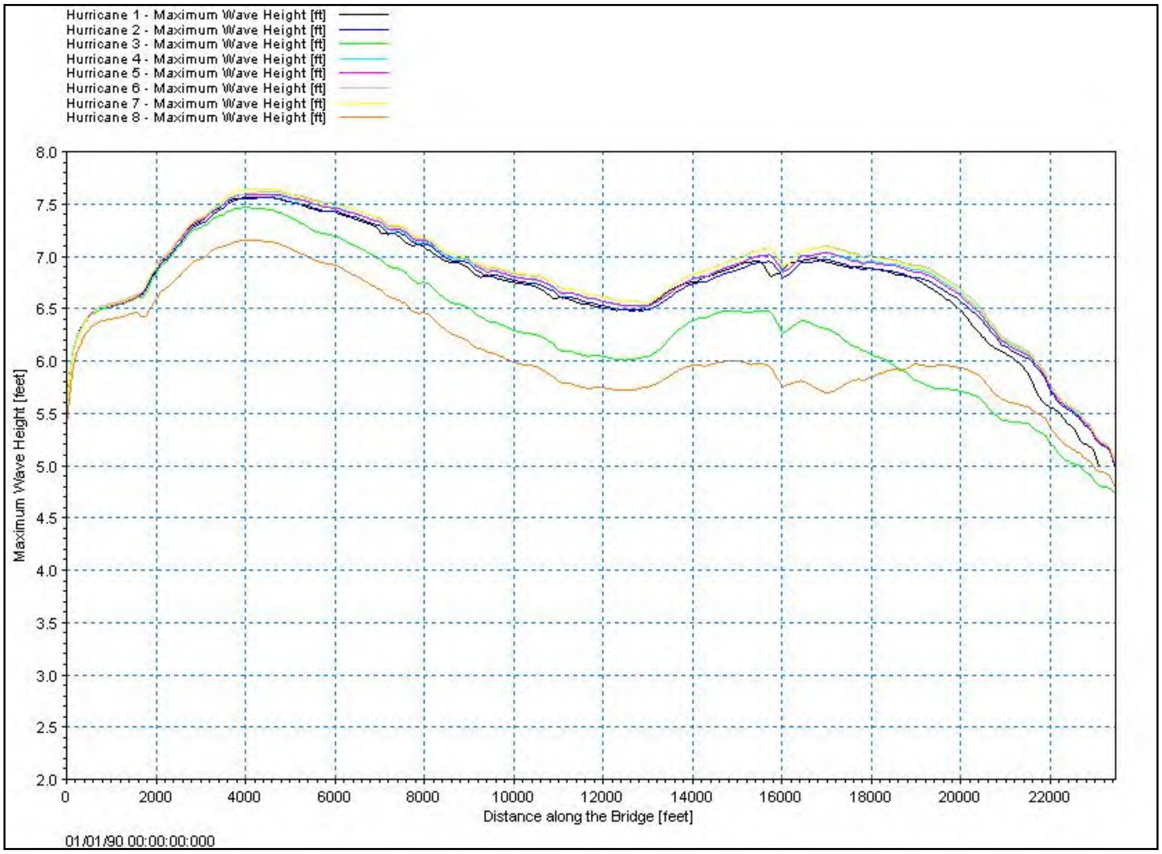

Figure 5.15: Maximum Wave Height along the Proposed Bridge Location

The wave crest above the still water level for the maximum wave height is approximately 70% of the total maximum wave height. Hence, the maximum wave height was multiplied by 0.7 to obtain the maximum wave crest elevation above still water level. This value was added to the conservative maximum storm surge elevation (+7 feet NAVD) to obtain the maximum wave crest elevation. Figure 5.16 shows the maximum wave crest elevations along the location of the proposed bridge.

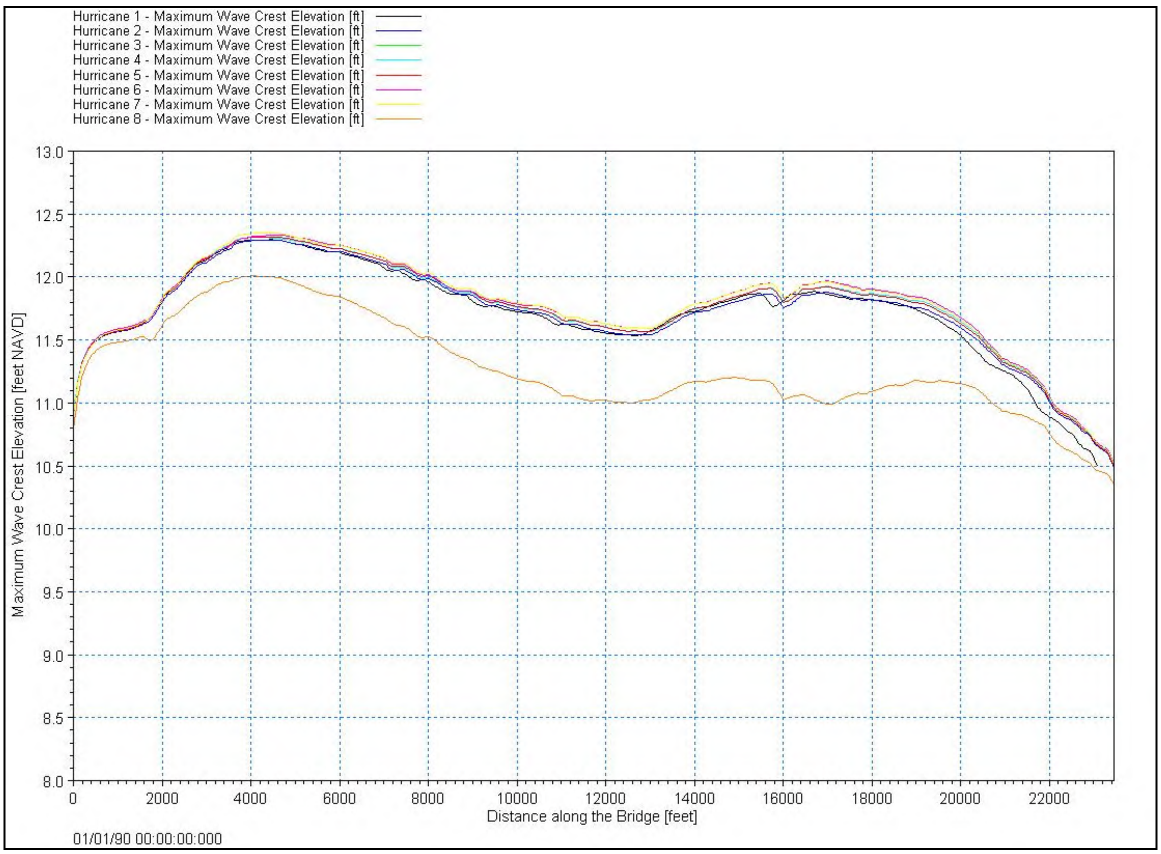

Figure 5.16: Maximum Wave Crest Elevation along the Proposed Bridge Location

6 Conclusion and Recommendations

The recommended low chord elevation is based on AASHTO's recently published "Guide Specifications for Bridges Vulnerable to Coastal Storms." These specifications state that "Wherever practical, the vertical clearance of highway bridges should be sufficient to provide at least 1 ft of clearance over the 100-year design wave crest elevation, which includes the design storm water elevation."

Analysis of the FEMA FIS for Currituck County determined that the maximum wave crest elevation along the bridge alignment is approximately 12.4 feet-NAVD. These waves though, are due to ocean generated storm surge and wave activity potentially overtopping the barrier island, with waves being regenerated due to easterly winds blowing across Currituck Sound. Thus, additional numerical modeling was performed to determine potential wave activity within Currituck Sound due to hurricanes traversing across the NC sound system inland of the barrier islands. Using a conservative constant storm surge within Currituck Sound, this analysis, coincidentally, also calculated a maximum wave crest elevation of approximately 12.4 feet-NAVD.

The high end estimate of sea-level rise during the life of the proposed bridge is about 19 inches (1.6 feet). Additionally, and additional allowance for the land subsidence of northeast North Carolina should be accounted for. While there are some suggestions that additional accelerations in sea-level rise may occur, basing the low-chord elevation on the estimated sea-level at the end of the bridge's projected life span (in addition to the 1 foot clearance) should provide any additional necessary conservatism to account for potential acceleration.

Thus, the recommended low-chord elevation for the proposed Mid-Currituck Bridge is +16 feet-NAVD. This is based on a maximum modeled wave crest elevation of +12.4 feet-NAVD; plus 1.6 feet of projected sea-level rise during the lifespan of the bridge; plus 1.0 feet of clearance as recommended by the AASHTO specifications; plus another 1.0 feet to account for uncertainties of regional land subsidence, additional contributions from polar ice melt, and potential increased storminess.

It must be noted, though, that the State of North Carolina is currently undertaking a very extensive storm surge numerical modeling program to update the published FEMA values. However, numerous delays have been incurred and the latest estimation is that preliminary results may be available near the end of 2009. **If these results do become available prior to final design of the bridge, they should be reviewed and the recommended low-chord elevation updated if necessary.**

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