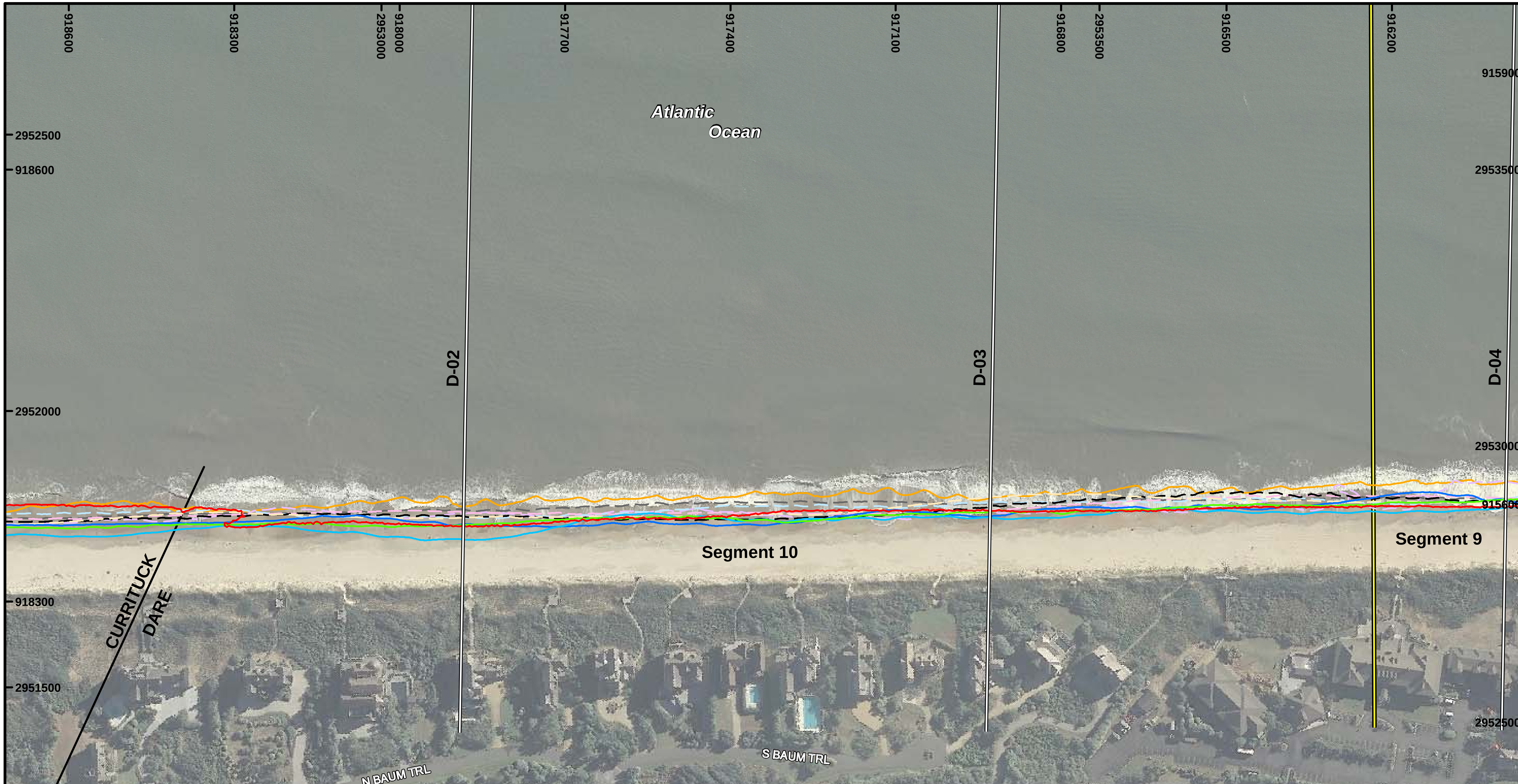
Appendix A – LIDAR Shorelines



G:\Enterprise\Dare\150440_DUCK Design and Permitting_Mxd\Duck_Historical_Shoreline_Series_sh1.mxd

Notes:

1. Coordinates are in feet based on the North Carolina State Plane Cooridinate System, North American Datum of 1983 (NAD83).
2. 2012 Post Hurricane Sandy aerial photography collected by NCDOT and provided by the Town of Duck, NC.

Legend:

Historical Shoreline

- USGS/Woolpert Post Sandy LiDAR
- 2011 Shoreline CLARIS
- 2010 Shoreline JALBTCX
- 2008 Shoreline
- 2005 Shoreline
- 2004 Shoreline
- 1999 Shoreline Post Floyd
- 1999 Shoreline Post Dennis
- 1999 Shoreline Late Fall
- 1998 Shoreline
- 1997 Shoreline ATM LiDAR
- 1996 Shoreline ATM LiDAR
- Town Limits
- Segment Boundary
- Transects

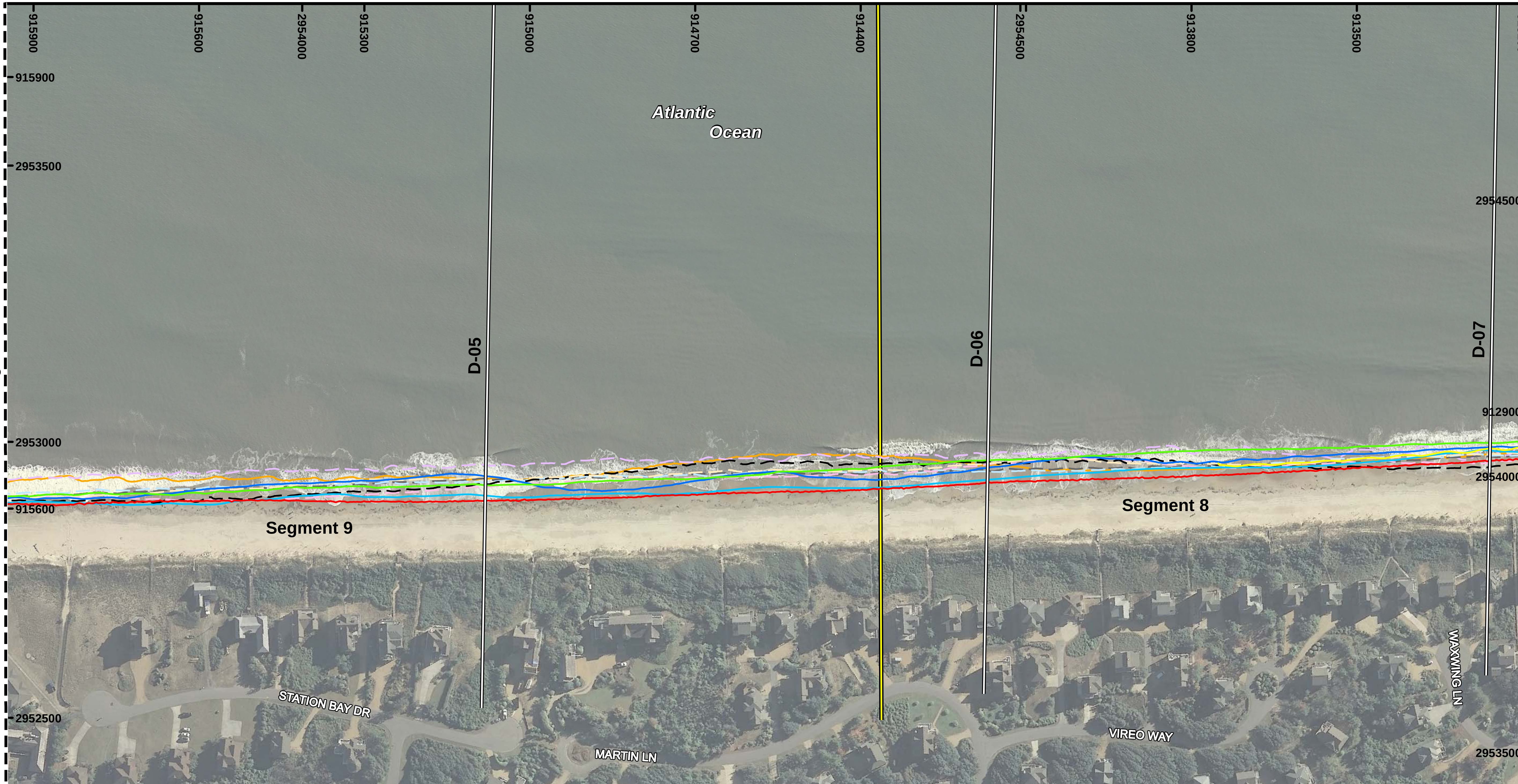
0 100 200 Feet

TITLE:

Historical Shorelines Town of Duck Duck, NC

COASTAL PLANNING & ENGINEERING OF NORTH CAROLINA, INC.
4038 MASONBORO LOOP ROAD
WILMINGTON, NC 28409
PH. (910) 791-9494
FAX (910) 791-4129

Date: 05/18/15	By: HMV	Comm No.150440	Figure No. 01



G:\Enterprise\Dare\150440_DUCK Design and Permitting_Mxd\Duck_Historical_Shoreline_Series_sh2.mxd

Notes:

1. Coordinates are in feet based on the North Carolina State Plane Cooridinate System, North American Datum of 1983 (NAD83).
2. 2012 Post Hurricane Sandy aerial photography collected by NCDOT and provided by the Town of Duck, NC.

Legend:

Historical Shoreline

- USGS/Woolpert Post Sandy LiDAR
- 2011 Shoreline CLARIS
- 2010 Shoreline JALBTCX
- 2008 Shoreline
- 2005 Shoreline
- 2004 Shoreline
- 1999 Shoreline Post Floyd
- 1999 Shoreline Post Dennis
- 1999 Shoreline Late Fall
- 1998 Shoreline
- 1997 Shoreline ATM LiDAR
- 1996 Shoreline ATM LiDAR
- Segment Boundary
- Transects

0 100 200 Feet

TITLE:

Historical Shorelines Town of Duck Duck, NC

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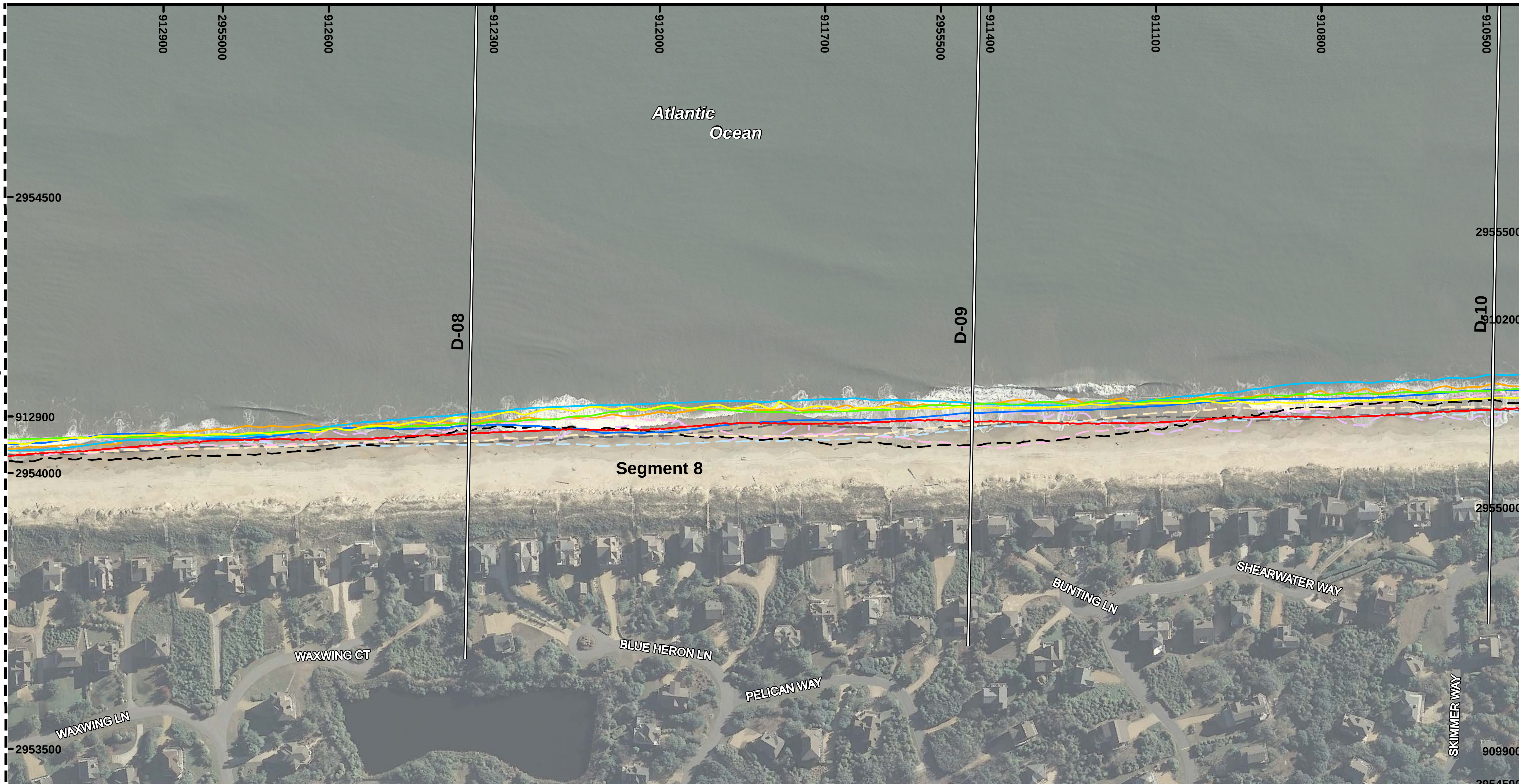
Date: 05/18/15	By: HMV	Comm No.150440	Figure No. 02

G:\Enterprise\Dare\150440_DUCK Design and Permitting_Mxd\Duck_Historical_Shoreline_Series_sh3.mxd



Notes:

1. Coordinates are in feet based on the North Carolina State Plane Cooridinate System, North American Datum of 1983 (NAD83).
2. 2012 Post Hurricane Sandy aerial photography collected by NCDOT and provided by the Town of Duck, NC.

Legend:

Historical Shoreline

- USGS/Woolpert Post Sandy LiDAR
- 2011 Shoreline CLARIS
- 2010 Shoreline JALBTCX
- 2008 Shoreline
- 2005 Shoreline
- 2004 Shoreline
- 1999 Shoreline Post Floyd
- 1999 Shoreline Post Dennis
- 1999 Shoreline Late Fall
- 1998 Shoreline
- 1997 Shoreline ATM LiDAR
- 1996 Shoreline ATM LiDAR
- Transects

N

0 100 200 Feet

TITLE:

Historical Shorelines Town of Duck Duck, NC

COASTAL PLANNING & ENGINEERING OF NORTH CAROLINA, INC.
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PH. (910) 791-9494
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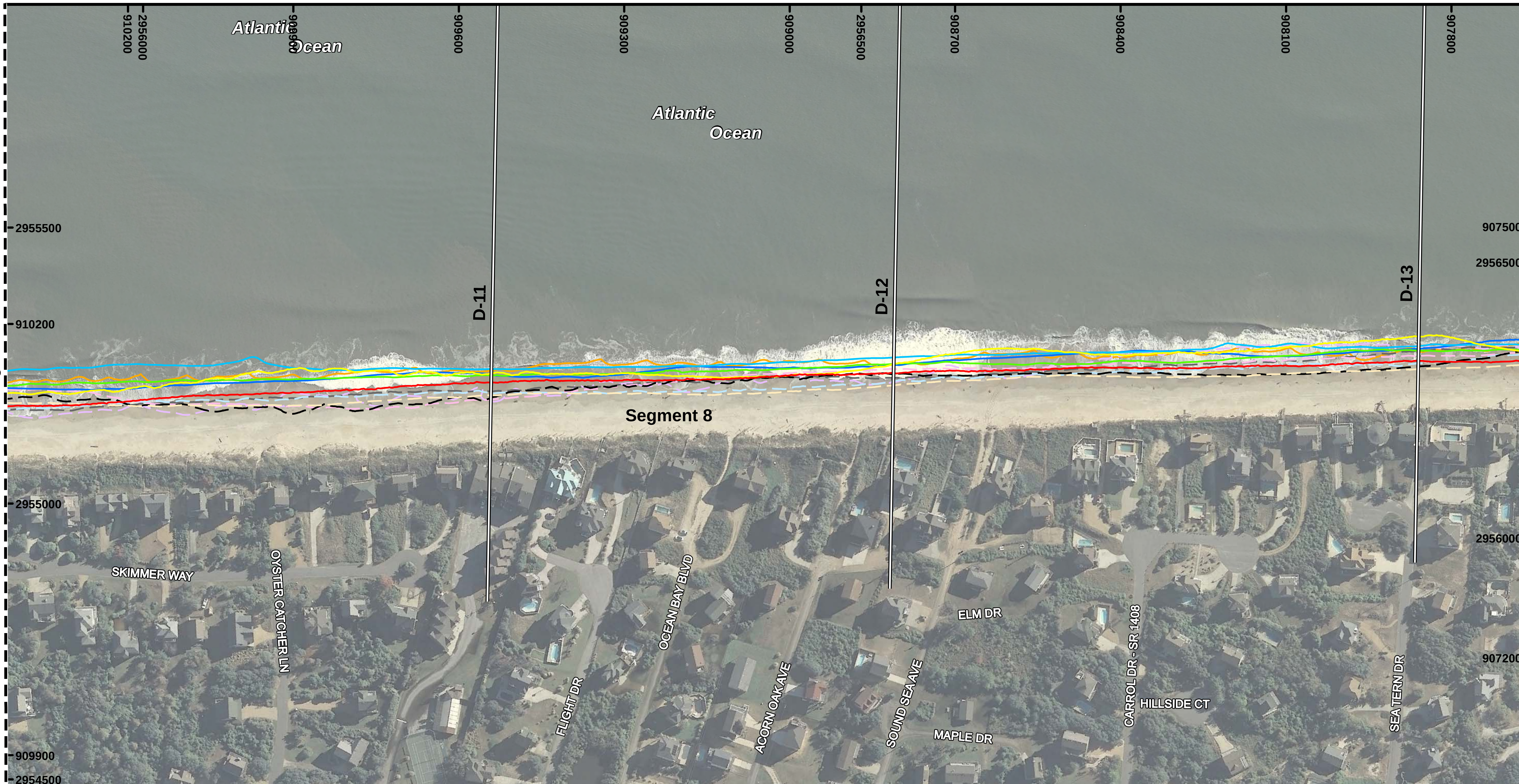
Date: 05/18/15	By: HMV	Comm No.150440	Figure No. 03



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Notes:

1. Coordinates are in feet based on the North Carolina State Plane Cooridinate System, North American Datum of 1983 (NAD83).
2. 2012 Post Hurricane Sandy aerial photography collected by NCDOT and provided by the Town of Duck, NC.

Legend:

Historical Shoreline

- USGS/Woolpert Post Sandy LiDAR
- 2011 Shoreline CLARIS
- 2010 Shoreline JALBTCX
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- 2005 Shoreline
- 2004 Shoreline
- 1999 Shoreline Post Floyd
- 1999 Shoreline Post Dennis
- 1999 Shoreline Late Fall
- 1998 Shoreline
- 1997 Shoreline ATM LiDAR
- 1996 Shoreline ATM LiDAR
- Transects

0 100 200 Feet

TITLE:

Historical Shorelines Town of Duck Duck, NC

COASTAL PLANNING & ENGINEERING OF NORTH CAROLINA, INC.
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Date: 05/18/15	By: HMV	Comm No.150440	Figure No. 04

G:\Enterprise\Dare\150440_DUCK Design and Permitting_Mxd\Duck_Historical_Shoreline_Series_sh5.mxd

Notes:

1. Coordinates are in feet based on the North Carolina State Plane Cooridinate System, North American Datum of 1983 (NAD83).
2. 2012 Post Hurricane Sandy aerial photography collected by NCDOT and provided by the Town of Duck, NC.

Legend:

Historical Shoreline

- USGS/Woolpert Post Sandy LiDAR
- 2011 Shoreline CLARIS
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- 2005 Shoreline
- 2004 Shoreline
- 1999 Shoreline Post Floyd
- 1999 Shoreline Post Dennis
- 1999 Shoreline Late Fall
- 1998 Shoreline
- 1997 Shoreline ATM LiDAR
- 1996 Shoreline ATM LiDAR
- Segment Boundary
- Transects

0 100 200 Feet

TITLE:

Historical Shorelines Town of Duck Duck, NC

COASTAL PLANNING & ENGINEERING OF NORTH CAROLINA, INC.
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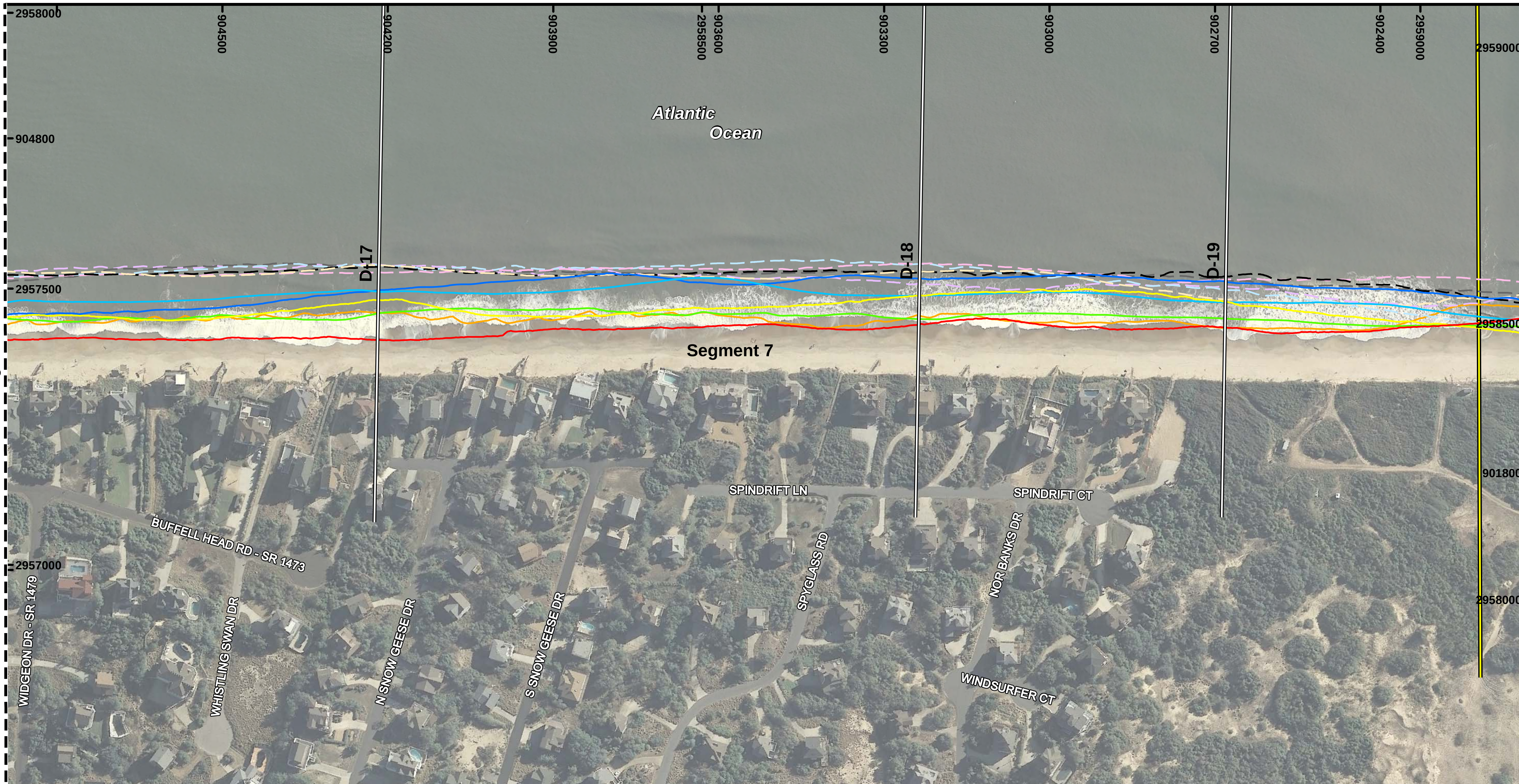
Date: 05/18/15	By: HMV	Comm No.150440	Figure No. 05



G:\Enterprise\Dare\150440 DUCK Design and Permitting\ Mxd\Duck Historical Shoreline Series sh6.mxd

Notes:

1. Coordinates are in feet based on the North Carolina State Plane Cooridinate System, North American Datum of 1983 (NAD83).
2. 2012 Post Hurricane Sandy aerial photography collected by NCDOT and provided by the Town of Duck, NC.

Legend:

Historical Shoreline

- USGS/Woolpert Post Sandy LiDAR
- 2011 Shoreline CLARIS
- 2010 Shoreline JALBTCX
- 2008 Shoreline
- 2005 Shoreline
- 2004 Shoreline
- 1999 Shoreline Post Floyd
- 1999 Shoreline Post Dennis
- 1999 Shoreline Late Fall
- 1998 Shoreline
- 1997 Shoreline ATM LiDAR
- 1996 Shoreline ATM LiDAR
- Segment Boundary
- Transects

0 100 200 Feet

TITLE:

Historical Shorelines Town of Duck Duck, NC

COASTAL PLANNING & ENGINEERING OF NORTH CAROLINA, INC.
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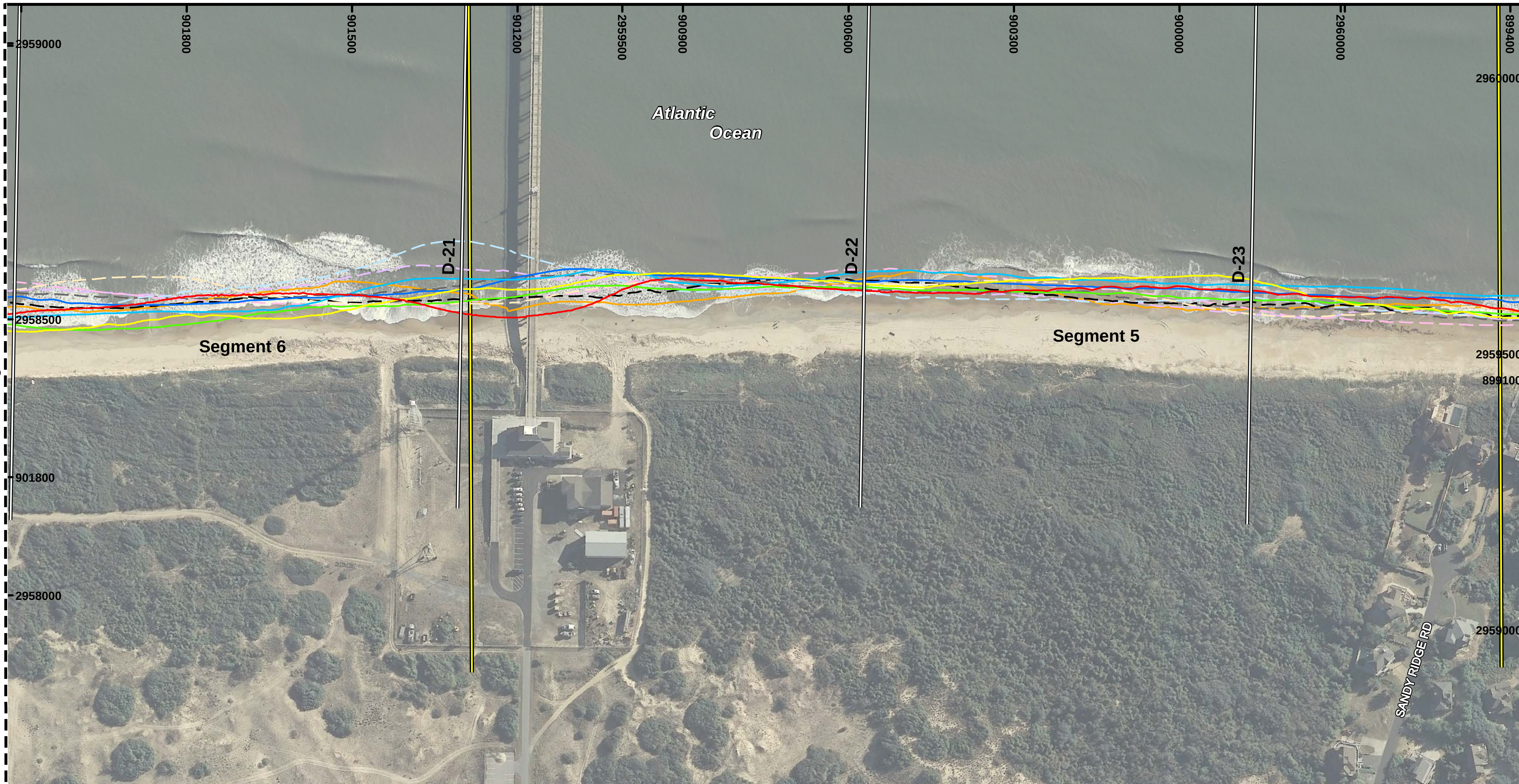
Date: 05/18/15	By: HMV	Comm No.150440	Figure No. 06



G:\Enterprise\Dare\150440_DUCK Design and Permitting_Mxd\Duck_Historical_Shoreline_Series_sh7.mxd

Notes:

1. Coordinates are in feet based on the North Carolina State Plane Cooridinate System, North American Datum of 1983 (NAD83).
2. 2012 Post Hurricane Sandy aerial photography collected by NCDOT and provided by the Town of Duck, NC.

Legend:

Historical Shoreline

- USGS/Woolpert Post Sandy LiDAR
- 2011 Shoreline CLARIS
- 2010 Shoreline JALBTCX
- 2008 Shoreline
- 2005 Shoreline
- 2004 Shoreline
- 1999 Shoreline Post Floyd
- 1999 Shoreline Post Dennis
- 1999 Shoreline Late Fall
- 1998 Shoreline
- 1997 Shoreline ATM LiDAR
- 1996 Shoreline ATM LiDAR
- Segment Boundary
- Transects

N

0 100 200 Feet

TITLE:

Historical Shorelines
Town of Duck
Duck, NC

COASTAL PLANNING & ENGINEERING
OF NORTH CAROLINA, INC.
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WILMINGTON, NC 28409
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FAX (910) 791-4129

Date: 05/18/15	By: HMV	Comm No.150440	Figure No. 07

Matchline Figure 7

Matchline Figure 9

Notes:

1. Coordinates are in feet based on the North Carolina State Plane Cooridinate System, North American Datum of 1983 (NAD83).
2. 2012 Post Hurricane Sandy aerial photography collected by NCDOT and provided by the Town of Duck, NC.

Legend:

Historical Shoreline

- USGS/Woolpert Post Sandy LiDAR
- 2011 Shoreline CLARIS
- 2010 Shoreline JALBTCX
- 2008 Shoreline
- 2005 Shoreline
- 2004 Shoreline
- 1999 Shoreline Post Floyd
- 1999 Shoreline Post Dennis
- 1999 Shoreline Late Fall
- 1998 Shoreline
- 1997 Shoreline ATM LiDAR
- 1996 Shoreline ATM LiDAR
- Transects

N

0 100 200
Feet

TITLE:

Historical Shorelines
Town of Duck
Duck, NC

COASTAL PLANNING & ENGINEERING OF NORTH CAROLINA, INC.
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Date: 05/18/15	By: HMV	Comm No.150440	**Figure No. 08**

G:\Enterprise\Dare\150440_DUCK Design and Permitting_Mxd\Duck_Historical_Shoreline_Series_sh8.mxd

Notes:

1. Coordinates are in feet based on the North Carolina State Plane Cooridinate System, North American Datum of 1983 (NAD83).
2. 2012 Post Hurricane Sandy aerial photography collected by NCDOT and provided by the Town of Duck, NC.

Legend:

Historical Shoreline

- USGS/Woolpert Post Sandy LiDAR
- 2011 Shoreline CLARIS
- 2010 Shoreline JALBTCX
- 2008 Shoreline
- 2005 Shoreline
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- Segment Boundary
- Transects

0 100 200 Feet

TITLE:

Historical Shorelines
Town of Duck
Duck, NC

COASTAL PLANNING & ENGINEERING
OF NORTH CAROLINA, INC.
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FAX (910) 791-4129

Date: 05/18/15	By: HMV	Comm No.150440	Figure No. 09

Matchline Figure 9

Matchline Figure 11

G:\Enterprise\Dare\150440 DUCK Design and Permitting\ Mxd\Duck Historical Shoreline Series sh10.mxd

Notes:

1. Coordinates are in feet based on the North Carolina State Plane Cooridinate System, North American Datum of 1983 (NAD83).
2. 2012 Post Hurricane Sandy aerial photography collected by NCDOT and provided by the Town of Duck, NC.

Legend:

Historical Shoreline

- USGS/Woolpert Post Sandy LiDAR
- 2011 Shoreline CLARIS
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- 1996 Shoreline ATM LiDAR
- Segment Boundary
- Transects

0 100 200 Feet

TITLE:

Historical Shorelines
Town of Duck
Duck, NC

COASTAL PLANNING & ENGINEERING
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WILMINGTON, NC 28409
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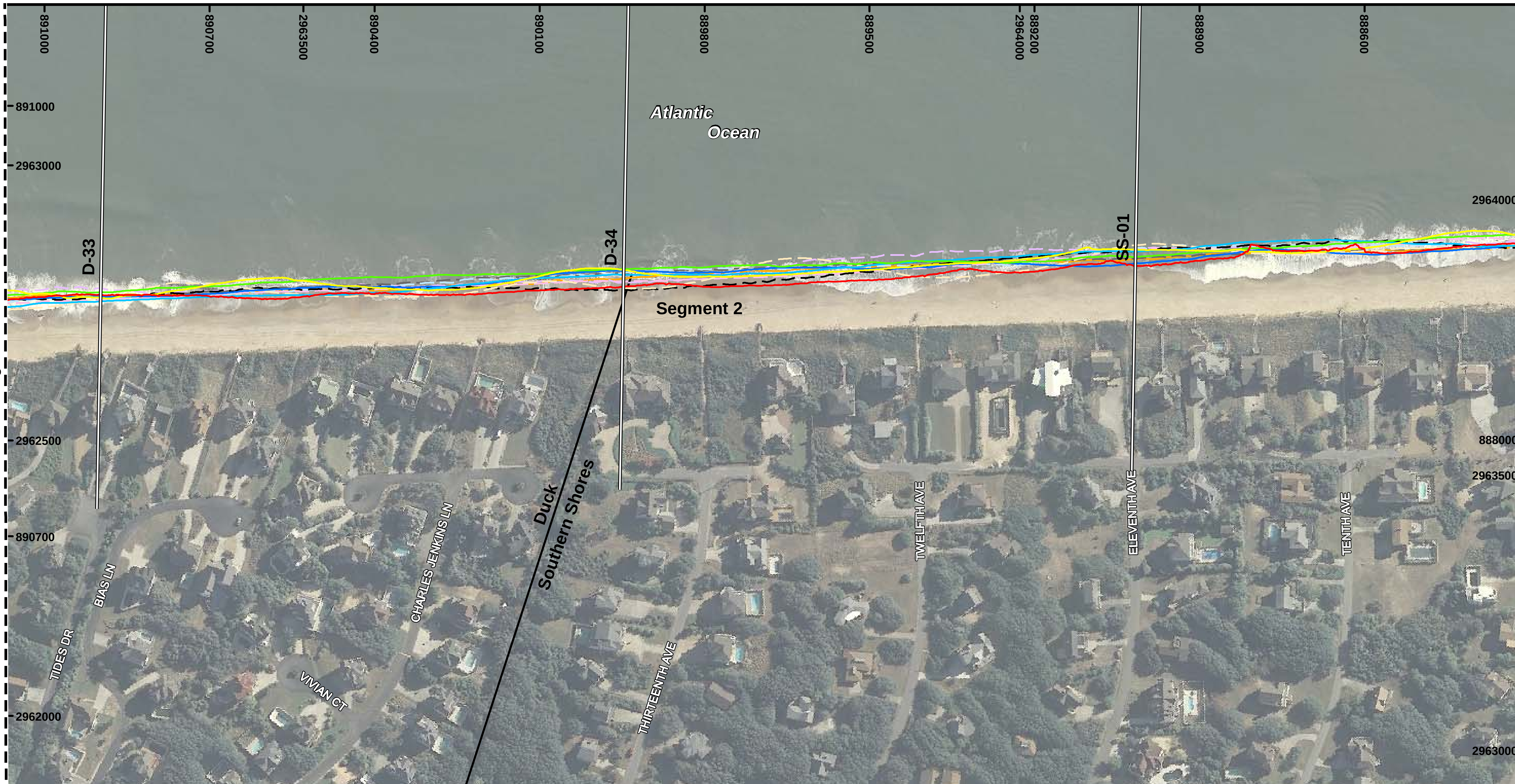
Date: 05/18/15	By: HMV	Comm No.150440	Figure No. 10

G:\Enterprise\Dare\150440 DUCK Design and Permitting\ Mxd\Duck Historical Shoreline Series sh11.mxd



Notes:

1. Coordinates are in feet based on the North Carolina State Plane Cooridinate System, North American Datum of 1983 (NAD83).
2. 2012 Post Hurricane Sandy aerial photography collected by NCDOT and provided by the Town of Duck, NC.

Legend:

Historical Shoreline

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- 2011 Shoreline CLARIS
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- 2004 Shoreline
- 1999 Shoreline Post Floyd
- 1999 Shoreline Post Dennis
- 1999 Shoreline Late Fall
- 1998 Shoreline
- 1997 Shoreline ATM LiDAR
- 1996 Shoreline ATM LiDAR
- Town Limits
- Transects

0 100 200
Feet

TITLE:

Historical Shorelines
Town of Duck
Duck, NC

COASTAL PLANNING & ENGINEERING
OF NORTH CAROLINA, INC.
4038 MASONBORO LOOP ROAD
WILMINGTON, NC 28409
PH. (910) 791-9494
FAX (910) 791-4129

Date: 05/18/15	By: HMV	Comm No.150440	**Figure No. 11**

Appendix B – GENESIS Calibration and Verification

COASTAL PLANNING & ENGINEERING OF NORTH CAROLINA, INC.
4038 Masonboro Loop Road, Wilmington, NC 28409
Telephone: (910) 791-9494 Fax: (910) 791-4129

TECHNICAL MEMORANDUM

TO:	Town of Duck Christopher J. Layton, Town Manager P.O. Box 8369 Duck, NC 27949
FROM:	J. Tom Jarrett, P.E.
CC:	Christopher M. Day, P.E., D.CE, CPE-NC Rob Neal, P.E. CPE-NC Andrew Wycklendt, P.E., CPE-NC Ken Willson, CPE-NC
RE:	Town of Duck, North Carolina Permitting and Engineering Support for Beach Nourishment SWAN and GENESIS Wave Transformation and Shoreline Change Model Calibration
DATE:	October 2013

TECHNICAL MEMORANDUM

TOWN OF DUCK, NORTH CAROLINA
PERMITTING AND ENGINEERING SUPPORT FOR BEACH NOURISHMENT
SWAN AND GENESIS WAVE TRANSFORMATION AND SHORELINE CHANGE MODEL CALIBRATION

Introduction

In May 2013, Coastal Planning & Engineering of North Carolina, Inc. (CPE-NC) completed an *Erosion Mitigation & Shoreline Management Feasibility Study* to investigate potential management options for the oceanfront shoreline along the Town of Duck (see Figure 1). The recommended option was a large scale beach fill project.

Since the completion of the Feasibility Study, the Town of Duck has authorized a larger effort to design and permit the recommended plan. Part of that effort includes a numerical modeling study to evaluate project performance. The focus of this document is the setup and calibration of the numerical model.

Methods

General

Long-term performance evaluations for the beach fill project utilize the Generalized Model for Simulating Shoreline Change (GENESIS) (Hanson and Kraus, 1991). This model can incorporate seawalls, groins, breakwaters, and beach fills. Inputs to the model include shoreline locations and a time series of offshore waves. Erosion control structures, beach nourishment operations, and tidal currents can be provided as additional input to the model as needed.

The effects of the offshore bathymetry can be added to the model by providing an optional set of wave refraction coefficients and refracted wave angles. The wave refraction coefficients and refracted wave angles are usually determined using an external wave transformation model such as STWAVE (Smith, 2001), SWAN (Delft University of Technology, 2008), or another industry-standard wave transformation model.

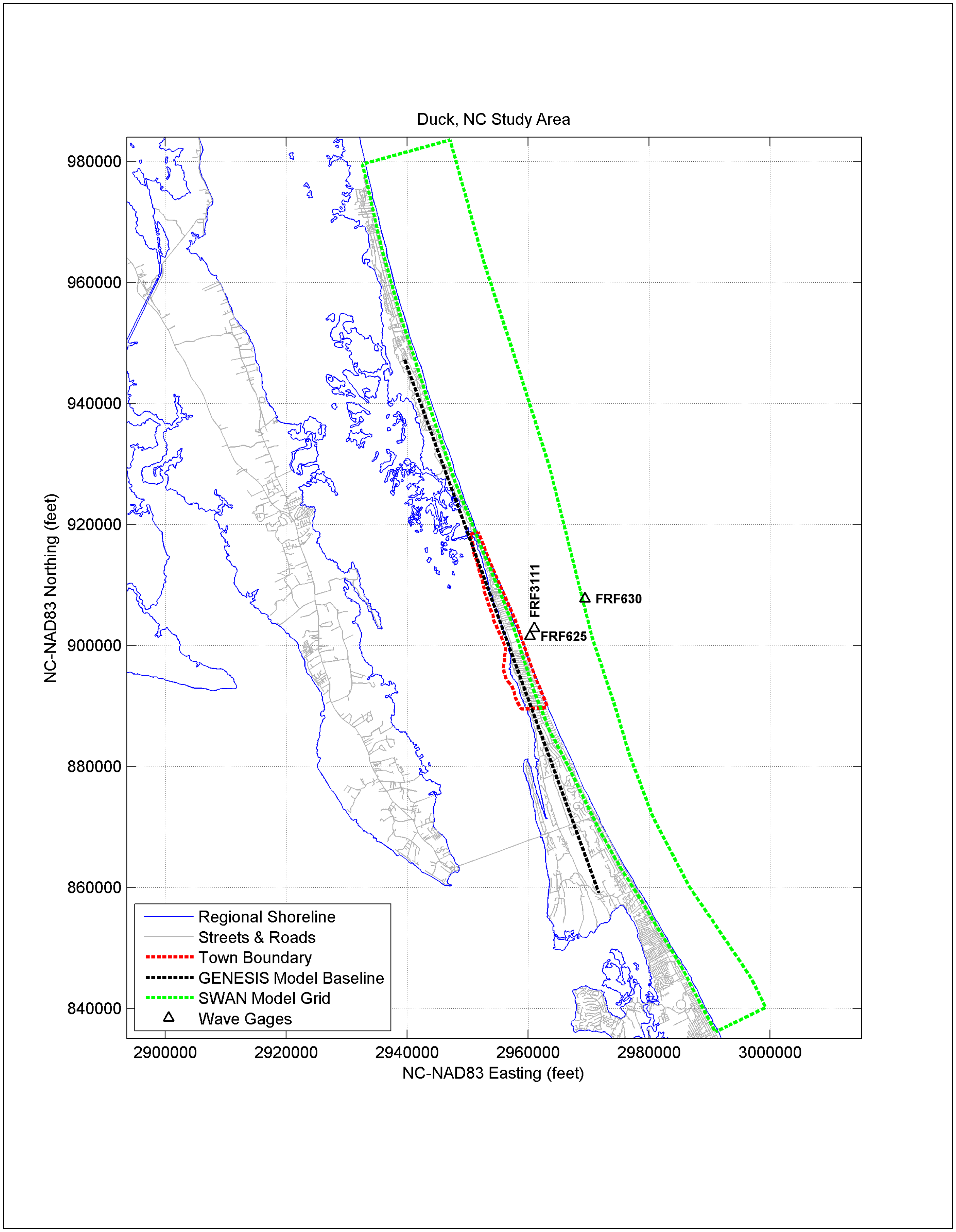

Figure 1: Study Area Location Map.

GENESIS Model

The GENESIS model determines shoreline changes relative to a fixed baseline (see Figure 1) based on the wave-driven, longshore sediment transport. Transport rates are calculated using the USACE (1989) formula (CERC Equation), with an additional term to account for longshore variations in the breaking wave height. To calibrate the model, two longshore transport coefficients are determined. Coefficient K1 governs the overall magnitude of the longshore transport based on the breaking wave height and wave direction while coefficient K2 governs the transport resulting from variations in the breaking wave height (Hanson and Kraus, 1991). GENESIS assumes that shoreline change is directly proportional to volume change, the profile shape is relatively constant with time, the berm elevation is uniform, and the depth of closure is uniform. When an external wave transformation model is utilized, it also assumes that the bathymetry between the offshore zone and the nearshore zone does not change with time.

SWAN Wave Transformation Model

Wave transformation estimates along the study area utilize the Simulating Waves Nearshore Model (SWAN), which accounts for the shoaling, refraction, diffraction, wind growth, whitecapping, and bottom damping of spectral waves (Delft University of Technology, 2008). SWAN has several advantages over other models. It includes most of the key processes that govern the transformation of nearshore and offshore waves, and it can utilize curvilinear grids with non-uniform grid spacing to follow the orientation of shorelines and offshore contours. Inputs to the SWAN model include bathymetric grids, offshore wave conditions, wind velocities, water levels, and the following input parameters:

- Wave height to water depth ratio for depth-limited wave breaking (γ).
- Secondary wave breaking coefficient (α).
- "Triad" coefficients for energy transfer from long waves to short waves in shallow water.
- Bottom friction coefficient.
- Diffraction coefficients, if desired.
- Whitecapping formulation.

In every GENESIS simulation, the forcing of the model is given sequentially. To simulate shoreline changes between two specific dates, a time series of offshore waves between the same two dates must be provided at 1 to 6 hour intervals. However, it is not practical to simulate shoaling, refraction, breaking, and other processes at every time step. Consider an 8 year simulation which utilizes an hourly wave record at an offshore gage. In such a simulation, it would be necessary to run the SWAN model 70,128 times (8 x 365.25 x 24). Computational efforts of these sorts are not possible.

To resolve this problem, the offshore wave record can be divided into a large, but reasonable number of wave cases (50-500) that encompasses the observed variability in wave height, wave period, and wave direction. Shoaling, refraction, breaking, and other processes can then be evaluated for each case using SWAN, STWAVE, or a similar model. The model results for each wave case along the depth of closure can then be utilized in the following manner (Hanson and Kraus, 1991; Bonanata, et al, 2010):

- Calculation of a nearshore propagation coefficient ($H_{nearshore}$ / $H_{offshore}$) and wave angle for each case.

- Interpolation of the propagation coefficient and wave angle for each time step and each grid point at the depth of closure. Specifically, the GENESIS model interpolates with respect to the offshore wave height, offshore wave period, and offshore wave direction at each time step to estimate the propagation coefficient and wave angle at each grid point along the depth of closure (see Figure 2). The wave height at the depth of closure is then equal to the propagation coefficient multiplied by the offshore wave height. The estimated waves along the depth of closure are the waves that determine sediment transport and the corresponding retreat rates in the GENESIS model.

SWAN Model Calibration

Model Forcing Data

Calibration of the SWAN model was based on wave, wind, and water level measurements collected by the U.S. Army Corps of Engineers Field Research Facility (FRF) during Hurricane Irene, which passed offshore August 26-29, 2011 (see Figure 3 through Figure 5). This storm event was closest to the date of the offshore bathymetric survey, which is discussed later in this document. Directional wave measurements were readily available at 2 nearshore gages – FRF630 and FRF3111 (see Table 1 and Figure 1). Non-directional wave measurements were available at gage FRF625 (see Table 1 and Figure 1).

Table 1: Wave Gages Used in SWAN Model Calibration

Gage Name	NC-NAD83 Easting (feet)	NC-NAD83 Northing (feet)	Latitude (deg. N)	Longitude (deg. W)	Nominal Depth (feet NAVD)
FRF630	2969396.8	907708.8	36.199883	75.714050	-58.3
FRF3111	2961043.9	902827.8	36.187239	75.742886	-25.7
FRF625	2960322.6	901486.7	36.183622	75.745478	-26.4

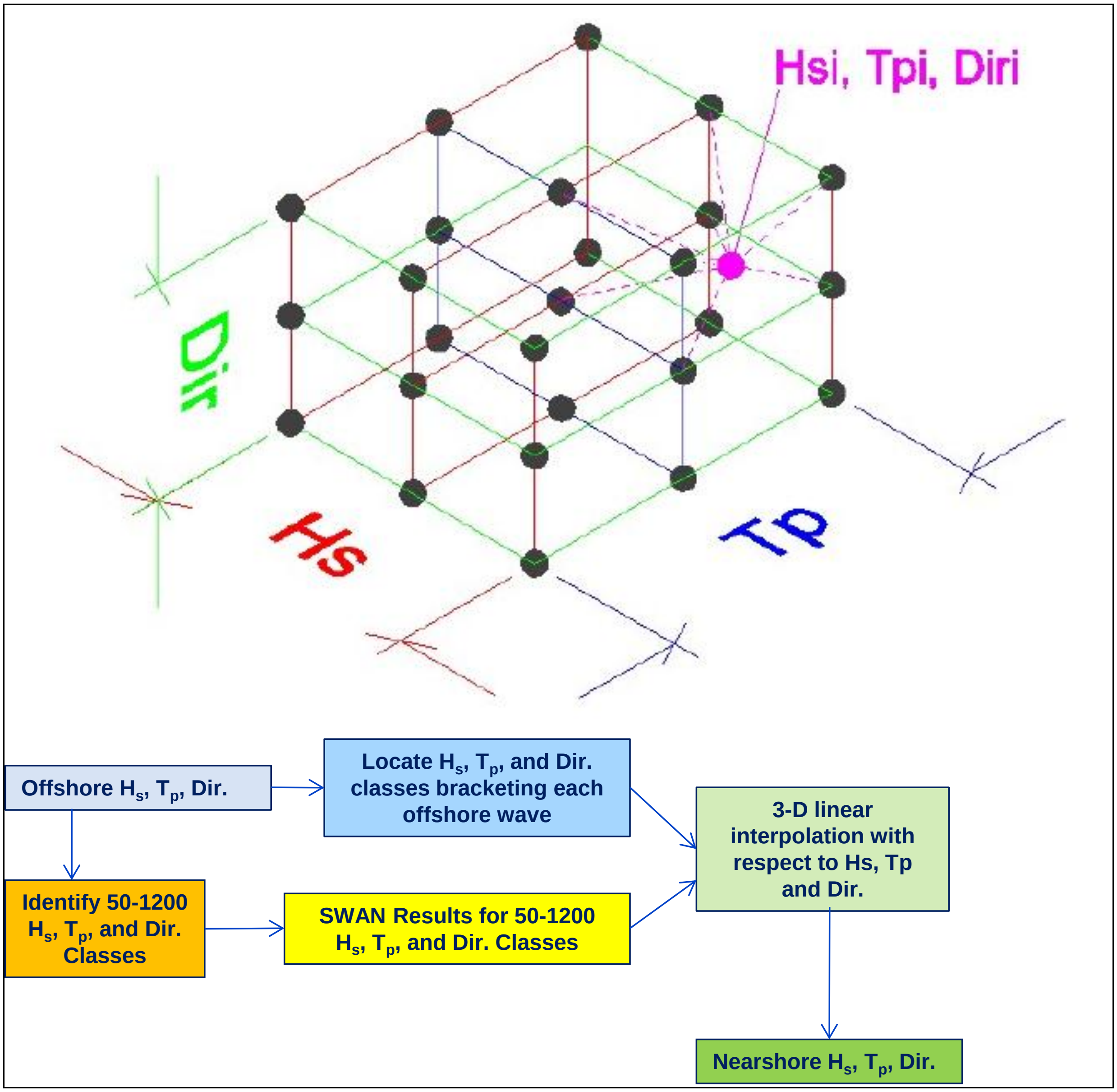

Figure 2: Use of External Wave Transformation Model with GENESIS (Day & Dobrochinski, 2012).

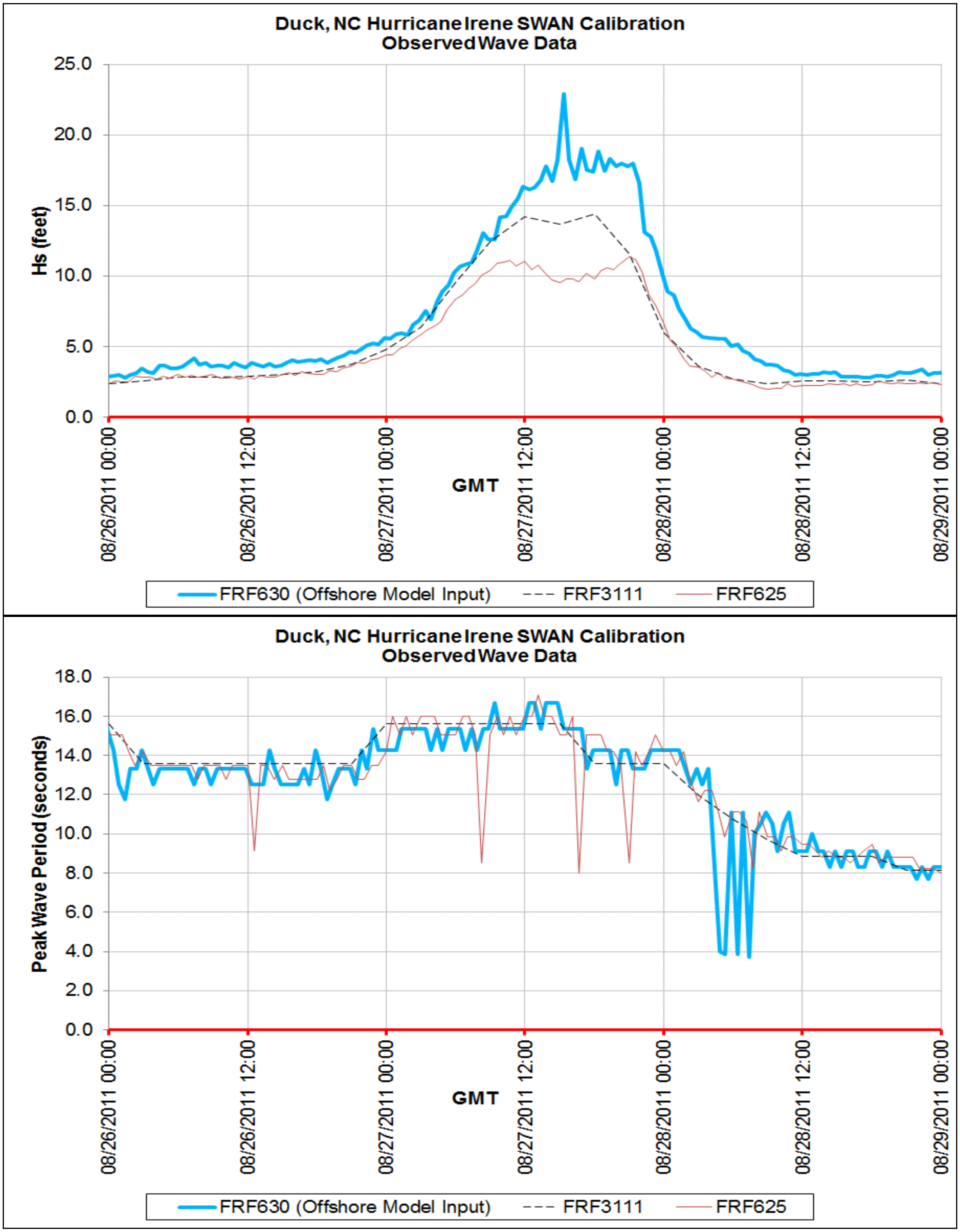

Figure 3: Observed Wave Heights and Wave Period during Hurricane Irene (FRF, 2013).

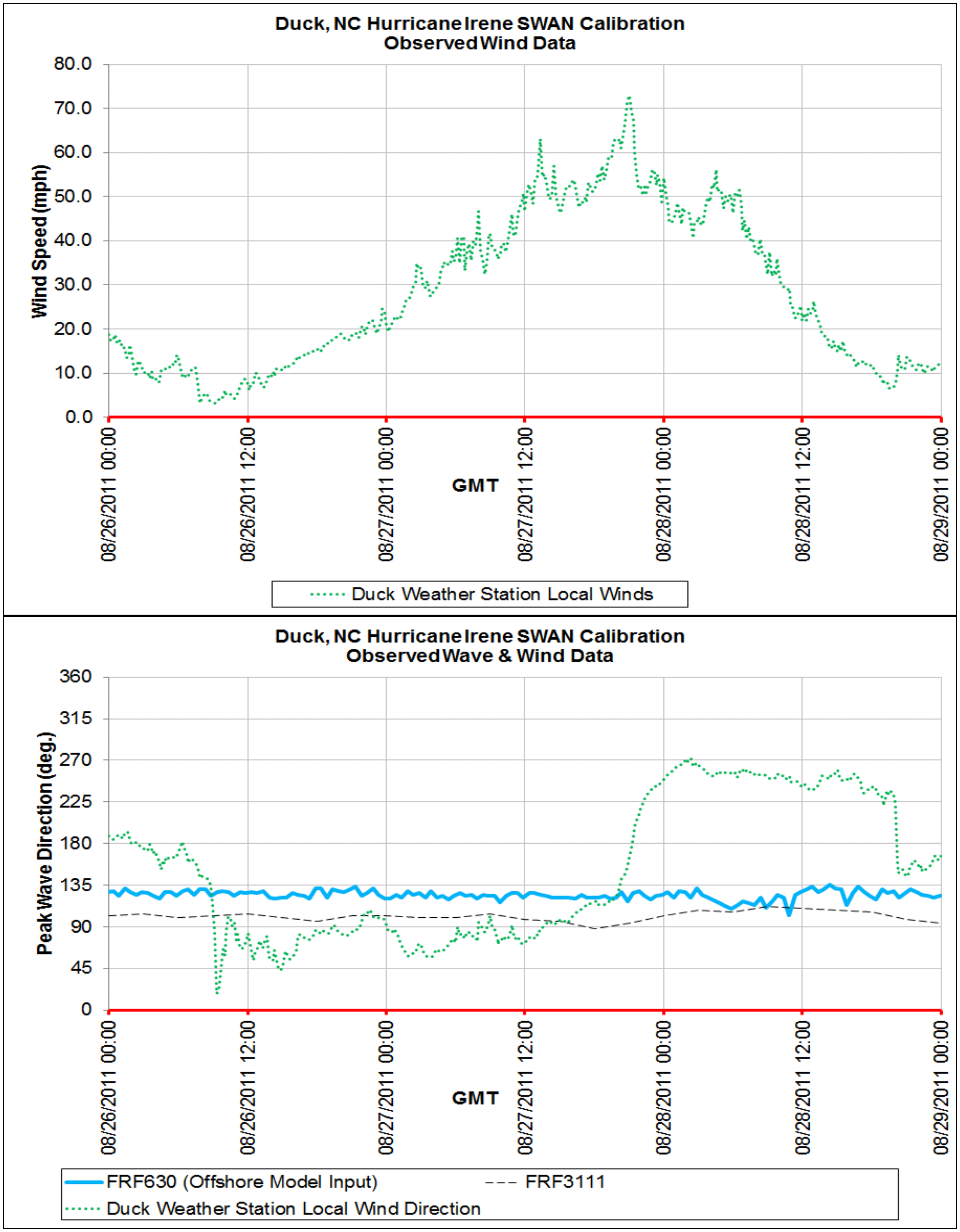

Figure 4: Observed Wind Velocities and Wave Directions during Hurricane Irene (FRF, 2013).

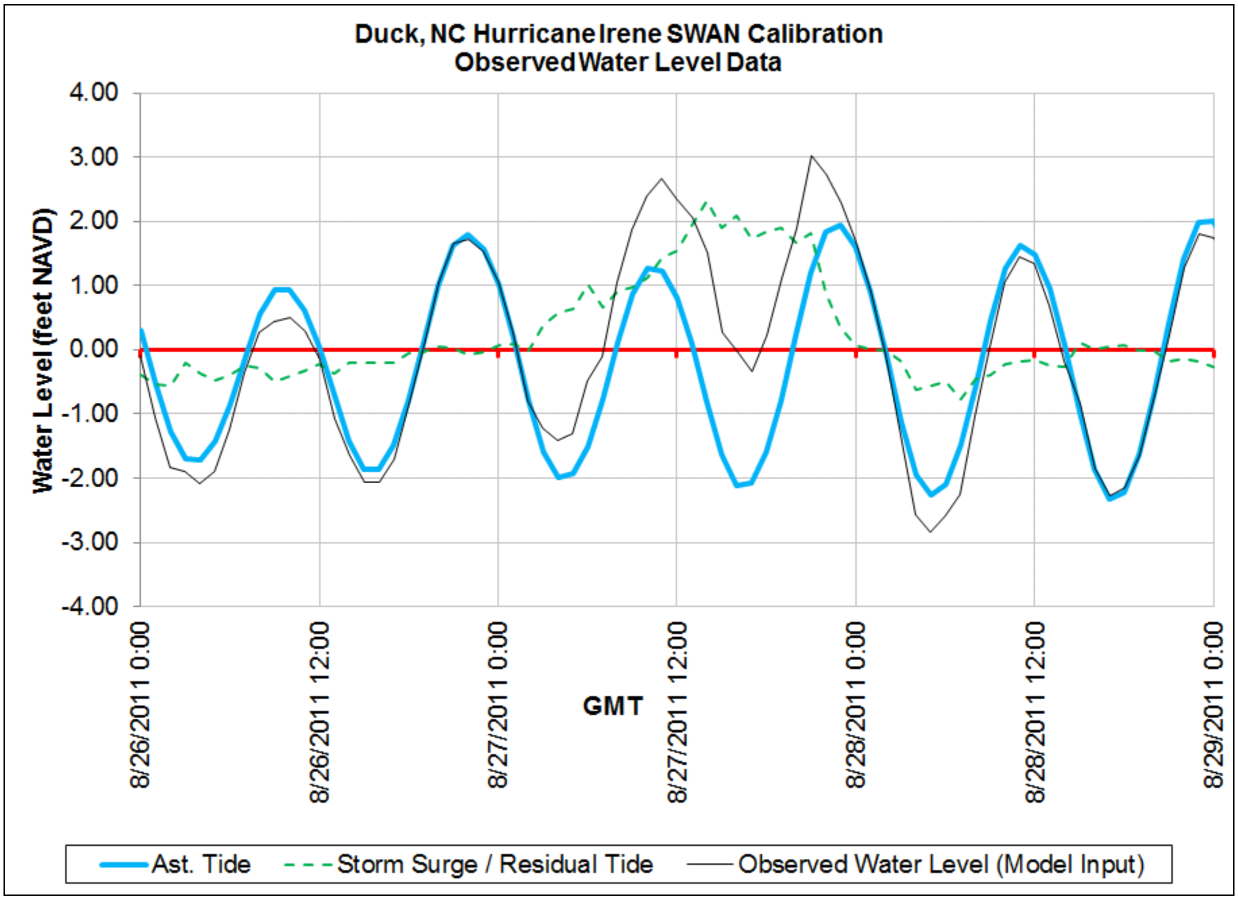

Figure 5: Observed Water Levels during Hurricane Irene (NOAA, 2013).

Grid

The grid used in the SWAN model appears in Figure 1 and Figure 6. The landward and seaward limits of the grid roughly follow the landward dune toe and the -58 foot NAVD depth contour. Overall, the characteristics of the grid follow the guidelines established by Deltares (2011). Grid spacing ranges from 160 to 1,300 feet in the longshore direction and 28 to 649 feet in the cross-shore direction. Changes in grid spacing between adjacent rows range from 0 to 10 percent. Angles between the longshore and cross-shore grid lines (in state plane coordinates) range from 88 to 90 degrees.

Bathymetry

The SWAN model grid bathymetry is shown in Figure 7, and is based on the following data sources:

- The November 2012 Light Detection and Ranging (LIDAR) survey.

- The November 2012 FRF survey.

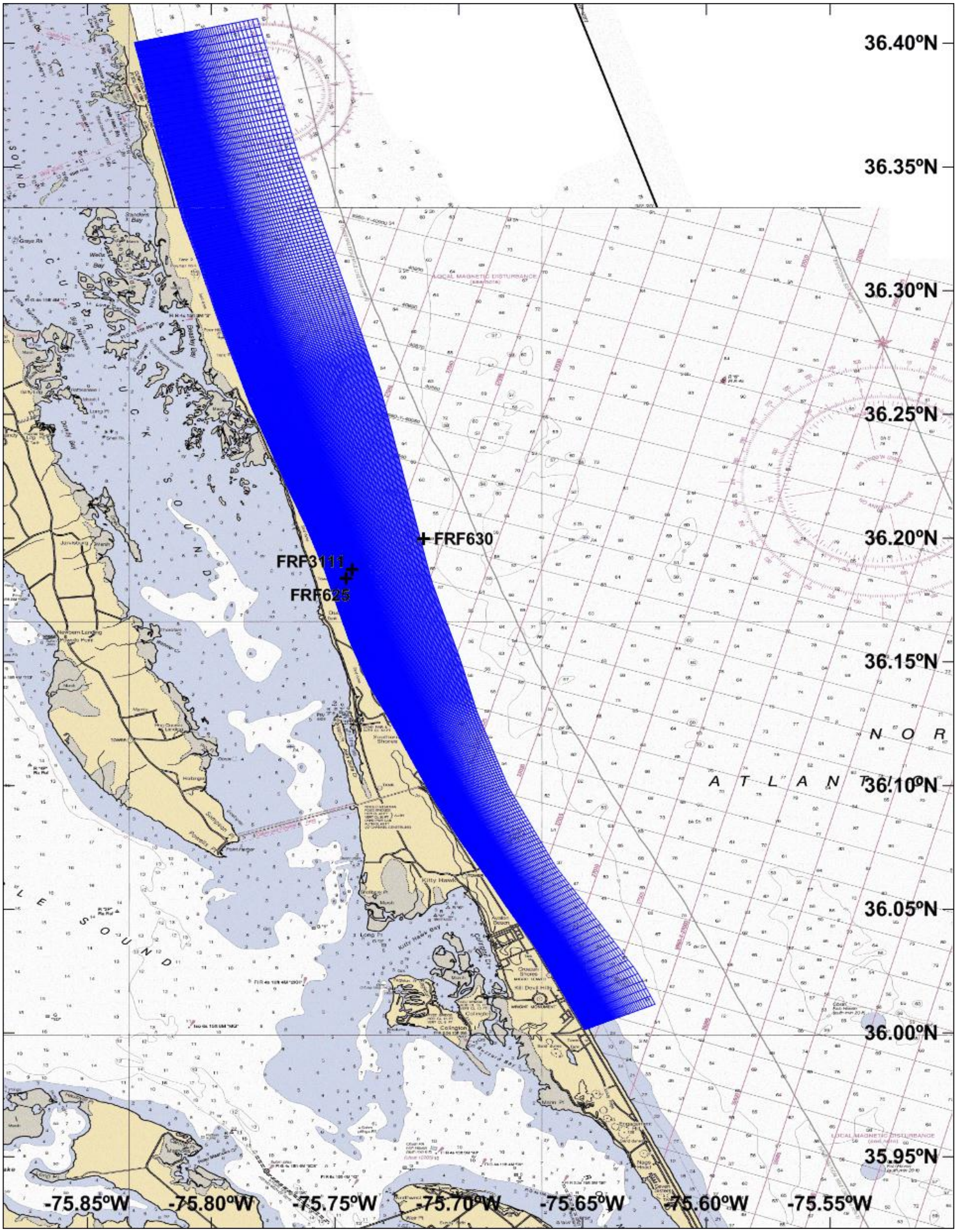

Figure 6: SWAN Model Grid with NOAA Nautical Charts 12204 and 12205.

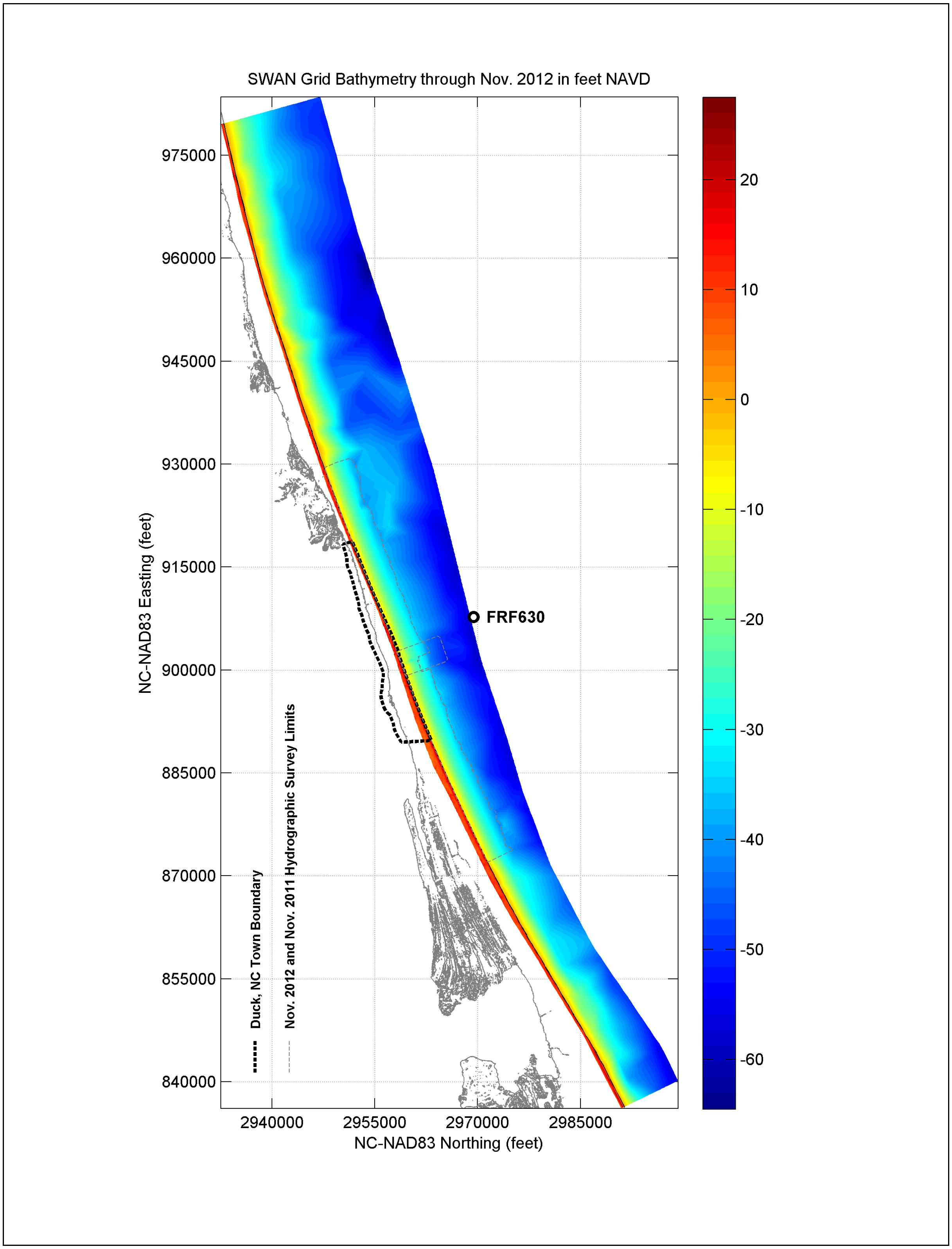

Figure 7: Bathymetry over the SWAN Model Grid.

- The November 2011 offshore bathymetric survey.

- Chart soundings and contours from National Oceanographic and Atmospheric Administration (NOAA) Charts 12204 and 12205 (see Figure 6).

As Figure 7 would suggest, combining the recent surveys with the chart soundings was difficult. The area typically surveyed by FRF was less ¾ mile long from north to south, while the available LIDAR data only covered the areas above wading depth. Prior to the bathymetric survey taken in November 2011, the most recent survey below the water line was taken in 1886. Although the nautical charts in Figure 6 were published between 2007 and 2009, the soundings and contours on the charts were based on the 1886 survey. These factors are primary reason for the appearance of the merged bathymetry near the limits of the recent survey data.

Structures along the study area were limited to the research pier at FRF. The pier was incorporated into the SWAN model as a "sheet" of infinite height. Based on the size and spacing of the pier's piles, a transmission coefficient of 92.5 percent was assumed.

Model Results

Calibration of the SWAN model was performed by varying the values of the bottom friction coefficient (see Table 2). Given the spacing of the grid, activating diffraction was not necessary; the directional spreading associated with each was sufficient to account for diffraction-like effects (Luijendijk, 2011). All other modeling parameters were set to their default values (see Table 3).

Table 2: SWAN Model Calibration Summary

JONSWAP Bottom Friction Coefficient	0.067	0.101	0.141 (selected)	0.152
FRF625				
Hs (simulated) - Hs (observed)				
Average (feet)	0.30	0.18	**0.03**	-0.01
RMS (feet)	0.83	0.79	**0.75**	0.75
FRF311				
Hs (simulated) - Hs (observed)				
Average (feet)	0.26	0.14	**0.00**	-0.03
RMS (feet)	1.15	1.14	**1.14**	1.15
Dir. (simulated) - Dir. (observed)				
Average (deg.)	-3	-3	**-3**	-4
RMS (deg.)	10	10	**10**	11
Both Gages				
Hs (simulated) - Hs (observed)				
Average (feet)	0.28	0.16	**0.02**	-0.02
RMS (feet)	1.00	0.98	**0.96**	0.97

Table 3: Final SWAN Model Parameters, Duck, NC

	Min.	Default	Max.	Selected Value
Breaking Parameter γ (Hb/db)	0.55	0.73	1.20	0.73
Breaking Parameter α	0.1	1.0	10.0	1.0
Bottom Friction Coef. for Waves (Optional):				
JONSWAP Friction Value (m^2/s^3)	0.000	0.067	None	0.141
Collins Friction Value	0.000	0.015	None	Not used
Madsen Roughness Scale (m)	0.0000	0.0500	None	Not used
Triads - Energy Transfer from low to high frequencies in shallow water	-N/A-	Off	-N/A-	On
Diffraction:	-N/A-	Off	-N/A-	Off
Diffraction Smoothing Coefficient	0	0.2	1.0	0.5
Diffraction Smoothing Steps	1	5	999	200
Wind Growth	-N/A-	On	-N/A-	On
JONSWAP Peak Enhancement Factor (for input waves specified in terms of height, period, and direction)	-N/A-	3.3	-N/A-	3.3

Model results were evaluated in terms of the significant wave height (Hs) and wave direction at gages FRF625 and FRF3111. A JONSWAP bottom friction factor of 0.141 led to the best fit between the simulated and observed waves (see Figure 8). Overall, the model results in terms of both wave height and wave direction are very good. Typical model results near the peak of Hurricane Irene appear in Figure 9.

GENESIS Model Calibration

Survey Data

LIDAR surveys along the study area were flown on the following dates:

- October 10-12, 1996.
- September 26-27, 1997.
- September 1-7, 1998.
- September 9, 1999.
- September 18, 1999 (Post Hurricane Floyd).
- October 6, 1999.
- January 3 – March 23, 2001.
- July 9-13, 2004.
- October 1 – November 26, 2005.
- March 18-27, 2008.
- November 27-29, 2009.
- May 25, 2010.
- November 5-29, 2012.

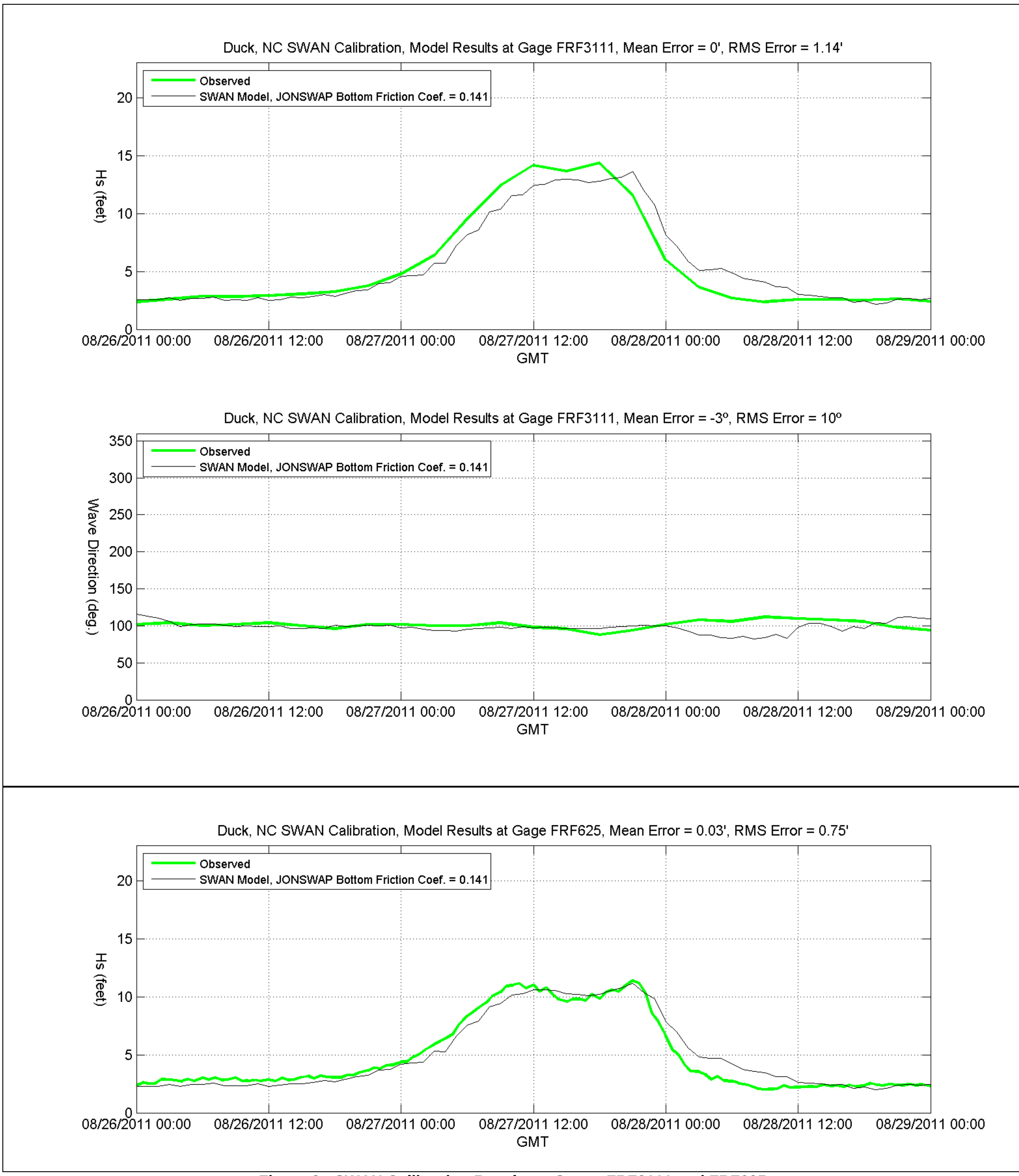

Figure 8: SWAN Calibration Results at Gages FRF3111 and FRF625.

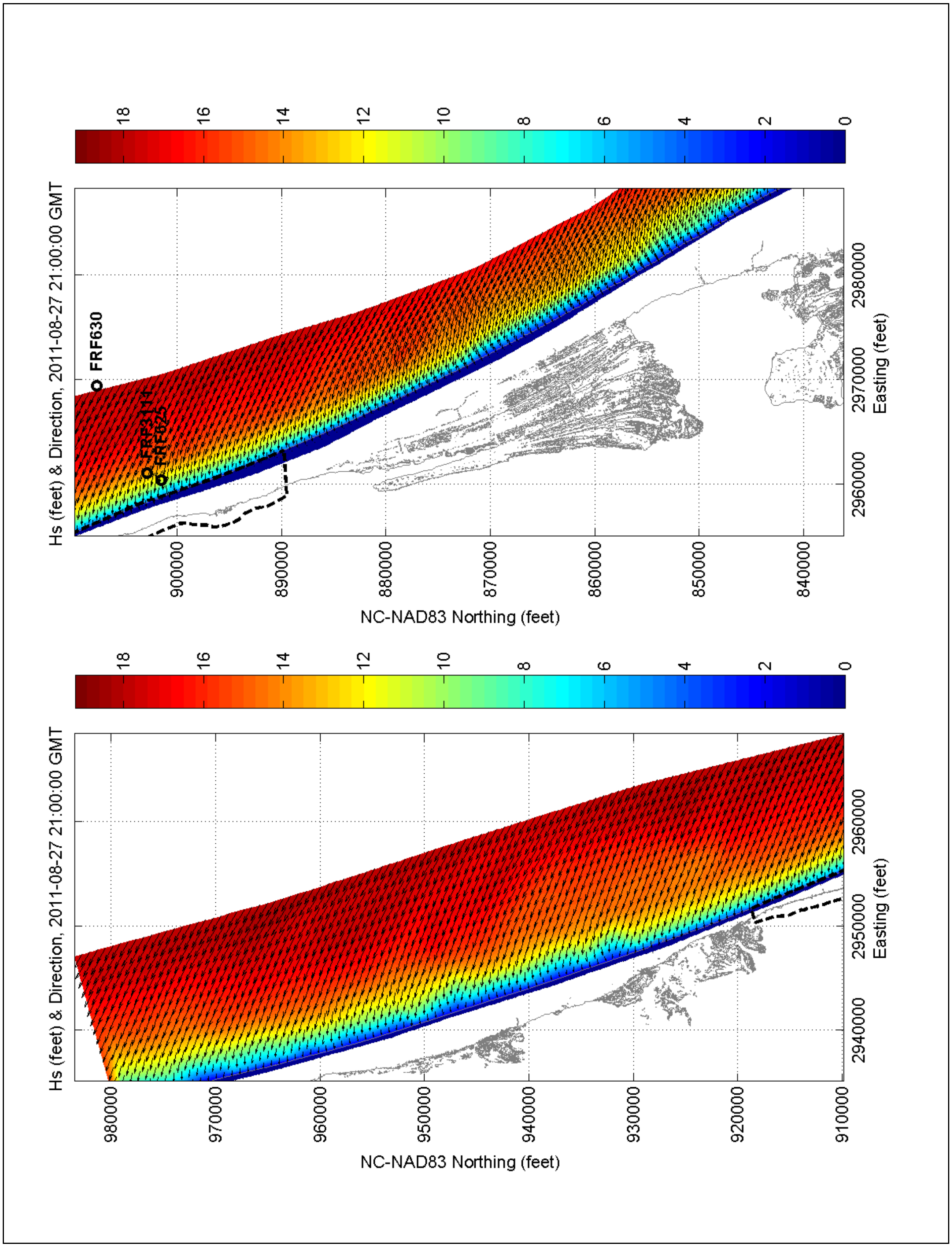

Figure 9: SWAN Model Results near the Peak of Hurricane Irene.

In addition to these surveys, a truck-based LIDAR survey was performed on November 30, 20111 using the Coastal LIDAR and Radar Imaging System (CLARIS).

In the 2013 Feasibility Study, the period of analysis was from 1996 to 2011. However, due to issues concerning the quality of the wave data, surveys prior to July 1, 1999 could not be used for the calibration of the GENESIS model. Accordingly, the remainder of the study period was roughly divided in half. The more recent portion extended from November 2005 to November 2012, and was used as the calibration period. The earlier portion extended from October 1999 to November 2005, and was used as the verification period.

Model Baseline

Shoreline positions in the GENESIS model are given in terms of a longshore and cross-shore distance relative to a fixed baseline. For this study, the modeling baseline is located 2,000 landward of the FRF survey baseline (see Figure 1). The orientation of the GENESIS baseline is identical to the FRF survey baseline, whose downcoast direction and shore normal are 160° and 70°, respectively. To account for the greatest possible range of beach fill spreading, the baseline covers the entire length the Town, plus equal distances upcoast and downcoast, for a total length of 94,000 feet (17.8 miles). Cell spacing along the modeling baseline is 100 feet.

Wave Data

The wave data used in the GENESIS model is taken from wave gage FRF630 (see Table 1 and Figure 1). The observed wave record at this gage extends from January 1, 1996 to the present, with directional measurements beginning on November 7, 1996.

When using gage measurements in a numerical modeling study, provisions must be made for the times at which the gage malfunctions. Gaps longer than 24 hours were filled using the NOAA Wavewatch hindcast for the Western North Atlantic, which extended from July 1, 1999 to the present. Available hindcast data prior to July 1, 1999 was limited to sites further offshore (see http://wis.usace.army.mil/wis.shtml). Given the distances between FRF630 and the locations of the older hindcast data, it was not possible to fill in the longer data gaps prior to July 1, 1999. For these reasons:

- Wave data used in the GENESIS model was limited to data collected after July 1, 1999, except for a short test described later in this report.

- Shoreline changes prior to July 1, 1999 were not simulated in the GENESIS model.

Directional wave statistics during the calibration period (November 2005 to November 2012) appear in Figure 10. The prevailing wave direction offshore is from the east, with a root-mean-square wave height of 3.5 feet. The largest wave during the calibration period occurred during Hurricane Sandy on October 29, 2012, measuring 20.4 feet in height. Based on the prevailing wave direction, the net sediment transport along the Town of Duck is most likely from south to north.

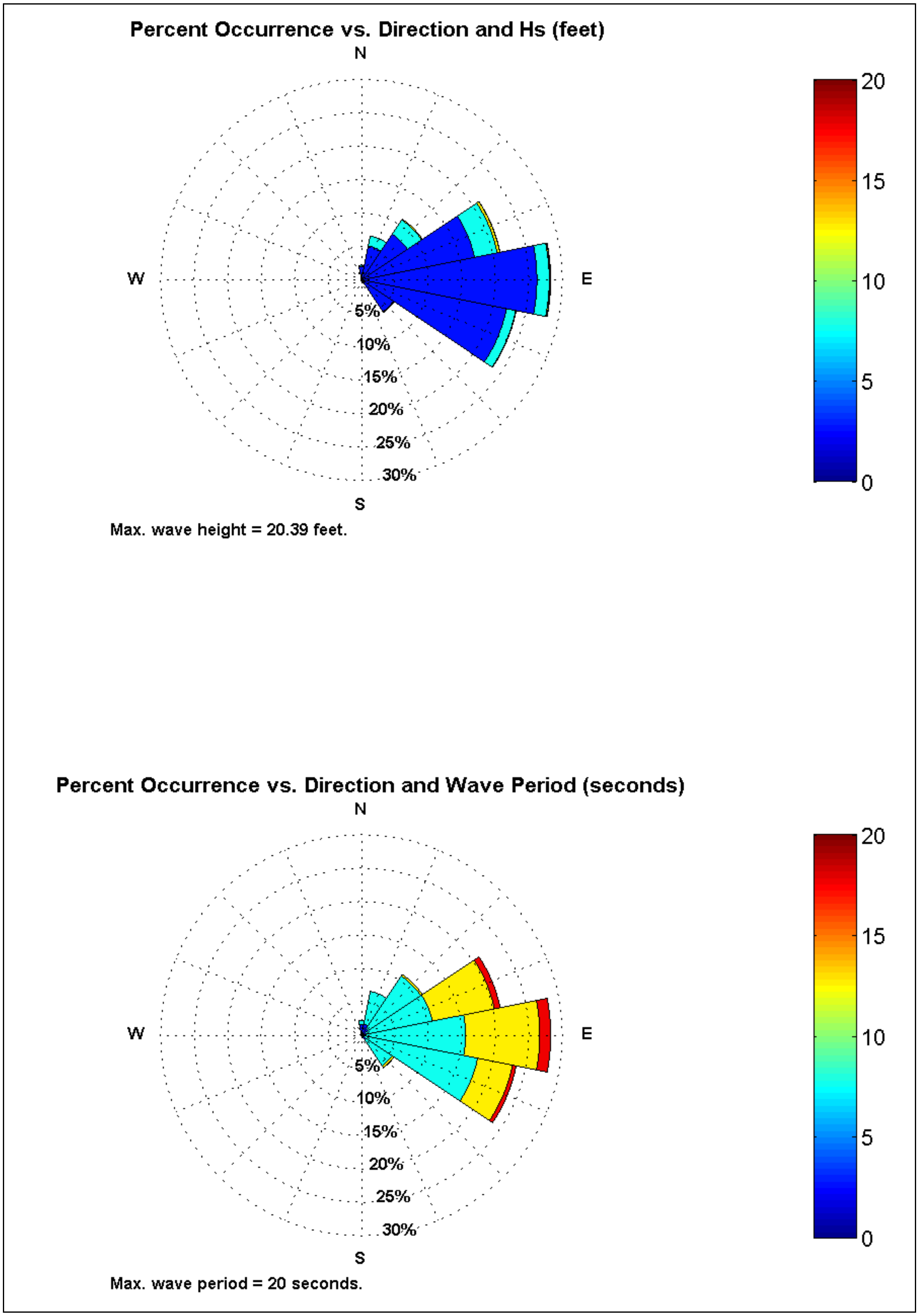

Figure 10: November 2005 to November 2012 Wave Rose at Wave Gage FRF630.

Structures

As noted earlier, structures along the study area were limited to the research pier at FRF. The pier was incorporated into the GENESIS model as a "non-diffracting" groin with a permeability of 92.5% based on the size and spacing of the pier's piles.

Grain Size

Genesis uses a characteristic grain size to determine the location of breaking waves alongshore and to calculate the average nearshore bottom slope used in the model's longshore transport equations (Hanson and Kraus, 1991). Beach materials were sampled during the SUPERDUCK Beach Sediment Sample Experiment (Stauble, et al, 1993). The mean grain size based on all samples that were reported was 0.84 mm (0.43 phi). However, approximately 2/3 of the samples were collected in the upper and lower swash zones. On most beaches, sediments within the swash zones tend to be coarser than those on the rest of the beach profile. Accordingly, the mean grain size used in the model, 0.59 mm (0.75 phi), was averaged from the samples that were not collected in the swash zones.

External Wave Refraction

Offshore waves were based on the wave record at wave gage FRF630 between November 2005 and November 2012. To transform the waves from the gage location to the depth of closure (-24 feet NAVD), the wave record was divided into the wave height, period, and direction classes shown in Table 4. In theory, Table 4 represents 448 wave cases (7 x 8 x 8). However, some of the theoretical wave cases were not present in the wave record. For example, the highest waves also tended to be the longest, making it unnecessary to simulate the 24.7 foot, 2.5 second wave cases. Based on the actual record, 287 cases were simulated in the SWAN model. Wind velocities for each case were averaged in terms of wind stress based on concurrent wind speeds near the FRF weather station. For the larger wave cases, water levels were based on the wave height versus return period curve at FRF630, and the storm tide versus return period tables for the Town of Duck (FEMA, 2006). Typical model results for an average wave condition and a storm condition appear in Figure 11 and Figure 12.

Table 4: GENESIS Wave Cases at Wave Gage FRF630

Sign. Wave Height (feet)			Peak Wave Period (sec.)			Wave Direction (deg.)		
Min.	Median	Max.	Min.	Median	Max.	Min.	Median	Max.
0.0	1.6	3.1	0.0	2.5	5.0	-20	-9	3
3.1	5.1	7.1	5.0	6.0	7.0	3	14	25
7.1	9.0	11.0	7.0	8.0	9.0	25	36	48
11.0	12.9	14.9	9.0	10.0	11.0	48	59	70
14.9	16.9	18.8	11.0	12.0	13.0	70	81	93
18.8	20.8	22.8	13.0	14.0	15.0	93	104	115
22.8	24.7	26.7	15.0	16.0	17.0	115	126	138
			17.0	20.0	23.0	138	149	160

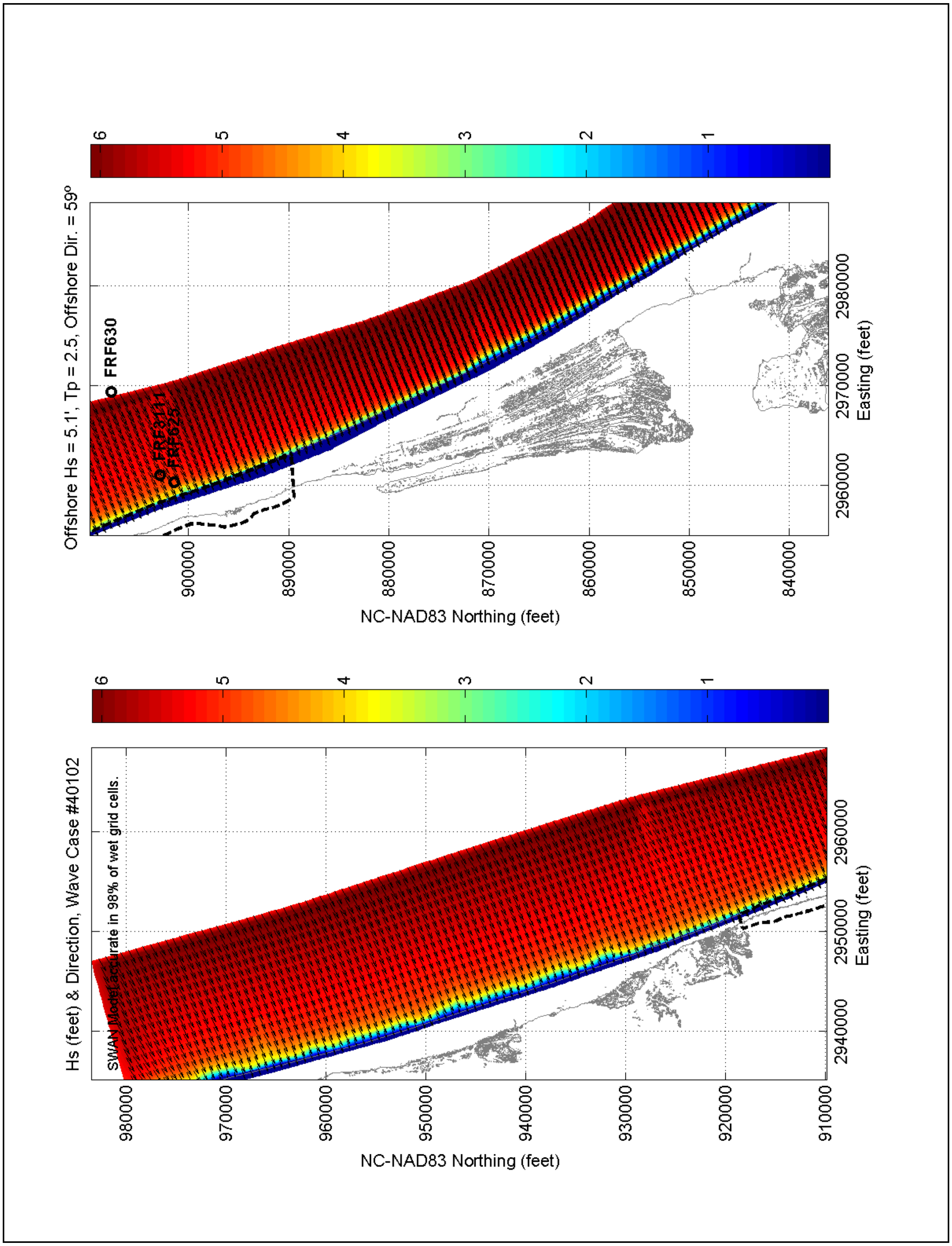

Figure 11: Typical SWAN Model Results for an Average Wave Case.

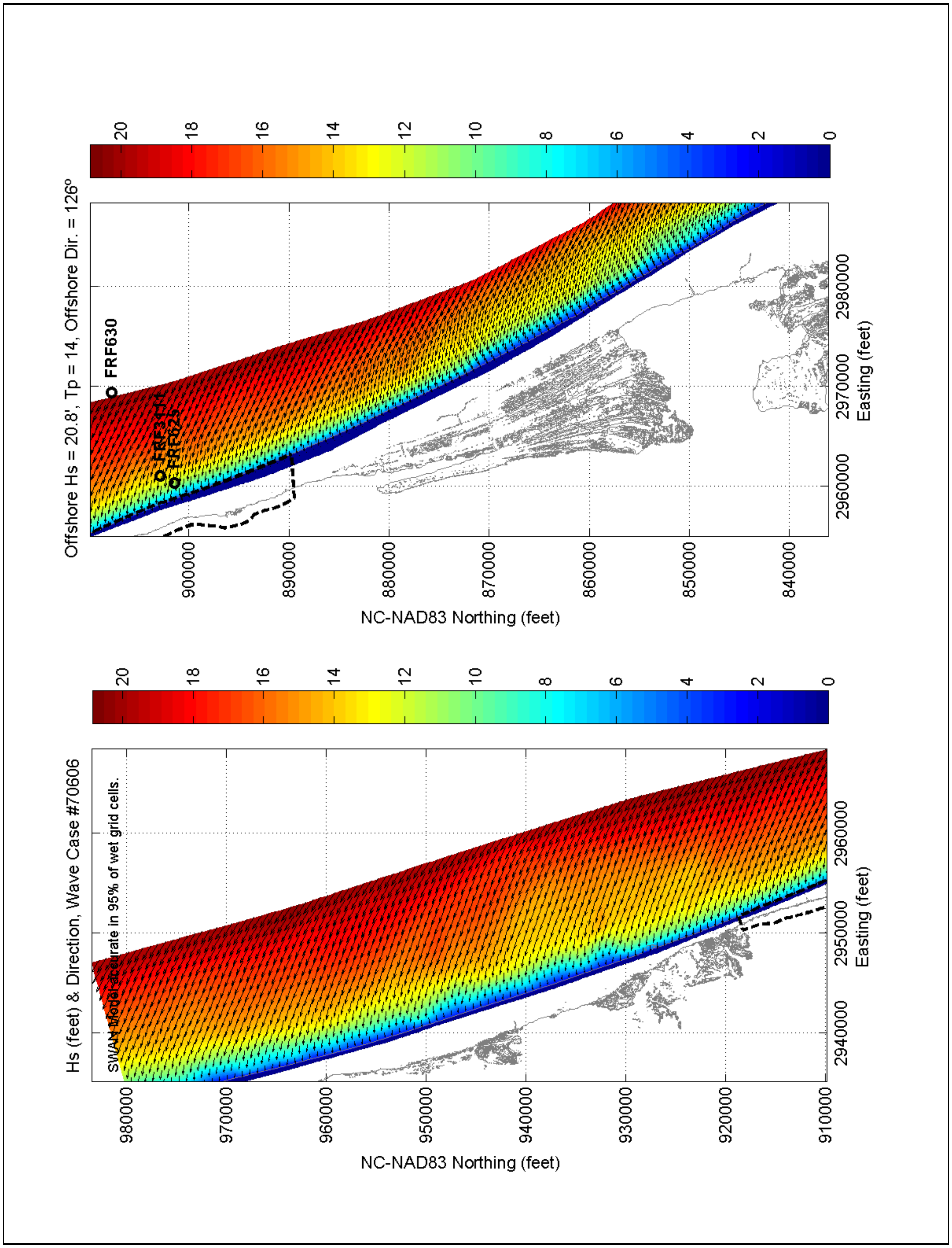

Figure 12: Typical SWAN Model Results for a Storm Wave Case.

Using the calibrated SWAN model, the wave cases in Table 4 were transformed from wave gage FRF630 to the depth of closure (-24 feet NAVD). Based on the output of the SWAN model, propagation coefficients ($H_{nearshore}$ / $H_{offshore}$) and wave angles were provided for each wave case and each grid cell along the GENESIS baseline. The resulting matrix of propagation coefficients and wave angles was provided as an input to the GENESIS model, along with the initial shoreline position, the time series of waves at FRF630, the average berm elevation (+6 feet NAVD), the depth of closure (-24 feet NAVD), and the characteristic grain size.

Model Results

Calibration of the GENESIS model was based on the observed shoreline changes between the November 2005 and November 2012 LIDAR surveys. Attention was also given to the net longshore transport, to ensure that sediment transport rates based on the model were of a reasonable magnitude. The initial condition was the mean high water line (MHW, +1.2 feet NAVD, NOAA, 2003) based on the November 2005 LIDAR survey. Since there are no inlets in close proximity to the study area, tidal currents were assumed to be negligible.

Calibration of the model typically involves the variation of two longshore transport coefficients. Coefficient K1 governs the overall magnitude of the longshore transport based on the breaking wave height and wave direction. The value of this parameter has the largest influence on the model results. Coefficient K2 governs the transport resulting from variations in the breaking wave height (Hanson and Kraus, 1991). Except for high-resolution simulations involving breakwaters or T-head groins, the value of K2 has, at most, a minor influence on the model results.

The default value of K1 is 0.4. However, longshore transport rates using this value were small, with an average value of only 13,000 c.y./year. To provide for more realistic sediment transport rates, values of K1 ranging from 0.8 to 4.0 were tested. Acceptable results were achieved by setting the value of K1 to 2.0, and the value of K2 to 0.0 (see Figure 13 and Figure 14). Although the erosional trends were not replicated exactly, the model was able to approximate the regional erosion trends. Final modeling parameters appear in Table 5.

Table 5: Final GENESIS Model Parameters

	Allowed Range and/or Default	Duck, NC
K1*	0.4 default	2.0
K2	0.0 to K2 = K1 0.0 default	0.0
Grain Size (mm)**	0.25 default	0.59
Berm Elev. (feet NAVD)**	+3 default	6
Closure Depth (feet NAVD)**	-15 default	-24

NOTES: * Originally, the recommended range for K1 was 0.1 to 1.0 (Gravens & Kraus, 1991). However, CPE (2007) found that this value could underestimate sediment transport rates in some areas. The GENESIS model can run and remain stable with K1 values greater than 1.0.
** No allowed range is given in Gravens & Kraus (1991).

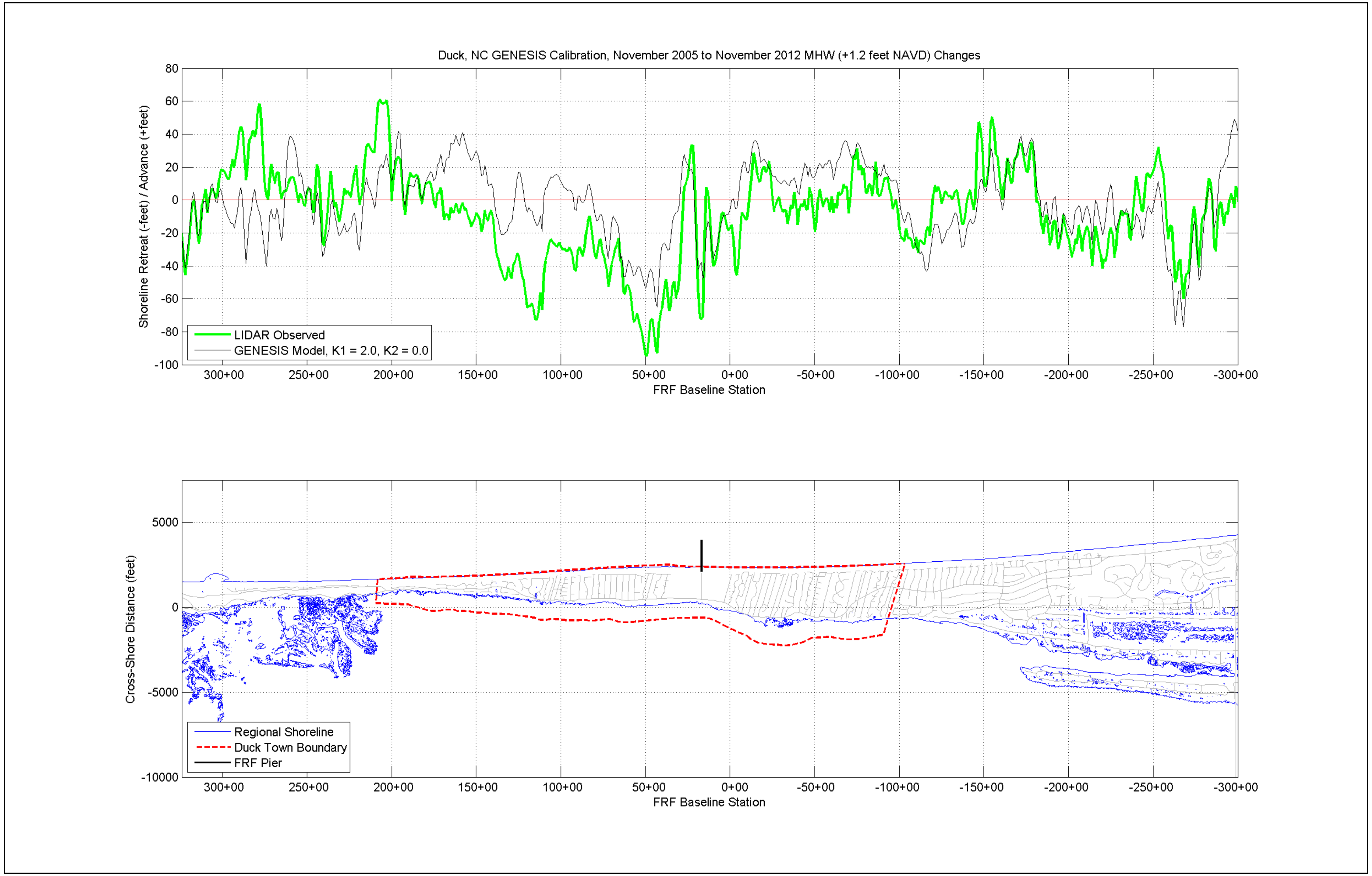

Figure 13: Observed and Simulated Shoreline Changes during the GENESIS Calibration Period.

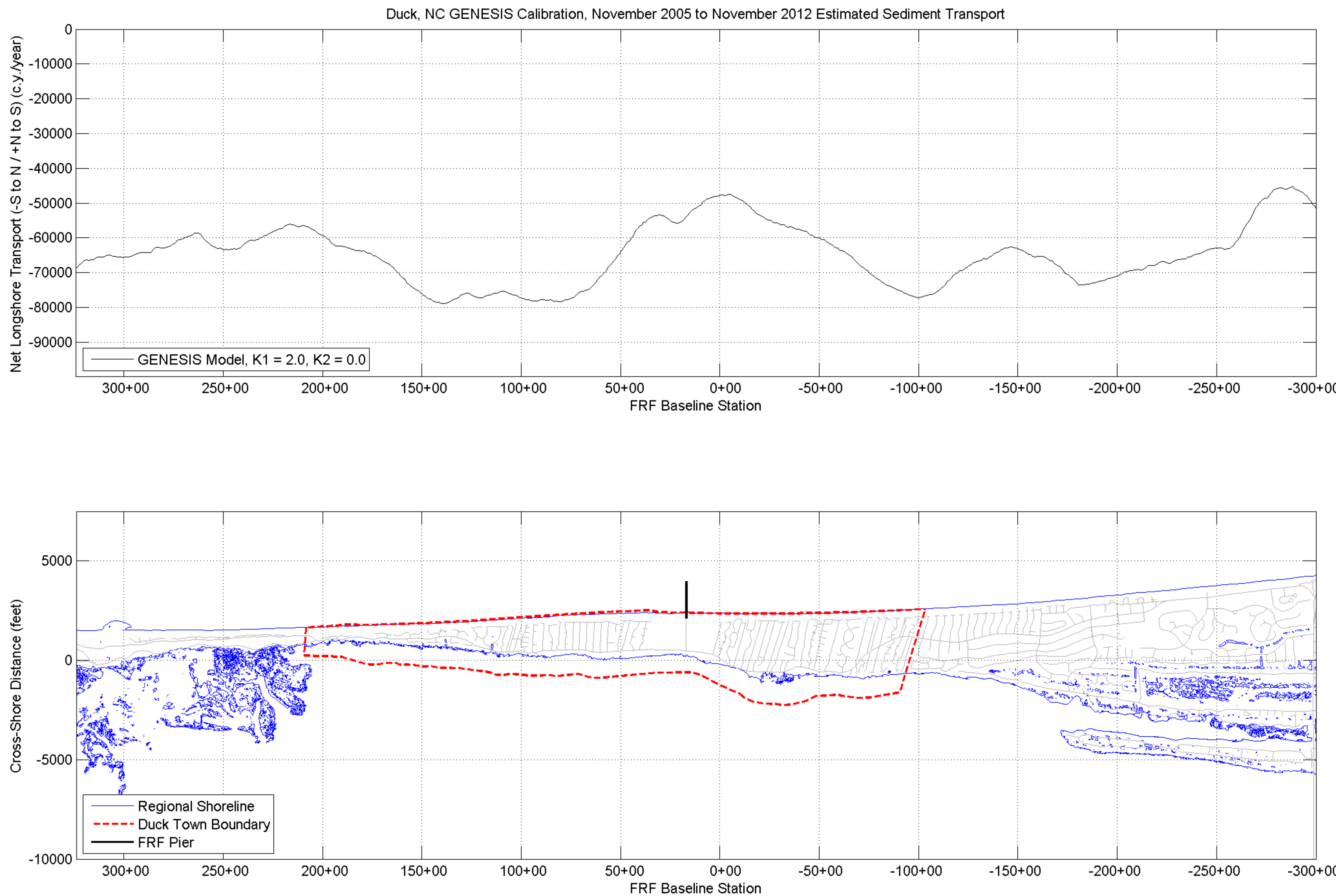

Figure 14: Estimated Longshore Transport during the GENESIS Calibration Period.

GENESIS Model Verification

Long-Term Model Verification

To ensure that the GENESIS model calibration was sufficient, additional verification runs were performed. The first verification period was from October 1999 and November 2005. The setup used in the GENESIS model was identical to the final calibration run, except for the initial conditions and the wave data, which were based on the October 1999 LIDAR survey and the offshore wave record between October 1999 and November 2005.

GENESIS model results between October 1999 and November 2005 appear in Figure 15 and Figure 16. Similar to the calibration period, the GENESIS model was able to approximate the regional erosion trends. Although the observed shoreline changes were not reproduced in an exact manner, agreement between the observed shoreline changes and the model results was equal to or better than the calibration (compare Figure 15 and Figure 13).

Duck97 Experiment

It should be noted that in many parts of North Carolina, accepted longshore transport rates are on the order 200,000 to 300,000 c.y./year. Near E. Driftwood Street in Kill Devil Hills, estimated transport rates are on the order of 92,000 c.y./year from north to south (Kaczkowski & Kana, 2012). In comparison, net transport rates based on the GENESIS results are on the order of 60,000 c.y./year from south to north (see Figure 10, Figure 14, and Figure 16). To evaluate whether these transport rates were reasonable, a second verification run was performed based on the Duck97 experiment.

The Duck97 experiment represented one of the few efforts to directly measure sediment transport in situ (Smith, 2006). Details regarding the measurements, which took place on October 18-19, 1997, appear in Smith (2006). Sediment transport measurements were taken at two transects. On Transect 19, the observed longshore transport rate was 2,943,000 c.y./year (2,250,000 m^3/year), with an average wave height of 4.9 feet. On Transect 15, the observed longshore transport rate was 144,000 c.y./year (110,000 m^3/year), with an average wave height of 3.2 feet. Observed waves on both transects were indicative of average conditions, suggesting that the higher value on Transect 19 may have been an outlier.

To evaluate whether the model could reproduce one of the observed rates, the model was run during the dates of the experiment. The initial shoreline position during this short simulation was based on the September 1997 LIDAR survey. Offshore waves were based on the observed wave record at gage FRF630. Average sediment transport rates during the dates of the experiment appear in Figure 17. Given the extremely short duration of the model run, there was a large

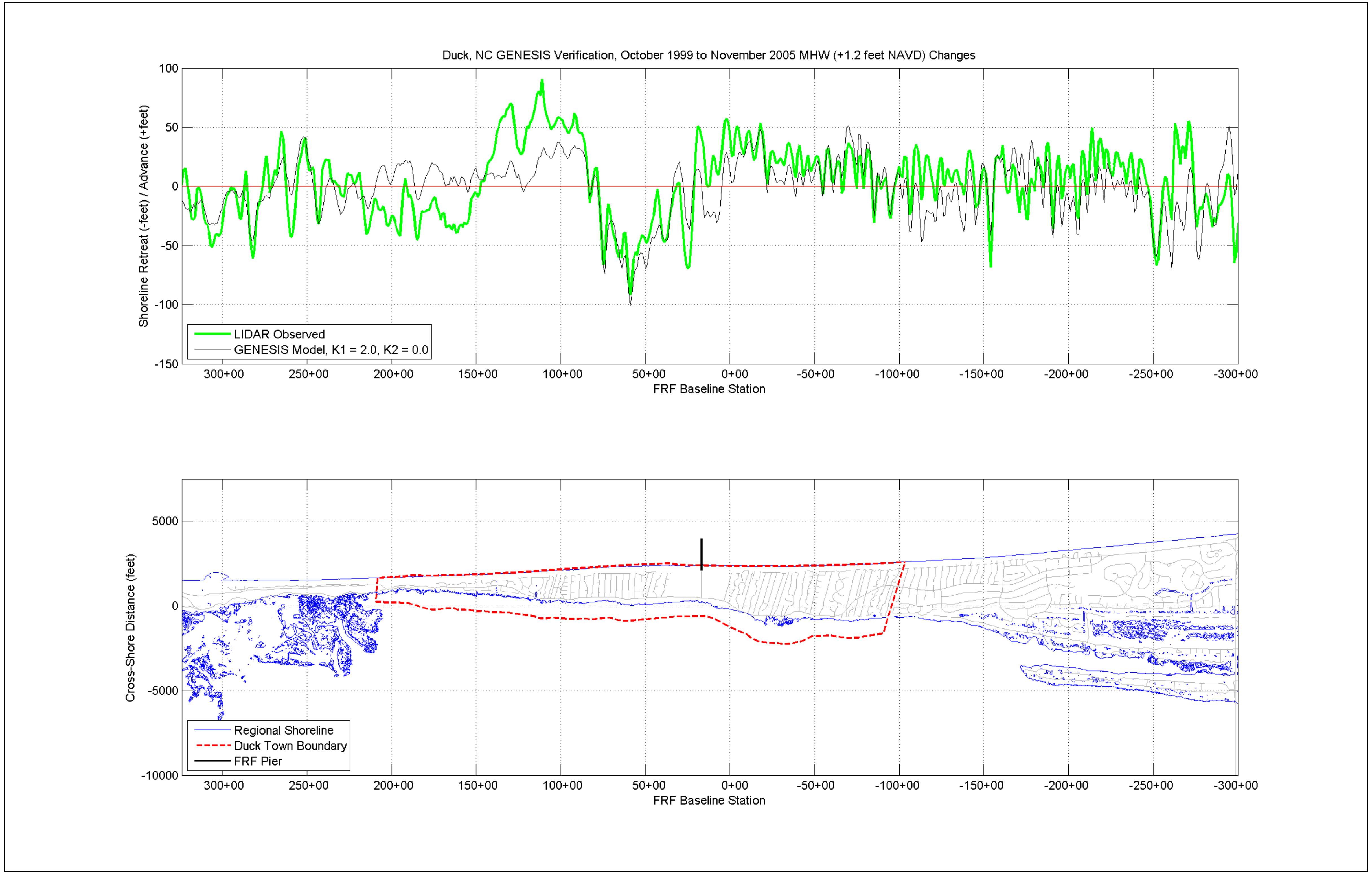

Figure 15: Observed and Simulated Shoreline Changes during the GENESIS Long-Term Verification Period.

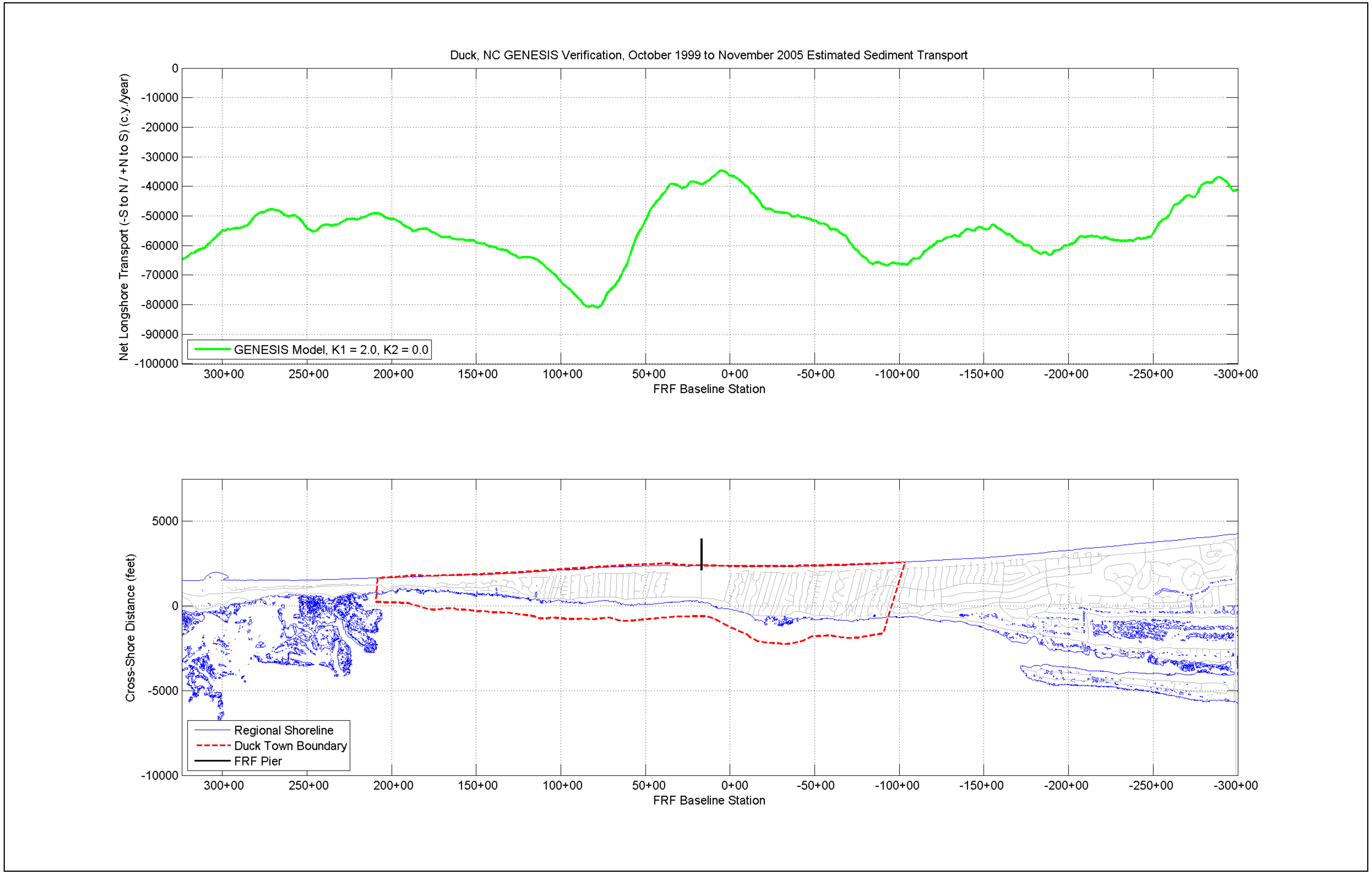

Figure 16: Estimated Longshore Transport during the GENESIS Long-Term Long-Term Verification Period.

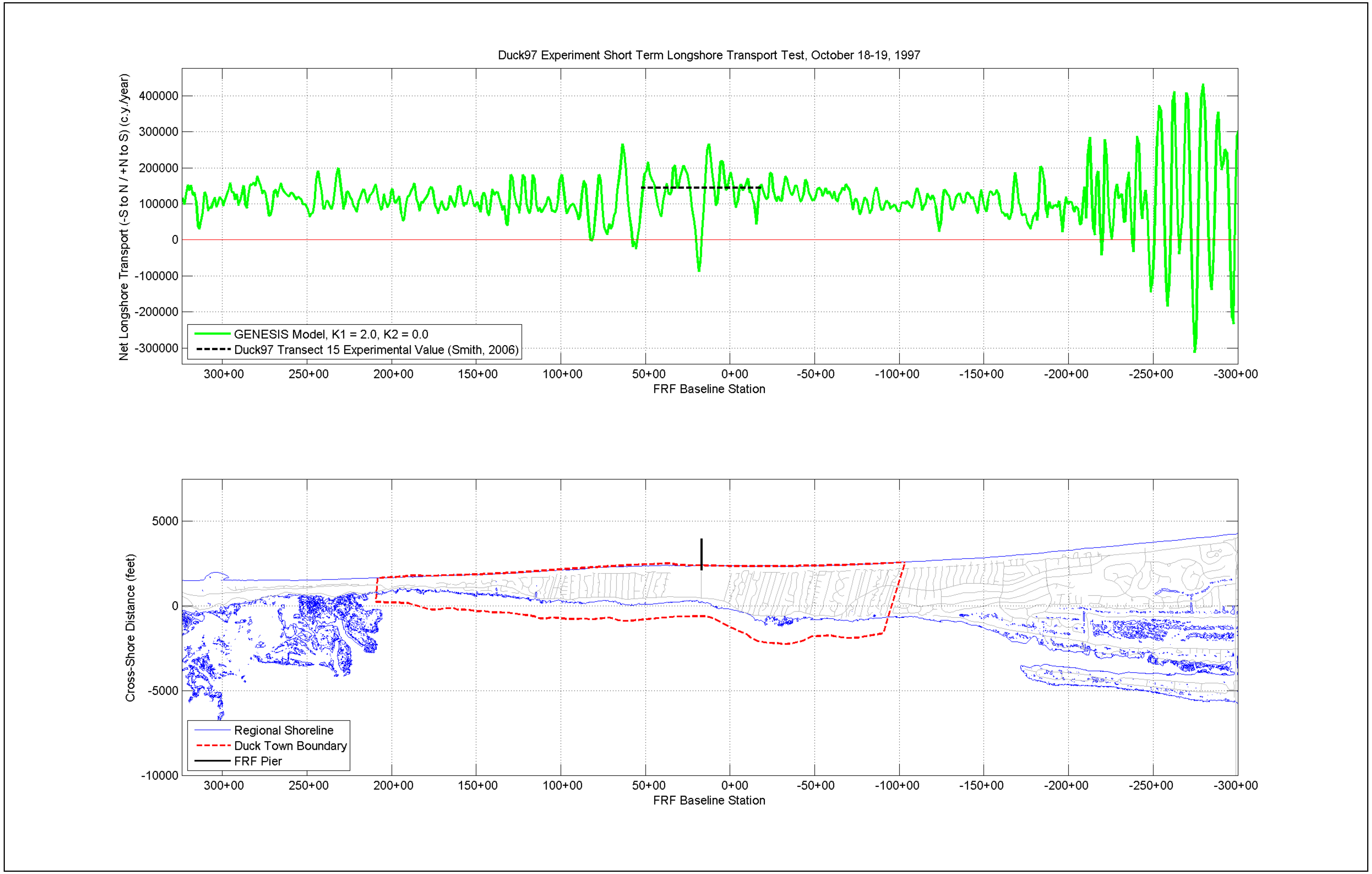

Figure 17: Simulated and Observed Sediment Transport Rates during the Duck97 Experiment.

degree of scatter in the model results (see Figure 17). However, near the FRF property, the model results were consistent with the observed rate on Transect 15. Given these results, the sediment transport rates during the calibration and the long-term model verification appeared to be reasonable (see Figure 14, Figure 16, and Figure 17). Accordingly, the model setup used during the final calibration run and long-term model verification was adopted for use in subsequent model runs.

References

Bonanata, R., Medina, R., Silveira, L., Benedet, L., 2010. Metodología para la Caracterización del Clima Maritimo en un Punto Cerca de la Costa a Partir de una Serie de Datos en Aguas Profundas (Methodology for the Characterization of the Marine Climate at a Point Near the Coast from a Series of Deep Water Data), VI Congreso Argentino de Ingeniería Portuaria Seminario Latinoamericano " Desarrollo Sustentable de la Infraestructura Portuaria Marítima y Fluvial en América Latina, Buenos Aires, Argentina.

Bonisteel-Cormier, J.M., Nayegandhi, Amar, Wright, C.W., Sallenger, A.H., Brock, J.C., Nagle, D.B., Vivekanandan, Saisudha, Klipp, E.S., and Fredericks, Xan, 2011. EAARL Coastal Topography–Northern Outer Banks, North Carolina, Post-Nor'Ida, 2009: U.S. Geological Survey Data Series 616, 1 DVD, http://pubs.usgs.gov/ds/616/.

Coastal Planning & Engineering, Inc., 2007. Coastal Engineering Study of Historic Structure Preservation, Cape Henlopen State Park, Lewes, Delaware, Coastal Planning & Engineering, Inc., Boca Raton, FL.

Coastal Planning & Engineering of North Carolina, Inc., 2013. Town of Duck North Carolina Erosion & Shoreline Management Feasibility Study, Coastal Planning & Engineering of North Carolina, Inc., Wilmington, NC.

Day, C., Dobrochinski, J., 2012. Application of the Hypercube Method for the Efficient Simulation of Long-Term, Nearshore Wave Records: Case Study and Verification Using Observed Wave Data Near the Mississippi/Alabama Coast, National Conference on Beach Preservation Technology, Florida Shore and Beach Preservation Association, Tallahassee, FL, http://fsbpa.com/2012TechPresentations/ChrisDay.pdf.

Delft University of Technology, 2008. SWAN Scientific and Technical Documentation, SWAN Cycle III version 40.72A, Delft University of Technology, Delft, the Netherlands.

Deltares, 2011. Delft3D-RGFGRID, Generation and Manipulation of Curvilinear Grids for Delft3D-FLOW and Delft3D-WAVE, User Manual, Part of Hydro-Morphodynamics, Deltares, Delft, the Netherlands.

EarthData International of North Carolina, 2001. Floodplain Mapping Program, North Carolina Division of Emergency Management, NC Floodplain Mapping: Phase 1a; LIDAR Full Return Mass Points, Jan-Mar 2001, EarthData International of North Carolina, High Point, NC.

Federal Emergency Management Agency 2006, Flood Insurance Study, a Report of Flood Hazards in Dare County, North Carolina and Incorporated Areas, Federal Emergency Management Agency, Atlanta, GA.

Field Research Facility, 2013. Field Research Facility Coastal Observations & Analysis Branch, http://frf.usace.army.mil/.

Gravens, Mark B., Kraus, Nicholas, C., 1991. GENESIS: Generalized Model for Simulating Shoreline Change Report 2, Workbook and System User's Manual, U.S. Army Corps of Engineers, Vicksburg, MS.

Hanson, Hans, Kraus, Nicholas, C., 1991. GENESIS: Generalized Model for Simulating Shoreline Change, Report 1, Technical Reference, U.S. Army Corps of Engineers, Vicksburg, MS, http://chl.erdc.usace.army.mil/chl.aspx?p=s&a=PUBLICATIONS;110&g=90.

Kaczkowski, H., & Kana, T., 2012. Final Design of the Nags Head Beach Nourishment Project Using a Longshore Numerical Model, Coastal Engineering Proceedings, 1(33), sediment.64. doi:10.9753/icce.v33.sediment.64.

Luijendijk, Arjen, 2011. E-mail to Christopher Day, Re: Input-Output problem(?) in Delft3D-WAVE / SWAN - further info, November 25, 2011.

National Oceanographic and Atmospheric Administration, 2003. Benchmark Sheet for 8651370, Duck NC, http://tidesandcurrents.noaa.gov/benchmarks.html?id=8651370

National Oceanographic and Atmospheric Administration, 2010. Vertical Datum Transformation, Welcome to VDATUM, http://vdatum.noaa.gov/.

National Oceanographic and Atmospheric Administration, 2013. Office of Coast Survey Historical Map & Chart Collection, http://historicalcharts.noaa.gov/.

National Oceanographic and Atmospheric Administration, 2013. ENC Direct to GIS, http://encdirect.noaa.gov/ENC_Direct/encdirect_download.html.

National Oceanographic and Atmospheric Administration, 2013. Meteorological Obs./ 8651370 Duck, NC, http://tidesandcurrents.noaa.gov/met.html?id=8651370.

National Oceanographic and Atmospheric Administration, 2013. NOAA Coastal Services Center Digital Coast, http://www.csc.noaa.gov/digitalcoast/.

National Oceanographic and Atmospheric Administration, 2013. WAVEWATCH III Model Data Access, http://polar.ncep.noaa.gov/waves/download.shtml.

Smith, Jane McKee, 2001. Modeling Nearshore Wave Transformation with STWAVE, Coastal and Hydraulics Engineering Technical Note I-64, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi, http://chl.wes.army.mil/library/publications/chetn/pdf/chetn-i64.pdf.

Smith, Ernest R., 2006. Longshore Sediment Transport Rate Calculated Incorporating Wave Orbital Velocity Fluctuations, U.S. Army Corps of Engineers, Vicksburg, MS.

Stauble, Donald K., Holem, Garry W., Byrnes, Mark R., Anders, Fred J., Meisburger, Edward, 1993. SUPERDUCK Beach Sediment Sample Experiment, Technical Report CERC 93-4, U.S. Army Corps of Engineers, Vicksburg, MS.

U.S. Department of Agriculture, 2013. United States Department of Agriculture National Resources Conservation Service Geospatial Data Gateway, http://datagateway.nrcs.usda.gov/.

U.S. Geological Survey, 2003. National Elevation Dataset 1/9 Arc Second - Northeastern Coast Topobathy, NC – 2003, http://nationalmap.gov.