North Carolina Floodplain Mapping Program
Coastal Flood Insurance Study

TR-10-06

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Coastal Flood Insurance Study

Submittal Number 2, Section 7:
Water Level Validation Study

Technical Report TR-10-06
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7. Storm Surge Validation

Each tropical and extratropical storm validation simulation is started from a 45-day tidal spinup. The tidal elevations (amplitude and phase) at the open boundary (60 degrees West) are specified as in the tidal validation simulation, with the exception of applying appropriate amplitude (nodal factor) and phase (equilibrium argument) adjustments to produce tides that are correct for the specific time period of each validation storm. The actual nodal factors, equilibrium arguments, and tidal and meteorological starting dates for each validation simulation are reported in Appendix 1.B. Calendar dates on which the various parts of the simulations start are reported in Table 7.1.

Tropical and extratropical simulations are conducted in a similar manner, except for the source of the wind/pressure fields; wind/pressure fields for the tropical storms are specified with the HBL model and wind/pressure fields for the extratropical storms are specified with the Oceanweather kinematic analysis (see Section 5). All models (waves and surge) are run for the duration of the wind/pressure event. The WWIII and SWAN model validation is presented in the wave validation section (Section 6). The tropical and extratropical storm validation simulations were performed on RENCI's high-performance Dell supercomputer.

In this section, two different modeled water levels are presented. (i) The surge (SWEL or ADCIRC.0) is the ADCIRC model response to tidal forcing, atmospheric pressure forcing and wind stress forcing. This result does not incude the SWAN wave model. (ii) The surge plus wave setup (SWEL+SETUP or ADCIRC.1) is the ADCIRC model response to the forces listed above plus the additional force produced by the wave radiation stress gradients derived from the SWAN model. We describe here the spatial character of these modeled water levels and the model skill versus observed water levels from available NOAA tide gauges and high-water mark (HWM) data collected after storms. All data analysis is performed in NAVD88. The NOAA gauge analysis uses detided observed and modeled water levels.

Maximum water levels (SWEL+SETUP, which includes the tides) for each storm are shown in Figure 7.1, the wave setup contributions to the total water level are shown in Figure 7.2, maximum significant wave heights are shown in Figure 7.3, and the maximum wave force magnitudes are shown in Figure 7.4. The maximum observed and modeled water levels, as well as comparison statistics, are reported in Table 7.3. These are cited below, where each storm is summarized. Overall, the six storms exhibited significantly different responses in coastal North Carolina and therefore form a comprehensive validation of the wind, wave and surge model suite.

TABLE 7.1. Start and end times for the validation simulation components, and run lengths in days.					
Storm	Tidal Start Date	Met Start Date	Rad-Stress Start Date	Simulation End Date	Met length, Total Run Length [days]
Emily (1993)	1993-07-13 00Z	1993-08-27 00Z	1993-08-31 00Z	1993-09-01 18Z	5.7, 50.7
Fran (1996)	1996-07-16 00Z	1996-08-30 00Z	1996-09-05 12Z	1996-09-07 00Z	7.8, 52.8
Isabel (2003)	2003-07-31 00Z	2003-09-14 00Z	2003-09-18 12Z	2003-09-19 12Z	5.5, 50.5
Ophelia (2005)	2005-07-24 00Z	2005-09-07 00Z	2005-09-10 12Z	2005-09-17 00Z	10.0, 55.0
ET20060827	2006-07-13 00Z	2006-08-27 00Z	2006-08-27 00Z	2006-09-03 12Z	8.0, 53.0
ET20061117	2006-10-03 00Z	2006-11-17 00Z	2006-11-17 00Z	2006-11-26 00Z	8.0, 53.0

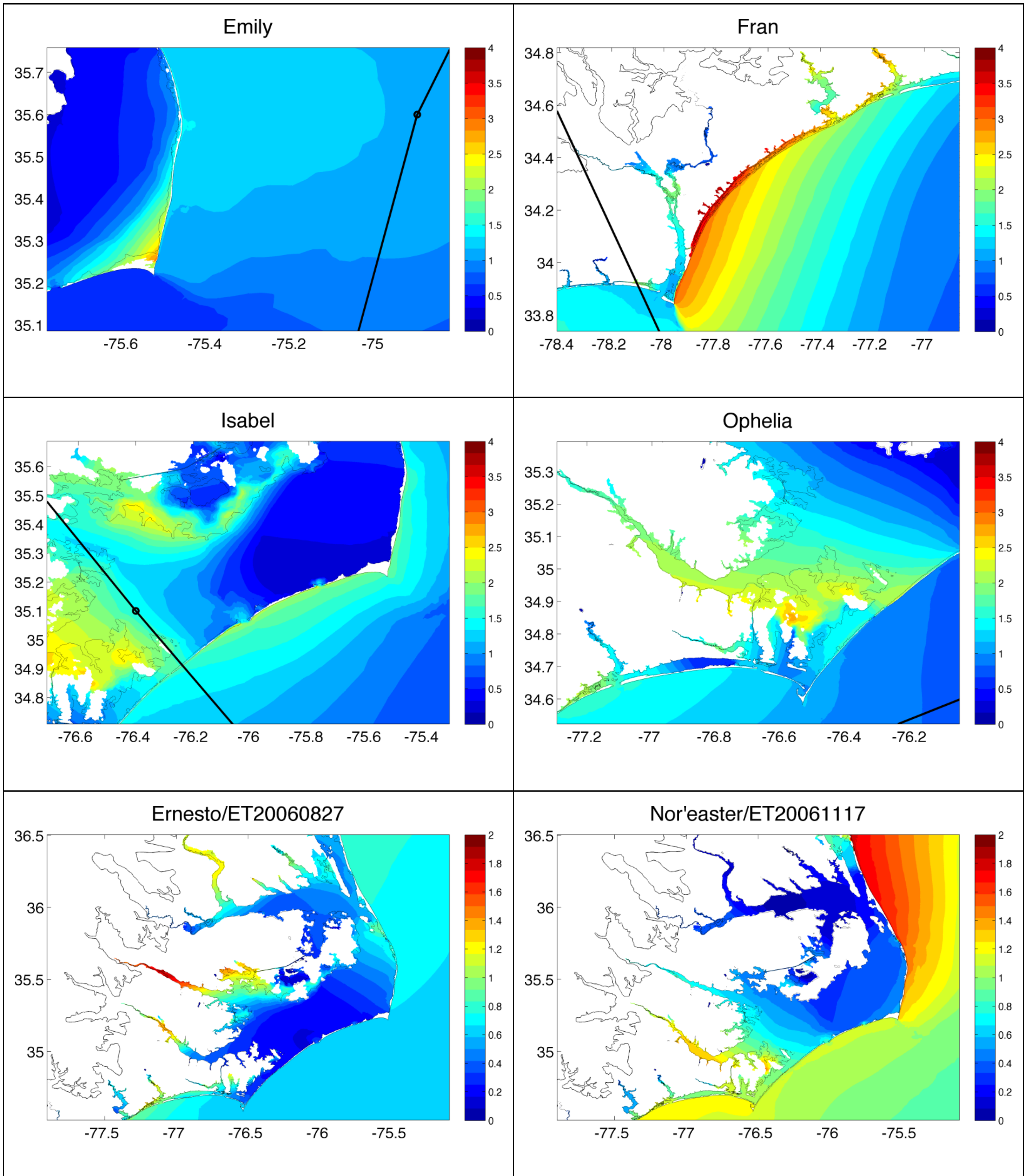


Figure 7.1. Spatial plots of the maximum water level for each validation simulation. The maximum elevations are from the SWEL+SETUP solutions and include the tides. The color scale for the tropical storms is 0 to 4 meters NAVD88. The color scale for the extratropical water levels is 0 to 2 meters NAVD88.

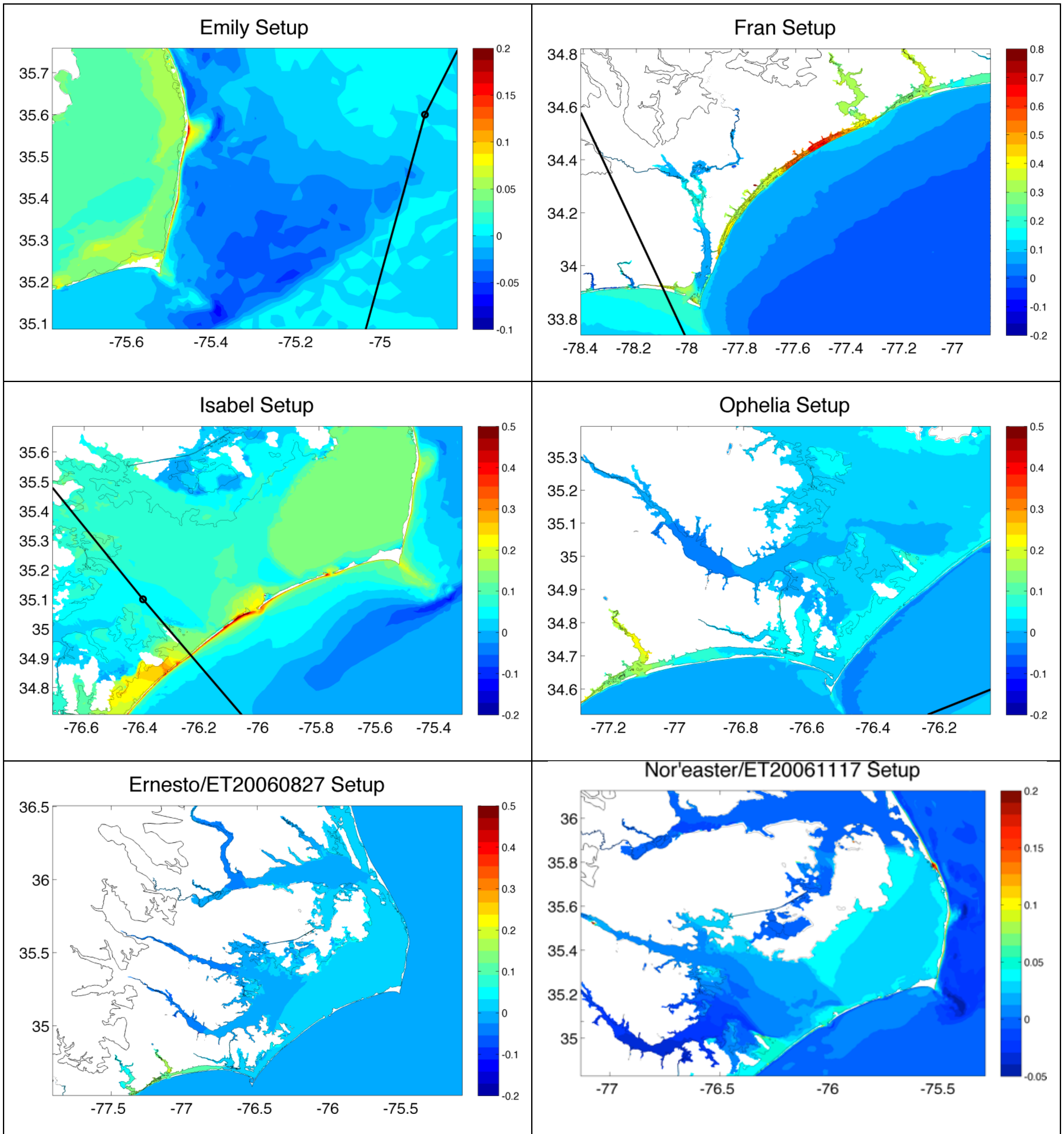


Figure 7.2. Spatial plots of the DIFFERENCE (SETUP) in meters between the SWEL+SETUP and SWEL solution maximum water levels.

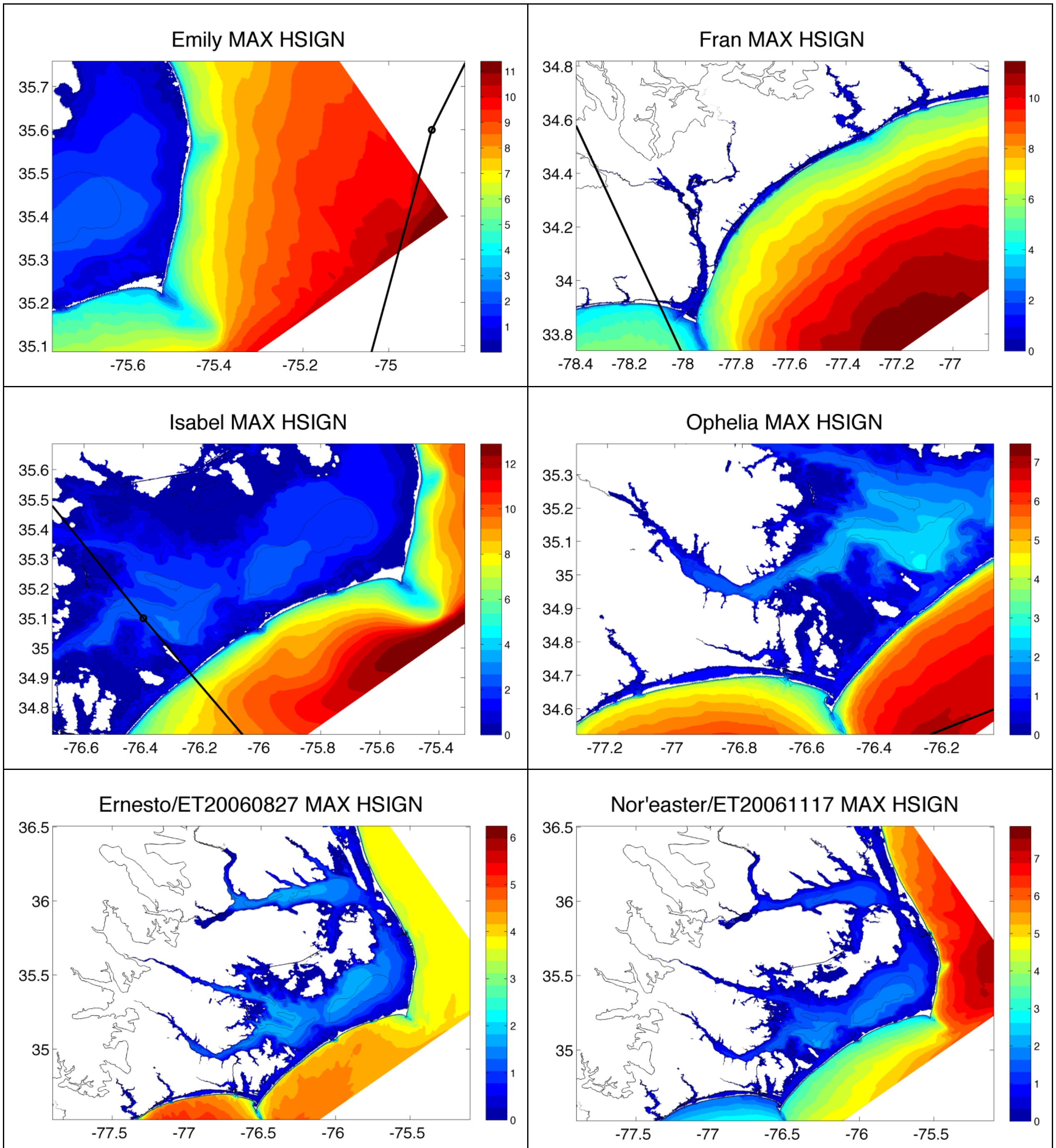


Figure 7.3. Spatial plots of the maximum significant wave height (m) over each simulation, in the region of maximum storm surge. Results are shown only for the relevant SWAN inner grid. The tropical storm tracks are shown with thick black lines.

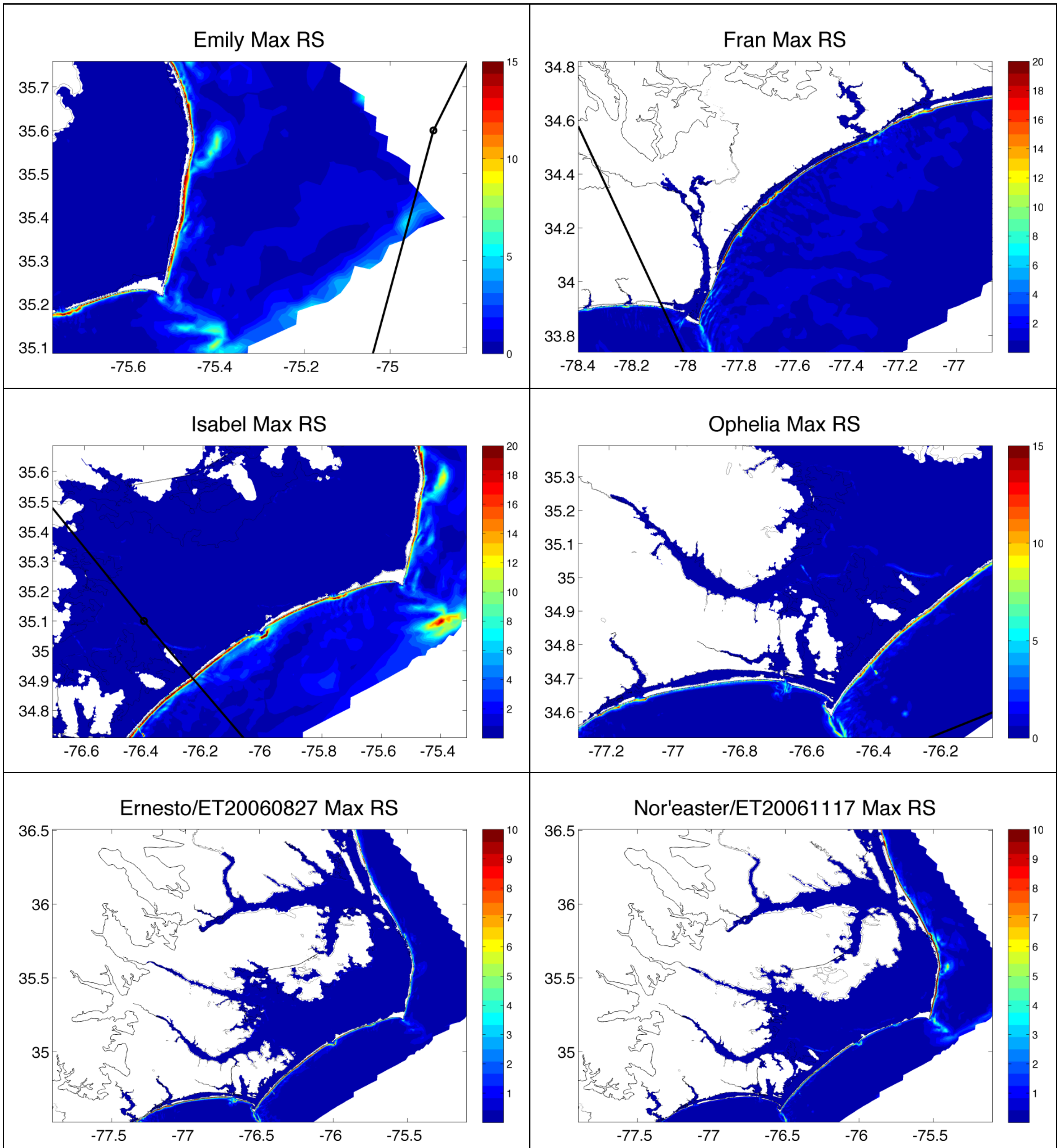


Figure 7.4. Spatial plots of the maximum radiation stress gradient magnitude (N/m^2) over each simulation, in the region of maximum storm surge. Results are shown only for the SWAN inner grid, as interpolated onto the ADCIRC grid. The tropical storm tracks are shown with thick black lines.

NOAA Gauge Comparisons

Hourly water level observations from the NOAA gauges in North Carolina were collected for comparison to the ADCIRC time series output. ADCIRC water levels were saved at each gauge station every 10 min for the analysis. For each storm, a 15-day time series of observations was retrieved from the NOS Tides Online website in NAVD88, except for the Beaufort station which is not available in NAVD88. The datum translation grid (see Submittal One) was used to translate this station data from MSL to NAVD88. The tidal content of the modeled and observed time series has been removed prior to the data analysis by subtraction of the tidal prediction from the total water level signals.

Analysis of long-term water level observations from the NOAA gauges in North Carolina indicates the existence of low frequency variability in the coastal water levels. For example, a 30-day low pass filter of the water level record from the Duck Pier gauge shows low frequency variability of approximately 25 cm above or below zero (Figure 7.5a). Coastal water levels are the result of forces explicitly included in the current model analysis (tides, event scale pressure and wind fields, waves) and processes that are not explicitly included in the current model analysis (seasonal and climatic scale wind and pressure fields, annual heating and cooling of ocean waters, long period tidal forcing, river runoff and Gulf Stream modulations). At weather event time scales, the low frequency coastal water level variation appears as an offset between the modeled and the observed water levels. The water level time series in Figure 7.5a, around the time of Hurricane Isabel, clearly shows this offset (Figure 7.5b). We have computed the mean difference between the modeled and observed water levels prior to each of the validation storms (Table 7.2). The pre-storm offsets vary both temporally and spatially among the storms, indicative of the complex nature of the variability. Most of the offsets are positive, indicating that the observed water levels were generally above the modeled water levels. Since these offsets represent unmodeled processes at the present event-scale analysis, observed NOAA gauge data has been adjusted by removing the offsets prior to comparison with the modeled water levels.

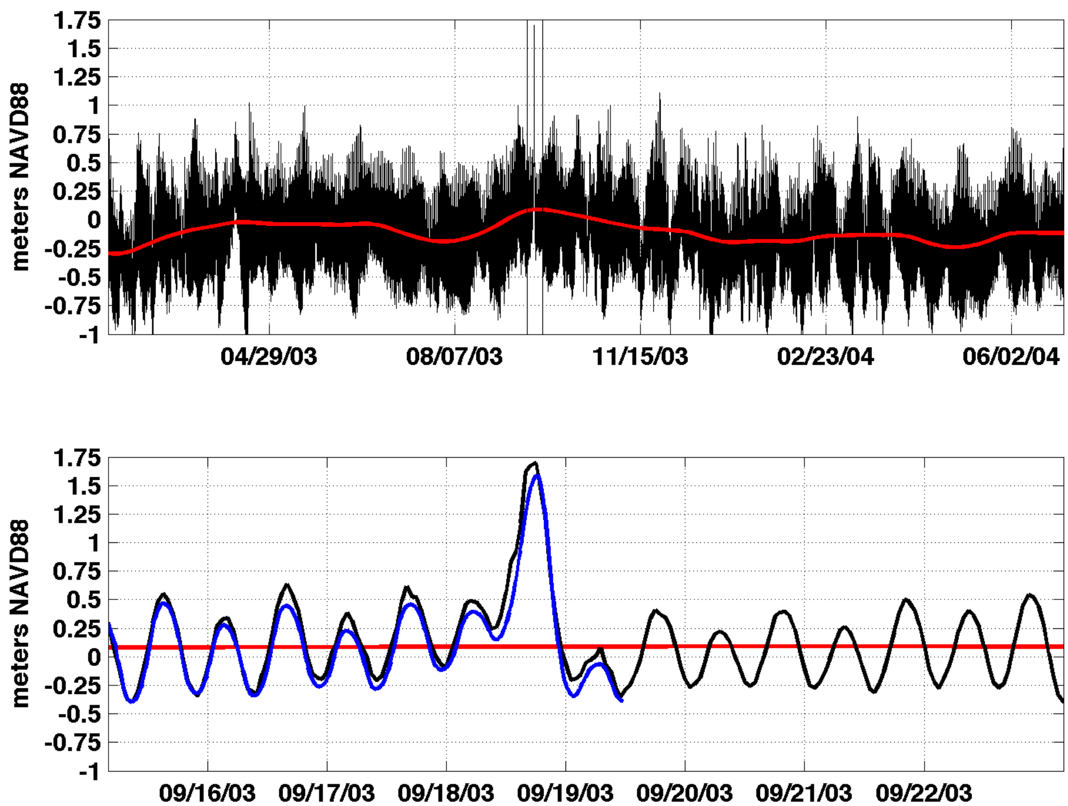


Figure 7.5a,b. Extended water level time series for Hurricane Isabel at the NOS Duck station. a) Observed water level (NAVD88) for the period Feb 2003 through Jun 2004. Raw water level is shown in black, and the 30-day lowpass filtered water level is shown in red. The vertical gray lines bracket the time period of maximum water level caused by Hurricane Isabel. b) Detail of the maximum surge, which occurred at 18Z on 18 Sep. At this time scale, the low-frequency signal appears as a relatively constant offset.

Table 7.2. Summary of pre-storm offsets in meters. The values are subtracted to the NOAA gauge observations for the adjusted statistics. Stations and storms without gauge observations are marked with a dash.

	Duck	**Oregon I.**	**Beaufort**	**Wilming.**	**Wrights.**	**Southport**	**Sunset B.**
Emily	-0.03	-	-	-0.06	-	-	-
Fran	0.12	0.17	0.10	0.05	-	-	-
Isabel	0.10	0.08	0.03	0.00	-	-	-
Ophelia	0.08	0.00	0.15	0.00	0.10	-	-
Ernesto	0.13	0.02	0.07	0.00	0.02	0.02	0.05
Nor'easter	0.07	0.15	0.05	0.05	0.00	0.05	0.10

Hurricane Emily (1993)

Hurricane Emily did not make landfall (Figures 4.1 and 7.1), but the storm surge was still substantial in some areas. The modeled SWEL+SETUP water level (Figure 7.2) was largest along the eastern interior side of Pamlico Sound with a maximum of 2.8 m, and along the ocean side of the Outer Banks with maxima of 1.0 to 1.5 m. The wave setup contribution to the total modeled water level (Figure 7.2; see Figure 7.4 for corresponding maximum radiation stress gradient force magnitude) reached approximately 0.2 m on the ocean side between Cape Hatteras and Rodanthe, and approximately 0.05 m on the eastern side of Pamlico Sound.

The only two NOAA stations available during Hurricane Emily are Duck Pier and Wilmington. Figure 7.6 shows the time series from the SWEL and SWEL+SETUP simulations and the observed NOAA gauge data. The storm had only a weak effect on the peak water level at Duck and no identifiable effect at Wilmington, due to the considerable distance that Emily passed offshore. Table 7.3 reports the observed and modeled peak water levels and the statistics of the difference time series. At the Duck Pier, the adjusted, detided observed peak water level reached 0.62 m versus the modeled SWEL+SETUP water level of 0.41 m. Wave setup was negligible at the gauge location (Figure 7.2). The rms error of the difference (observed-modeled) water level is 0.12 m. The modeled and observed time series are well correlated, although it appears that the modeled surge occurs roughly 4 hours prior to the observed surge. SinceHurricane Emily was a bypassing storm and was a fair distance from shore, it is likely that the HBL wind fields this far from the RMW are missing the true phasing of the peak winds in the area.

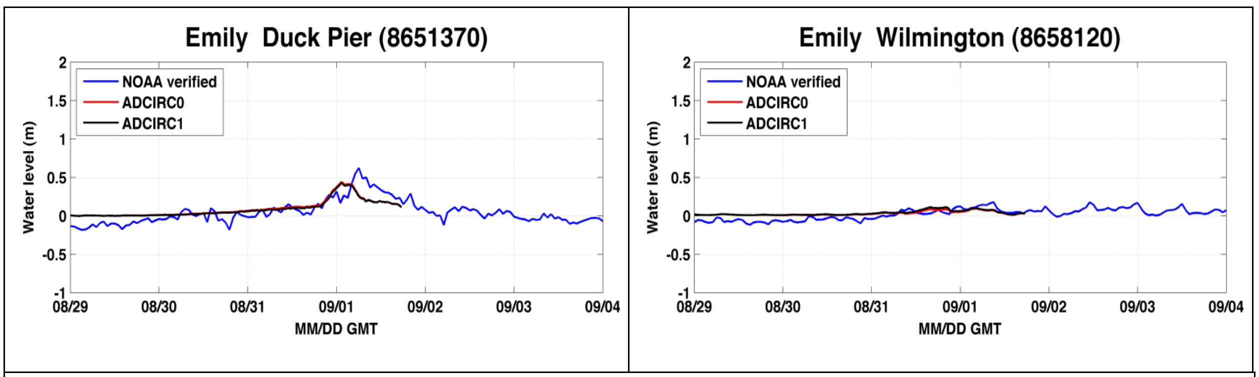


Figure 7.6. Time series of observed (adjusted, detided**)** and modeled (detided) water levels for Hurricane Emily at available NOAA tide gauges. The observed water levels are in blue, and the modeled water levels are in red and black for the SWEL (ADCIRC.0) and SWEL+SETUP (ADCIRC.1) simulations, respectively.

Table 7.3. Statistics for NOAA water level gauge comparisons, computed over the time span in common between the observations and the ADCIRC simulations. Observed Peak Water Levels: Obs = raw, Adj Obs = detided and offset. Skill statistics are computed computed using detided model results and detided/offset observation time series.

		Peak Water Level				RMS		Mean		Correlation		Difference	
Storm	**Statn**	**Obs**	**Adj Obs**	**Adc.0**	**Adc.1**	**Adc.0**	**Adc.1**	**Adc.0**	**Adc.1**	**Adc.0**	**Adc.1**	**Adc.0**	**Adc.1**
Emily	Duck	0.90	0.62	0.42	0.41	0.12	0.12	-0.03	-0.03	0.80	0.81	0.20	0.21
	Wilm	0.78	0.18	0.09	0.11	0.06	0.07	-0.03	-0.04	0.79	0.76	0.09	0.07
Fran	Duck	0.95	0.24	0.19	0.18	0.09	0.08	-0.01	-0.01	0.47	0.48	0.05	0.06
	Oregon	0.63	0.38	0.36	0.43	0.09	0.10	-0.05	-0.07	0.88	0.87	0.02	-0.05
	Beauf	1.35	1.43	1.11	1.26	0.07	0.07	-0.01	-0.03	0.98	0.98	0.32	0.17
	Wilm	1.39	1.52	2.02	2.21	0.15	0.16	-0.01	-0.04	0.95	0.96	-0.50	-0.69
Isabel	Duck	1.83	1.26	1.20	1.27	0.08	0.08	0.04	0.03	0.98	0.97	0.06	-0.01
	Oregon	1.48	1.34	0.59	0.73	0.26	0.21	0.11	0.05	0.83	0.89	0.75	0.61
	Beauf	1.20	0.80	0.66	0.74	0.13	0.10	0.04	0.01	0.82	0.89	0.14	0.06
	Wilm	0.73	0.44	0.37	0.40	0.07	0.08	-0.03	-0.05	0.90	0.89	0.07	0.04
Ophelia	Duck	1.06	0.25	0.17	0.17	0.09	0.09	0.00	0.00	0.61	0.60	0.08	0.08
	Oregon	0.49	0.30	0.27	0.29	0.14	0.14	-0.02	-0.04	0.44	0.46	0.03	0.01
	Beauf	1.48	0.73	0.56	0.62	0.11	0.11	-0.02	-0.03	0.79	0.82	0.17	0.11
	Wilm	0.90	0.37	0.17	0.23	0.26	0.24	0.10	0.08	0.65	0.66	0.20	0.14
	Wright.	1.32	1.14	1.17	1.17	0.12	0.11	0.00	0.01	0.94	0.95	-0.03	-0.03
Ernesto	Duck	0.87	0.42	0.38	0.36	0.10	0.10	0.00	0.00	0.79	0.78	0.04	0.06
	Oregon	0.90	0.70	0.67	0.69	0.09	0.08	0.04	0.03	0.93	0.93	0.03	0.01
	Beauf	0.81	0.51	0.58	0.64	0.10	0.11	-0.07	-0.07	0.85	0.85	-0.07	-0.13
	Wilm	0.90	0.58	0.74	0.80	0.08	0.09	0.02	0.01	0.88	0.89	-0.16	-0.22
	Wright	1.17	0.88	0.88	0.88	0.11	0.11	-0.02	-0.02	0.83	0.84	0.00	0.00
	Southp	0.84	0.47	0.67	0.74	0.08	0.09	-0.02	-0.03	0.81	0.82	-0.20	-0.27
	Sunset	0.84	0.26	0.77	0.80	0.16	0.16	-0.10	-0.10	0.63	0.63	-0.51	-0.54
N'easter	Duck	1.66	0.92	1.08	1.10	0.18	0.18	-0.06	-0.06	0.91	0.91	-0.16	-0.18
	Oregon	0.64	0.43	0.35	0.38	0.10	0.08	0.07	0.04	0.96	0.97	0.08	0.05
	Beauf	1.01	0.40	0.50	0.52	0.07	0.08	0.00	-0.01	0.93	0.92	-0.10	-0.12

	Wilm	0.97	0.38	0.60	0.62	0.21	0.20	0.09	0.07	0.75	0.75	-0.22	-0.24
	Wrights	1.01	0.51	0.76	0.77	0.14	0.14	-0.05	-0.05	0.88	0.88	-0.25	-0.26
	Southp	1.07	0.25	0.62	0.64	0.12	0.13	-0.03	-0.04	0.84	0.84	-0.37	-0.39
	Sunset	1.18	0.19	0.71	0.72	0.21	0.22	-0.15	-0.16	0.75	0.74	-0.52	-0.53
ALL		1.05	0.62	0.64	0.69	0.12	0.12	-0.01	-0.02	0.81	0.82	-0.03	-0.07

Hurricane Fran (1996)

Hurricane Fran made landfall just west of the mouth of the Cape Fear River. Among all of the simulated storms, Hurricane Fran generated the highest surge. The modeled SWEL+SETUP water level reached 3.5 to 4.0 m along the ocean side, southern portion of Onslow Bay (Figure 7.1) and decreased northward along the coast. Wave setup contributions to the total water levels (Figure 7.2) are largest (0.8 m) in the middle of Onslow Bay, on the coast near Sneads Ferry, North Carolina.

Data from the NOAA gauges indicate that the primary surge associated with Fran occurred early on September 6th at Beaufort and Wilmington (Figure 7.7). These locations were subject to onshore blowing winds from the right hand side of the storm (Figure 5.4a,b). At Oregon Inlet, the onshore winds were weaker and initially created a drawdown along the backside of the barrier island followed by a modest surge as the winds rotated from easterly to southerly (Figure 5.4a). The surge at Duck was much smaller; the most significant effect was the drawdown that occured at approximately the same time as the surge at the Oregon Inlet gauge.

The observed and modeled peak water levels at the available NOAA gauges are given in Table 7.3. The difference in peak water level ranged from -0.05 m at Oregon Inlet to 0.06 m at Duck, 0.17 m at Beaufort and 0.69 m at Wilmington. The rms error ranged from 0.07 to 0.16 m. Figure 7.7 compares the water level time series during Hurricane Fran for the SWEL and SWEL+SETUP simulations and the adjusted, detided observed water level. The large observed water level of about 1.52 m at Wilmington is over predicted by 0.69 m, which is consistent with the wind model over predicting the wind speed on the rising side of the storm at Frying Pan Shoals and Wilmington, (Figure 5.4b). The water level timeseries are well captured at each of the other stations. The increased water level due to wave setup is 0.07 m at Oregon Inlet, 0.15 m at Beaufort and 0.19 m at Wilmington (Figure 7.7, Table 7.3). In these cases the wave setup does not appear to be locally generated, but rather is due to the inland influence of wave setup generated in open coastal waters.

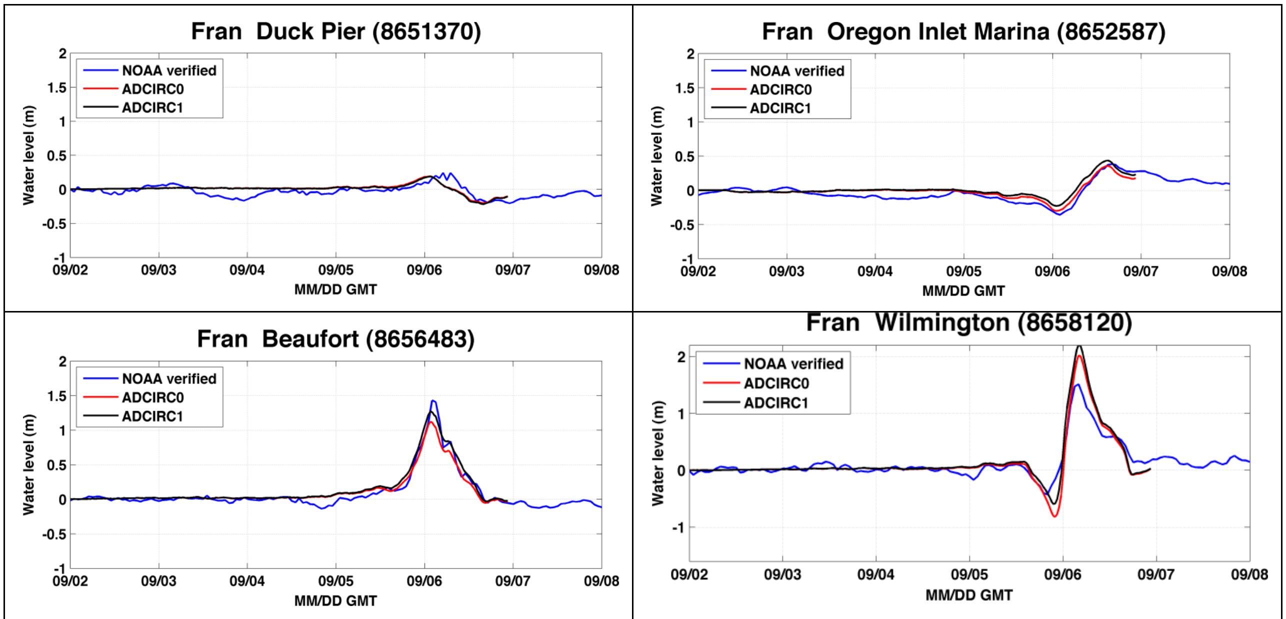


Figure 7.7. Time series of observed (adjusted, detided) and modeled (detided) water levels for Hurricane Fran at available NOAA tide gauges. The observed water levels are in blue, and the modeled water levels are in red and black for the SWEL (ADCIRC.0) and SWEL+SETUP (ADCIRC.1) simulations, respectively.

Hurricane Isabel (2003)

Hurricane Isabel made landfall along the Outer banks, midway between Cape Lookout and Ocracoke Inlet. The modeled SWEL+SETUP water levels are between 1.20 and 2.00 m from Cape Lookout up the Outer Banks (Figure 7.1), with maximum water levels of 2.75 m occurring in the lower Neuse River Estuary. The wave setup contribution to the total water level for the nearshore region reached 0.37 m on the ocean-side of Ocracoke Inlet (Figure 7.2).

The observed and modeled water levels at the available NOAA gauges are shown in Figure 7.8, with statistics reported in Table 7.3. Observed surge at the NOAA gauge locations reached 1.26, 1.34, 0.80, and 0.44 m at Duck, Oregon Inlet, Beaufort, and Wilmington, respectively. The peaks are well modeled at Duck, Beaufort, and Wilmington. At the Oregon Inlet gauge, the primary surge corresponds to the time when the backside of the storm drives water from west to east across Pamlico Sound. The model under predicts this by 0.61 m. The Wilmington NOAA station is well to the left of the storm and the direct effect of the hurricane winds appear to be a negative surge of roughly 40 cm. Both the model and the observations indicate a positive water level response from late on September 18th into the early part of the 19th. While the exact forcing mechanism is not clear, this appears to correspond to winds blowing in the offshore direction in the Cape Fear region and therefore may represent a remotely triggered process. Regardless, it is well captured by the model.

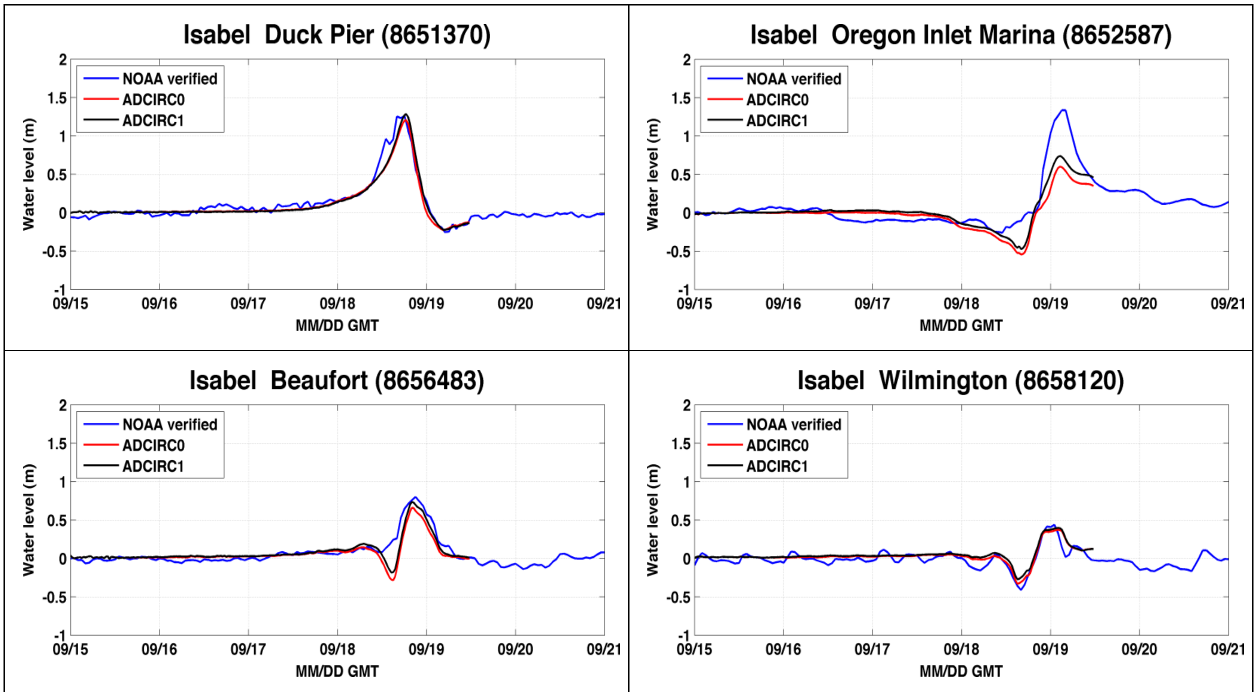


Figure 7.8. Time series of observed (adjusted, detided) and modeled (detided) water levels for Hurricane Isabel at available NOAA tide gauges. The observed water levels are in blue, and the modeled water levels are in red and black for the SWEL (ADCIRC.0) and SWEL+SETUP (ADCIRC.1) simulations, respectively.

Hurricane Ophelia (2005)

Hurricane Ophelia was a slow-moving, bypassing storm that spent about 7 days off the North Carolina coast. Peak modeled water levels (SWEL+SETUP+TIDES, Figure 7.1) reached 1.50 to 2.00 m in Onslow Bay, with larger water levels exceeding 2.50 m in southern Pamlico Sound. Wave setup was relatively small (Figure 7.2) at 0.10 to 0.15 m along the Onslow Bay shore.

The adjusted, detided peak water levels at the NOAA gauges (Table 7.3) reached 0.73 and 1.14 m at Beaufort and Wrightsville Beach, respectively, with smaller peak values of 0.30 and 0.37 m at Oregon Inlet and Wilmington. Figure 7.9 shows time series of the modeled and observed water levels for Hurricane Ophelia. The timing of the minimum and maximum surge levels is very good. The observed surge and setdown after the storm passes is well modeled at Beaufort and Wrightsville Beach. The modeled water level set down at Wilmington is stronger than the observed set down. This is consistent with the model wind speed being substantially stronger than the observed wind speed at Southport and Kure Beach (Figure 5.8b, Table 5.4), thereby forcing too strong of a model water level response.

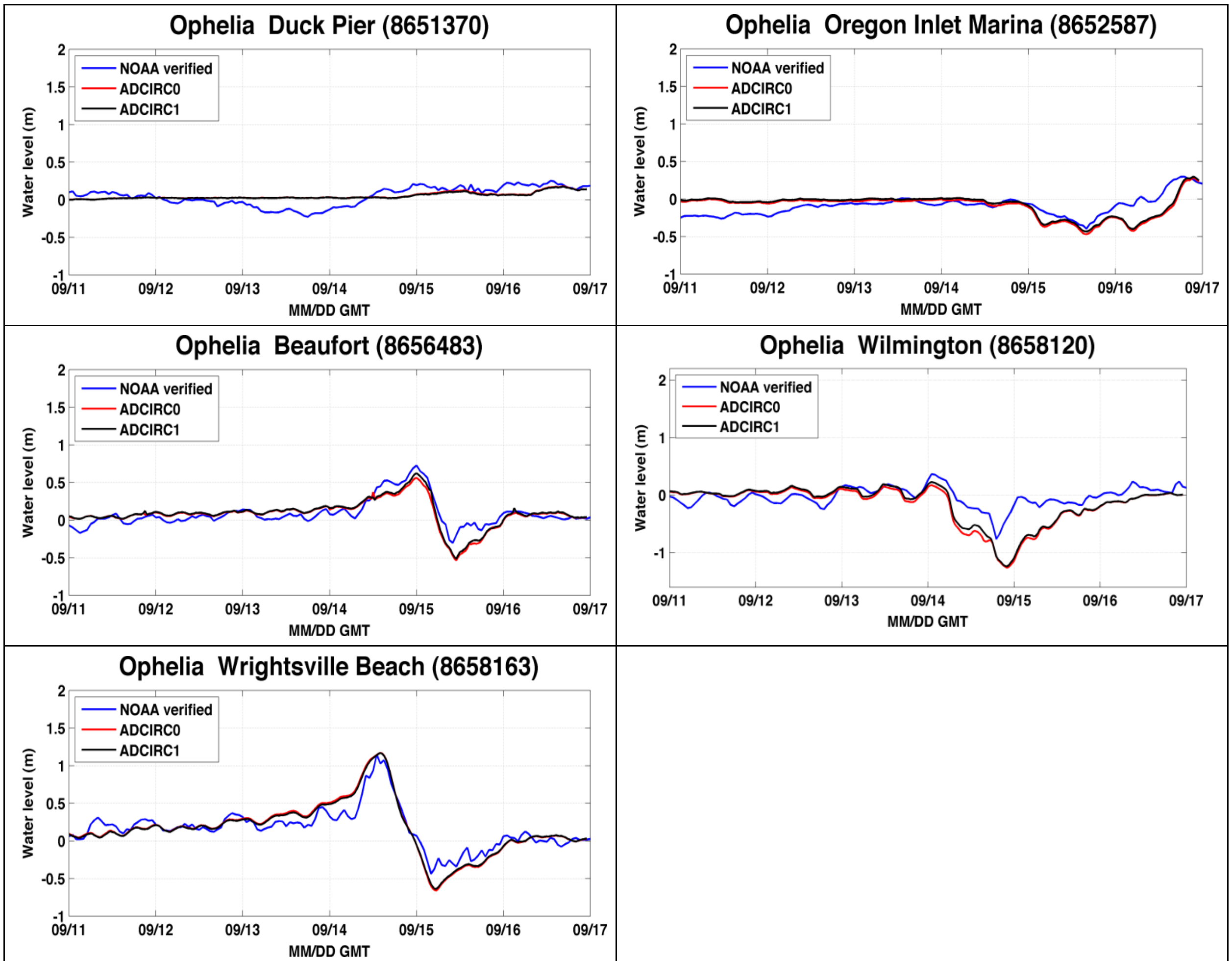


Figure 7.9. Time series of observed (adjusted, detided) and modeled (detided) water levels for Hurricane Ophelia at available NOAA Tide gauges. The observed water levels are in blue, and the modeled water levels are in red and black for the SWEL (ADCIRC.0) and SWEL+SETUP (ADCIRC.1) simulations, respectively.

Extratropical 20060827 (Ernesto)

The Ernesto storm system made landfall near Oak Island as a strong tropical storm, and continued its inland path as an extratropical system. Adjusted peak water levels (Table 7.3) reached 0.88 m at Wrightsville Beach, and were 0.26 to 0.70 m at the other NOAA gauge stations. The rms error among all stations is small at 0.08 to 0.16 m. Time series plots for all NOAA stations for ET20060827 (Ernesto) are shown in Figure 7.10. Adjusted, detided peak water levels are well captured at Duck, Oregon Inlet, Beaufort, and Wrightsville Beach. Water levels at Wilmington and Southport are overpredicted by about 0.20-0.25 m, while the small peak at Sunset Beach (0.26 m) is overpredicted by about 0.50 m. The contribution to the total water level from wave breaking forces is small.

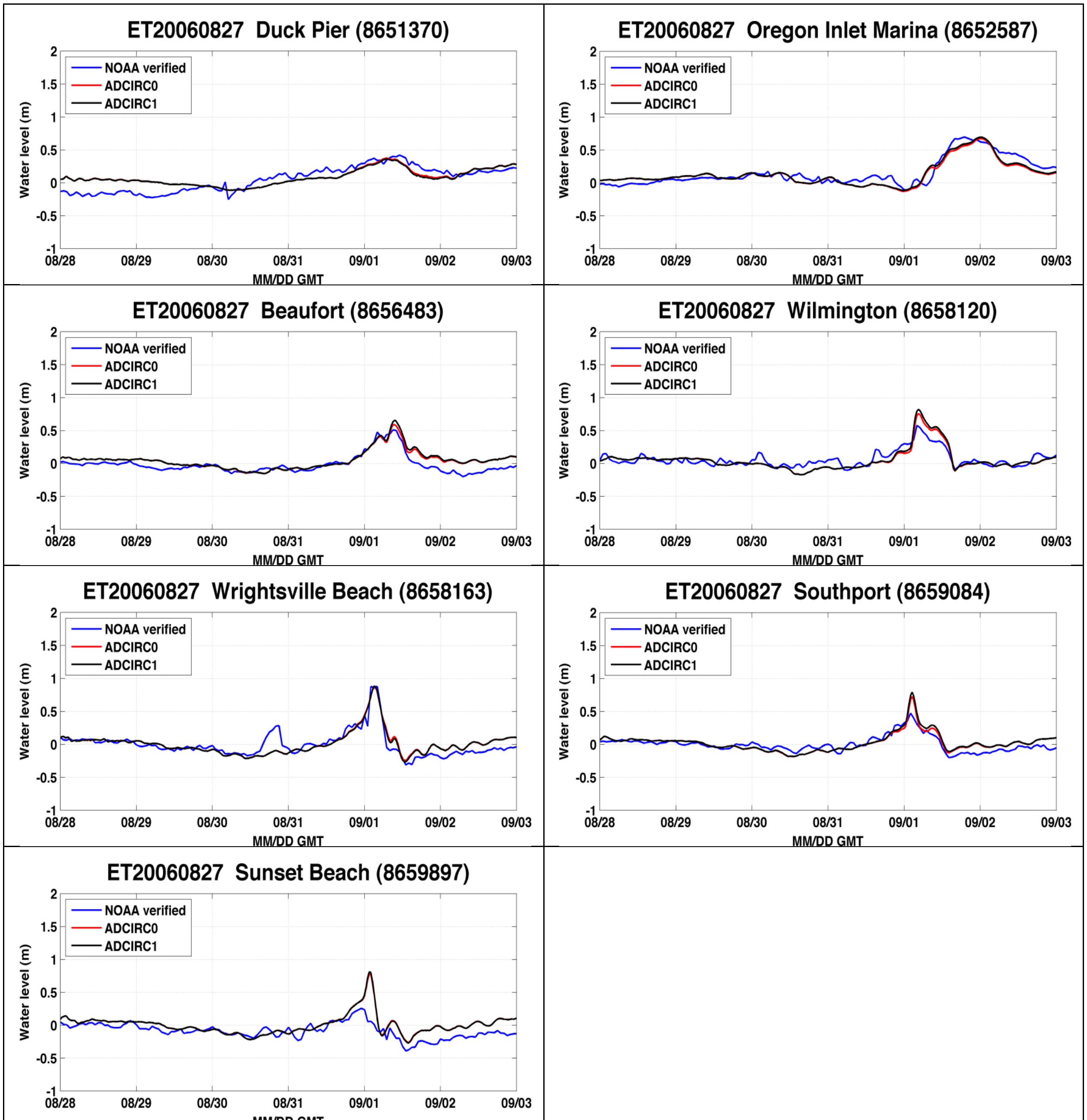


Figure 7.10. Time series of (adjusted, detided) observed and modeled (detided) water levels for extratropical storm 20060827 (Ernesto) at available NOAA tide gauges. The observed water levels are in blue, and the modeled water levels are in red and black for the SWEL (ADCIRC.0) and SWEL+SETUP (ADCIRC.1) simulations, respectively.

Extratropical 20061117 (Nor'easter)

Extratropical storm 20061117 was a typical nor'easter storm. The simulated total surge (including tides) exceeded 1.25 m along much of the northern North Carolina coast. Time series plots of the adjusted, detided water levels are shown in Figure 7.11 for ET20061117. The northern stations (Duck, Oregon Inlet, Beaufort) show moderate observed surges of 0.40 to 0.93 m. The modeled surge is reasonably well captured at Oregon Inlet and Beaufort, and the phasing of the peak surge is very good. However, the smaller observed response south of Cape Hatteras is generally over predicted, by about 0.50 m at Sunset Beach. The contribution to the total water level from the wave breaking forces is negligible.

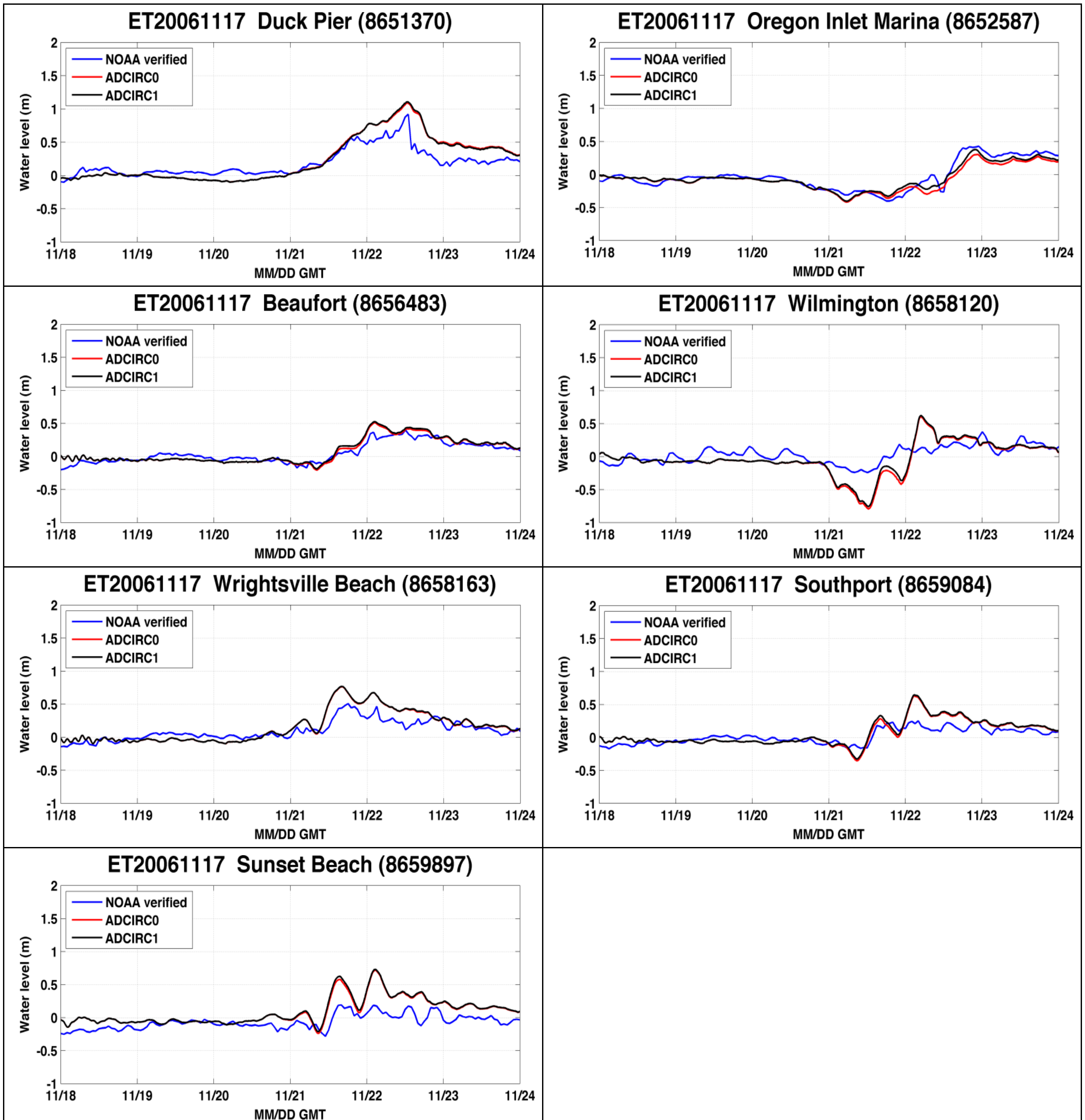


Figure 7.11. Time series of (adjusted, detided) observed and modeled (detided) water levels for extratropical storm 20061117 (Nor'easter) at available NOAA tide gauges. The observed water levels are in blue, and the modeled water levels are in red and black for the SWEL (ADCIRC.0) and SWEL+SETUP (ADCIRC.1) simulations, respectively.

High-Water Mark Analysis

High-water mark observations are collected by a variety of agents with minimal reporting standards. This makes it difficult to implement a common strategy for screening the HWMs for quality, and consequently each data set has been scrutinized independently. An initial quality screening and elimination of suspicious HWM data was made based on personal knowledge of North Carolina Sea Grant Coastal Specialist Spencer Rogers and consistency between closely spaced HWM values. Thereafter, locations were examined against Google Earth imagery to mark each as being oceanside (defined as toward the open ocean from the dune crest line), backside (defined as behind the dune crest line), or waterway (not on land, but rather in open water behind the barrier islands). In conjunction with the HWM metadata classification of inside/outside, this was used to further classify the HWMs as sheltered or exposed storm surge. Sheltered encompasses all "inside" HWMs as well as outside locations in waterways (so as to minimize contamination by unmodeled effects such as water level excursions associated with individual wave heights, wave runup and wave splash up).

Comparisons with model results were made using the ADCIRC maximum elevation file, which is updated every model time step to provide the highest water levels computed throughout the simulation. For each storm simulation, the ADCIRC maximum water levels are converted to NAVD88 from MSL (using the translation grid described in Submittal One), interpolated to the HWM locations, and compared to the observed HWM values. Only locations that were wetted in the ADCIRC (SWEL or ADCIRC.0) and ADCIRC+SWAN (SWEL+SETUP or ADCIRC.1) simulations are included in the statistical analysis, although all of the locations are included in the spatial plots for reference. There were no HWMs collected for Hurricane Ophelia or the extratropical storms **(**ET20060827 and ET20061117). The comparison between the model simulations and the observed HWMs will be affected by the same offsets as identified in the gauge data section. However, since we do not have enough observations to construct a spatially varying offset field for each storm to interpolate to the HWM locations, no effort has been made to remove the offset from the HWM data. Rather, the implications of the offset are discussed for each storm as it relates to model error and bias. Table 7.4 reports the HWM analysis statistics and is referred to in the text below. The actual HWM data and modeled values are reported in Appendix 1.E.

Table 7.4. Highwater mark comparison statistics for Hurricanes Emily, Fran, and Isabel. N is the number of wetted locations, rms is the root-mean-square error, mae is the mean absolute-valued error, and mean, min, and max are the average, minimum, and maximum errors, respectively. Errors are computed as the observations minus the modeled values.

			N	rms	mae	mean	min	max
Emily	Sheltered	Adc.0	13	0.33	0.28	0.24	-0.10	0.58
	Sheltered	Adc.1	13	0.29	0.25	0.19	-0.17	0.53
	Exposed	Adc.0	21	0.44	0.40	0.31	-0.33	0.70
	Exposed	Adc.1	21	0.41	0.38	0.26	-0.40	0.64
	Combined	Adc.0	34	0.39	0.34	0.28	-	-
	Combined	Adc.1	34	0.35	0.32	0.23	-	-
Fran	Sheltered	Adc.0	90	0.48	0.43	0.42	-0.23	1.16
	Sheltered	Adc.1	98	0.26	0.19	0.08	-0.54	1.10
	Exposed	Adc.0	39	0.58	0.51	0.48	-0.25	1.17
	Exposed	Adc.1	47	0.32	0.26	0.10	-0.70	0.73
	Combined	Adc.0	129	0.53	0.47	0.45	-	-
	Combined	Adc.1	145	0.29	0.23	0.09	-	-
Isabel	Sheltered	Adc.0	53	0.37	0.27	-0.09	-0.98	0.76
	Sheltered	Adc.1	53	0.37	0.27	-0.15	-1.03	0.50
	Exposed	Adc.0	70	0.34	0.25	-0.07	-0.87	0.72
	Exposed	Adc.1	69	0.35	0.27	-0.13	-0.94	0.60
	Combined	Adc.0	123	0.36	0.26	-0.08	-	-
	Combined	Adc.1	122	0.36	0.27	-0.14	-	-
3 storms	Sheltered	Adc.0	156	0.43	0.36	0.23		
	Sheltered	Adc.1	164	0.30	0.22	0.01		
	Exposed	Adc.0	130	0.43	0.35	0.16		
	Exposed	Adc.1	137	0.35	0.28	0.01		
	Combined	Adc.0	286	0.43	0.36	0.20		
	Combined	Adc.1	301	0.32	0.25	0.01		

Hurricane Emily (1993)

HWM values were gathered from several sources, including the USGS event summary of Weaver and Zembrzuski (1993), and HWM collection materials from Dewberry. Values were used for which the survey report classified the locations as “good” quality or better, based on a reported “error” of 0.05 m or less. High water mark elevations were referenced to NAVD88. The resulting dataset contains 40 HWM locations, as listed in Appendix 1.E.

The HWM locations and values are shown in Figure 7.12. All HWMs are located in the Cape Hatteras area, primarily on the sound side of the dune line. Figure 7.13 shows the HWM locations separated into sheltered/exposed storm surge (based on the HWM data processing described above) and wet/dry (based on whether the locations were wetted during the SWEL+SETUP simulation). Six of the 40 HWM locations remained dry during the SWEL+SETUP simulation. This is discussed further below.

The difference between the observed and modeled HWMs are shown in Figure 7.14, for the sheltered and exposed categories. The same data is shown in scatter plots in Figure 7.15. For both the sheltered and exposed categories, the addition of wave setup increases the modeled maximum water levels by approximately 5 cm at the HWM locations. Due to the surge occurring along the backside of the barrier island, wave heights are depth (and possibly fetch) limited in the shallow sounds and therefore wave setup is expected to be much smaller than it would be for a storm impacting the open coast (e.g., Fran). A histogram of the errors indicates that the distribution is minimally effected by the inclusion of wave setup and that the modeled elevations are biased low by 0.2 to 0.3 m (Figure 7.16). Table 7.4 reports the error statistics; the rms error is approximately 0.3 m for the sheltered locations and approximately 0.4 m for the exposed locations. The mean error ranges from 0.19 to 0.26 m (ADCIRC biased low) with a maximum error of 0.64 m. It is clear from both the histogram and the statistics that the model error is less at the sheltered sites than the exposed sites, suggesting that the exposed sites may be systematically contaminated by wave effects. The observed HWMs, SWEL+SETUP maximum elevation, and the SWAN significant wave heights are shown in Figure 7.17. The SWAN wave heights (red contours) range from 0.25 to 0.75 m in the area of the HWM locations, and may account for some of the discrepancy between the observed and simulation elevations, particularly at the exposed sites. Based on the small pre-storm offset determined at the Duck Pier (2 cm, Table 7.2), which is the closest gauge location to the HWM locations, we are unable to attribute any of the ADCIRC bias to the low-frequency offset.

Figure 7.18 shows the location (Emily_27) of one of the larger HWM errors and the corresponding Google Earth imagery. The error is 0.64 m. This particular location is in a small embayment that is not geometrically represented by the ADCIRC grid and therefore the under prediction of the actual surge at this location can be anticipated.

Figure 7.19 shows two areas that contain HWM locations that were close to wet elements but that did not actually inundate during the SWEL+SETUP simulation. While these have been excluded from the error statistic calculation, in both cases, the closest modeled maximum water levels are in good agreement with the observed HWM elevations.

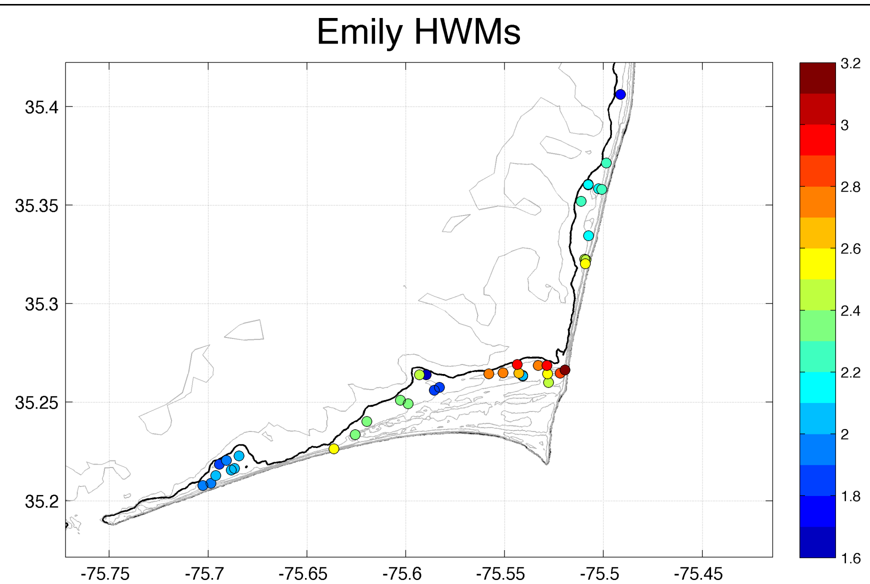


Figure 7.12. Location of HWMs for Hurricane Emily. The color scale is the observed watermark height in meters NAVD88. The coastline is shown with the dark line, and the -1, 1, 2, and 3 meter elevation contours are shown with the solid lines.

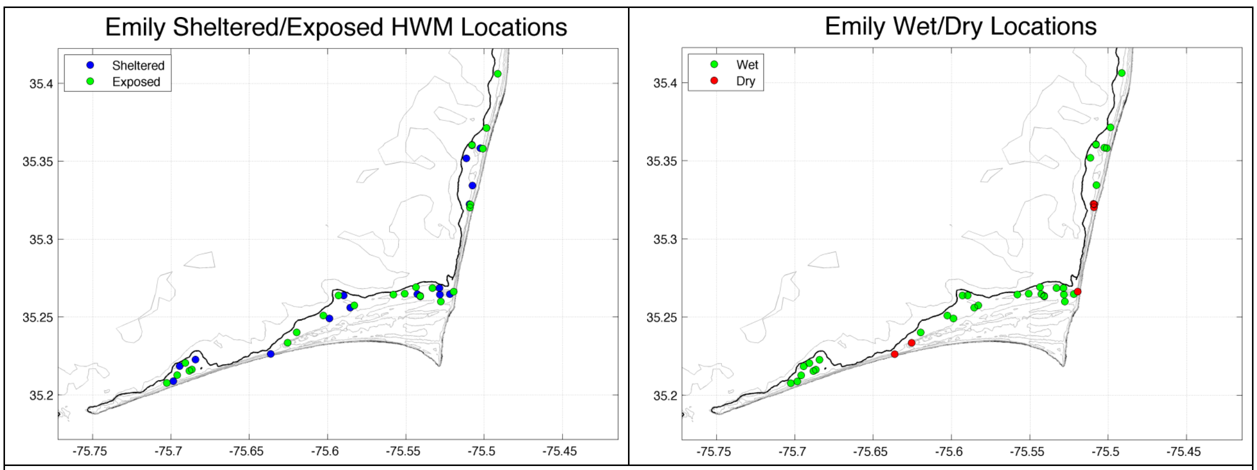


Figure 7.13. Left) Location of HWMs classified as Sheltered and Exposed. Right) Location of HWMs that wet (green) during both ADCIRC.0 and ADCIRC.1 simulations and remained dry (red). The 0 m contour is shown with the black line. The -1, 1, 2, 3 and 4 m elevation contours are shown with the gray lines.

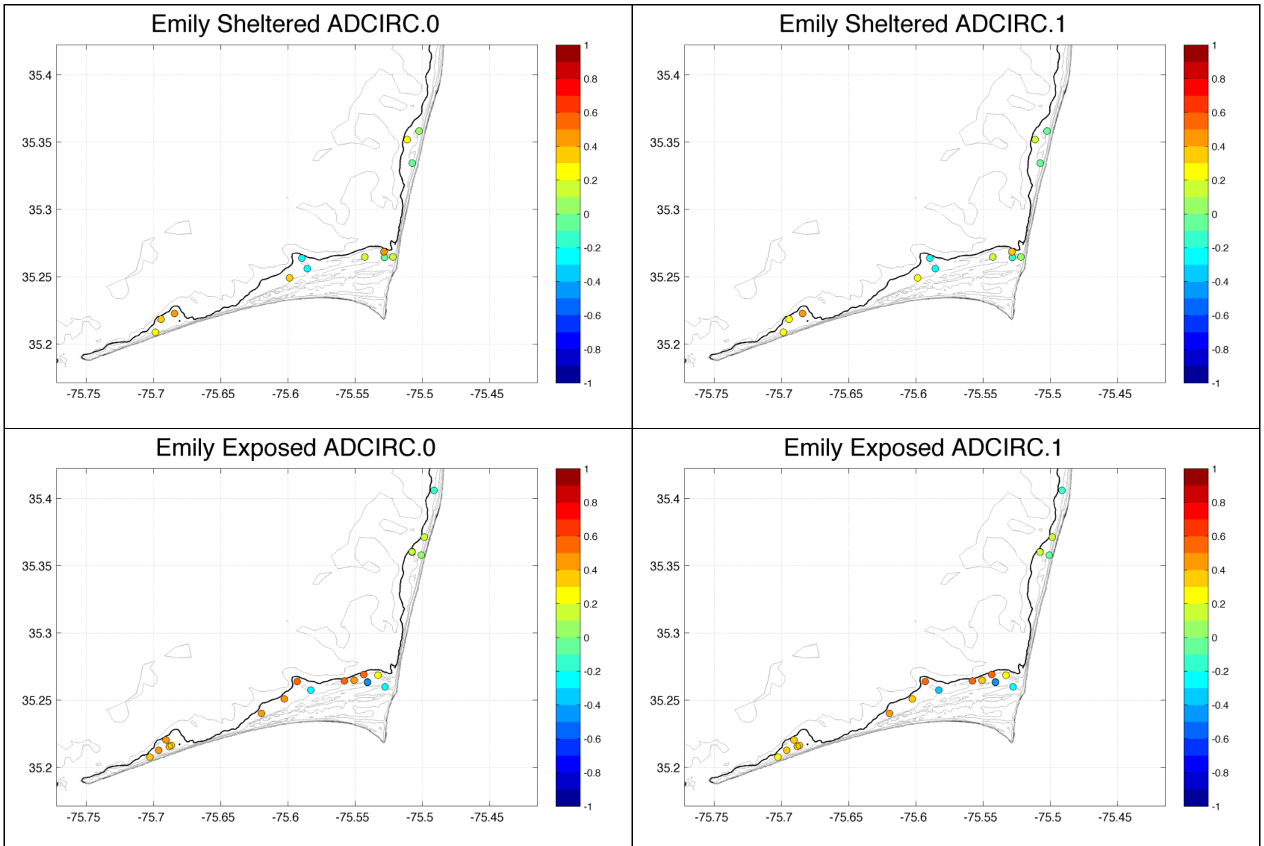


Figure 7.14. Difference between observed HWMs and wetted modeled values (observed – modeled values) for Hurricane Emily. The sheltered locations are shown in the top row, and the exposed locations are shown in the bottom row.

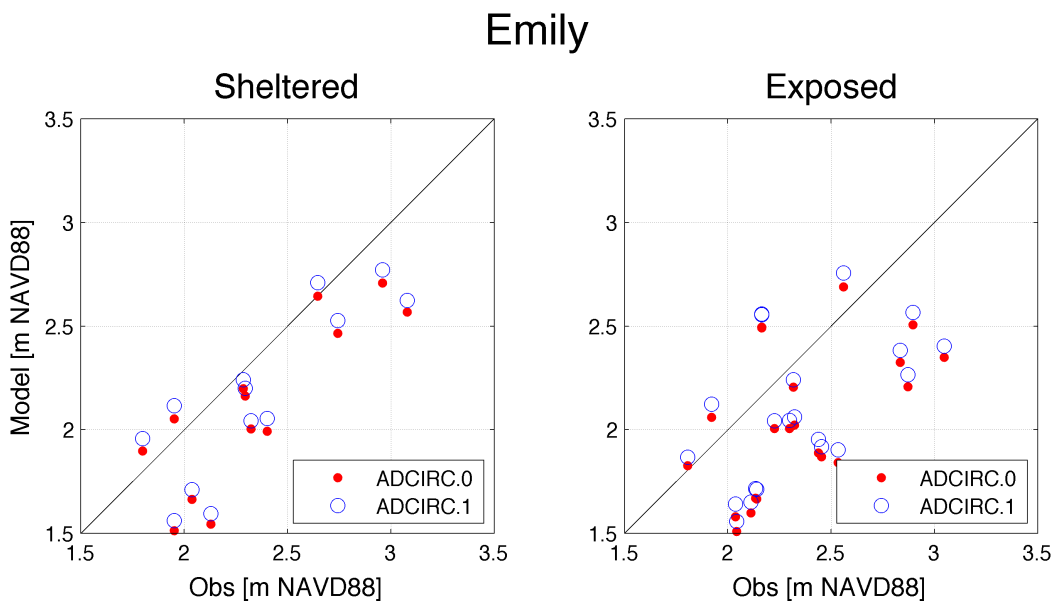


Figure 7.15. Scatter plot of observed and modeled HWMs for sheltered (left) and exposed (right) locations for Hurricane Emily. In each plot, the ADCIRC.0 values are shown with the red dot, and the ADCIRC.1 values are shown with the open, blue circle.

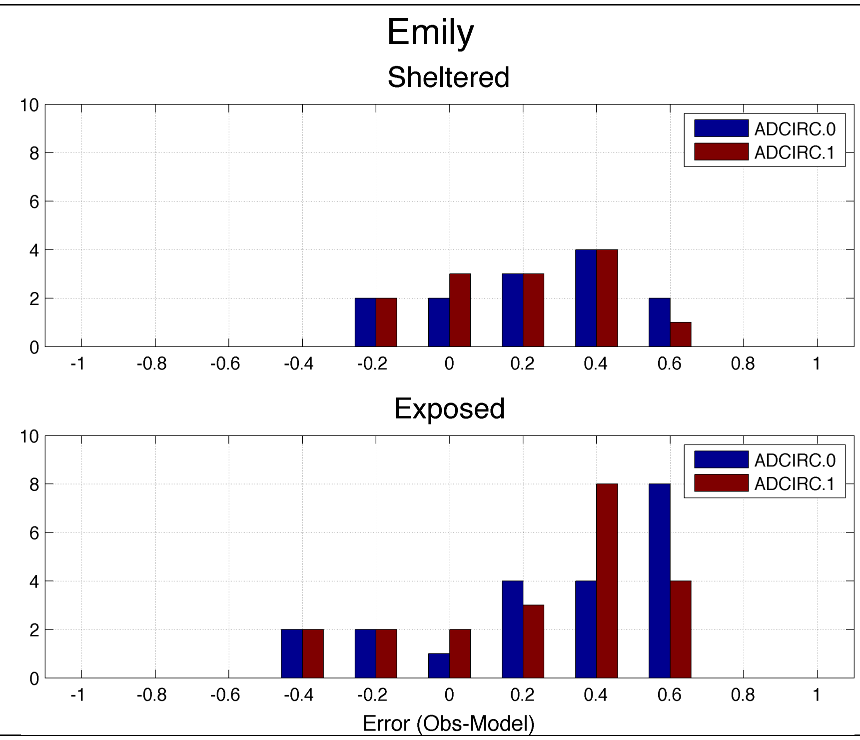


Figure 7.16. Histogram of difference between observed and modeled HWMs for Hurricane Emily separated by sheltered (top) and exposed (bottom) locations. The ADCIRC.0 values are shown with the blue bars, and the ADCIRC.1 values are shown with the red bars.

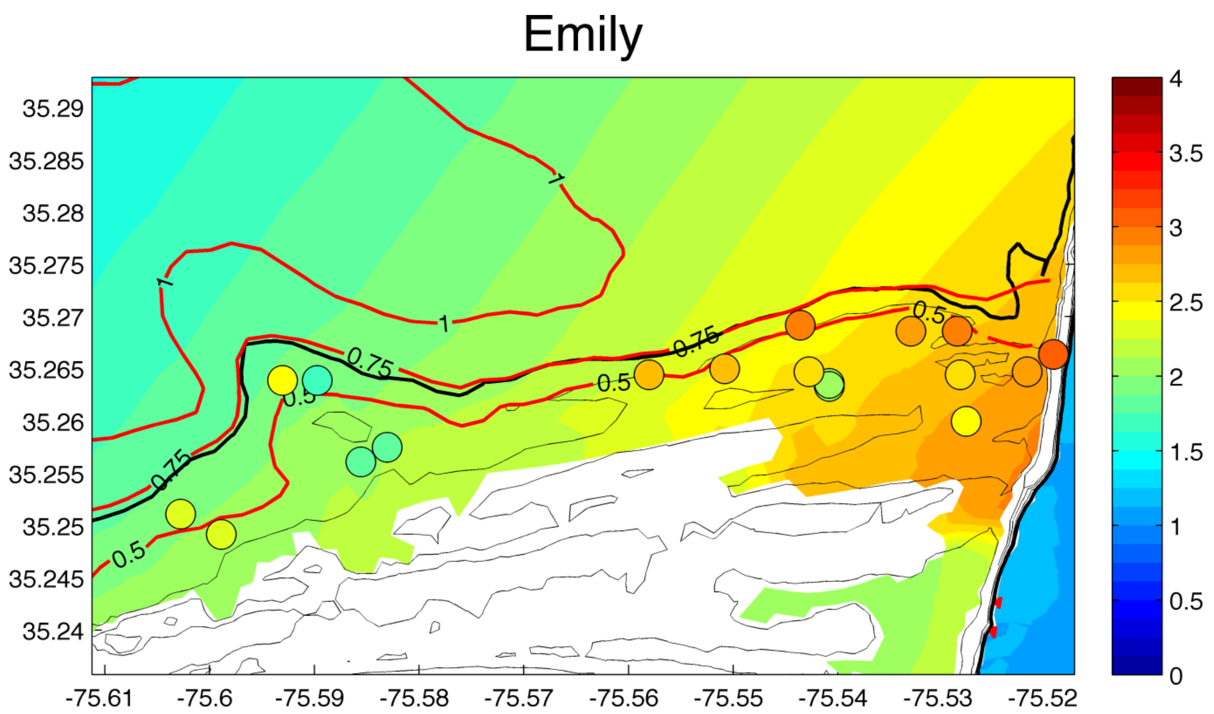


Figure 7.17. Detail plot of the sound side of the Cape Hatteras area, where the highest HWMs were recorded after Hurricane Emily. The maximum simulated SWEL+SETUP water level is shown with the colormap, the HWMs are shown with colored dots on the same scale as the water level, and contours of the SWAN significant wave height are drawn in red for the 0.25, 0.50, 0.75, 1.00, 1.25, and 1.50 meter levels. Contours of land elevation (thin, black lines) are drawn at 0, 1, 2, and 3 m NAVD88.

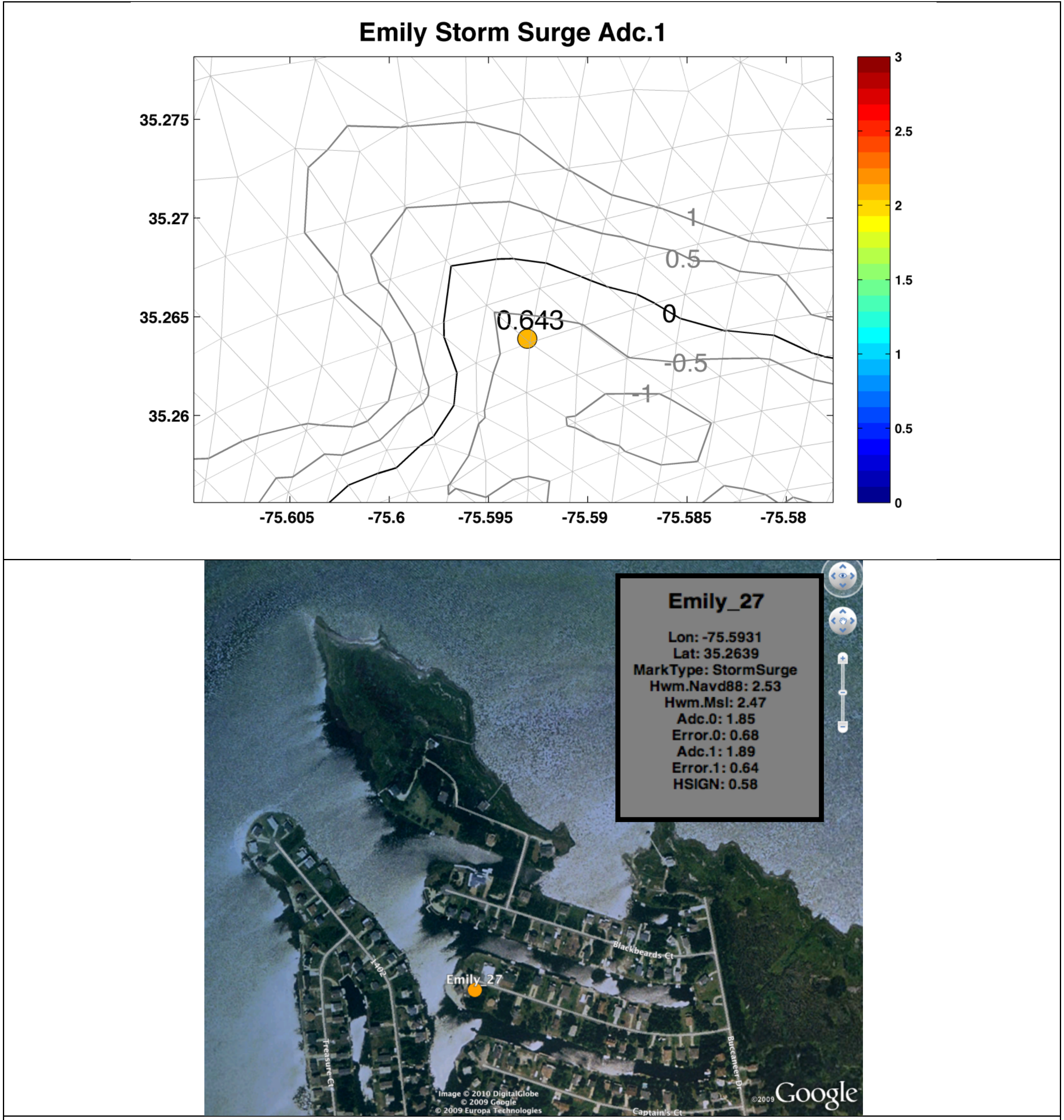
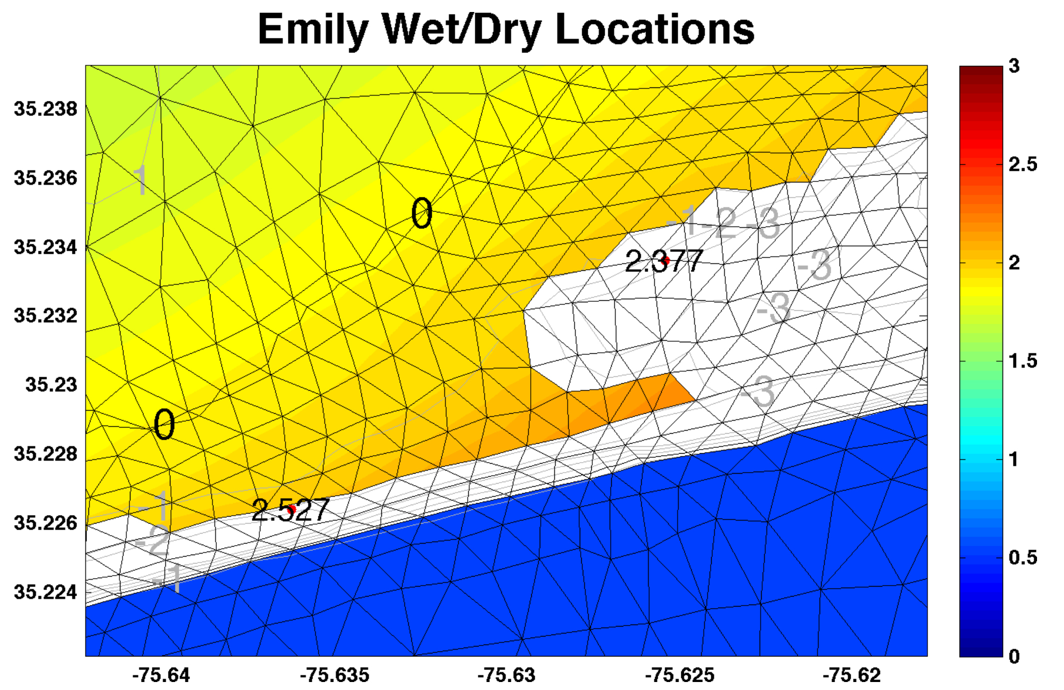


Figure 7.18. Top) Location of HWM Emily_27, which shows an error of 0.64 m. The ADCIRC grid is shown. Contours of grid elevation are drawn at -1, -0.5, 0, 0.5, and 1 m NAVD88. Bottom) Google Earth imagery in the same location. The data at this HWM location is shown in the gray box.



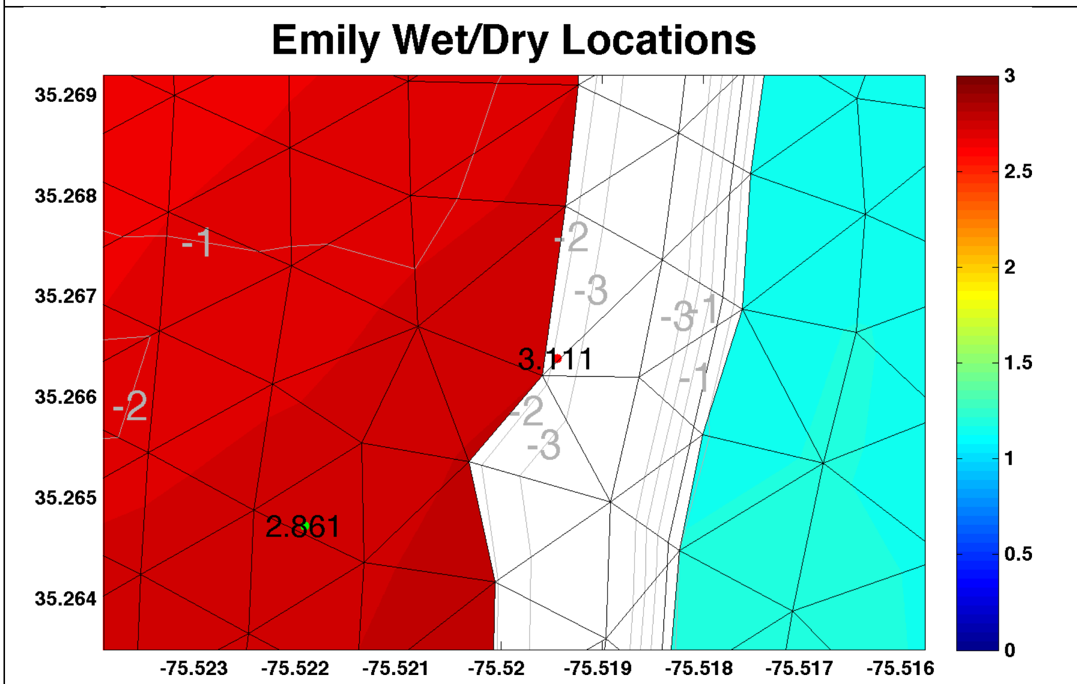


Figure 7.19. Detailed plots of HWM locations and maximum simulated storm surge for Hurricane Emily. Top) HWMs Emily_31 (2.38 m NAVD88) and Emily_32 (2.53 m NAVD88); Bottom) HWMs Emily_12 (3.11 m NAVD88) and Emily_13 (2.86 m NAVD88). The ADCIRC grid is shown, as well as contours of the -1, 0, 1, 2, 3 and 4 m elevations. The observed HWM values [m NAVD88] are labeled over the HWM locations.

Hurricane Fran (1996)

The HWM data available for Hurricane Fran consists of collections by the Wilmington District of the U.S. Army Corps of Engineers (USACE). Values in the report were visually confirmed using Google Earth imagery at each location, and classified as inside/outside and oceanside/backside/waterway and then further into sheltered and exposed as indicated above. High water mark elevations were reported with respect to MSL, and were converted to the NAVD88 vertical datum. The original HWM data files are available through the NOAA Coastal Services Center:

http://www.csc.noaa.gov/hes/docs/stormEffects/FRAN_HWM.zip.

Nineteen HWM observations have been eliminated due to concerns that the recorded values are not consistent with nearby observations or are otherwise suspect. For example, the HWM denoted as ON-110-NT is close to ON-109-NT and ON-111-NT, but its recorded water level is 2 meters larger than its neighbors. This is shown in Figure 7.20A, along with Google Earth imagery for the same area. Of the three HWMs, ON-110-NT is the most exposed to waves, while the other two were behind buildings or further away from the shoreline on a second row of structures. Therefore ON-110-NT was eliminated from further analysis. Another example of an eliminated HWM location is tsl1021, shown in Figure 7.20B. While the HWMs at nearby locations O-5F and O-6F are consistent with each other, the much higher observed water level at tsl1021 (3.45 m NAVD88) may be a result of the complexity of structures that form the surrounding condominium complex or because it is more exposed to waves. In general, these situations can lead to substantial uncertainty in observed HWM values. The HWM values are listed in Appendix 1.E, with eliminated HWMs noted with a comment.

The locations and values of the HWMs used in the Fran comparison are shown in Figures 7.21 and 7.22. Almost all of the locations are in the lower half of Onslow Bay. The largest water levels were observed in the southern portion of the bay, in the Kure Beach area, and generally decreased up the coast toward the north.

The differences between the observed HWM values and the SWEL and SWEL+SETUP simulations are shown in Figure 7.23. Scatter and histogram plots of the errors are shown in Figures 7.24 and 7.25 and the overall statistics are reported in Table 7.4. Inclusion of the wave setup in the model significantly decreases the rms error (by 0.24 m) and the mean error (by 0.36 m). Thus, a substantial portion of the bias present in the SWEL simulation is accounted for by the contributions of wave setup to the total water level. If the offset measured at the Beaufort gauge location (10 cm, Table 7.2) is representative of the offset throughout Onslow Bay, it would explain much of the remaining bias error between ADCIRC and the HWMs.

We also note that more locations are inundated in the SWEL+SETUP simulation, indicating further inland flooding due to the incorporation of wave breaking forces. This is illustrated in Figure 7.26 for HWM location wr1013. The SWEL simulation does not inundate this location, with the adjacent simulated water level reaching only about 2.8 m. The incorporation of wave setup increases the simulated water level to about 3.2 m and inundates this particular location. The HWM value is 3.37 m NAVD88.

There are a substantial number of HWM locations that are not inundated during the SWEL+SETUP simulation, as indicated in Figure 7.22. Two representative locations are shown in Figure 7.27, where the maximum simulated water level is compared with the observed HWM values. In these locations, the SWEL+SETUP solution is very consistent with the wetted HWM locations as well as the nearby model solution in the wetted area. In general, these locations are within an element of the wetted surface and in areas of relatively steep topographic gradient.

A close-up of the Cape Fear River, Southport and Wrightsville Beach region is shown in Figure 7.28. This shows the SWEL+SETUP maximum water level, the observed HWMs, and the SWAN significant wave height (black contour lines). The patch of dark red HWM values at approximately 33.97 degrees latitude is in the Kure Beach area. Expert judgment (Spencer Rogers, NC-SeaGrant) has indicated that these HWM locations/water levels are likely to have been significantly affected by wave runup (that is not included in the SWEL+SETUP model) causing pooling of water upslope. As was true for Hurricane Emily, the error metrics are less for the sheltered sites compared to the exposed sites, suggesting that the HWM data at the exposed sites may be more subject to wave contamination.

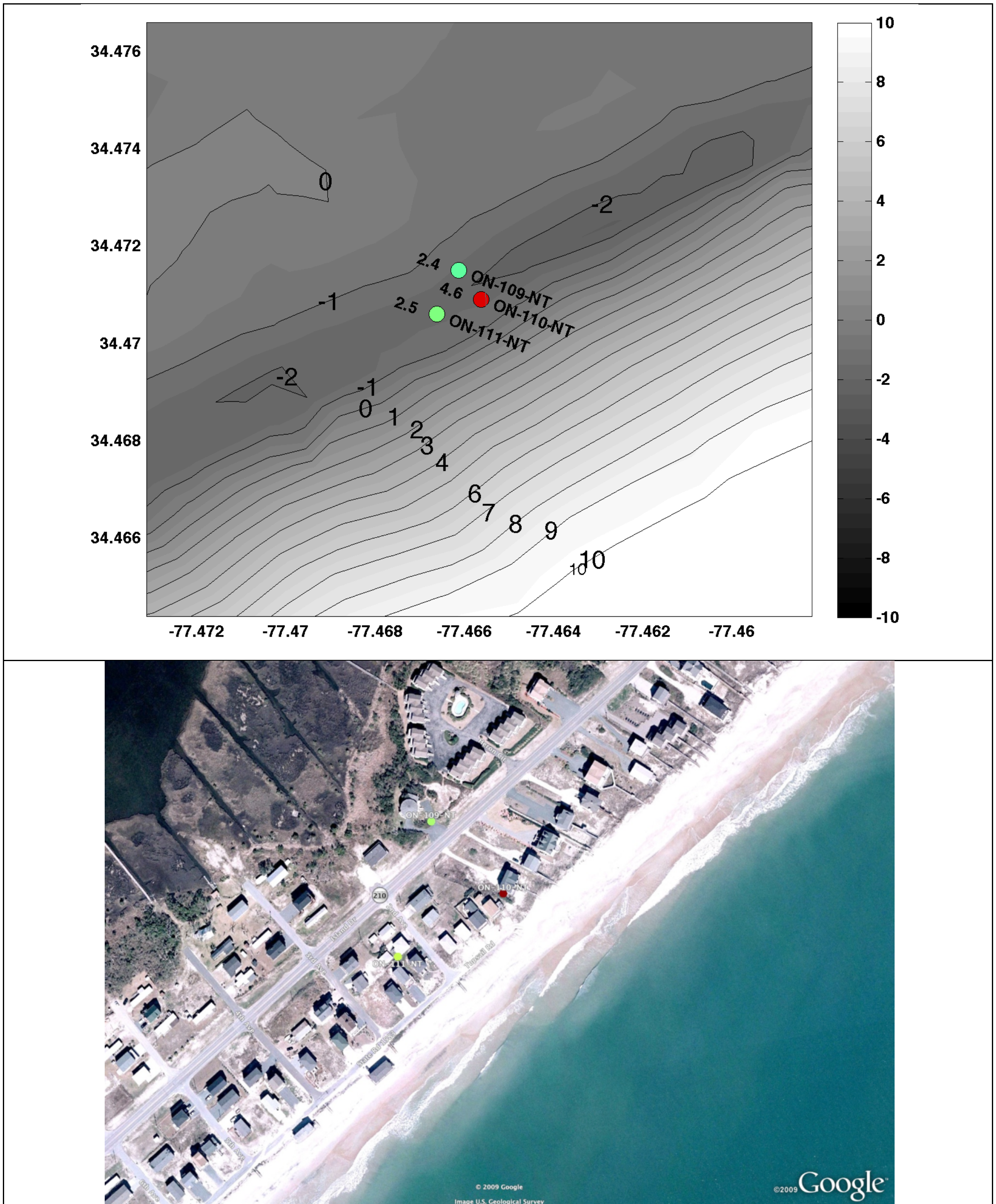


Figure 7.20A. Detail of three HWMs for Hurricane Fran in the area of HWM ON-110-NT. The top figure shows the HWMs in relation to the ADCIRC grid, shown in the grayscale colormap with specific contours drawn with black lines. The bottom figure shows Google Earth imagery for the same area, with the HWMs indicated.

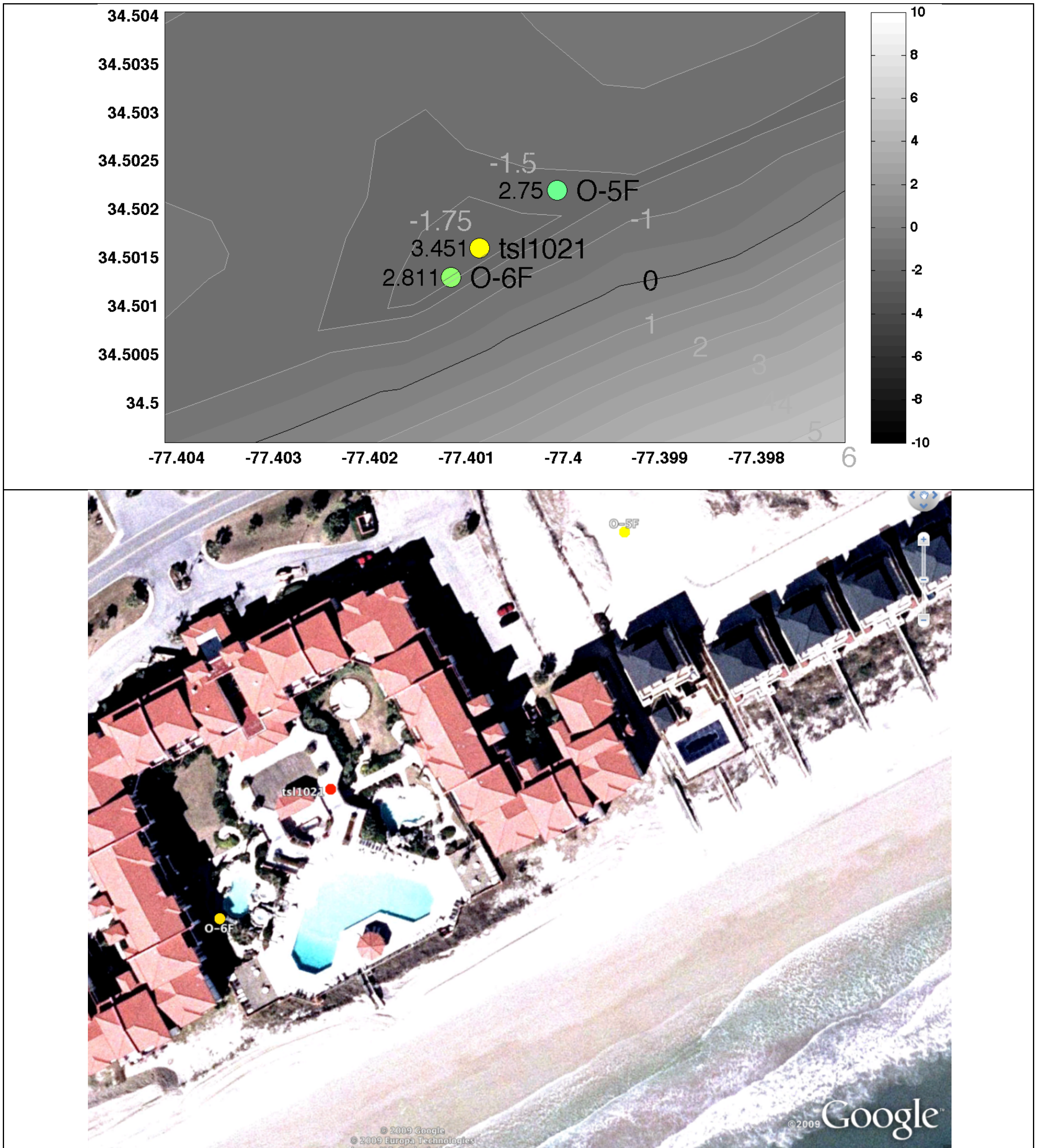


Figure 7.20B. Detail of three HWMs for Hurricane Fran in the area of HWM tsl1021. The top figure shows the HWMs in relation to the ADCIRC grid, shown in the grayscale colormap with specific contours drawn with black lines. The bottom figure shows Google Earth imagery for the same area, with the HWMs indicated. tsl1021 is the red dot just north of the pool.

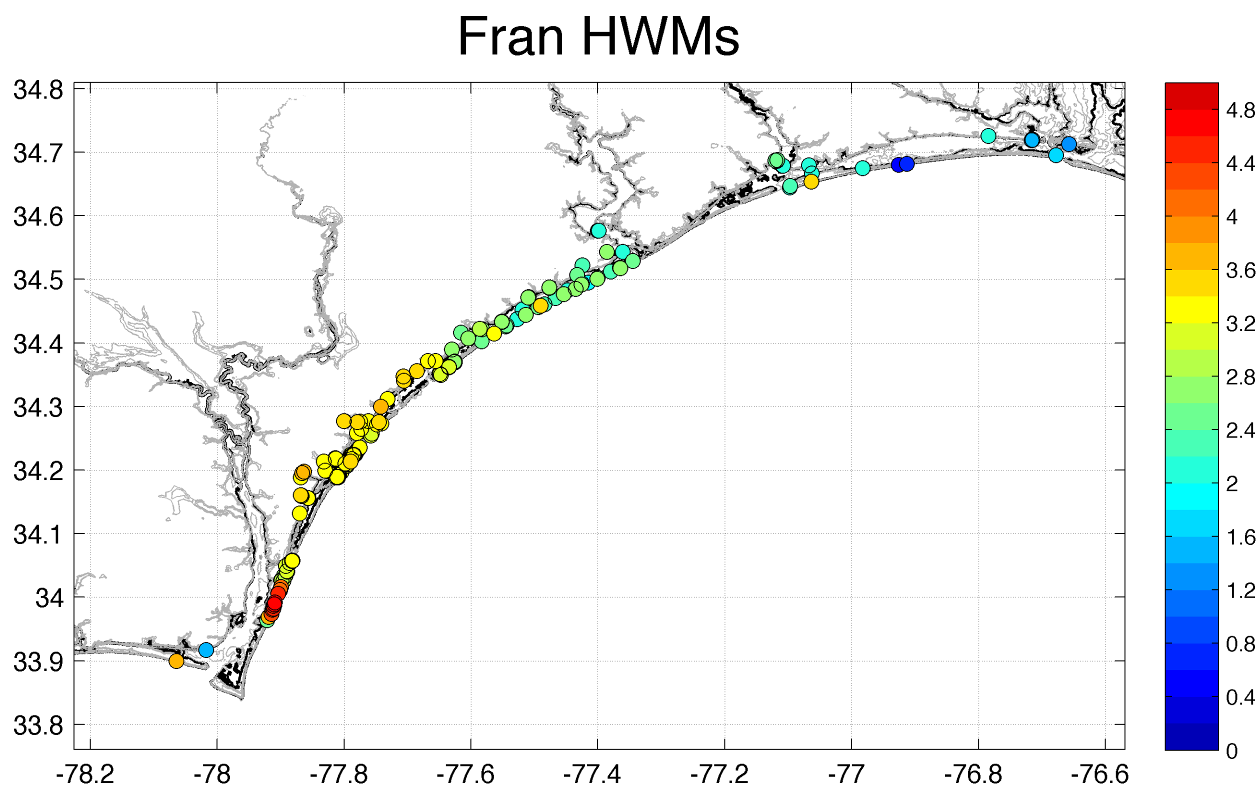


Figure 7.21. Location of HWMs for Hurricane Fran. The color scale is the observed watermark height in meters NAVD88. The 0, 1, 2, and 3 meter topographic contours are shown with the solid lines.

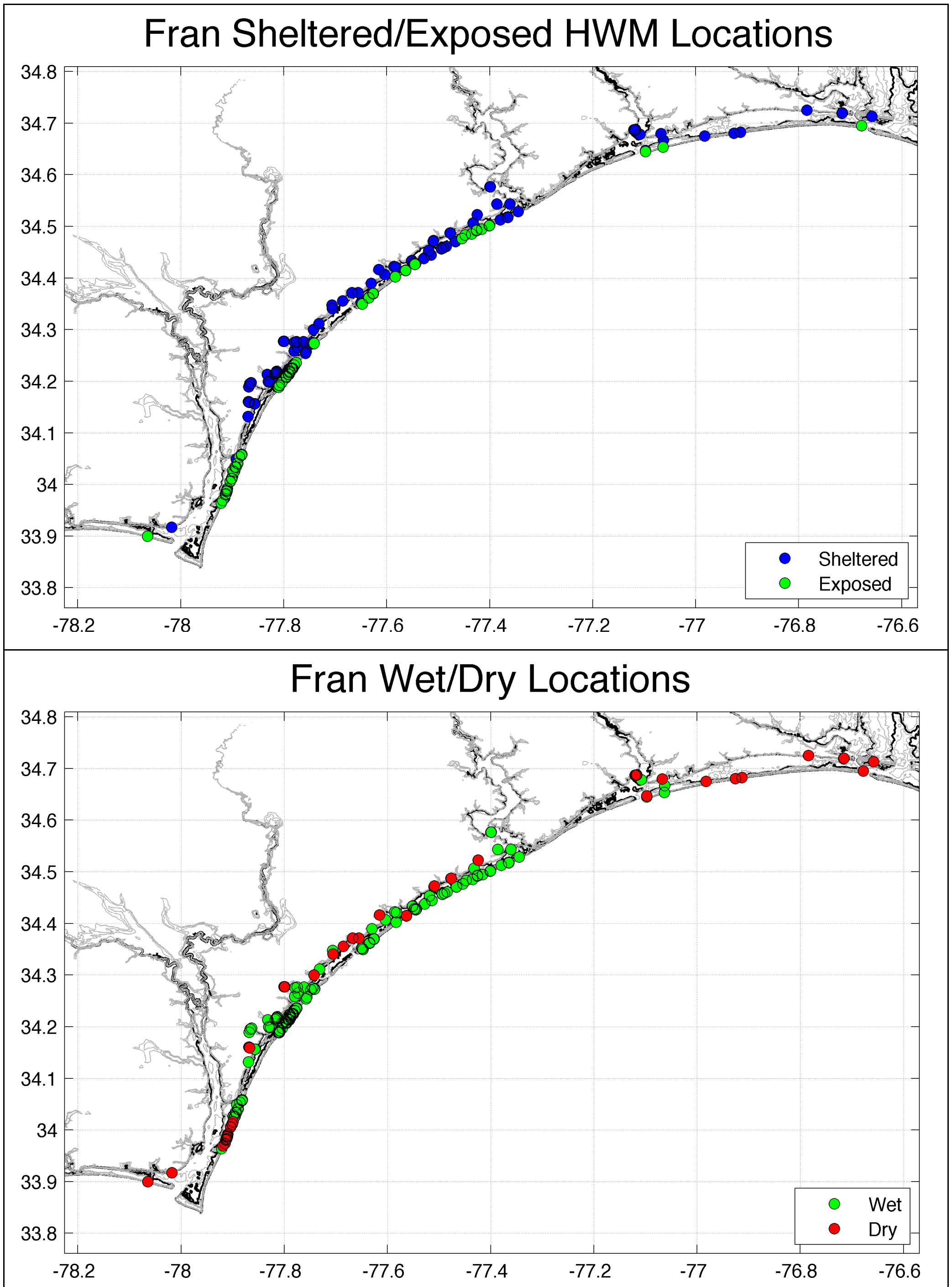


Figure 7.22. Top) Location of HWMs classified as sheltered and exposed. Bottom) Location of HWMs that wet during both Adc.0 and Adc.1 simulations. The 0 m contour is shown with the black line. The 1, -1, -2, -3, -4 m contours are shown with the gray lines.

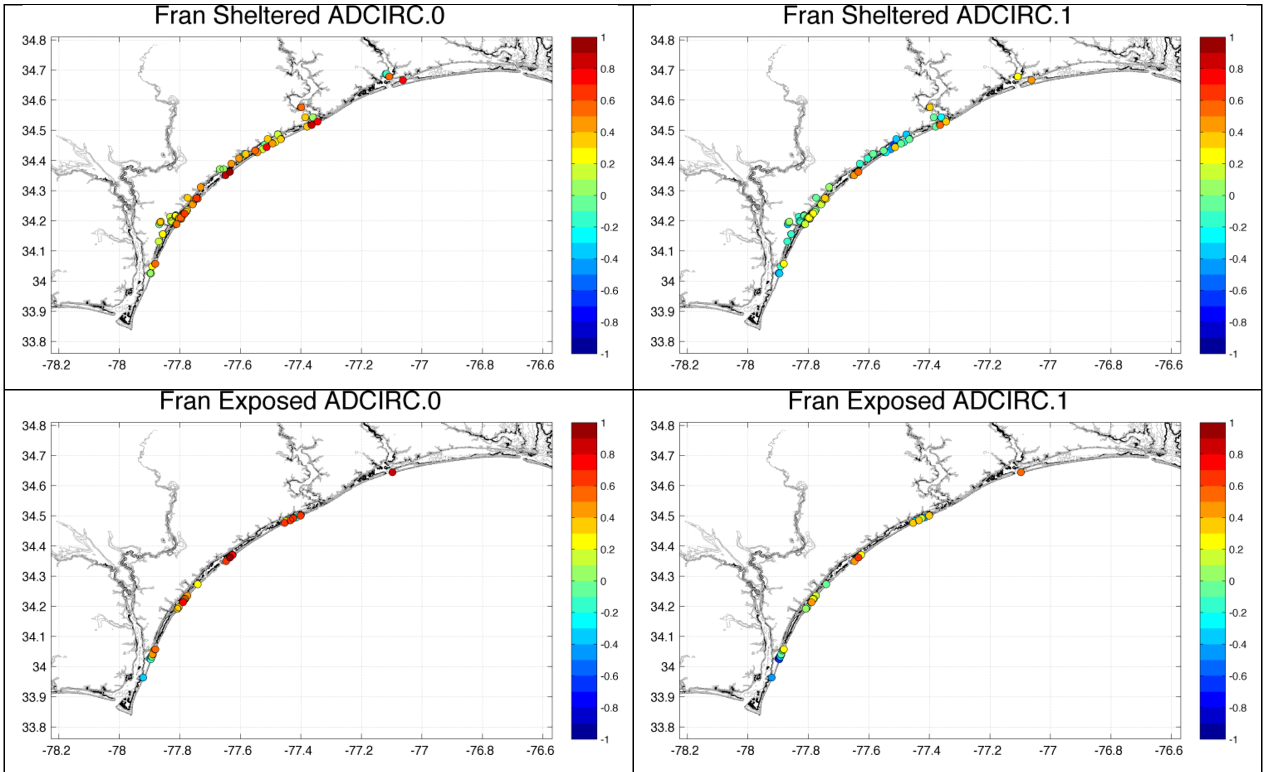


Figure 7.23. Difference between observed HWMs and wetted modeled values (observed – modeled) for Hurricane Fran. The sheltered locations are shown in the top row, and the exposed locations are shown in the bottom row.

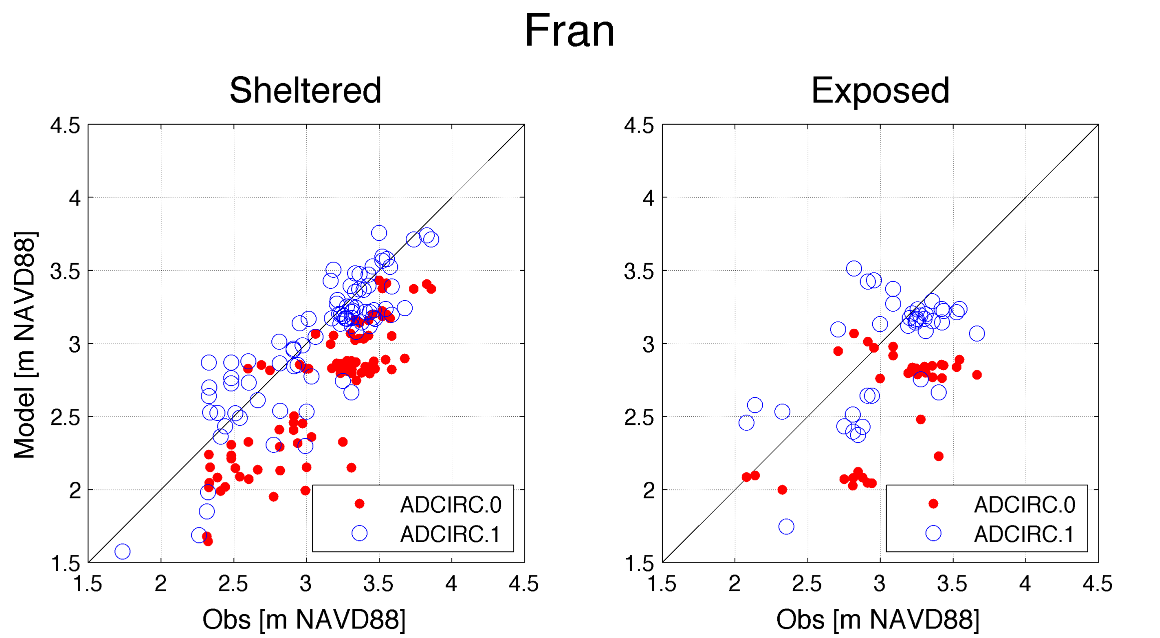


Figure 7.24. Scatter plot of observed and modeled HWMs for sheltered (left) and exposed locations for Hurricane Fran. In each plot, the ADCIRC.0 values are shown with red dots, and the ADCIRC.1 values are shown with open, blue circles.

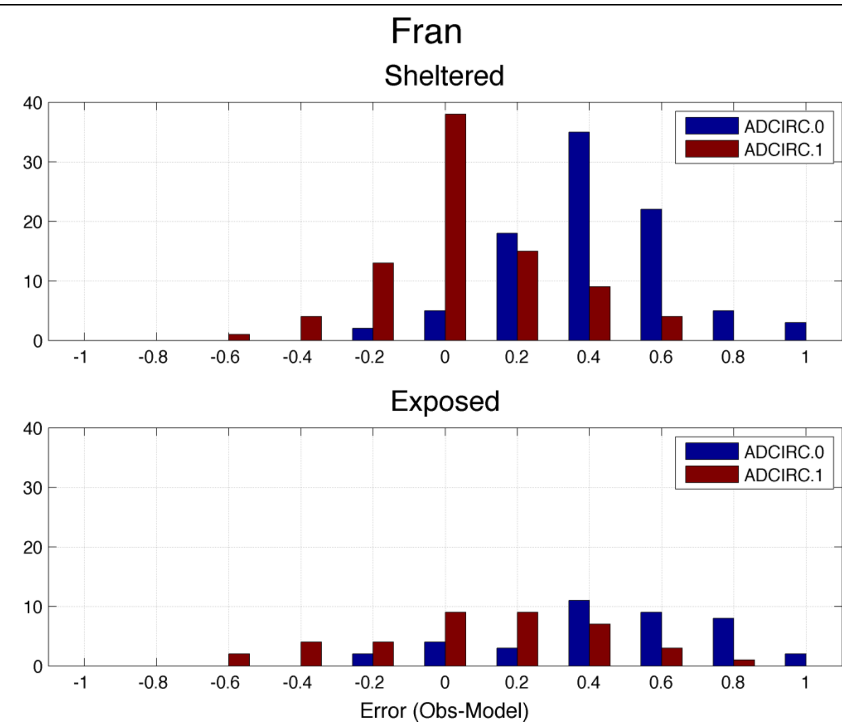


Figure 7.25. Histogram of difference between observed and modeled HWMs for Hurricane Fran separated by sheltered (top) and exposed (bottom) locations. The ADCIRC.0 values are shown with the blue bars, and the ADCIRC.1 values are shown with the red bars.

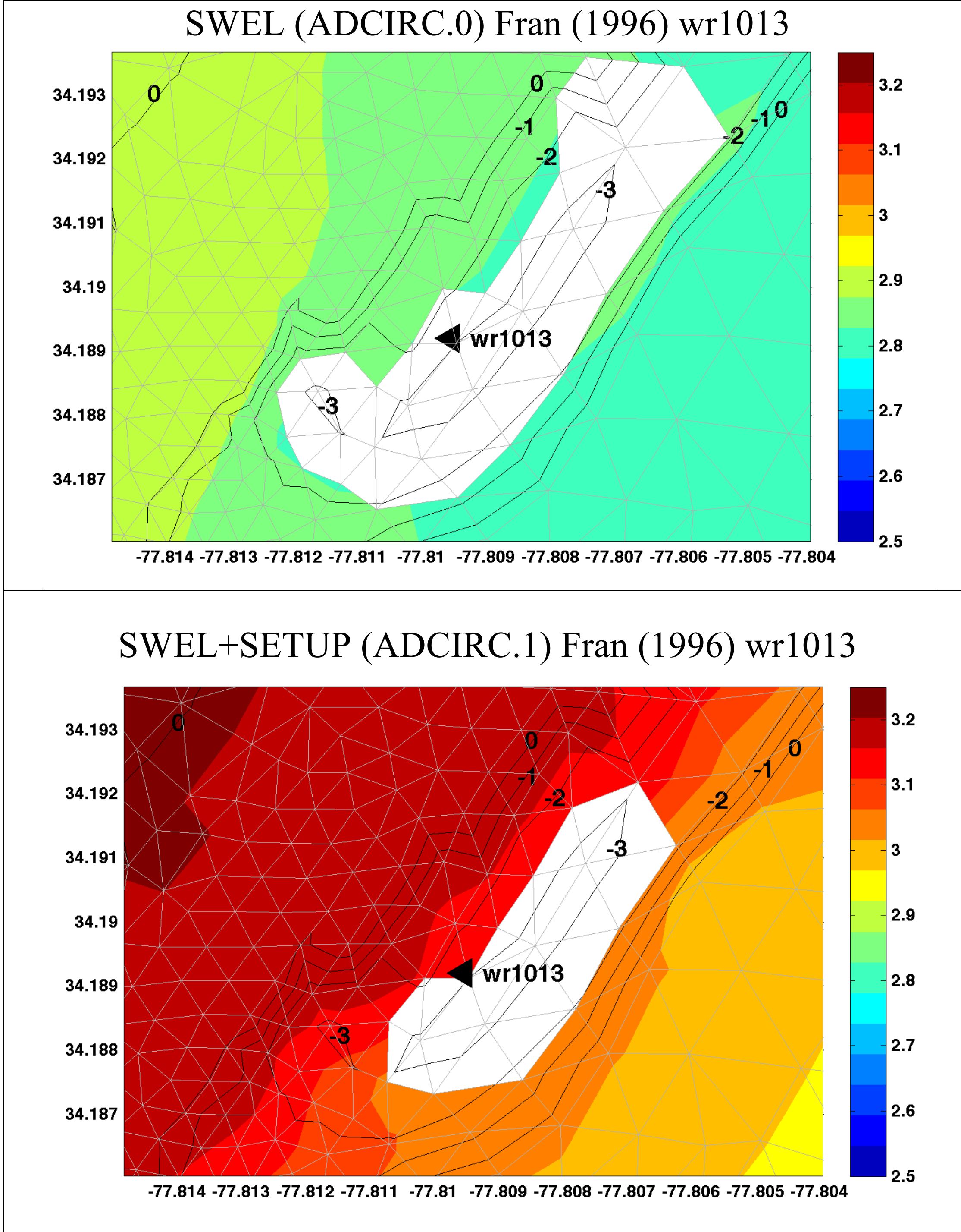


Figure 7.26. Detail plot of HWM wr1013 (black triangle) of Hurricane Fran. Top) ADCIRC.0 maximum water level; Bottom) Adc.1 maximum water level. The ADCIRC grid and topographic contours are shown. The observed HWM value at wr1013 is 3.37 m NAVD88. The ADCIRC.1 simulated value is 3.17 m NAVD88.

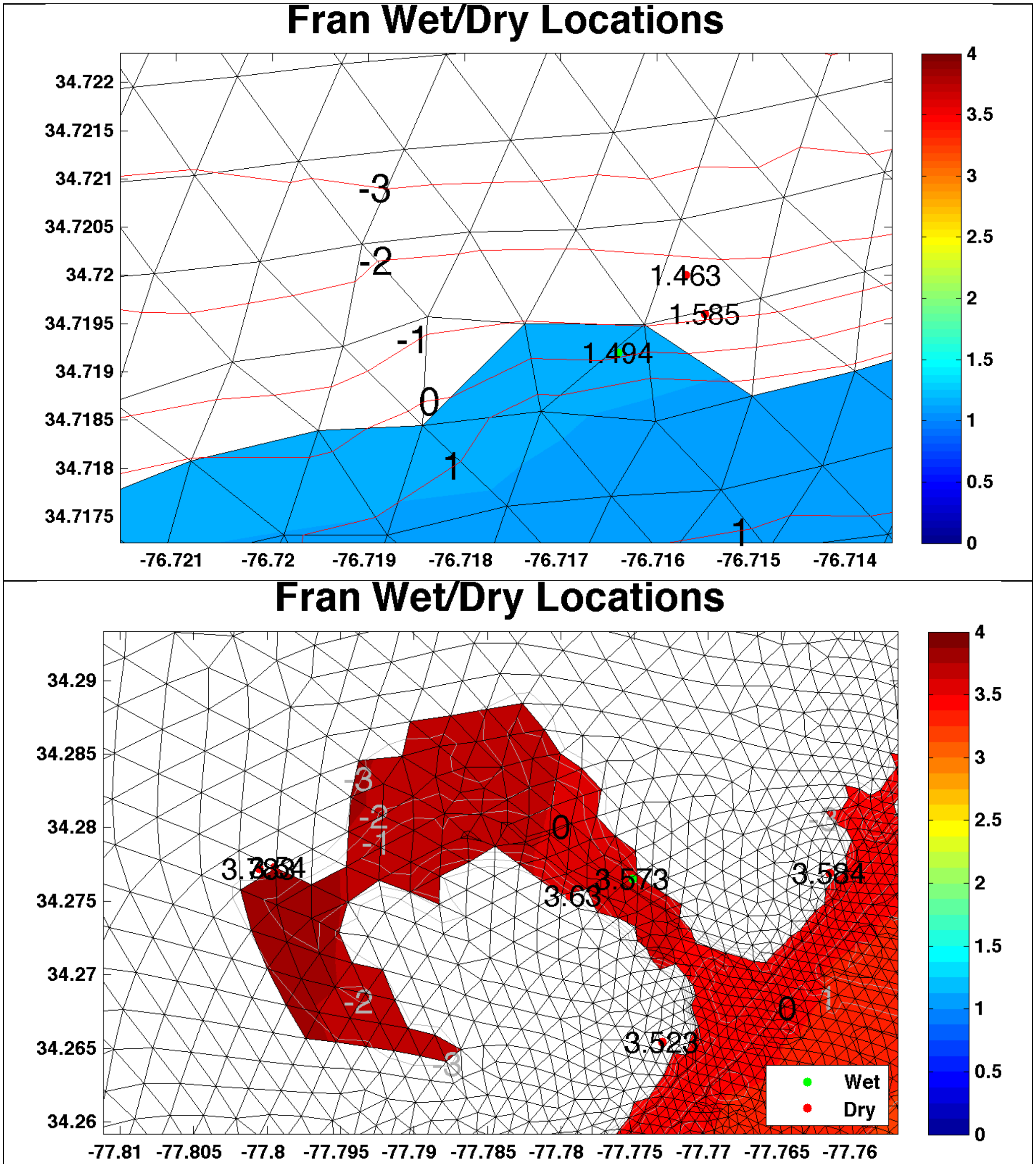


Figure 7.27. Detailed plot of dry locations and maximum simulated storm surge for Hurricane Fran. The ADCIRC grid is shown, as well as contours of the -1, 0, 1, 2, 3, 4 m elevations. The observed HWM values [m NAVD88] are labeled over the HWM location.

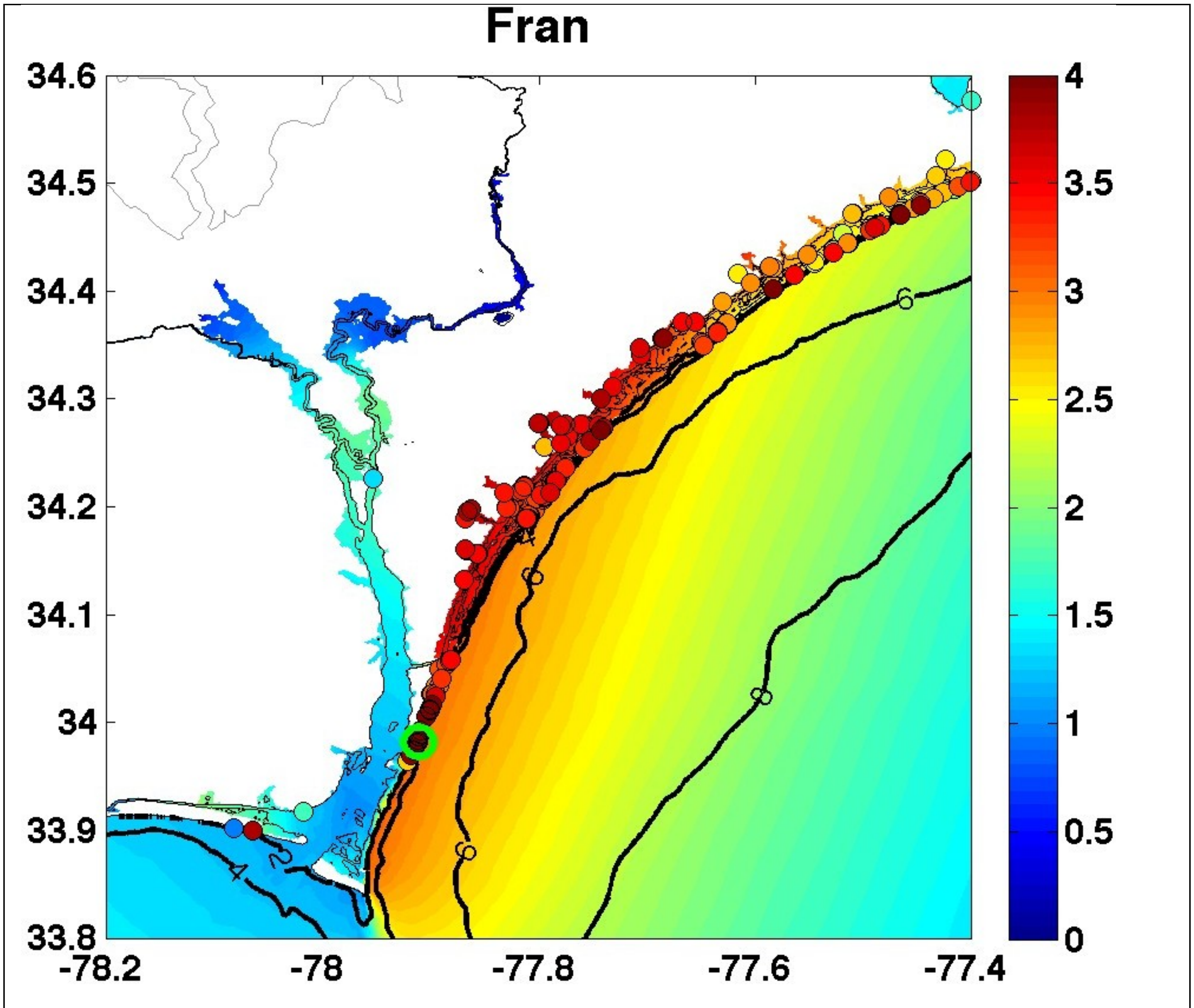


Figure 7.28. Detail plot of the Adc.1 maximum water level and the HWMs for Hurricane Fran. Water levels are in meters, NAVD88, and the HWMs are shown with colored dots on the same color scale. The contours (thick, black) are the maximum significant wave height, drawn at 2, 4, 6, and 8 m. The patch of dark red HWM values within the green circle is in the Kure Beach area.

Hurricane Isabel (2003)

FEMA reports 271 and 272 document the HWM collection in two separate surveys following Isabel. These HWMs were filtered to exclude riverine values based on the descriptions provided in the reports. The resulting HWM locations and classifications were confirmed visually using pictures in the report and Google Earth imagery. HWMs contained in a third FEMA report (#274) were not used based on the expert opinion of Spencer Rogers (NC Sea Grant), who provided an alternate set of HWMs collected in Hyde and Dare counties near the discarded HWM locations. Additional HWMs that were eliminated include HWM ISA-03-0616 that is a duplicate of ISA-03-0615, and HWM ISA-03-0011 that is outside (inland) of the ADCIRC domain. Figure 7.29 shows an eliminated HWM example for which the observed water level is inconsistent with a nearby mark. The HWM values are reported in Appendix 1.E, with eliminated locations indicated with a comment. The locations and values are shown in Figures 7.30 and 7.31. Most of the observed locations are on the western sides of Pamlico and Albemarle Sounds, with concentrations of locations in the Neuse and Tar Rivers. The HWMs measured on the Outer Banks comprise the alternate set provided by NC Sea Grant.

The differences between the simulations and the observed HWM values are shown in Figure 7.32. As in the Emily simulations, there is minimal (6 cm) difference between the SWEL and SWEL+SETUP solutions at the HWM locations located around the periphery of the shallow sounds. This is further illustrated in Figures 7.33 and 7.34, which shows the scatter plots and error histograms for Hurricane Isabel. We note the small contribution from the wave breaking forces, and little change in the shape of the error distributions. The combined rms error is 0.36 m, and the mean error (bias) is -0.14 m, (Table 7.4).

The HWM locations along the Outer Banks do not inundate during either the SWEL or the SWEL+SETUP simulation. This is shown in Figure 7.35 for two areas. The HWM values are shown with the SWEL+SETUP maximum elevation, the ADCIRC model grid, and contours of topography near shore. The SWEL+SETUP solution in these areas ranges from 1.5 – 2 m and closely matches the NOAA gauge data at the Duck Pier (Figure 7.8). Therefore, we suspect that the observed HWMs that are along the dune crests and in excess of 2.5 m are likely to be contaminated by wave runup and splashup. The modeled water levels encroach upon the frontal dunes but do not rise sufficiently to overtop the higher elevations and inundate the areas behind the dunes. Examination of the grid in these areas indicates that the frontal dune elevations are consistent with 2004 lidar data and current conditions.

However, Isabel caused extensive dune erosion and in fact cut a substantial inlet through the Outer Banks just east of Hatteras Village. A lidar survey immediately after Hurricane Isabel shows the extensive erosion that occurred in this area (Sallenger et al, 2004). Both the inlet and frontal dunes were repaired by the USACE and thus the model grid represents "current conditions”. Accounting for this erosion, e.g., to the elevation of highway 12 in the model permits inundation of the greater Hatteras area where many of these HWMs are located.

As opposed to Emily and Fran, the SWEL+SETUP result is biased slightly high (14 cm) vs the HWMs during Isabel. Applying an offset based on those measured at the Duck, Oregon Inlet and Beaufort gauge locations (22, 11, 11 cm, Table 7.3) would worsen this bias. However, since these HWMs are located along the western periphery of Pamlico and Albemarle Sounds, it is not clear how appropriate it is to apply an offset derived from open coastal gauges. For example, the western portions of the sounds will be affected by river discharge that is unlikely to show up in the coastal gauge locations. As noted above, along the ocean side of the Outer Banks, the SWEL+SETUP model results do not overtop and inundate land that was observed to flood during the storm. While we believe this is primarily due to these areas experiencing substantial erosion of frontal dunes, the model may also be low in these areas which would be consistent with the direction of the offset.

Figure 7.29. Google Earth imagery of the area near Hurricane Isabel HWM ISA-03-1115. ISA-03-1115 was eliminated from the HWM analysis based on the reported location as well as the nearby location ISA-03-1116.

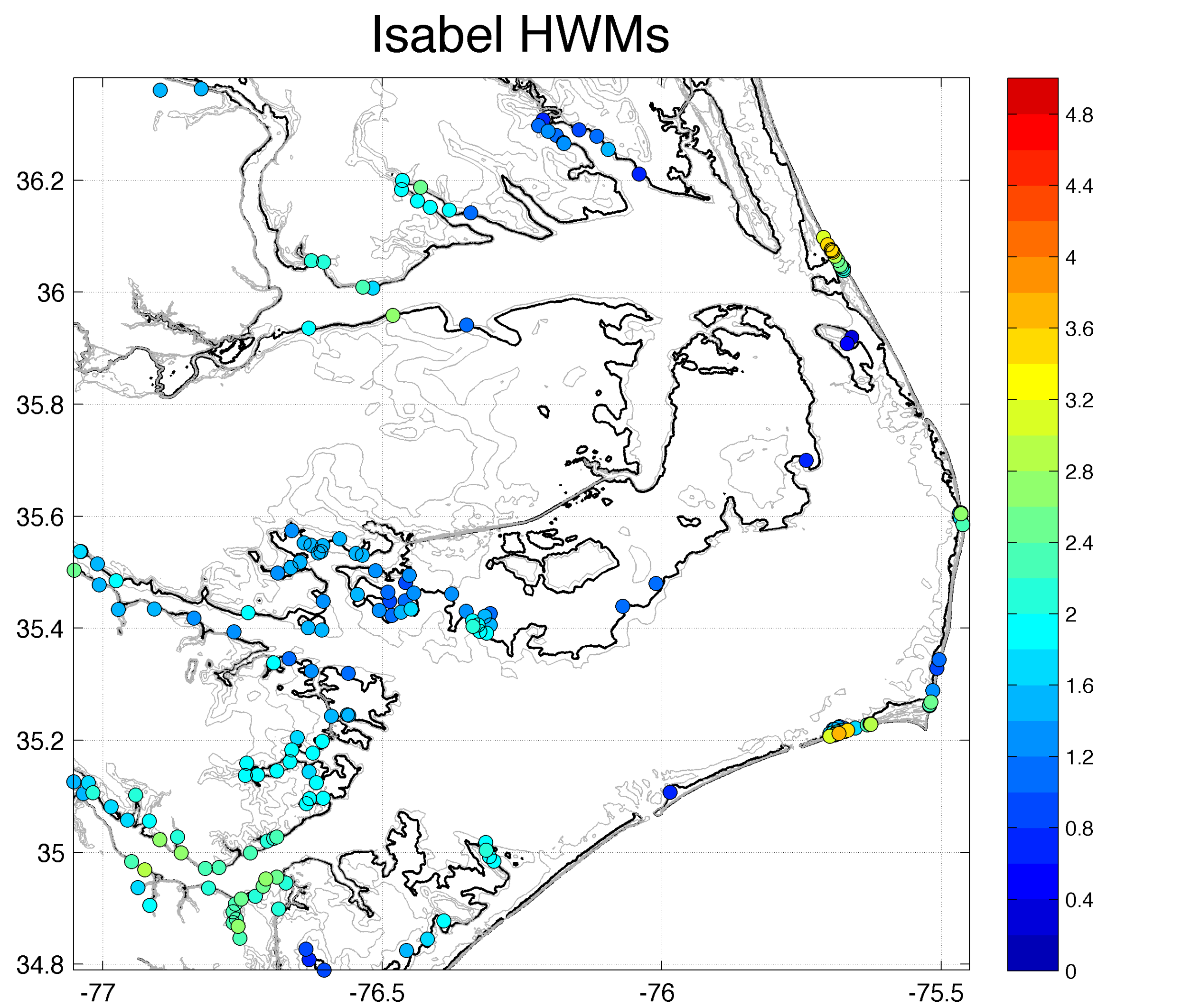


Figure 7.30. Locations of HWMs for Hurricane Isabel. The color scale is the observed watermark height in meters NAVD88. The coastline is shown with the thick line. Elevation contours at -1, 1, 2, and 3 meters are shown with gray lines.

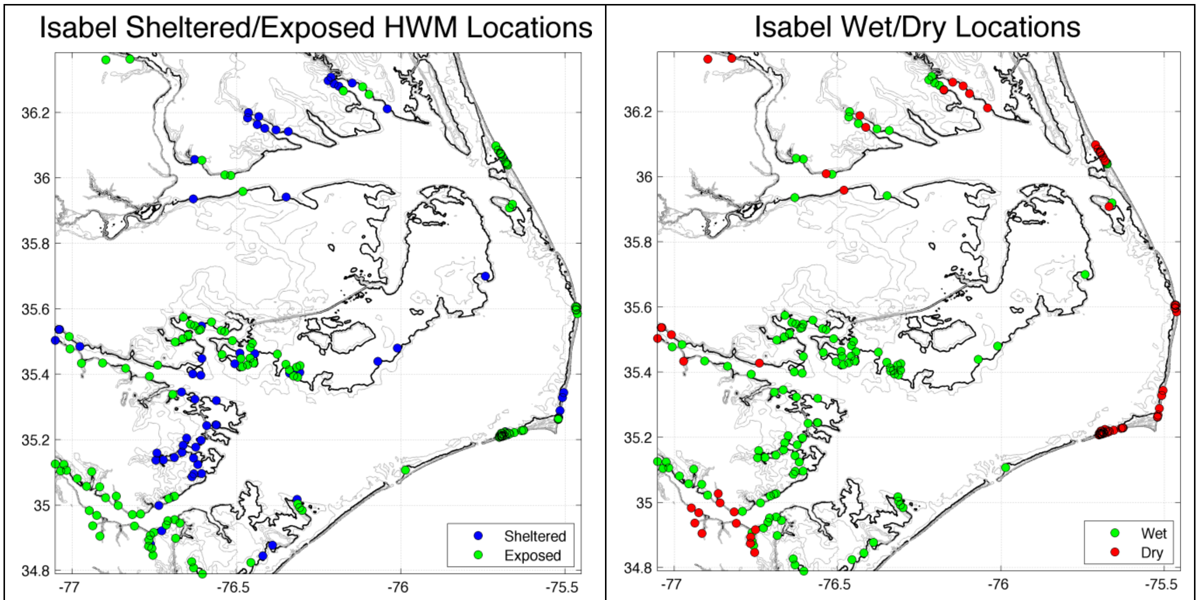


Figure 7.31. Hurricane Isabel. Left) Location of HWMs classified as Sheltered and Exposed. Right) Location of HWMs that wet during both ADCIRC.0 and ADCIRC.1 simulations. The 0 m contour is shown with the black line. The -1, 1, 2, 3, and 4 m contours are shown with gray lines.

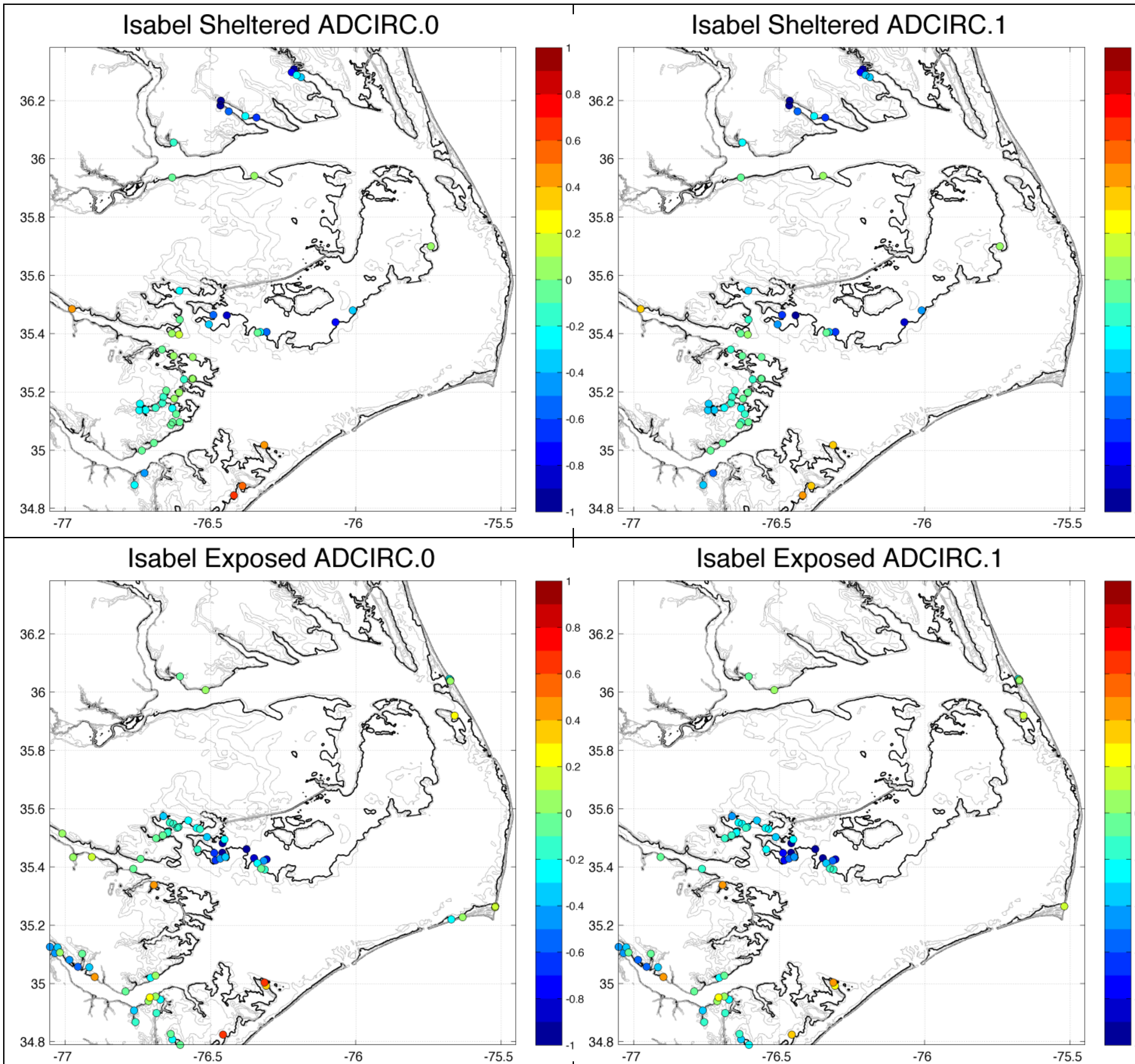


Figure 7.32. Difference between observed HWMs and wetted modeled values (observed – modeled) for Hurricane Isabel. The sheltered locations are shown in the top row, and the exposed locations are shown in the bottom row.

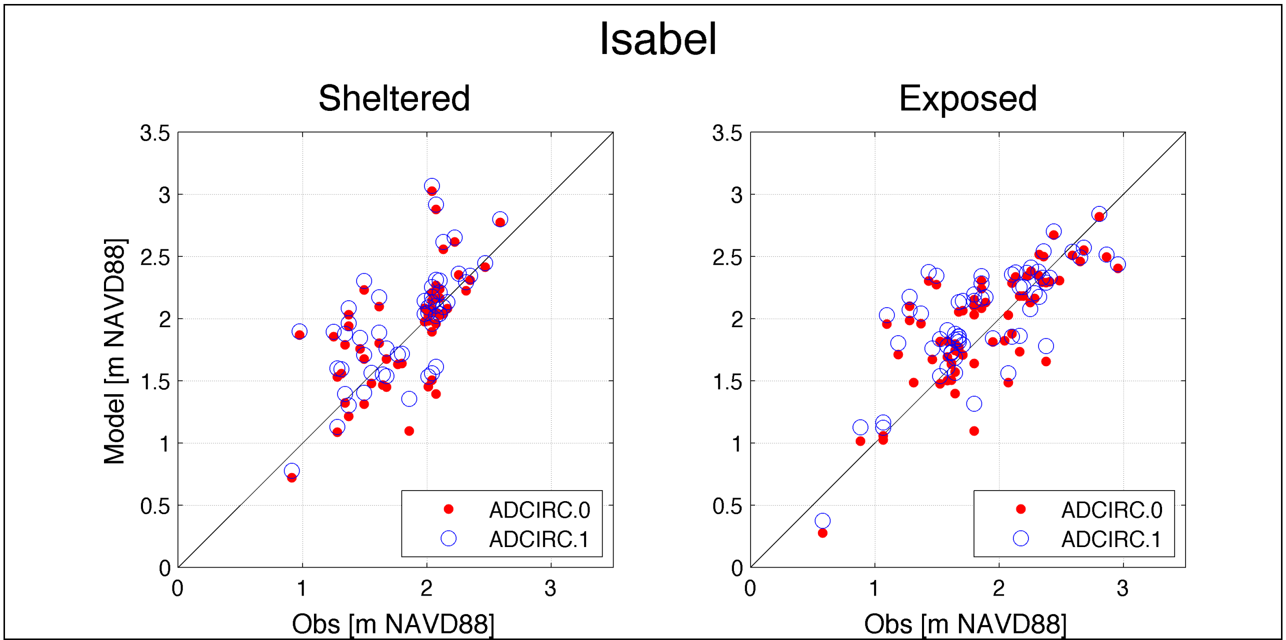


Figure 7.33. Scatter plots of observed and modeled HWMs for sheltered and exposed (right) locations for Hurricane Isabel. In each plot, the ADCIRC.0 (SWEL) values are shown with the red dot, and the ADCIRC.1 (SWEL+SETUP) values are shown with the open, blue circle.

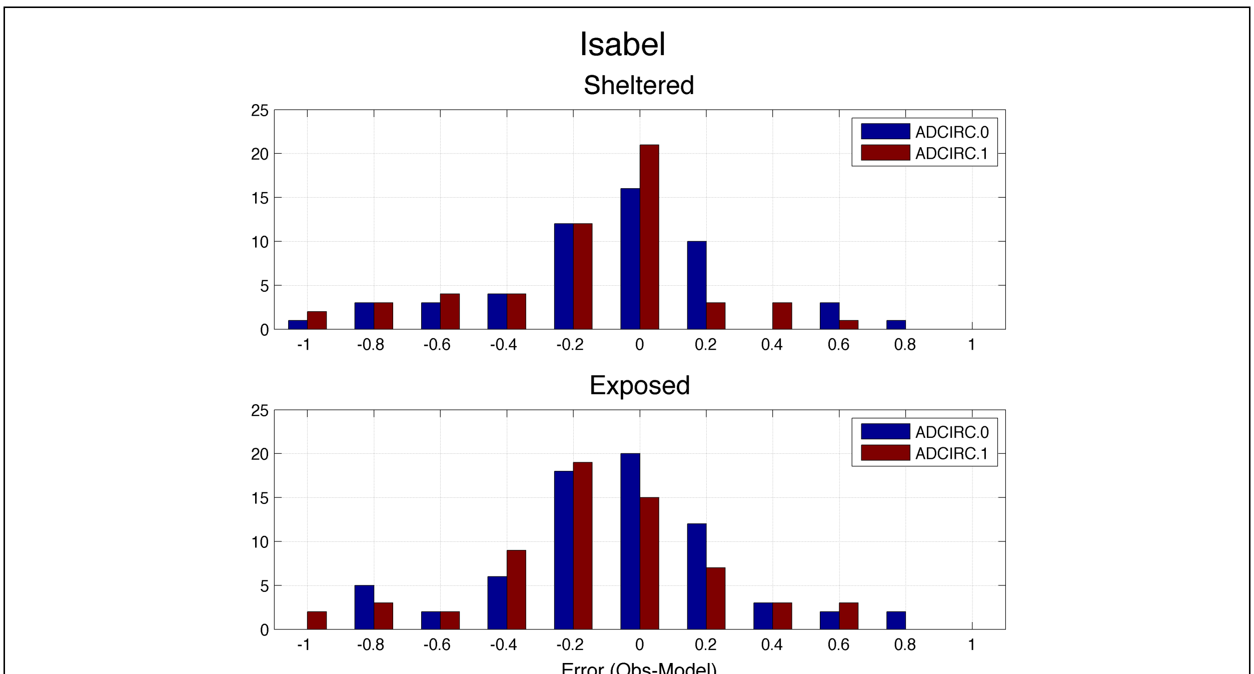


Figure 7.34. Histogram of difference between observed and modeled HWMs for Hurricane Isabel separated by sheltered (top) and exposed (bottom) locations. The ADCIRC.0 values are shown with the blue bars, and the ADCIRC.1 values are shown with the red bars.

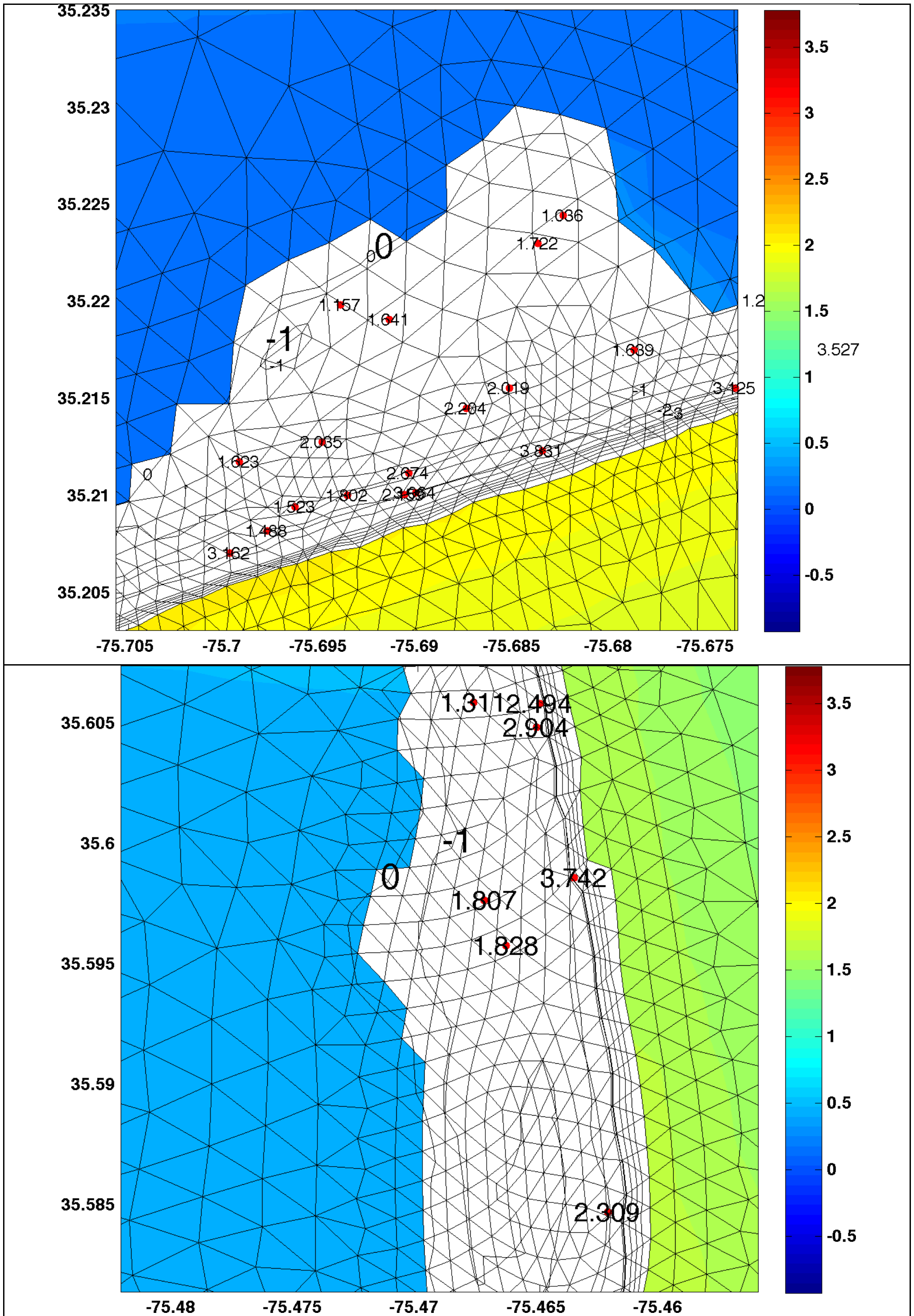


Figure 7.35. Detailed plot of dry locations and Adc.1 maximum water level for Hurricane Isabel. The ADCIRC grid is shown, as well as contours of the -1, 0, 1, 2, 3 and 4 m elevations. The observed HWM values [m NAVD88] are labeled over the HWM location.

Conclusions

In this section, water levels and inundation produced by the ADCIRC model are compared to available data from NOAA gauge stations and high water marks for the four tropical cyclones and two extratropical storms described in Section 4. Results are presented for the ADCIRC model response to tidal forcing, atmospheric pressure forcing and wind stress forcing (SWEL) and for the ADCIRC response to these forcings plus the additional forcing cause by wave radiation stress gradients (SWEL+SETUP). This set of six storms provides a reasonably comprehensive evaluation of the ADCIRC model along the North Carolina coast.

Low pass filtering of water levels from the NOAA gauge stations indicates the presence of low frequency variability of approximately ±0.15 m along the North Carolina coast that is due to processes not included in the present, event-based modeling study. Offsets (Table 7.2) were removed from the gauge data prior to comparison with ADCIRC results and are used to interpret bias between ADCIRC and the HWMs. The offsets are typically positive (observations higher that model) and in the range of 0.0 to 0.15 m during the tropical cyclone season.

A comparison between the SWEL and the SWEL+SETUP model runs suggests that wave setup contributed minimally (i.e., less than 10 cm) to surge in the large, shallow North Carolina sounds due to Emily and Isabel. However, along the open coast, wave setup contributes much more significantly to the storm surge (i.e., as much as 0.80 m in hurricane Fran). Inclusion of wave setup consistently improved (open coast) or had minor inpact (in the sounds) on model skill vs observations.

Mean model SWEL+SETUP errors compared to the NOAA gauge data range from -0.16 m to 0.08 m across the entire storm set (Table 7.3). Errors were generally the largest at the Wilmington gauge, which is approximately 45 km up the Cape Fear River from the coastal ocean. In at least two of the hurricanes, it appears that over predictions of water level response by the ADCIRC can be traced to systematic errors in the wind field.

Mean model SWEL+SETUP errors range from -0.14 to 0.23 m and rms errors range from 0.29 to 0.36 m vs the HWM data. Model skill is consistently improved by the inclusion of wave setup with mean and rms errors decreasing by 0.36 and 0.24 m, respectively, for hurricane Fran, which was subject to significant coastal wave action. Wave setup was much less significant for hurricanes Emily and Isabel where HWM data was mostly inside Pamlico Sound. Mean and rms errors were consistently larger for exposed vs sheltered HWMs, suggesting that unmodeled wave effects such as the crest height, run up and splash up may be contaminating the exposed HWM data.

Averaging the mean errors for the SWEL+SETUP from all six storms from the entire NOAA gauge analysis yields a mean error of -0.02 m. Similarly, the mean error for the SWEL+SETUP from the three storms having HWM data yields a mean error of 0.01 m. Given the uncertainty due to the unmodeled offset and wave processes, it does not appear that the SWEL+SETUP results exhibit any systematic bias. Composite rms errors of 0.12 and 0.32 m were obtained for the NOAA gauge data and HWM data, respectively.