NORTH CAROLINA
Cooperating Technical State
FEMA'S COOPERATING TECHNICAL PARTNER

Storm Surge Study Methodology

The State of North Carolina, through the Federal Emergency Management Agency's (FEMA's) Cooperating Technical Partnership initiative, has assumed primary ownership and responsibility for the **Flood Insurance Rate Maps (FIRMs)** for all North Carolina communities as part of the **National Flood Insurance Program (NFIP).** As part of this effort, the State of North Carolina funded a storm surge study which is to update the **stillwater elevations (SWELs)** for all coastal counties. The study, coordinated by the North Carolina Flood Mapping Program (NCFMP), has been conducted in partnership with public and private agencies and consultants such as the Renaissance Computing Institute (RENCI),the University of North Carolina Institute of Marine Science (UNC IMS), the U.S. Army Corps of Engineers (USACE), Applied Research Associates Inc. (ARA) and Dewberry, leaders in floodplain mapping.

The purpose of this fact sheet is to provide information on the **methodology** utilized to perform the North Carolina storm surge study and how its products contribute to determining the flood elevations that will be shown on the Digital Flood Insurance Rate Maps (DFIRMs) for coastal areas.

Why is a storm surge study needed?

Current effective stillwater elevations along the North Carolina coastline, were determined by a FEMA study from 1981. The State of North Carolina recognizes the need to update the stillwater elevations as part of a new state-wide storm surge study that is employing state-of-the-art models capable of providing better resolution of the hydrodynamic processes. In addition, new methodologies have been established by FEMA for studies in coastal areas, in response to Hurricane Katrina. New base data such as topographic and bathymetric data are now available, allowing for a more accurate estimate of flooding risks. The study results will ultimately determine more accurate SWELs and more precise flood risk areas shown on DFIRMs.

What is a storm surge study?

In coastal areas, the primary contributor to flood elevations is the phenomenon known as storm surge. **Storm surge** is defined as an increased water surface elevation due to a low-barometric system. **Tropical** (hurricanes) and **extratropical cyclones** (decayed hurricanes and nor'easters) are usually the systems responsible for this increase in water elevation. Surge flooding coastal areas allows for **waves** to propagate much further inland than normal, contributing to the increase in flooding elevation. Furthermore, an increase of flooding depth will occur if a cyclone occurs at high **tide**. A storm surge study combines the modeling of the physical properties of winds, surge and waves, and their mutual interaction. A **frequency analysis** of the results is conducted at the end of the study to obtain updated return periods for the 10%, 2%, 1% and 0.2% annual chance stillwater elevations for all coastal areas.

How is a storm surge study performed?

In order to perform a storm surge study, a suite of different models is needed to simulate the hydrodynamics and the climatology of the area. The central modeling component of the North Carolina storm study is the **ADvanced CIRCulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC)** (Luettich et al, 1992, Westerink et al, 2008) currently the best-known storm surge model for computation of flood levels for FEMA NFIP studies. It was chosen by the NCFMP for this storm surge study for its computational efficiency, ability to model inundation and its capability to resolved complex coastal morphology.

<u>Modeling Setup</u>
The NCFMP storm surge study uses a suite of state-of-the-art numerical wind, wave, and surge models to compute stillwater elevations along the North Carolina coast. The model suite consists of: the Hurricane Boundary Layer (HBL) (Vickery et al. 2008a, 2008b) wind model for tropical storms; the Planetary Boundary Layer (PBL) model for extratropical storms; the offshore wave model WaveWatch3 (WW3) (Tolman et al. 1996;

Tolmand 2002); the 2-Dimension Simulating Waves Nearshore model (SWAN) (Booij et. al., 1999, Rogers et. al. 2002, Zijlema and van der Westhuysen, 2005) and the ADCIRC storm surge and tidal model. This modeling approach is very similar to recent FEMA-sponsored projects in Louisiana and Mississippi. The surge model and the wave model are coupled (results at each time step are exchanged between the two models) in order to obtain water elevations inclusive of wave effects.

Study Area Climatology

Approximately 130 **hurricanes** crossed North Carolina during the years 1853-2005. The tropical storm data utilized for the study are selected from 1940 to present. Historic storm data earlier then 1940 is known to be subject to inaccuracies and, therefore, not accounted for in the study. Storms are selected upon evaluation of track location, intensity, maximum wind speed and flooding history. In addition to tropical storms, the North Carolina coastal region experiences flooding and inundation from **extratropical** (Nor'easters) systems. Both types of cyclones have been accounted and modeled as part of this study.

Figure 1. North Carolina DEM

Digital Elevation Model

Several topographic and bathymetric datasets are combined together to generate a Digital Elevation Model (DEM). Once developed, the DEM is interpolated to the surge model in order to provide it with the correct elevations of the study area. Among the dataset utilized, the primary source is the statewide 2000-2001 LiDAR (http://www.ncfloodmaps.com/lidar.htm). For the nearshore areas the USACE has extensive combined bathymetric/topographic data from annual surveys conducted in 2004, including a Scanning Hydrographic Operational Airborne LiDAR Survey SHOALS data set along the barrier islands. Bathymetric databases include the Coastal Relief Model, the Cape Hatteras and Myrtle Beach tsunami DEMs, and the NOAA Sea Level Rise DEM. The final DEM for North Carolina is shown in Figure 1.

ADCIRC Storm Model Mesh

ADCIRC utilizes, as a base for the water level computation, a triangular mesh. Each mesh node represents the ground elevation obtained by interpolation from the DEM. Water level solutions are provided, by the model, at each node of the mesh. The North Carolina mesh has approximately 500,000 nodes (Figure 2). In addition to land surface elevation, roughness lengths (described in term of land use), canopy (vegetation) coverage and frictional characteristics, are specified at each of the mesh nodes. Also at the nodes, wind stress and atmospheric pressure are input from the wind model HBL, as well as the wave component from SWAN in the coupled part of each simulation. Application of ADCIRC in the North Carolina coastal study is consistent with other recent FEMA-sponsored projects in the Gulf of Mexico. The model domain covers the North Atlantic region west of 60 degrees West. The mesh extends inland to the 15-meter topographic elevation line. The minimum mesh resolution is approximately 50 meter, with the nearshore resolution typically about 100 meter and grades out to resolution on the outer continental shelf of 2-10 kilometer.

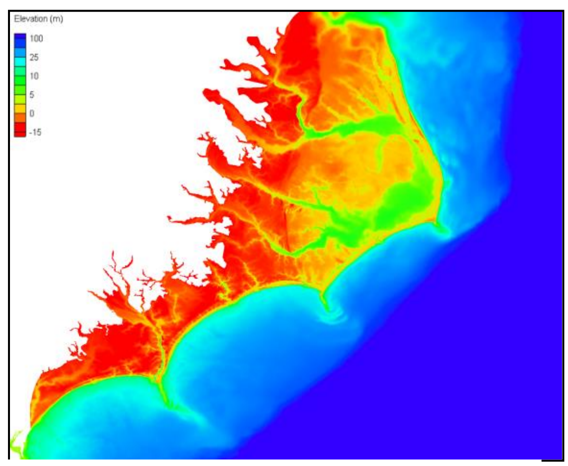

Figure 2. North Carolina ADCIRC mesh

2D Wave Modeling

Two wave models are used in the model suite. WW3, an offshore wave model, simulates the wave fields produced by the evolution of the storm prior to entering the coastal region. These offshore waves provide the necessary boundary forcing for the higher-resolution nearshore wave model SWAN. The 2-D wave model SWAN is configured using a nested approach, with outer grids (5 km resolution) providing boundary conditions to inner grids (200 m resolution) (Figure 3). Waves breaking in shallow water adds to the mean currents that push water towards the coast originating an increase in water surface elevation. SWAN is forced along the outer boundaries by the WW3 wave spectra. Wind fields for both wave model are provided by the HBL model.

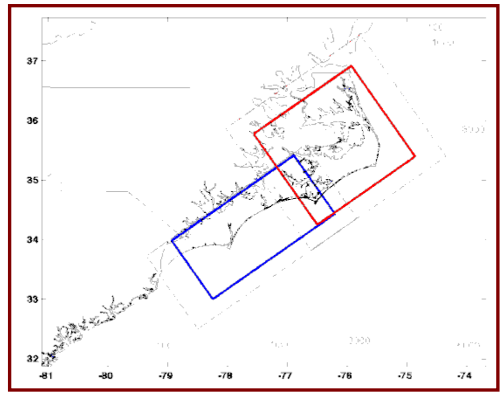

Figure 3. SWAN nested grids

Modeled Storm Set

The determination of the suite of storms to be modeled for the North Carolina storm surge study differs by the type of storm. For **hurricanes**, the modeled storm set is created through the investigation of the tropical cyclones meteorological parameters (such as central pressure, radius of maximum winds, translation speed, Holland-B, and heading). This approach defined as **Joint Probability Method (JPM)** is a simulation methodology that relies on the development of statistical distributions of key hurricane parameters and sampling from these distributions. The simulation results in a group of modeled storms that preserves the relationships with the historical storms but provides a means to model the effects and probabilities of storms that have not yet occurred. For this study, a weighted JPM is used, which reduces the number of required simulated storms. **Synthetic storm tracks** are then generated (675 for this study) using all the parameter combinations. A weight is associated with each discrete value chosen for each storm parameter.
For extratropical storms, historical weather annuals and National Oceanic Service (NOS) water levels were investigated: 20 extratropical storms were selected to be modeled as part of this study.

Tidal Calibration and Model Validation

A tidal calibration is performed to ensure the mesh properly simulates the tides for the region. The calibration is verified by comparing the modeled tides with tidal water levels provided by the NOS and a harmonic analysis of the tidal constituents. Once the tidal calibration is completed, Hindcast storms are run for both wave and surge models to verify that the simulated results reasonably match observed wave and surge elevations determined during the passage of historical storms. Four tropical storms (Emily, Fran, Isabel, and Ophelia) and two extratropical storm (extratropical storm Ernesto and the nor'easter of November 2006) are used for the verification simulations (Figure 4). The validation is performed by comparing modeled water levels to High Water Marks (HWMs) collected in the aftermath of those storms, where available, and by comparison with observed water levels at NOS gauges.

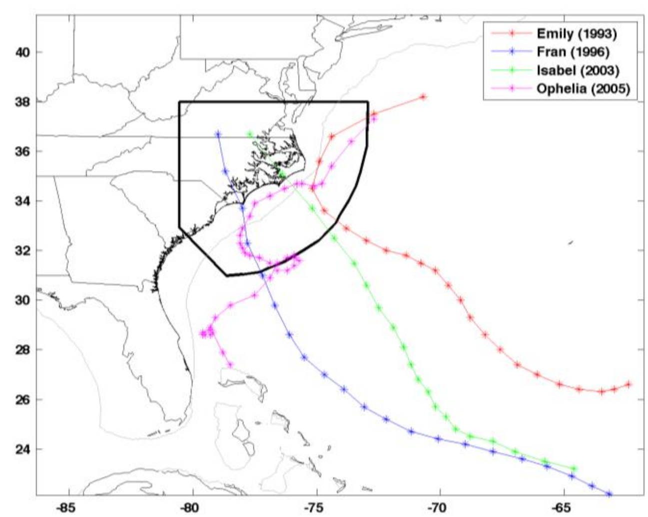

Figure 4. Historical storms used for Hindcast

Production Runs

Approximately 700 probabilistic storms will be run with the same model system on a super computer provided by the Renaissance Computing Center (RENCI). For each probabilistic storm, the model system is executed and the model results are archived for further processing and analysis (return period analysis).

Frequency analysis
The results of the computational/model system developed above provide water surface elevations that will be statistically analyzed to produce probability curves for determination of the SWELs. Two different statistical methods will be implemented to perform the frequency analysis, due to the different meteorological nature of the two types of cyclones. The **Joint Probability Method (JPM)** will be applied to obtain the return periods associated with the tropical storm events. Extratropical storms will be statistically analyzed with the **Empirical Simulation Technique (EST)**. The results of the two frequency analysis will be combined to obtain final return periods.

What are the products of a storm surge study?

The result of the modeling is a water surface elevation measured above ground and provided at each node of the North Carolina mesh. For the purpose of computing base flood elevations, two sets of runs are performed within this study. One set of water surface elevations will represent surge only, the other will include wave effect as well. There are, therefore, two sets of model results for each of the approximate 700 storms run.
In addition to the computation of water surface levels, wave height and wave periods for the 1% annual chance event will be extracted from the 2-D wave modeling.

How are the results of the study converted in Stillwater Elevations?

Once the modeling is completed, a frequency analysis will be performed and return period for the 10%, 2%, 1% and 0.2% annual chance stillwater elevations will be computed. One set of return period is computed for surge only water levels, and one for surge+wave water levels. The above data is available for the entire coastal region.

How are the products of this study implemented as part of the Digital Flood Insurance Rate Maps?

The 1% annual chance stillwater elevation will be employed to perform coastal hazard analyses at specific transect locations. At these locations, the stillwater elevations will be used as input to coastal models. Erosion analysis will be performed where appropriate; overland wave heights will be computed using the Wave Height Analysis for Flood Insurance Studies (WHAFIS) model and wave runup will calculated on dunes and bluffs. Resulting flood zone boundaries and base flood elevations will be mapped to produce updated DFIRMs for all coastal counties.

Additional information about the implementation of the North Carolina storm surge study results, and their use for overland analysis and mapping, can be found at (http://www.ncfloodmaps.com/). This and other fact sheets are part of the NCFMP outreach program attempts to explain the process and results of the current coastal restudy.

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