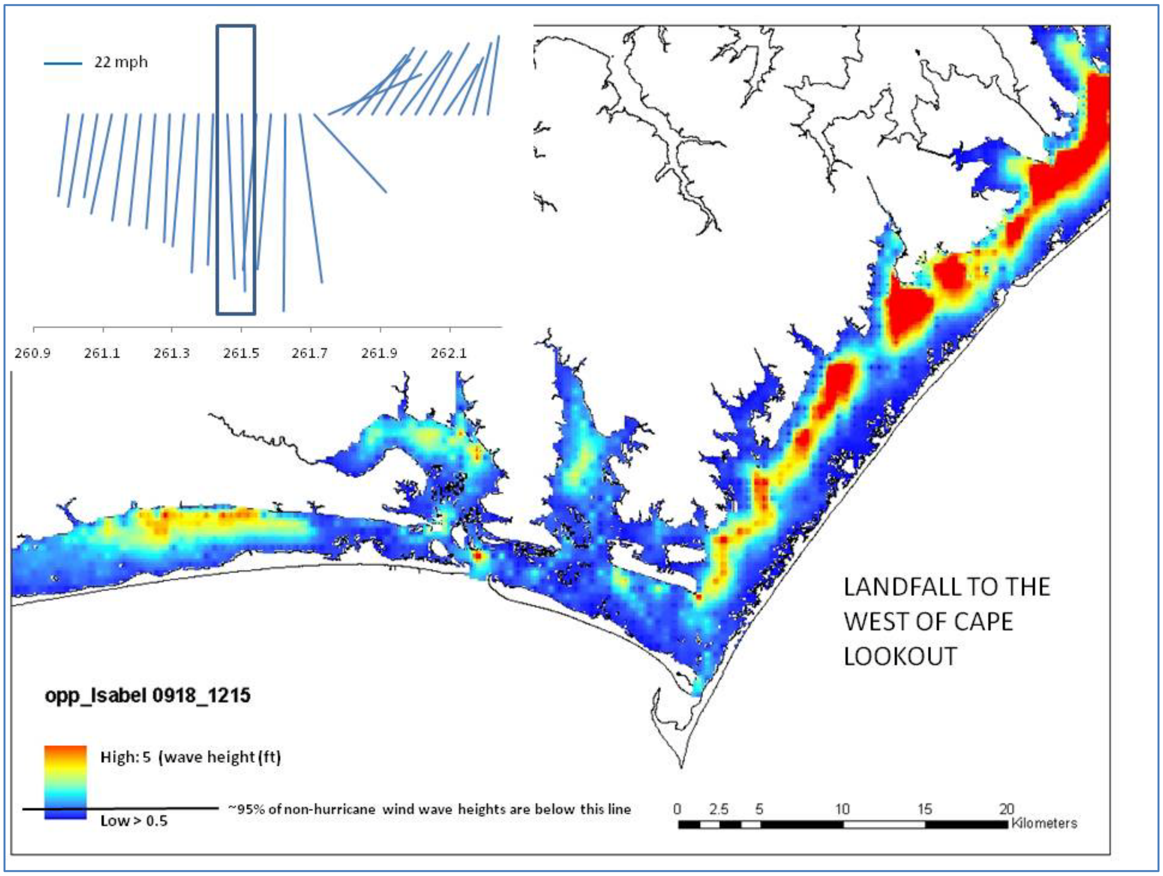
WAVE FORECASTS ASSOCIATED WITH HURRICANE LANDFALLS IN THE VICINITY OF CAPE LOOKOUT, NORTH CAROLINA



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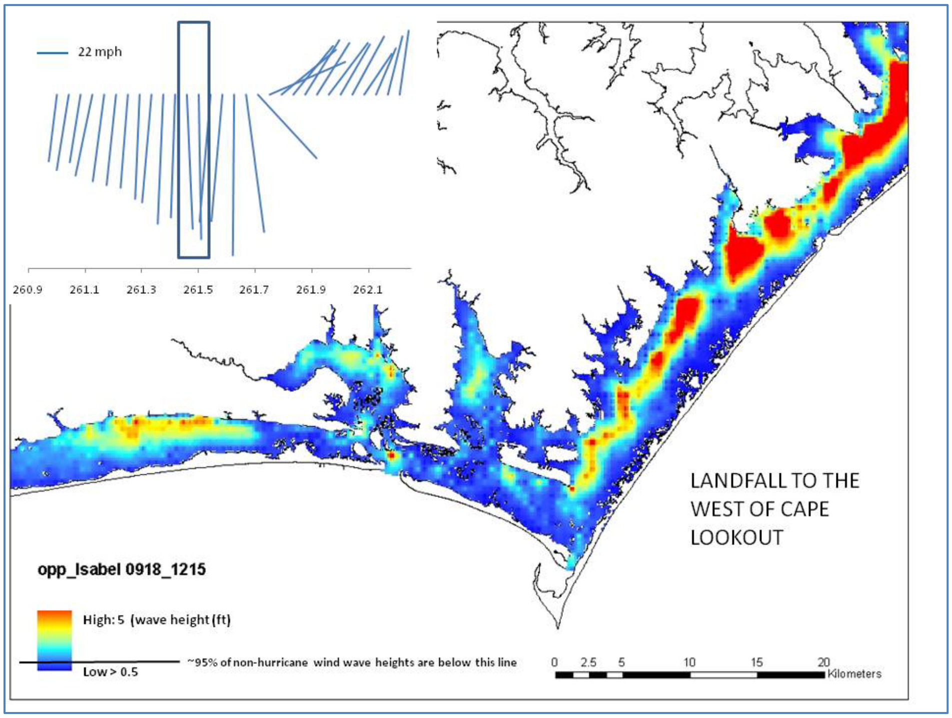

Mark Fonseca and Amit Malhotra

National Centers for Coastal Ocean Science (NCCOS)
National Ocean Service, NOAA
Center for Coastal Fisheries and Habitat Research
101 Pivers Island Road
Beaufort, North Carolina 28516-9722
mark.fonseca@noaa.gov amit.malhotra@noaa.gov

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Abstract

Hurricanes can cause extensive damage to the coastline and coastal communities due to wind-generated waves and storm surge. While extensive modeling efforts have been conducted regarding storm surge, there is far less information about the effects of waves on these communities and ecosystems as storms make landfall. This report describes a preliminary use of NCCOS' WEMo (Wave Exposure Model; Fonseca and Malhotra 2010) to compute the wind wave exposure within an area of approximately 25 miles radius from Beaufort, North Carolina for estuarine waters encompassing Bogue Sound, Back Sound and Core Sound during three hurricane landfall scenarios. The wind wave heights and energy of a site was a computation based on wind speed, direction, fetch and local bathymetry. We used our local area (Beaufort, North Carolina) as a test bed for this product because it is frequently impacted by hurricanes and we had confidence in the bathymetry data. Our test bed conditions were based on two recent Hurricanes that strongly affected this area. First, we used hurricane Isabel which made landfall near Beaufort in September 2003. Two hurricane simulations were run first by passing hurricane Isabel along its actual path (east of Beaufort) and second by passing the same storm to the west of Beaufort to show the potential effect of the reversed wind field. We then simulated impacts by a hurricane (Ophelia) with a different landfall track, which occurred in September of 2005. The simulations produced a geographic description of wave heights revealing the changing wind and wave exposure of the region as a consequence of landfall location and storm intensity. This highly conservative simulation (water levels were that of low tide) revealed that many inhabited and developed shorelines would receive wind waves for prolonged periods of time at heights far above that found during even the top few percent of non-hurricane events. The simulations also provided a sense for how rapidly conditions could transition from moderate to highly threatening; wave heights were shown to far exceed normal conditions often long before the main body of the storm arrived and importantly, at many locations that could impede and endanger late-fleeing vessels seeking safe harbor.. When joined with other factors, such as storm surge and event duration, we anticipate that the WEMo forecasting tool will have significant use by local emergency agencies and the public to anticipate the relative exposure of their property arising as a function of storm location and may also be used by resource managers to examine the effects of storms in a quantitative fashion on local living marine resources.

Keywords: *Hurricanes, Fetch, Emergency response, Forecasting, North Carolina, Hurricane Isabel, Hurricane Ophelia, Impacts, Landfall, Waves, Shorelines, WEMo.*

Introduction

Hurricanes are severe storms with wind speed exceeding 62 knots or 72 mph that form in the North Atlantic Ocean, the Northeast Pacific Ocean or South Pacific Ocean. Hurricanes can cause widespread damage, a threat that is increasing with growing development of the coastal zone. Hurricane damages may be caused by high winds, torrential rains, floods, storm surge, high waves or combinations of these factors. Damage due to high winds, rains and flooding could occur hundreds of kilometers inland of landfall; whereas, storm surge and wave damage are restricted to the coastline and coastal communities. While storm surge models exist, information regarding associated wave effects in estuarine areas is essentially non-existent. Moreover, many studies involving wave effects utilize comparatively complicated wave modeling techniques that are intimidating (if not inaccessible) to many ecologists, coastal resource managers and private sector (e.g. insurance companies) groups. In an attempt to overcome these limitations, we have developed and refined a wave exposure model (WEMo: Wave Exposure Model; Fonseca and Malhotra 2010) as a forecasting tool. This model was originally based upon work in freshwater systems (Keddy 1982) and adapted for estuarine ecosystems with complex bathymetry (Fonseca et al. 2002).

The information presented in this study likely reinforces the experience and understanding of coastal residents who have lived in this area long enough to have witnessed many hurricane events. However, a large portion of the today's coastal residents have not experienced such storm events and may not have adequate appreciation of the severity and location of associated waves and may not be sufficiently prepared for such an event. Therefore, it is important to provide graphical representations such as these for inexperienced stakeholders in hopes of informing them of the vulnerability of both shoreline assets and vessels during these events.

In this study we focused on simulating the distribution and intensity of local wind waves that would be generated during hurricanes, especially at the shoreline. Our study included simulating alternate paths of hurricanes and presenting only the wind waves impact on our study areas during the course of hurricanes. We utilized WEMo to recognize the areas along shorelines where maximum damage could occur. It should be noted that these computations were done in the absence of storm surge which could propagate waves on and inshore of the current shoreline; integration of WEMo and storm surge modeling represents the next generation of forecasting effort.

WEMo utilizes a computational approach which yields wave heights (meters; converted here to feet) and representative wave energy (RWE; joules m^{-1} wave crest) to provide a georeferenced forecast of both wave heights and energy distribution during a wind event.

Methods

The criteria for selecting what we call the 'test bed' area were the landfall of recent major hurricanes in the area and easy availability of the required data such as bathymetry, shoreline vector files and hourly wind speed and direction. For this preliminary evaluation, we chose the Beaufort area in North Carolina (see Figure sequence) and two hurricanes of differing intensities that occurred recently in hopes of using the findings of this report to reinforce the experience of people who were in the area for these particular storms. We used hurricane Isabel made landfall over Core Banks moving southeast to Northwest over Cedar Island, North Carolina in September 2003[1] as a Category Two on the Saffir-Simpson Scale. We also used hurricane Ophelia was a Category 1 storm that approached Carteret County from the west and slowly tracked along the coast before moving back out to sea between Capes Lookout and Hatteras[2] (see Methods for more detail; additional information on these storms can be found at the State Climate Office of North Carolina[3]). Here we report on simulations of these storms conducted by taking wind field data at various stages of their passage and running our wave exposure model (WEMo) to produce geographically correct maps of wave height[4] distribution during the various stages of their passage near Cape Lookout, North Carolina.

We chose to simulate east and west landfall events using Hurricane Isabel, which actually made landfall to the east of Cape Lookout (which is the landfall reference point because of the location of the wind data collection from the National Weather Service station there; CLKN7[5]). To create the west landfall we simply subtracted 180 degrees from the direction associated with every wind speed observation. We simulated only the actual path of Hurricane Ophelia; it was included here because of its comparatively greater intensity.

Trial Hurricanes

The structure of a hurricane often includes an area in the middle called an 'eye' which is variable in size but often from 12-30 miles in diameter. The eye is the focus of the hurricane, the point about which the rest of the storm rotates and has the lowest surface pressure, while within the eye there can be very light winds, sometimes even calm. Surrounding the eye is the region of most intense winds and rainfall called the eye wall. This is generally the location within a hurricane where the most damaging winds are found and may range out dozens of km from the eye in all directions. Spiraling from the eye wall are large bands of cloud and precipitation called spiral rain or 'feeder' bands. This spiraling rotation of wind in a hurricane is in a counter-clockwise direction in the northern hemisphere.

[1] http://csc-s-maps-q.csc.noaa.gov/hurricanes/viewer.html
[2] http://csc-s-maps-q.csc.noaa.gov/hurricanes/viewer.html
[3] http://www.nc-climate.ncsu.edu/climate/hurricane.php
[4] Heights are in meters; to convert to feet, multiply the value in meters by 3.281.
[5] http://www.ndbc.noaa.gov/station_page.php?station=clkn7

Keeping this in mind, if we simulate any hurricane making landfall on our North Carolina study area to the east of Beaufort, the western spiral rain bands of the hurricane will produce winds from the north and during the course of the storm winds moves from north to southwest and then southerly direction. If the hurricane makes landfall to the west of the Beaufort area, the eastern spiral bands start hitting that area with the winds from south and during the course of storm move from south to northeast and north directions. Thus, landfall location can dramatically reverse the sequence and direction of wind effects.

As mentioned previously, the two named storms used in this study were 1) Isabel in September 2003 (maximum sustained winds at Cape Lookout were 52 knots [60 mph]) and, 2) Ophelia in September 2005 (maximum sustained winds at Cape Lookout were 68 knots [78 mph]). It is important to note that the maximum waves generated by Isabel in our simulations reached ~1.15 m (~3.8 ft) while for Ophelia wave heights reached ~1.7 m (~5.6 ft). Although the forecast wave heights given here may appear to be modest, it has been our experience that wave heights (like currents speeds) are frequently overestimated by the casual observer, especially in sounds and bays (as opposed to the ocean) as reported here. Nonetheless, the ~1-2 m (3 to 6.5 ft) wave heights described here represent extremely dangerous conditions especially in the shallow sounds and bays where shoaling and wave breaking occur. Also, the reader should keep in mind that excluding hurricanes, the top 5% of wind wave heights in the bays and sounds rarely exceed 0.6 m (2 ft; except in channels where opposing wind and tide can cause increased wave heights) so that these wave heights are much greater than normally experienced. Moreover, wave energy – and the damage that a wave can inflict –does not increase linearly with wave height, but increases as the square of wave height. Therefore, while wave height was predicted to be only ~30% greater during Ophelia as compared with Isabel, the wave energy was predicted to be ~ twice that forecast for Isabel.

Following are the brief descriptions of the storms, edited from National Hurricane Center, NOAA (http://www.nhc.noaa.gov/pastall.shtml):

> *Hurricane Isabel* was a long lived storm from 6th to 19th September 2003 that made landfall near Drum Inlet on the Outer Banks of North Carolina as a Category 2 hurricane on the Saffir-Simpson Hurricane Scale. Isabel is considered to be one of the most significant storms to affect Eastern North Carolina since Hurricane Hazel in 1954. The highest observed wind on land was sustained at 79 knots [69 mph) with a gust to (87 knots [100 mph) at an instrumented tower near Cape Hatteras, North Carolina on 18th September. The lowest pressure observed was 962.8 (mb) from a tower in Atlantic Beach, North Carolina. Isabel produced storm surges of 1.8-2.5 m above normal tide levels near the point of landfall along the Atlantic Coast of North Carolina. In North Carolina estuaries, storm surge values were generally 4-6 ft above normal tide levels over the eastern portions of the Pamlico Sound and ~6-10 ft above normal tide values in western end of Pamlico Sound with a maximum value of 10.5 ft reported on the Neuse River in Craven County.

> *Hurricane Ophelia* was a category 1 hurricane on the Saffir-Simpson Hurricane Scale that brushed the North Carolina Outer Banks, its center staying just offshore from the coast. Ophelia moved generally east-northeastward parallel to the North Carolina coast for much of 14-15 September 2005, with the northern eye wall passing over the coastal area from Wilmington to Morehead City. During this time, the hurricane reached its peak intensity of 75 knots (86 mph) although the strongest winds remained offshore. Ophelia turned eastward late on 15 September while passing south of Cape Hatteras. The strongest reported winds were at Cape Lookout, which reported 2-min average winds of 65 knots or 74 mph (9.8 m elevation) on September 14th with a gust to 80 knots or 91 mph. There was an unofficial report of a gust of 90 knots or 104 mph in Davis. Ophelia caused storm surges of 4 to 6 ft above normal tide levels in the Pamlico Sound including the lower reaches of the Neuse, Pamlico, and Newport Rivers. Surges of 4 to 6 ft also occurred along the open coasts in Onslow and Carteret counties. Storm surges of 3 to 4 ft above normal tide levels were common elsewhere along the affected areas of the North Carolina coast. Ophelia also caused tides of 1 to 2 ft above normal along the Florida coast

As with any disturbance event, the extent and duration are important factors determining the magnitude of the event. For this study, the passage of the storm was considered as the time from when winds exceeded tropical storm velocities (~34 knots or ~39 mph) to the time when winds dropped below that level. Wind data for these storms were obtained from National Data Buoy Center (NDBC), NOAA station Cape Lookout, North Carolina[6]. This site was the closest to the hurricane approach path and had the most reliable data available in the area. Hourly data were downloaded for the above time period and were grouped into nine ~three hour periods (Table 1) and WEMo was run for the entire area at points gridded out at 100 m (328 ft) apart.

Assumptions and limitations

Following are the assumptions and limitations for techniques used in this study.

- Wind data were assumed to be equal over the whole study area due to lack of detailed, spatial availability.
- Bathymetry is of good quality.
- Bathymetry used for the study was at mean low tide and the study does not include the effects of high tide and storm surge; storm surge and a high tide will result in wave effects being propagated inland of the shoreline used in this study; ***this makes the wave height results of these simulations highly conservative***.
- Classical diffraction and refraction (the 'wrapping around' or bending of waves as they pass points of land or very shallow water) effects of waves were not considered in WEMo, which could be substantial for some areas close to shore; the model overcomes this limitation through

[6] http://www.ndbc.noaa.gov/station_page.php?station=clkn7

the density of the point computation approach and other aspects of the modeling including use of effective fetch (a mathematical averaging of fetch [downwind distance over which the wind blows over water without interruption by land] to account for shoreline shape effects).

Landfall to the East: Isabel

Key areas that will be referenced in the landfall narratives are shown in Figure 1. The first model simulation (Figure 2) included the time from 00:00 hrs on September 18, 2003 to 03:06 hrs on September 18; winds were slightly above the annual average and from the North (note that the average monthly wind speed at Cape Lookout was 12.1 knots (14 mph). From 0306h to 0609h winds continued from the north with small increase; (Figure 3) wave height began to build in the open parts of the sounds especially against the sandy shoals that extend westward from the sound side of Core Banks and against the sound side of Bogue Banks. From 0609h to 0912h (Figure 4) winds were at ~75% of their maximum and wave height rapidly increased in the central basins of Core Sound and North River; the north facing shorelines of Morehead City abutting the Newport River as well as the sound side of Bogue Banks experienced intensified waves. The State Port basin at Morehead City, particular the docks to the north of the Morehead City – Beaufort high rise bridge would also experience intense wave action. From 0912h to 1215h (Figure 5) the patterns of wave height distribution changed little and with little change; note that these effects at moderate to high levels of wave action had now persisted for over three hours. The next three hours from 1215h to 1518h (Figure 6) signaled the beginning of the rapid change in wind direction that accompanies passage of the storm's eye with some minor diminishment of wave height but with little change in its distribution meaning that wave battering for these areas has now persisted for almost six hours. Figure 7 from 1518h to 1821h shows the resulting rapid change in wave height and distribution as the eye passes; winds are now from the west-southwest and at ~65% of peak storm wind speeds. Wave height has diminished in Core Sound but with the wind swinging to the southwest, wave height intensified at Beaufort Inlet. Waves have dramatically diminished on the sound side of Bogue Banks and are now building on the sound side of Morehead City. Figure 8 from 1821h to 2100h shows the continuing diminishment of the wind speeds but with continued westerly component; the Morehead City shoreline continued to experience lowered but moderate wave height. Figure 9 from 2100h to 0003h on September 19th indicate that waves are still present along the Morehead City shoreline and in the central basins of Core Sound, but at much lower levels, comparable to commonly observed strong summertime (sea breeze) condition; waves at Beaufort Inlet remain at elevated intensity. Figure 10 from 0003h to 0306 shows the winds becoming more southerly with increased exposure of the sound side portions of the mainland shoreline of Core Sound; again these conditions are comparable to a strong summertime event but unlike that type of event, this initiated in the early morning hours.

Landfall to the West : Isabel's wind data reversed

Our simulations of what might have occurred had Isabel made landfall to the west of Cape Lookout begin with Figure 11. In the early morning hours of September 18, over 12h before the eye arrived, southerly winds measurably stronger than a strong summertime sea breeze would already be affecting the south-facing (sound-side) shoreline of Morehead City and the mainland shoreline of Core Sound. Also at this time waves at Beaufort Inlet would already had become comparatively (compared to the peak of the storm) high, a condition that might not be anticipated by late-arriving vessels seeking safe harbor. From 0003h to 0609h wave intensity has begun to rise sharply at Beaufort inlet and along the mainland shoreline of Core Sound (Figure 12). Over the next three hours (0609-0912h) wave height has in many areas reached over 80% of the maximum conditions (Figure 13); the Morehead City shoreline, south-facing shorelines of the Newport River (potentially impeding and endangering vessels attempting to flee up the Atlantic Intracoastal Waterway), parts of Harker's Island and the mainland shoreline of Core Sound, especially parts of Marshallberg, the entrance to Jarrett's Bay, and Sea Level would now be under extreme wave conditions. The next two Figures (14 and 15) indicate continued, high wave height along the aforementioned shorelines with only a slight reduction in intensity in the upper Newport River towards 1500h; extreme wave battering of these shorelines has now been ongoing for nearly nine hours. Between 1518h and 1821h (Figure 16) conditions begin to abate but still wave energies are present at the Core Sound communities in the top ~75% of the storm's maxima. However, between 1821h and 2100h (Figure 17) the eye has passed on winds are now approaching from the east-northeast at much reduced velocities; some minor wave height may now be experienced on the sound side of Bogue Banks but the Core Sound condition would have attenuated dramatically. Figures 18 (September 19th 0300h) and 19 (to 0306h) winds continue at moderated levels with only the central basins and sand shoals of Core Sound experiencing continued (but much reduced from 6h previous) wave action.

Landfall to the West and offshore: Ophelia

Simulations for Hurricane Ophelia began at ~0900h to 1214h on September 14, 2005 (Figure 20); winds were from the southeast and moderate levels causing wave heights along exposed shorelines not unlike that of a strong summertime sea breeze, almost 12h before the storm eye arrived. From 1214h to 1618h (Figure 21) winds continued from the east-southeast with some intensification especially along the south facing shoreline of Morehead City and the mainland shorelines of Core Sound. From 1618h to 1820h (Figure 22) wave height from the southeast has continued to build with increasing and sustained winds, but would now have become noticeably stronger in the northwestern portions of the Newport River, North River (again, potentially impeding and endangering vessels attempting to flee up the Atlantic Intracoastal Waterway) and the entrance to Jarrett's Bay; some localized high wave height points can be seen building also off the southwestern end of Harker's Island and at Marshallberg point. From 1820h to 2022h the previous trend has continued with increased intensity also in the Port of Morehead City turning basin (Figure 23); conditions particularly at locations such as Sea Level, Thorofare Bay and Cedar Island Bay have begun to deteriorate sharply with wave energies in some cases reaching ~half of the storm's maxima. From 2022h to 2200h (Figure 24), many areas such as the Morehead City shoreline, the upper Newport River and the Core Sound communities are all experiencing near-maximum wave energies. From 2200h on September 14 to the early hours of September 15, wave heights have reached their maximum prior to the passage of the eye (Figure 25); shorelines have now been battered for over 12h, with the last 4-6h being at extreme levels. From 0002h to 0204h on the 15th (Figure 26) wind direction has shifted rapidly with the passage of the eye, coming from nearly due east with concomitant reductions in wave height regionally except for continued intense pockets at locations such as Sea Level, Thorofare Bay and Cedar Island Bay. Because Ophelia lingered in many ways unchanged for so long, we will now skip some time periods in our simulation. Jumping ahead to the time from ~0600h to 0810h (Figure 27) wave energies have diminished considerably from ~8h previous but waves have begun to shift southerly along many shorelines such as the Newport River and also to the central basin of the North River and onto the sandy shoals that extend westward from the sound side of Core Banks. Jumping ahead to the period from ~0800h to 1012h (Figure 28) winds have now set up from the north-northwest again at increased velocities, bringing high wave height to the sound side of Bogue Banks, Crab Point on the Newport River side of Morehead City and across to the Deerfield Shores area of Beaufort; wave height is also now intensifying along the sandy shoals behind (extending westward from) Core Banks and near Bottlerun Point on the sound side of Shackleford Banks, including a point of wave concentration covering the Barden's Inlet Channel.

Conclusions

Wind waves in shallow sounds and bays can become highly destructive during major storms; here our model simulations forecast wave heights reaching ~5.5 ft (1.7 m) in the most exposed areas of the bays and sounds for two storms in the lower range of the Saffir-Simpson scale. As we pointed out, wave energy and thus, its destructive potential increases as the square of wave height meaning that larger storms (e.g., Category 3 and beyond) have the potential to generate disproportionately larger waves and destructive impacts.

We have shown that WEMo is a potentially important tool to map the distribution of wave energy during the passage of coastal storms, such as hurricanes. The change in wave height and energy distribution provides guidance to property owners and emergency managers as to where areas of concern may develop during the different landfall locations and intensities of storms. This exercise serves also to demonstrate the potential not only for specific areas of concern along inhabited shorelines, but also the potential danger of rapidly shifting loci of wave heights and their associated energy. Wave heights were shown to far exceed normal conditions and often long before the main body of the storm arrived. Dangerous wave conditions were shown to occur at many locations that could impede and endanger late-fleeing vessels seeking safe harbor.

Future work will include utilizing storm surge forecasting along with WEMo so that the impact of wind wave events may be forecast as the water level rises, thereby introducing wave effects into areas landward of the shoreline; a scenario that would benefit from such spatially explicit information. In order to forecast actual impacts on property or ecological resources, WEMo results will likely be used to best effect when modeled with additional factors. For example, the effects of disturbance events are typically characterized by extent, severity, duration, and frequency. While extent and severity are embedded in the wave height value for a given event, duration of the event is not, and may be a powerful explanatory variable when joined with wave height to examine the response of resources to a storm event.

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Table 1. Chronology of storm simulations for each hurricane along with Julian Day conversion which is the x-axis on the inset wind – stick diagram in Figures 2-28.

Hurricane Isabel			Hurricane Ophelia	
Day and hour	Julian day conversion		Day and hour	Julian day conversion
9/18 0306	261.125		9/14 1214	257.5
9/18 0609	261.25		9/14 1618	257.66
9/18 0912	261.375		9/14 1820	257.75
9/18 1215	261.5		9/14 2022	257.83
9/18 1518	261.625		9/14 2200	257.92
9/18 1820	261.75		9/14 0002	258
9/18 2100	261.875		9/14 0204	258.1
9/19 0003	262		9/14 0810	258.33
9/19 0306	262.125		9/14 1012	258.42

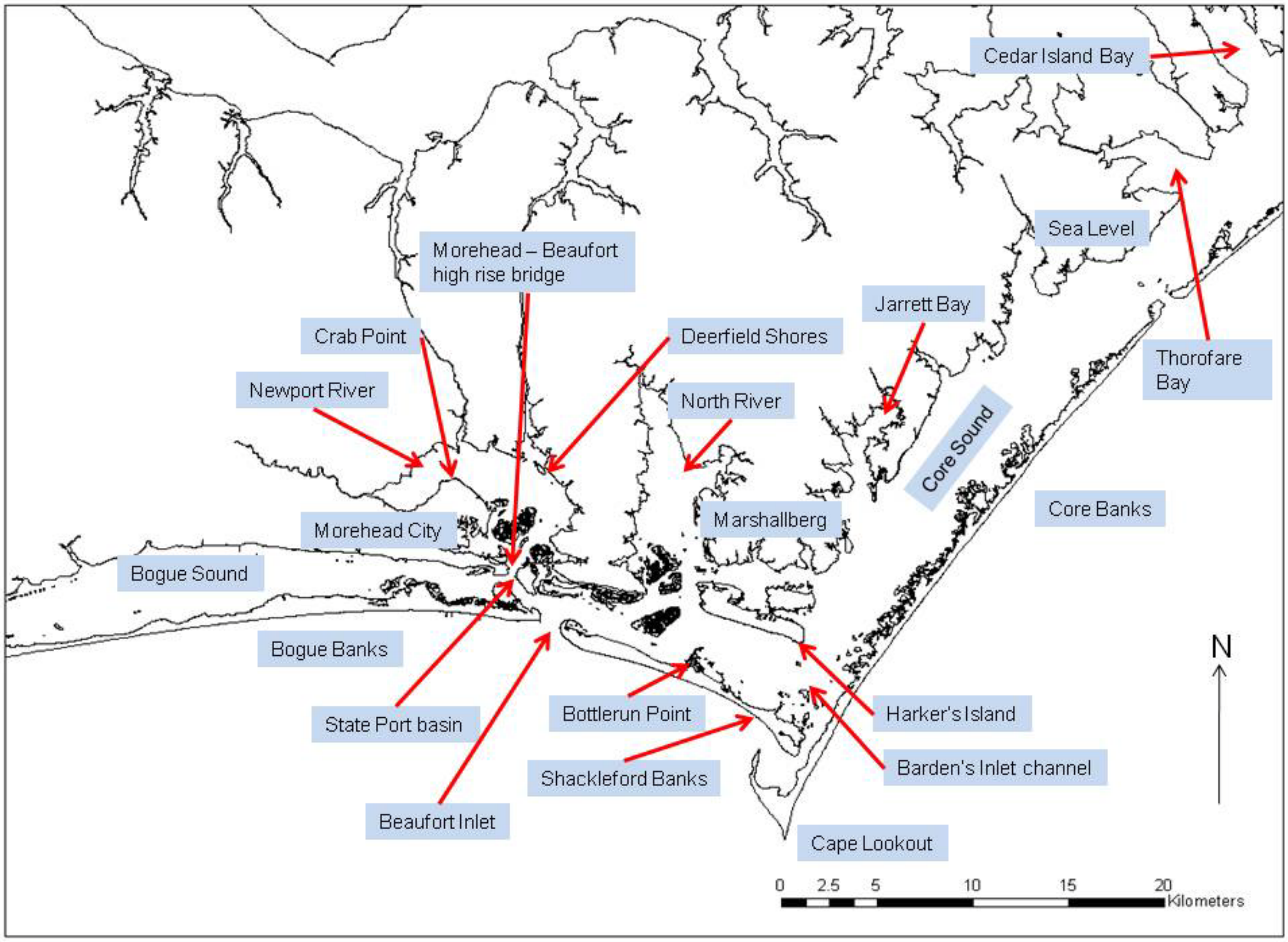

Figure 1. Key place names described in the landfall narratives.

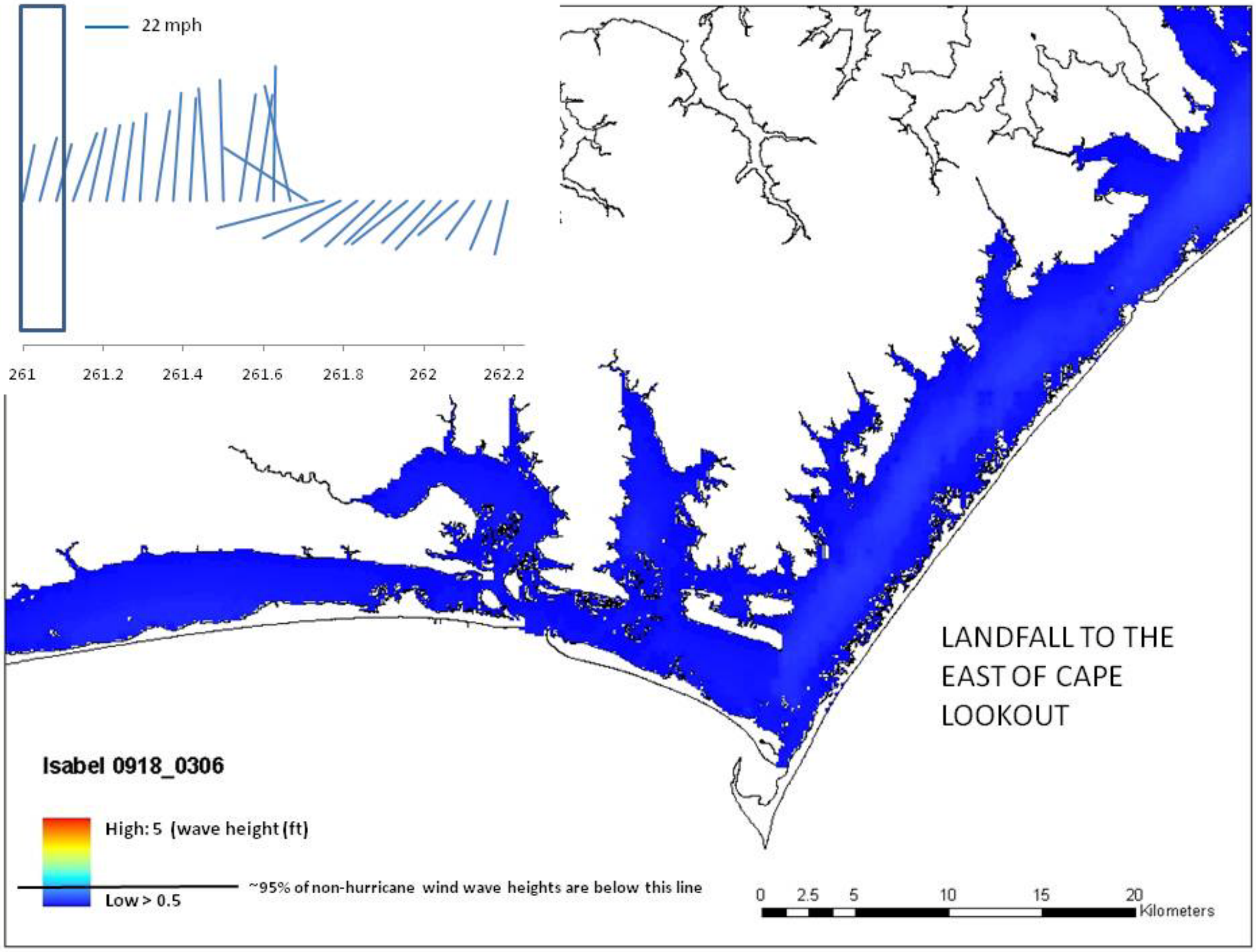

Figure 2. Simulation for hurricane Isabel, east landfall, September 18 2003: 0306h.

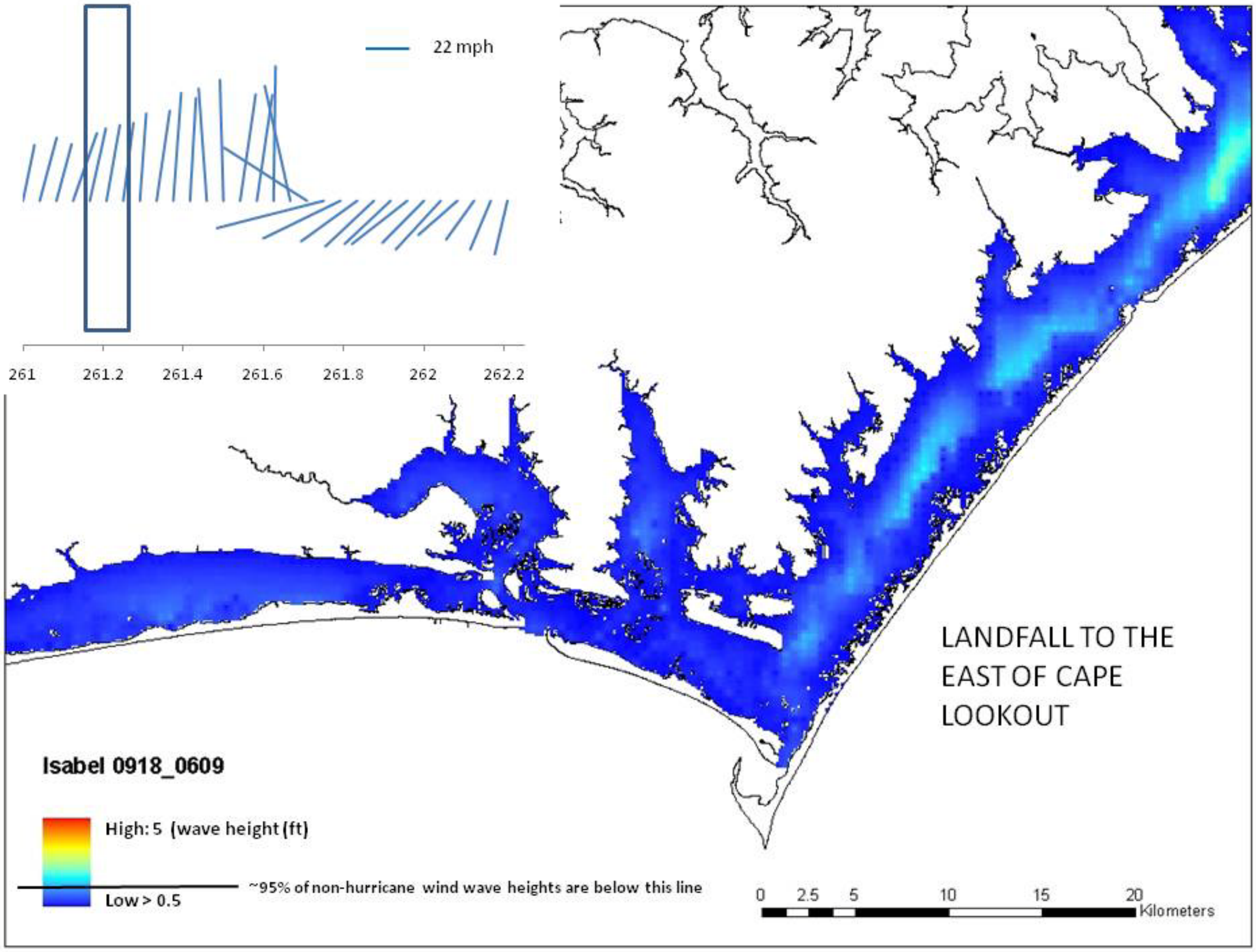

Figure 3. Simulation for hurricane Isabel, east landfall, September 18 2003: 0609h.

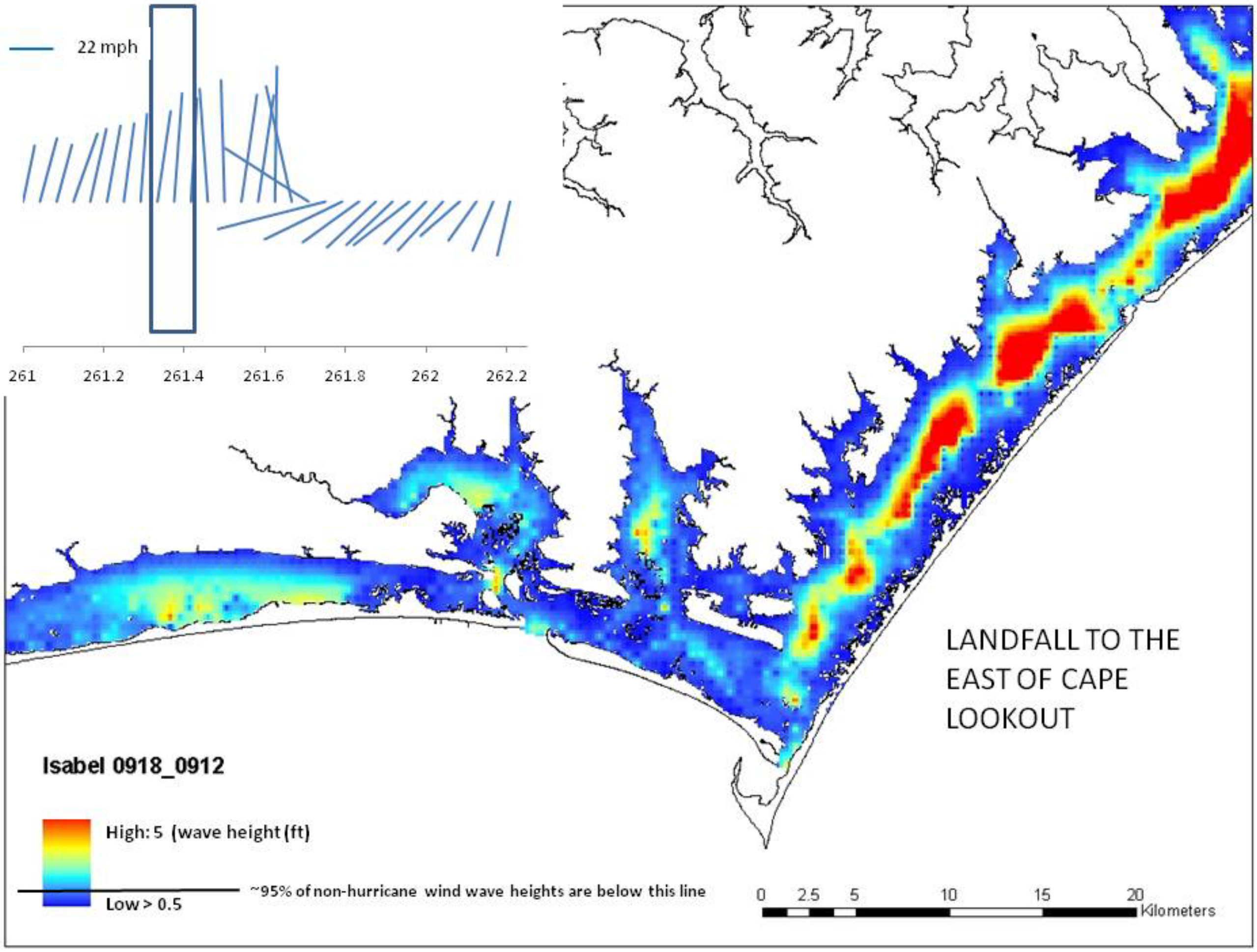

Figure 4. Simulation for hurricane Isabel, east landfall, September 18 2003: 0912h.

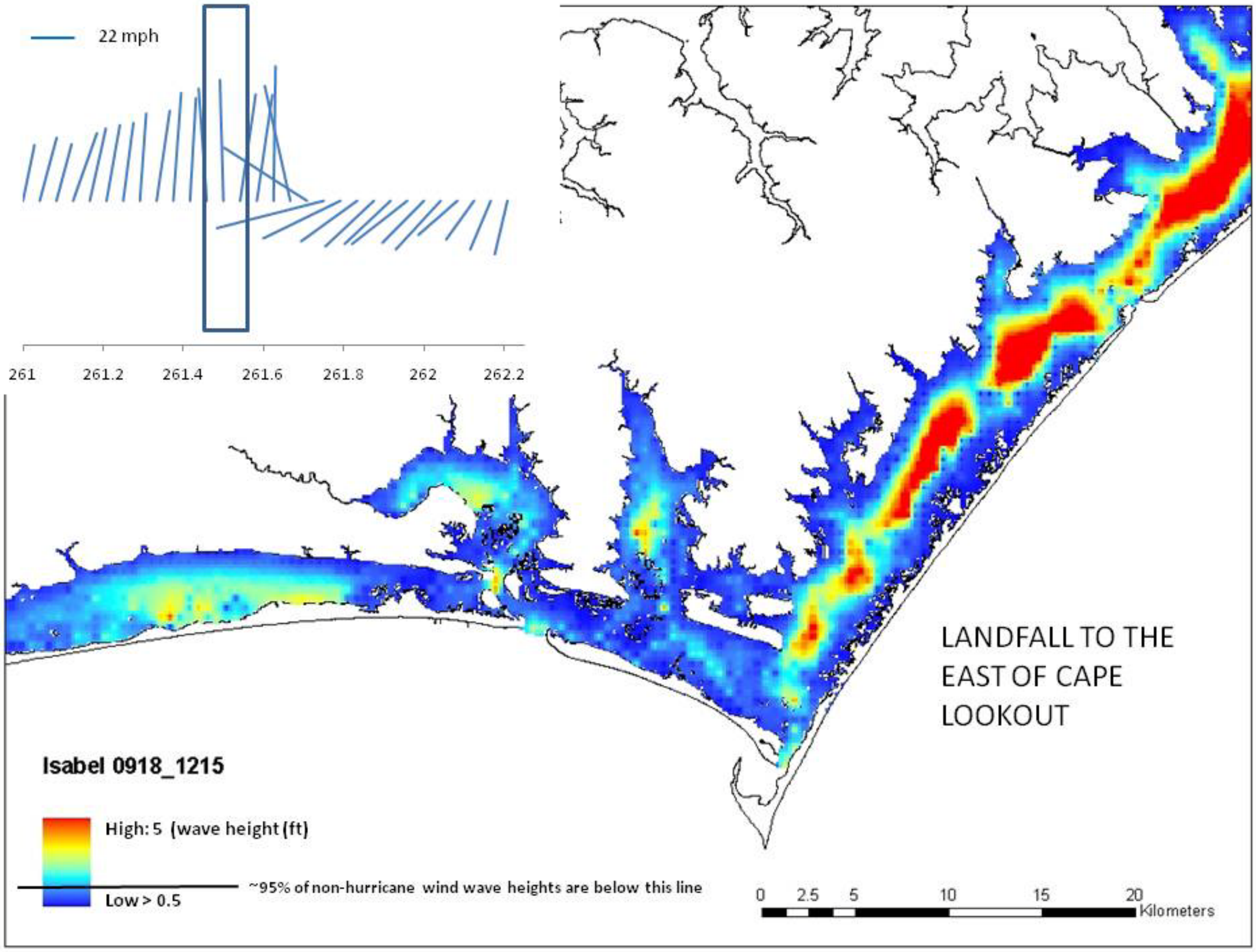

Figure 5. Simulation for hurricane Isabel, east landfall, September 18 2003: 1215h.

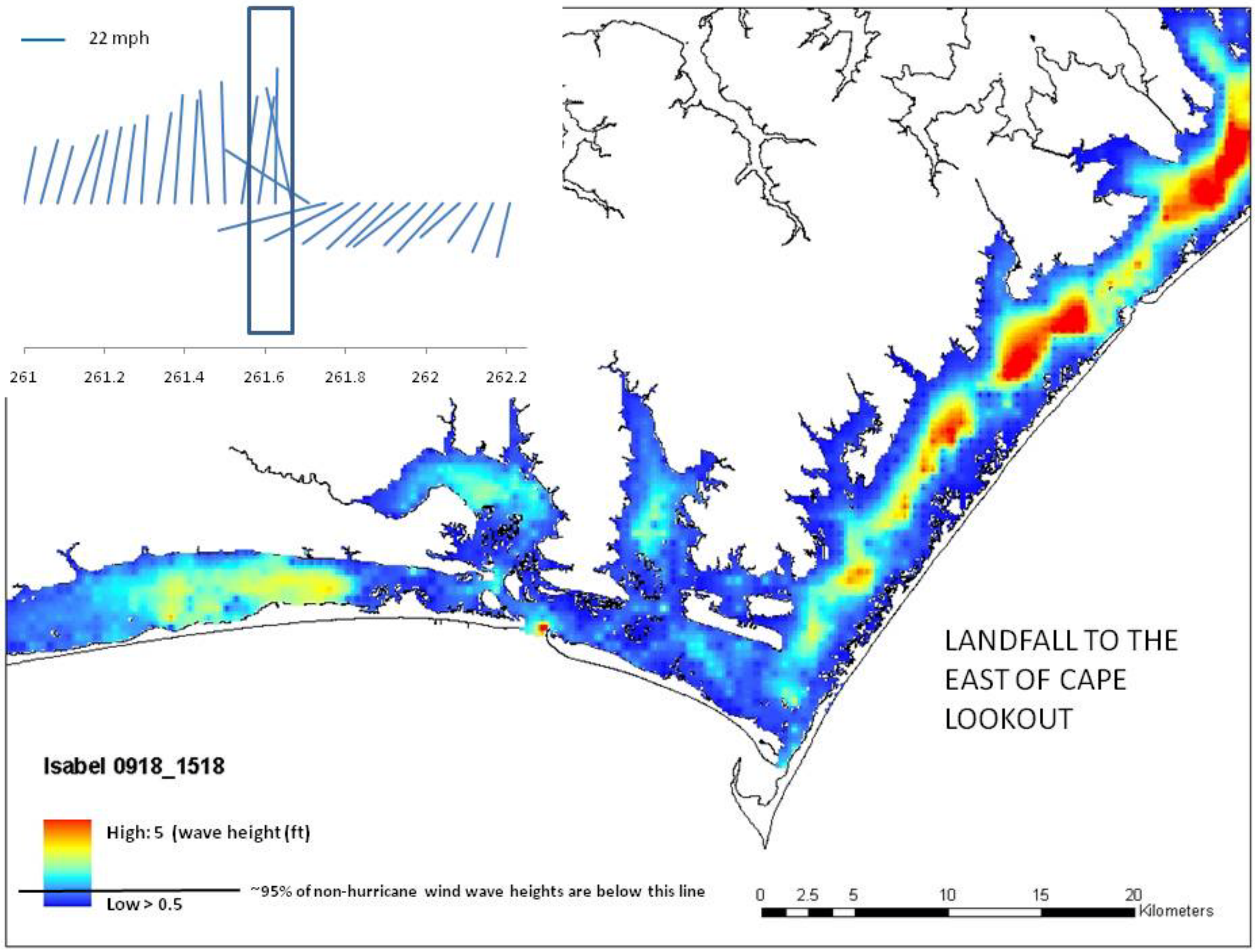

Figure 6. Simulation for hurricane Isabel, east landfall, September 18 2003: 1518h.

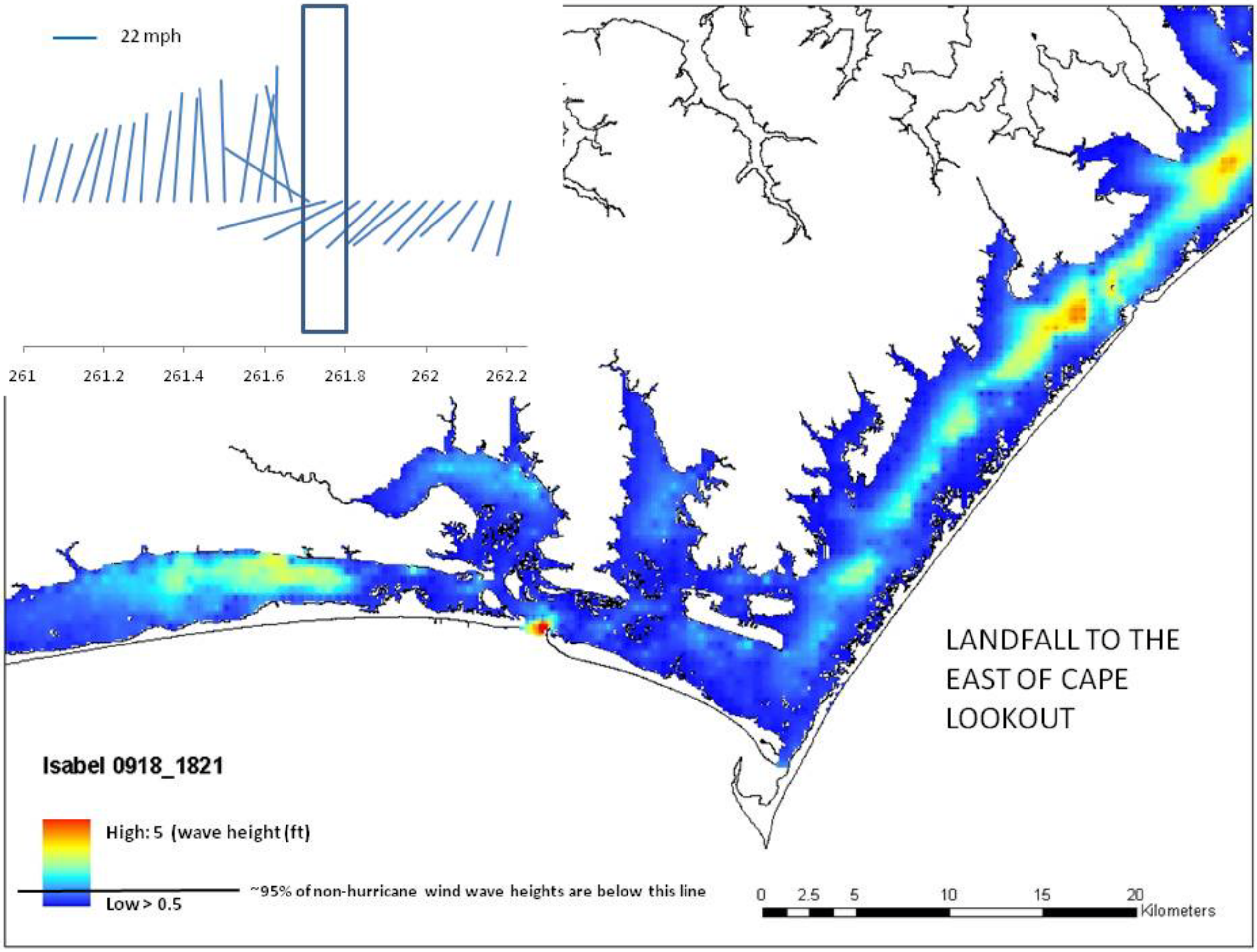

Figure 7. Simulation for hurricane Isabel, east landfall, September 18 2003: 1821h.

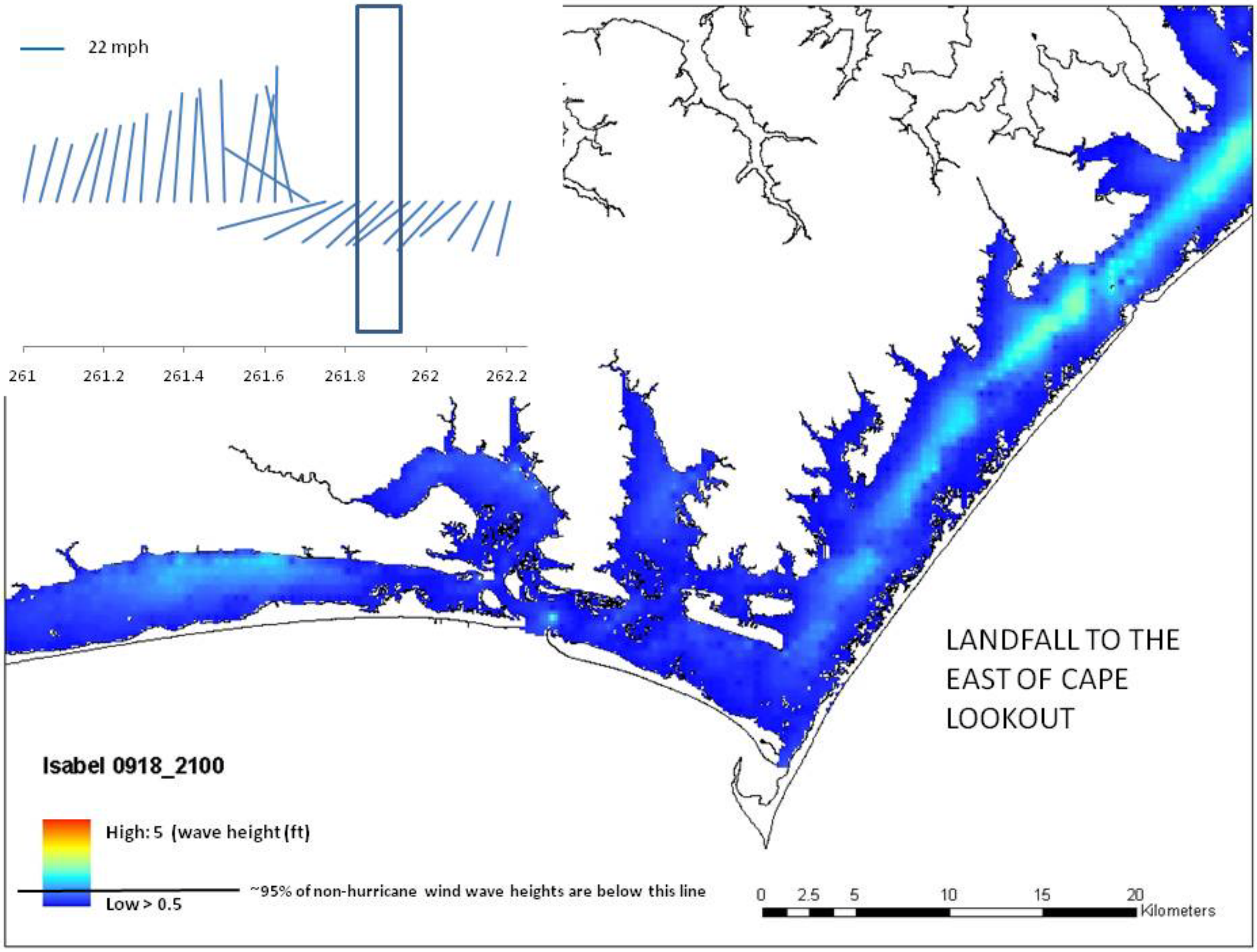

Figure 8. Simulation for hurricane Isabel, east landfall, September 18 2003: 2100h.

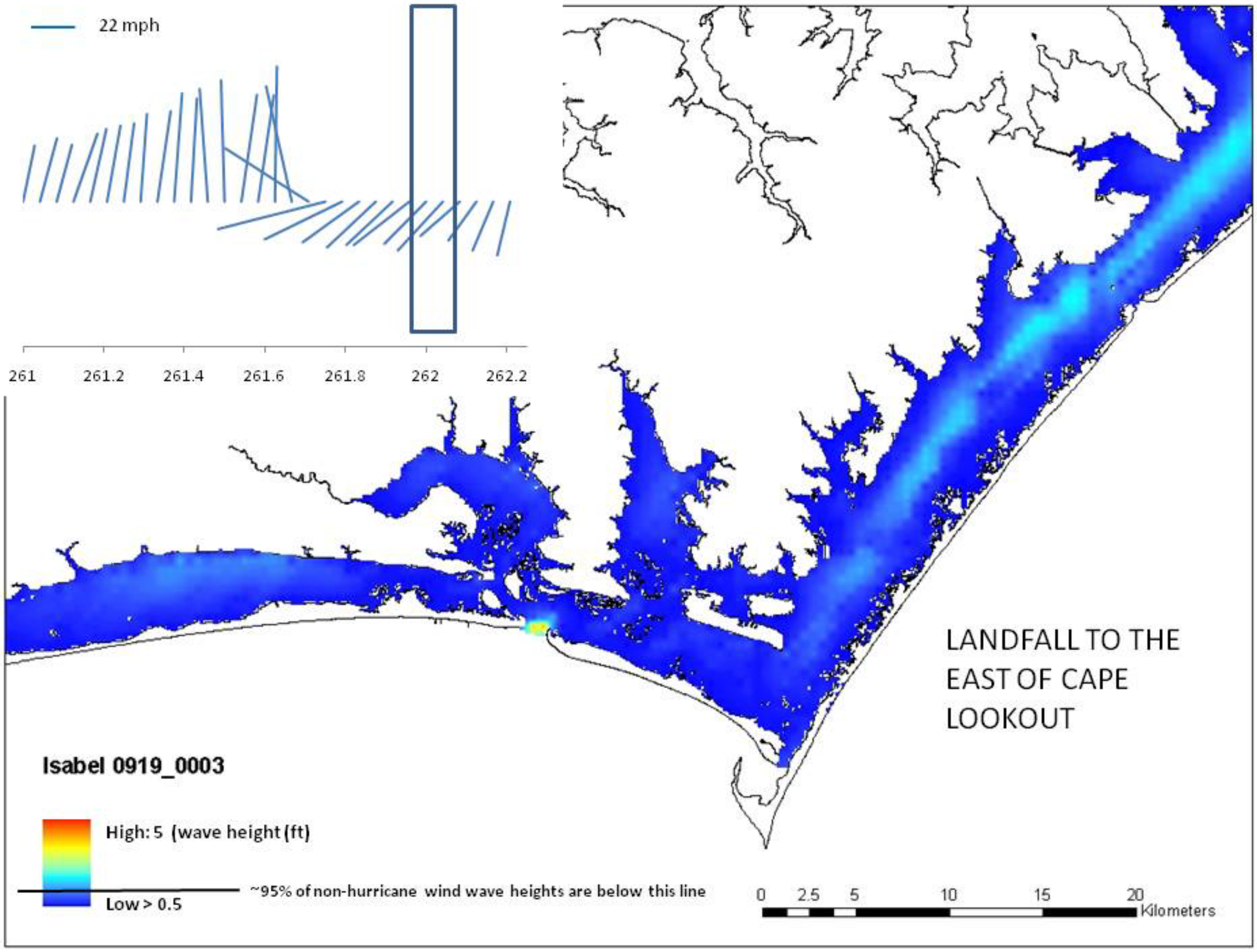

Figure 9. Simulation for hurricane Isabel, east landfall, September 19 2003: 0003h.

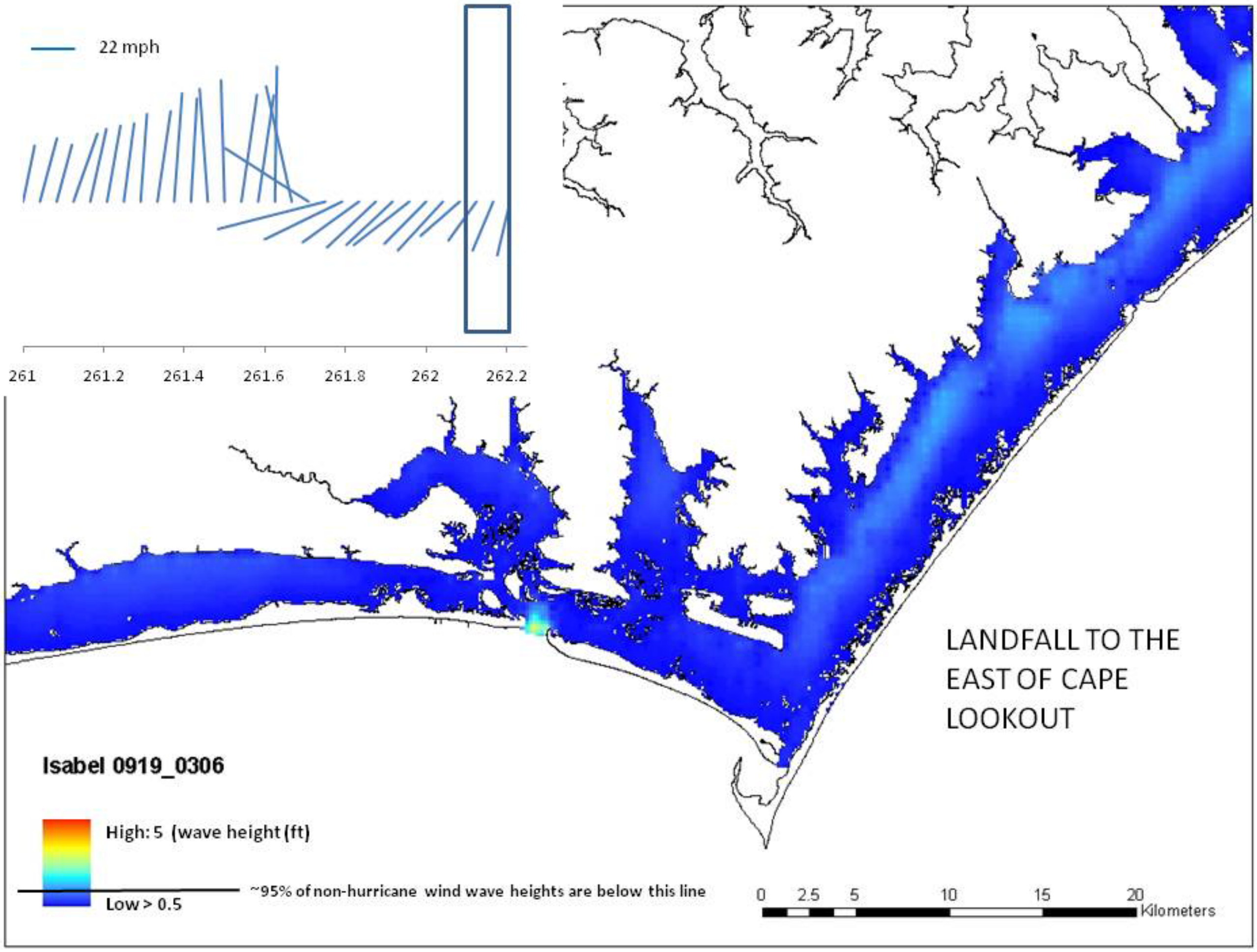

Figure 10. Simulation for hurricane Isabel, east landfall, September 19 2003: 0306h.

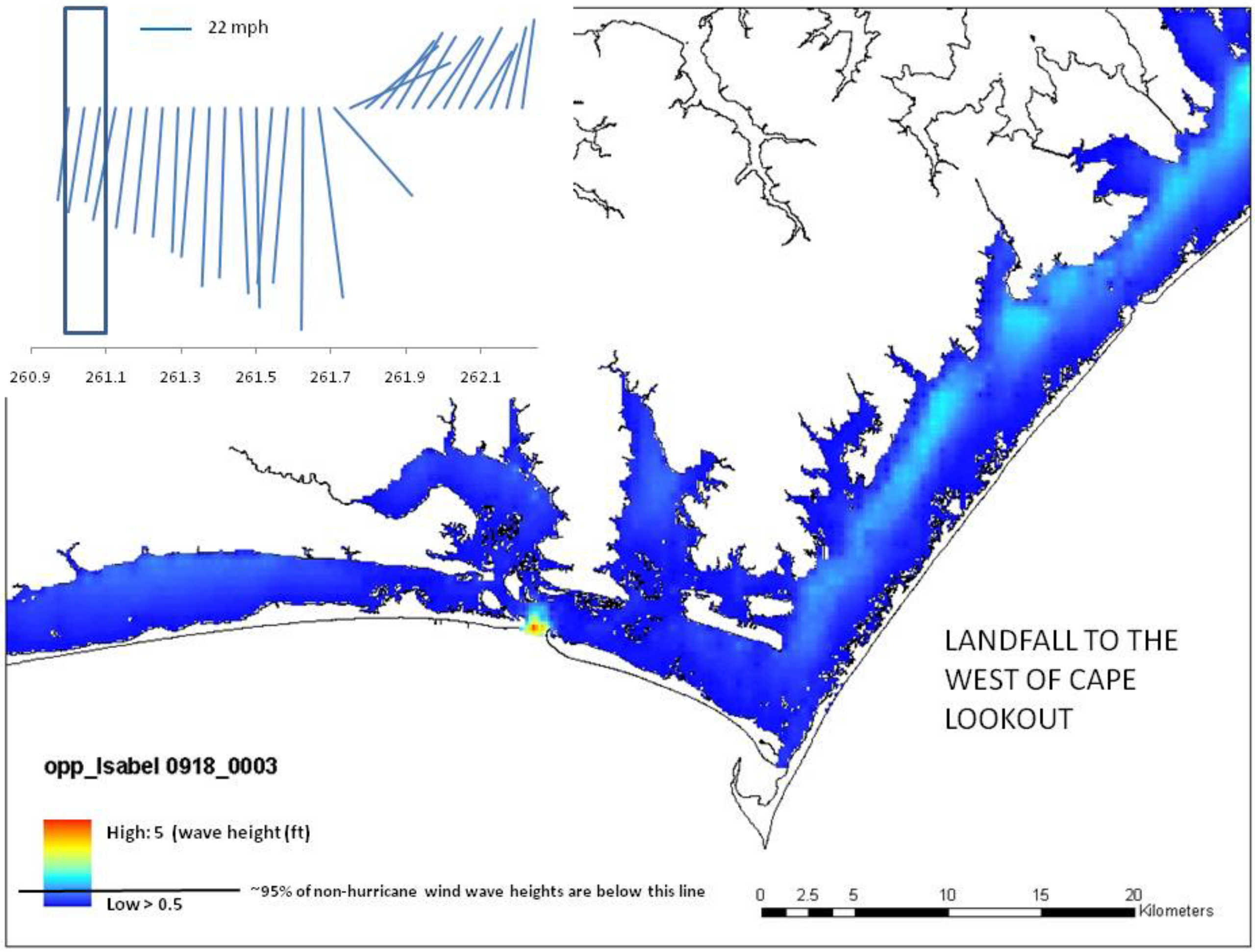

Figure 11. Simulation for hurricane Isabel, by inverting the actual east landfall to create a west landfall, September 18 2003: 0003h.

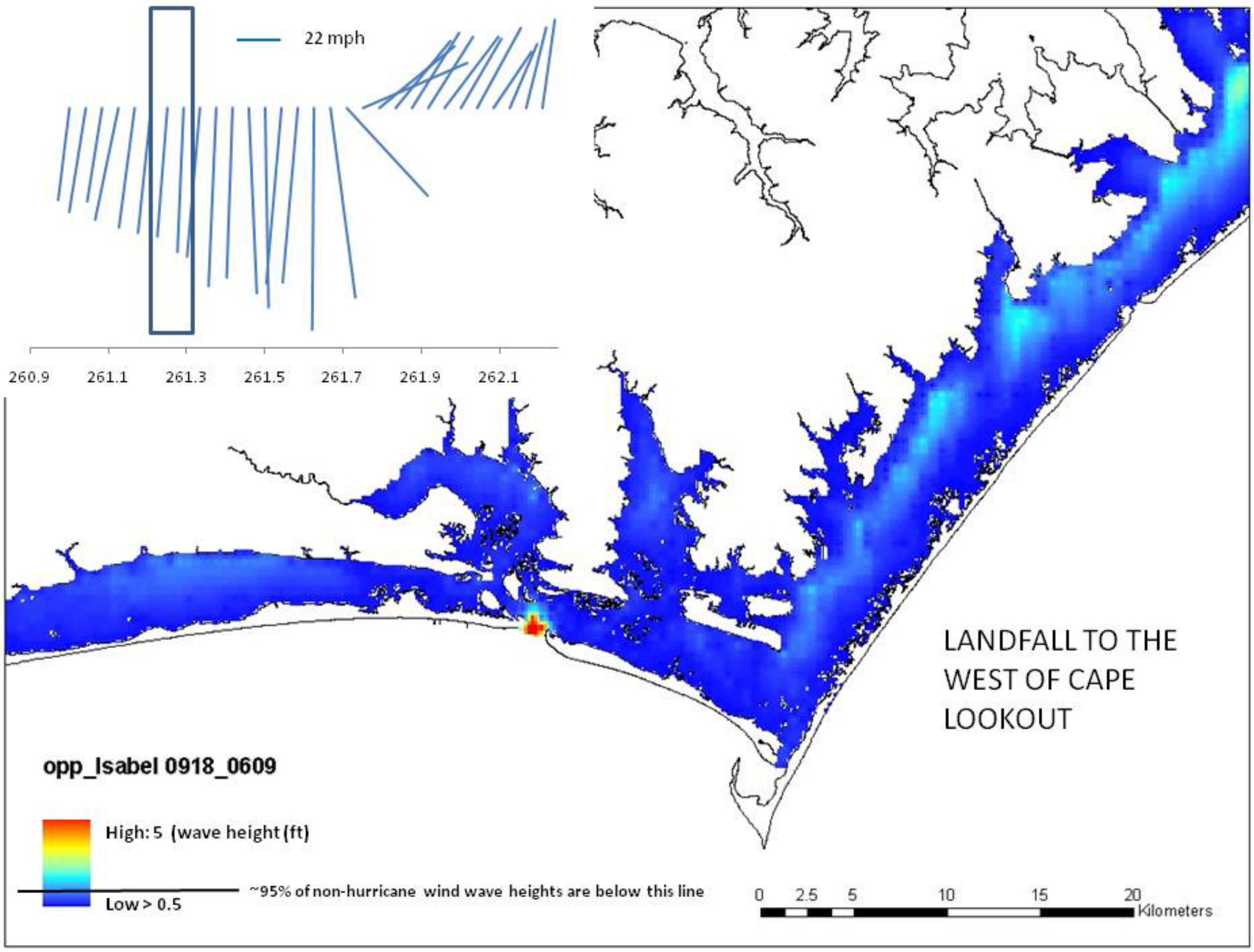

Figure 12. Simulation for hurricane Isabel, by inverting the actual east landfall to create a west landfall, September 18 2003: 0609h.

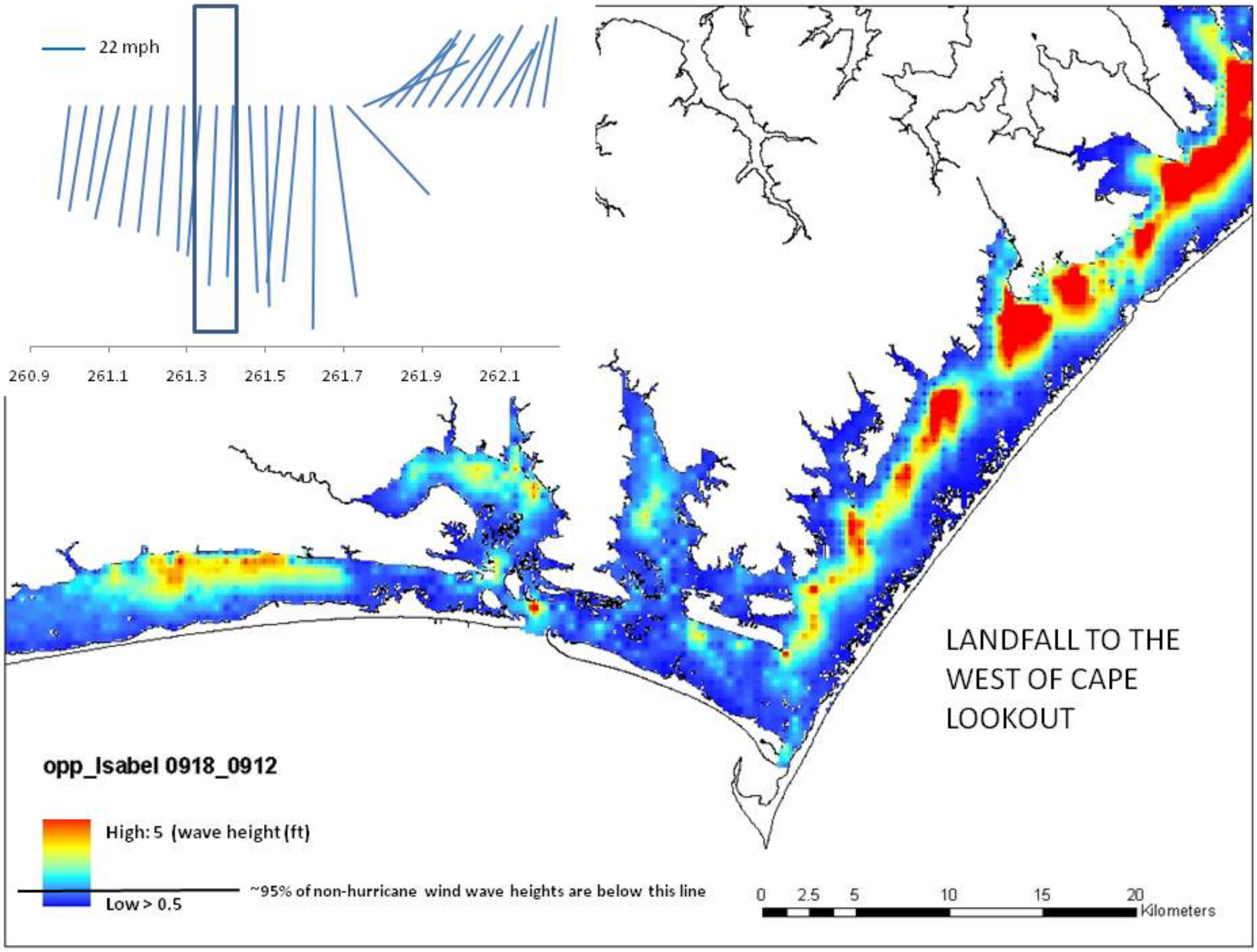

Figure 13. Simulation for hurricane Isabel, by inverting the actual east landfall to create a west landfall, September 18 2003: 0912h.

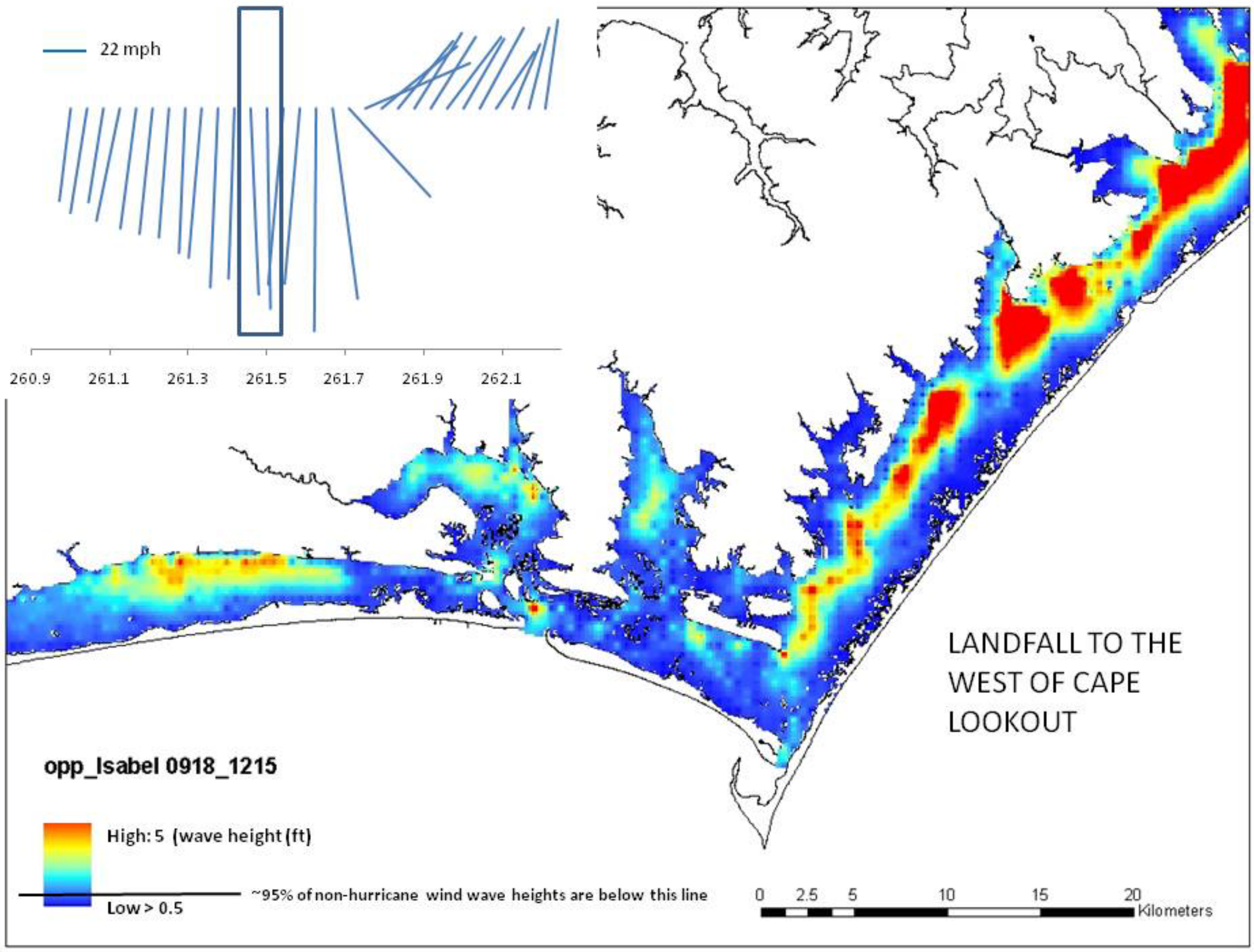

Figure 14. Simulation for hurricane Isabel, by inverting the actual east landfall to create a west landfall, September 18 2003: 1215h.

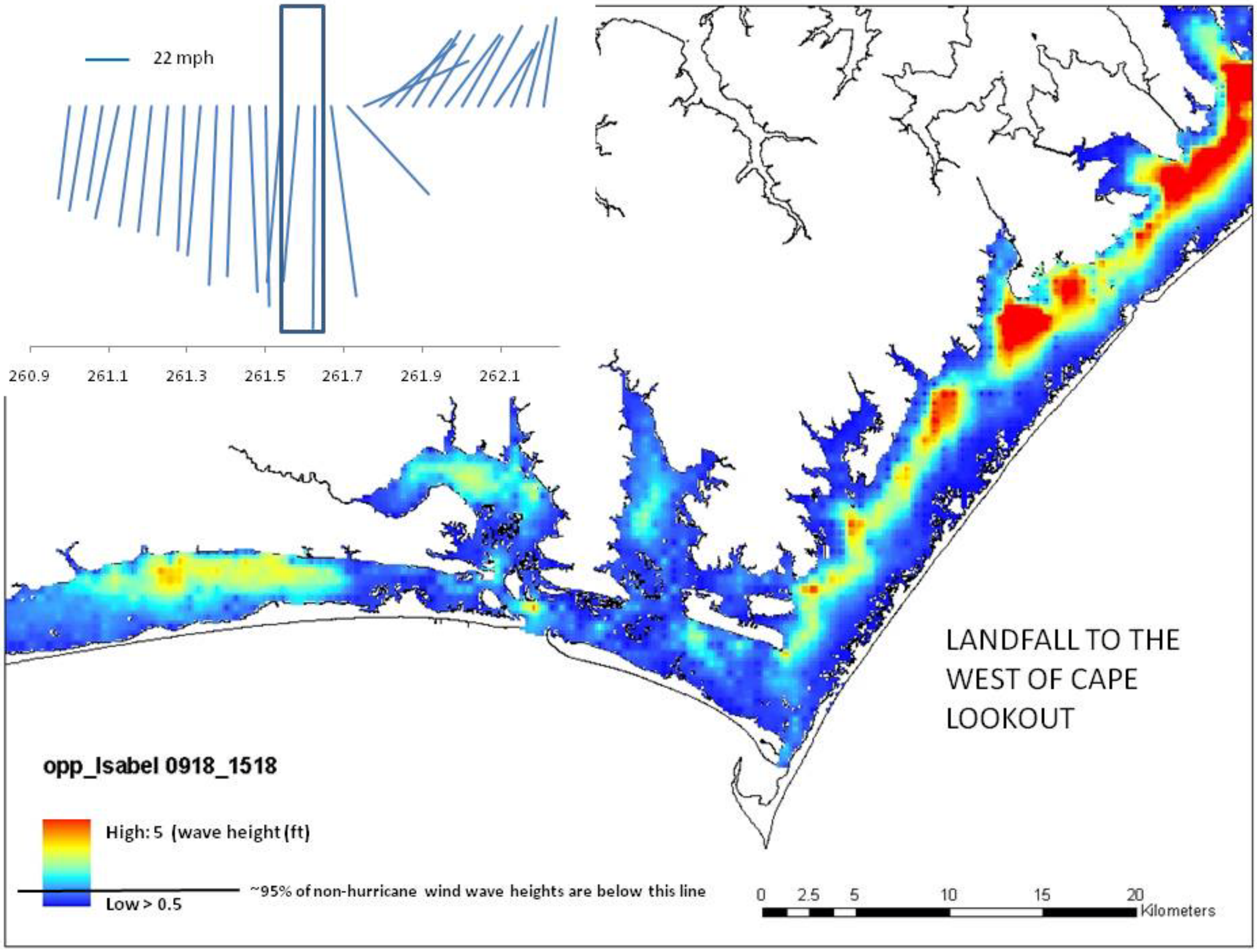

Figure 15. Simulation for hurricane Isabel, by inverting the actual east landfall to create a west landfall, September 18 2003: 1518h.

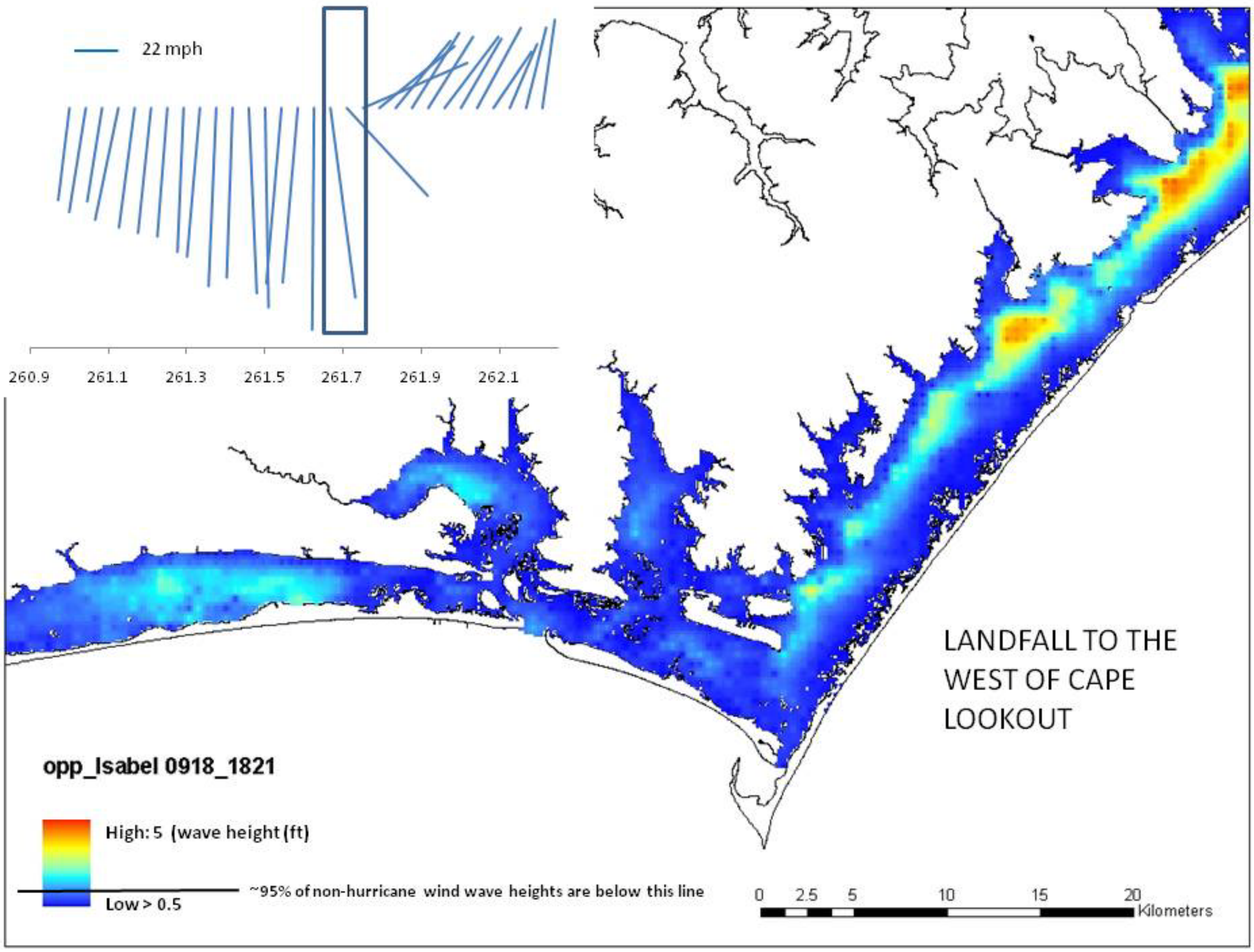

Figure 16. Simulation for hurricane Isabel, by inverting the actual east landfall to create a west landfall, September 18 2003: 1821h.

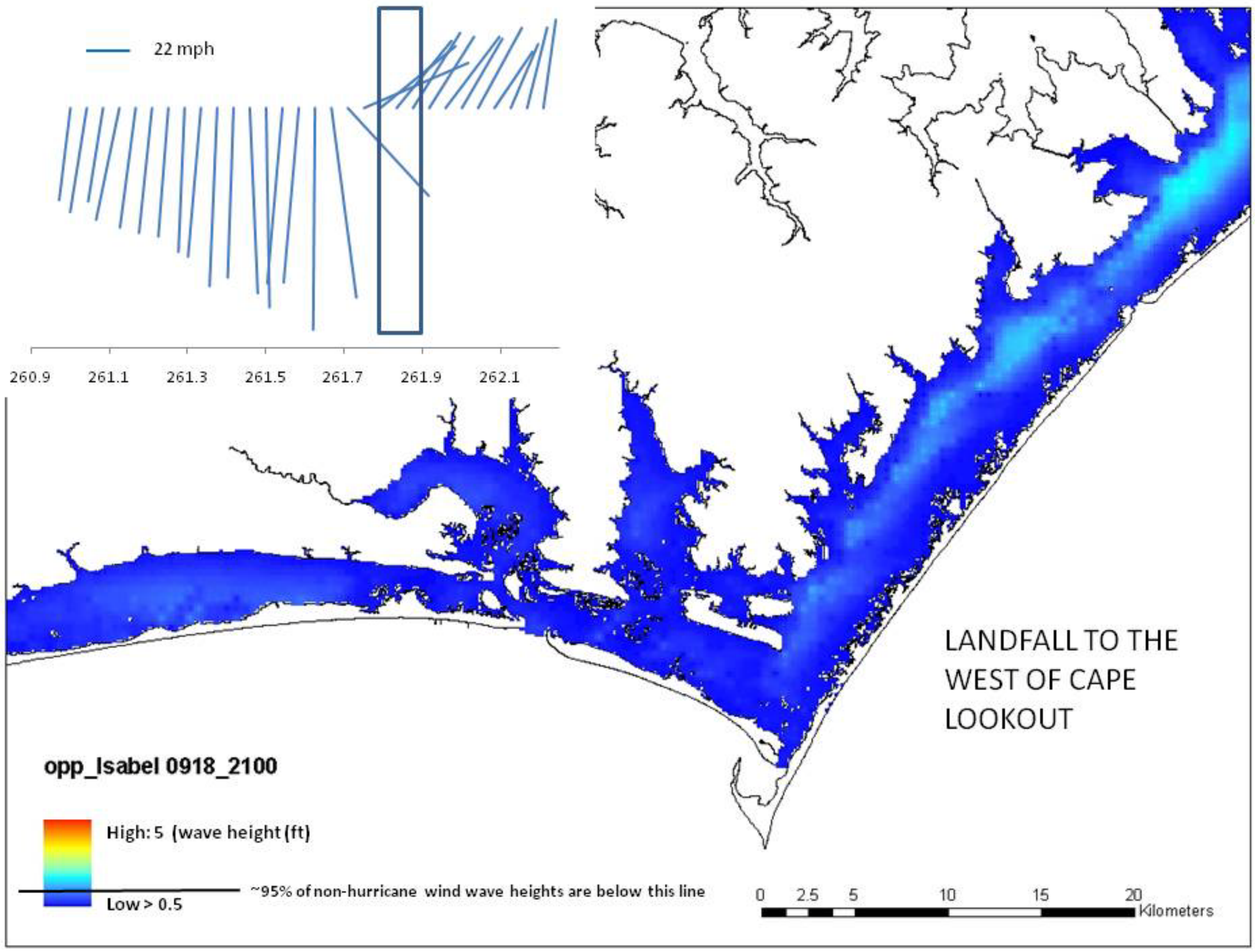

Figure 17. Simulation for hurricane Isabel, by inverting the actual east landfall to create a west landfall, September 18 2003: 2100h.

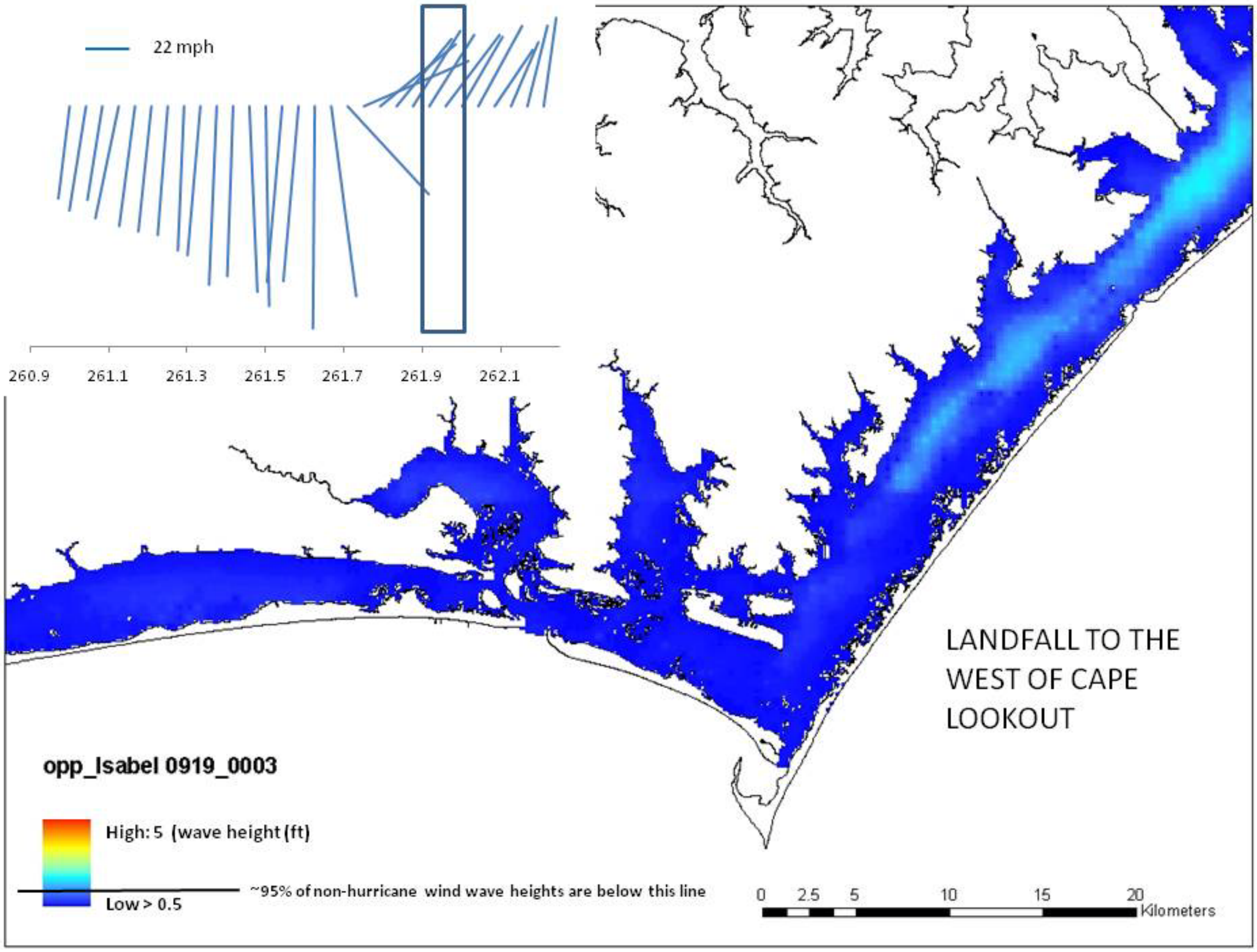

Figure 18. Simulation for hurricane Isabel, by inverting the actual east landfall to create a west landfall, September 19 2003: 0003h.

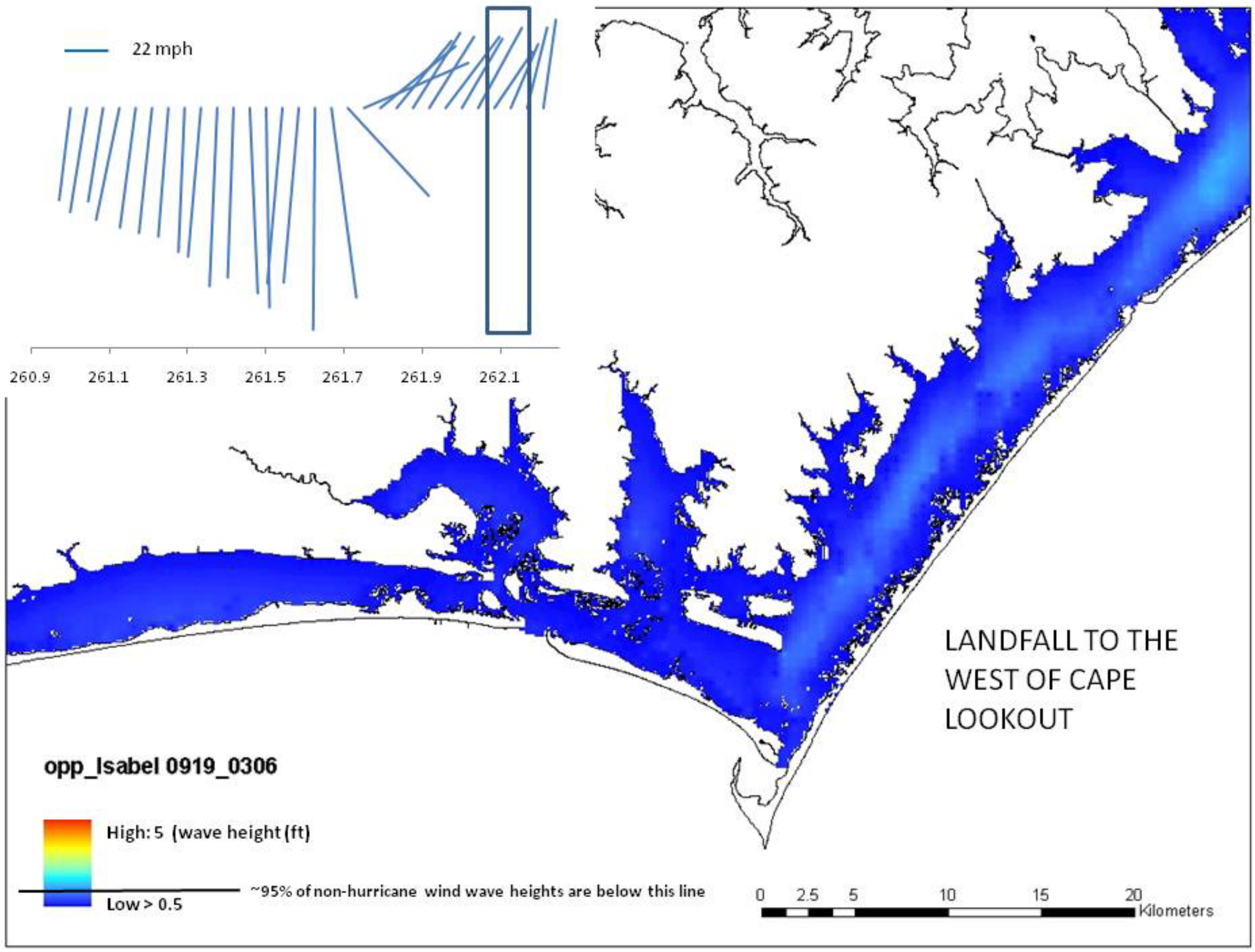

Figure 19. Simulation for hurricane Isabel, by inverting the actual east landfall to create a west landfall, September 18 2003: 0306h.

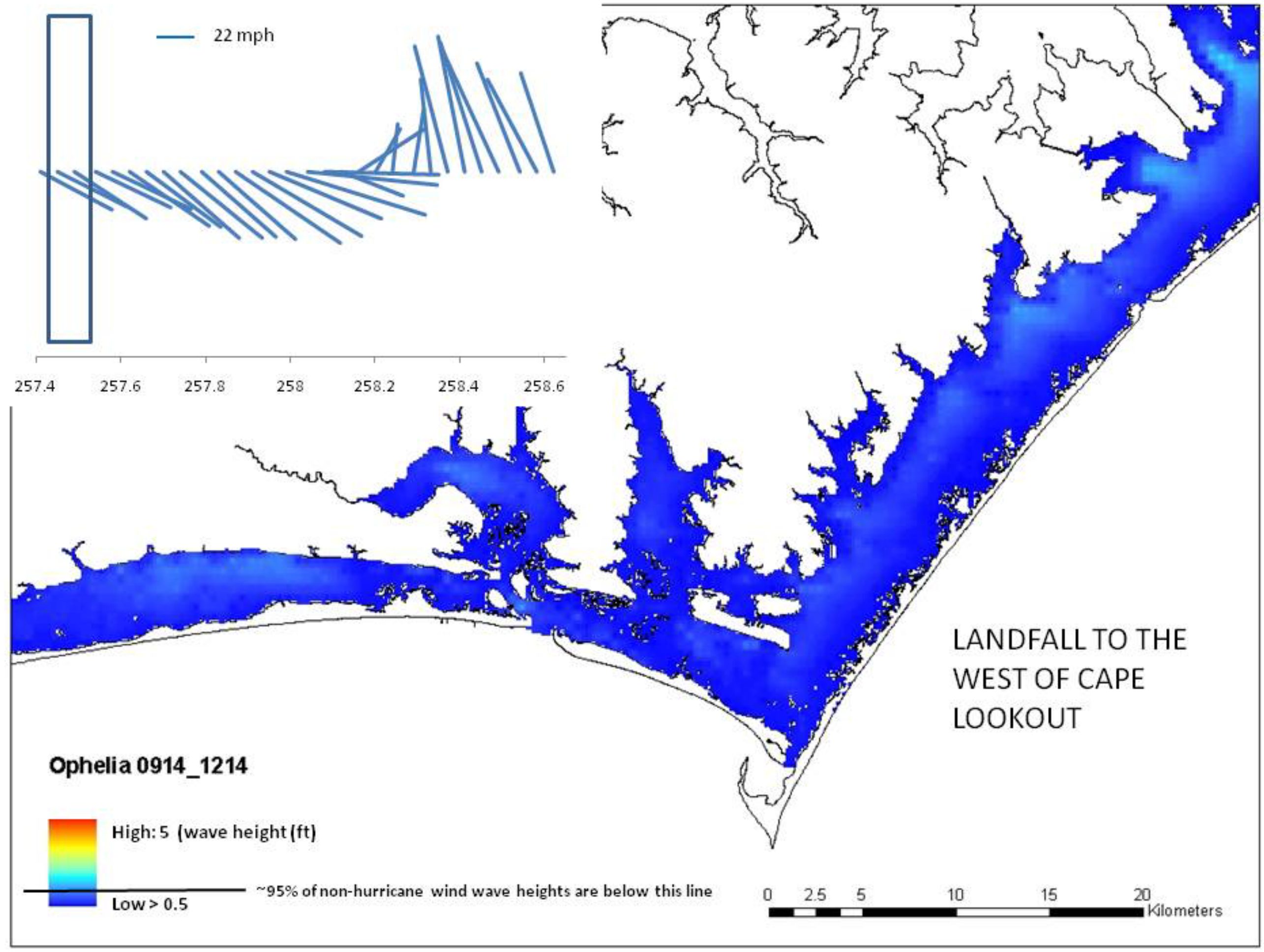

Figure 20. Simulation for hurricane Ophelia with west landfall, September 14, 2005: 1214h.

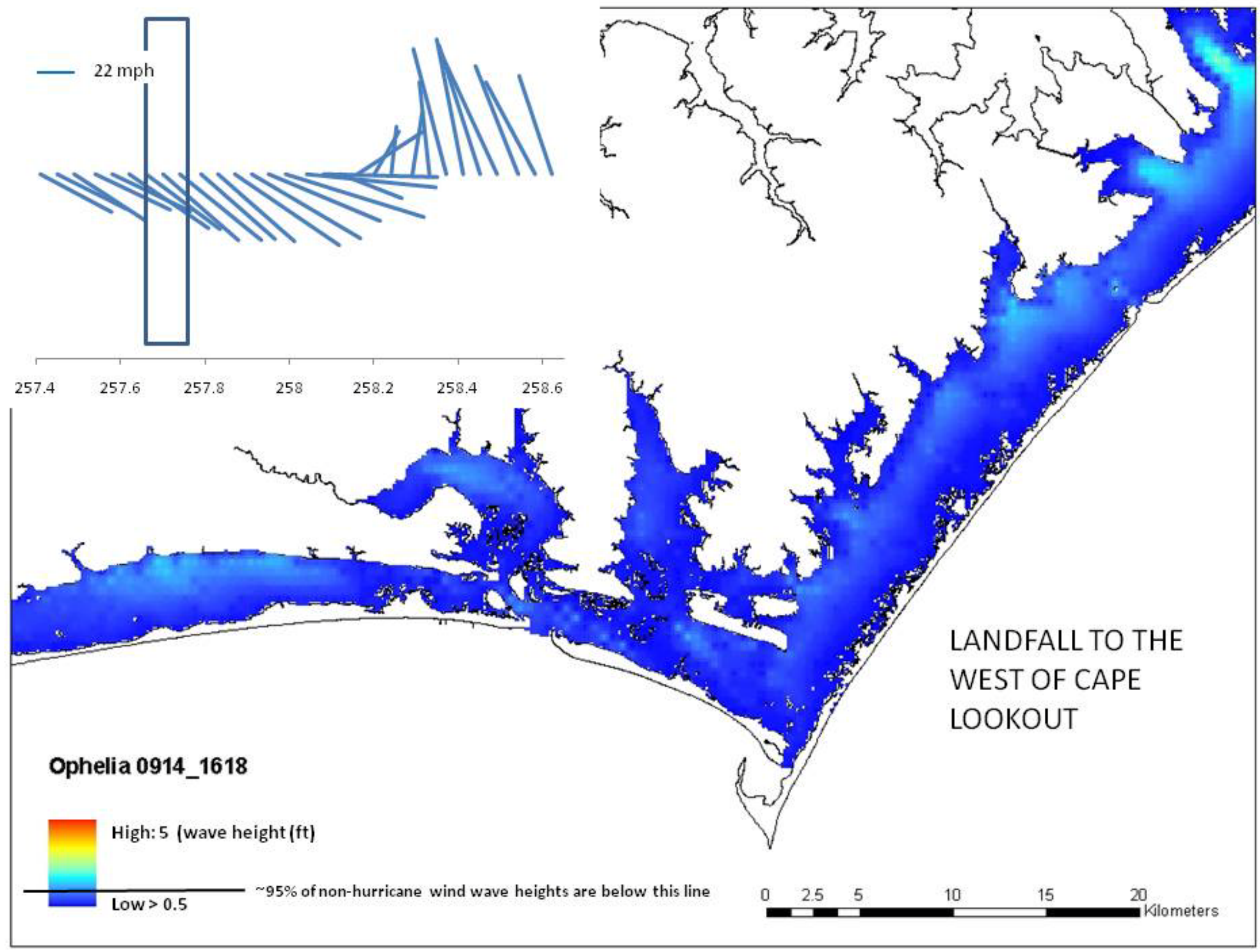

Figure 21. Simulation for hurricane Ophelia with west landfall, September 14, 2005: 1618h.

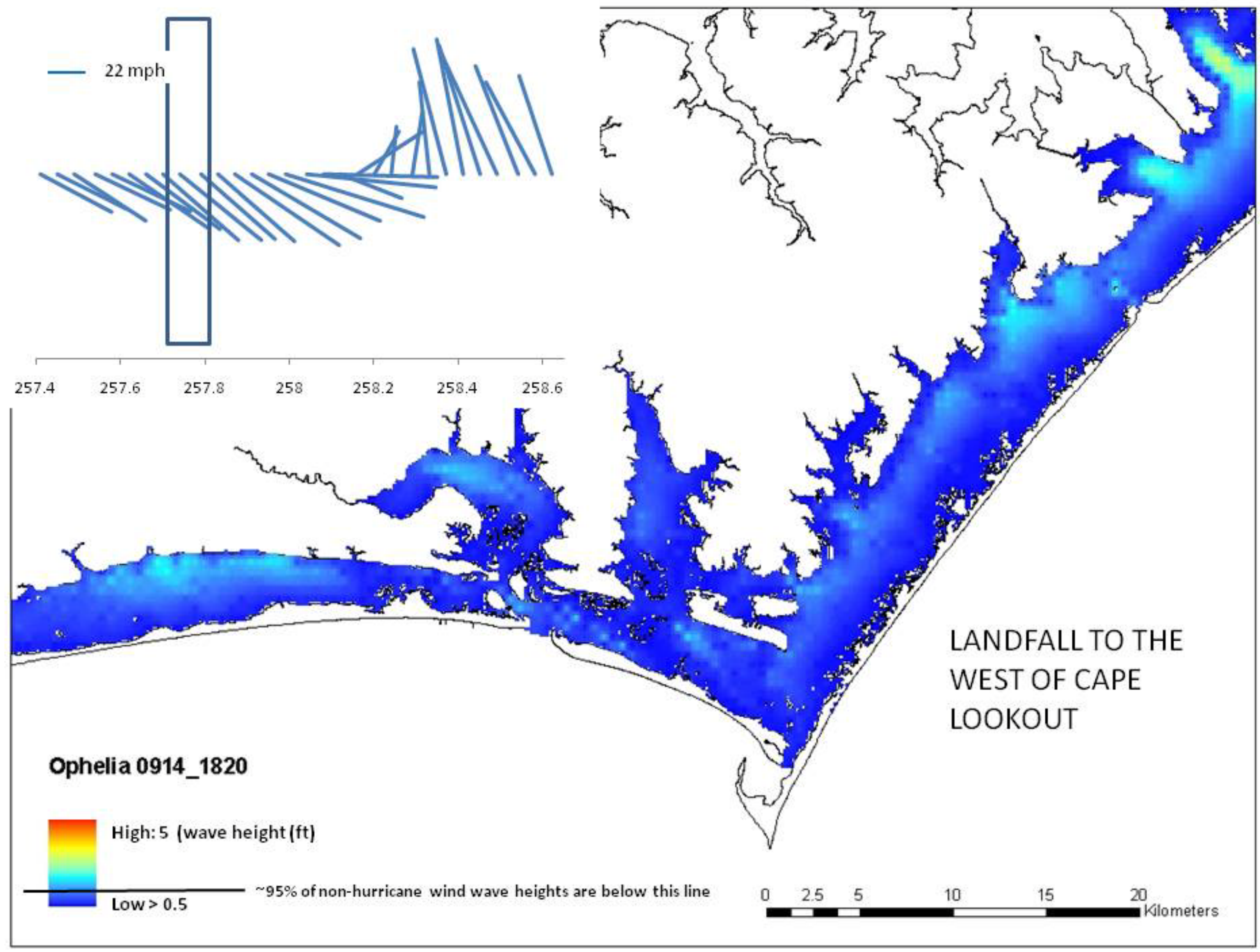

Figure 22. Simulation for hurricane Ophelia with west landfall, September 14, 2005: 1820h.

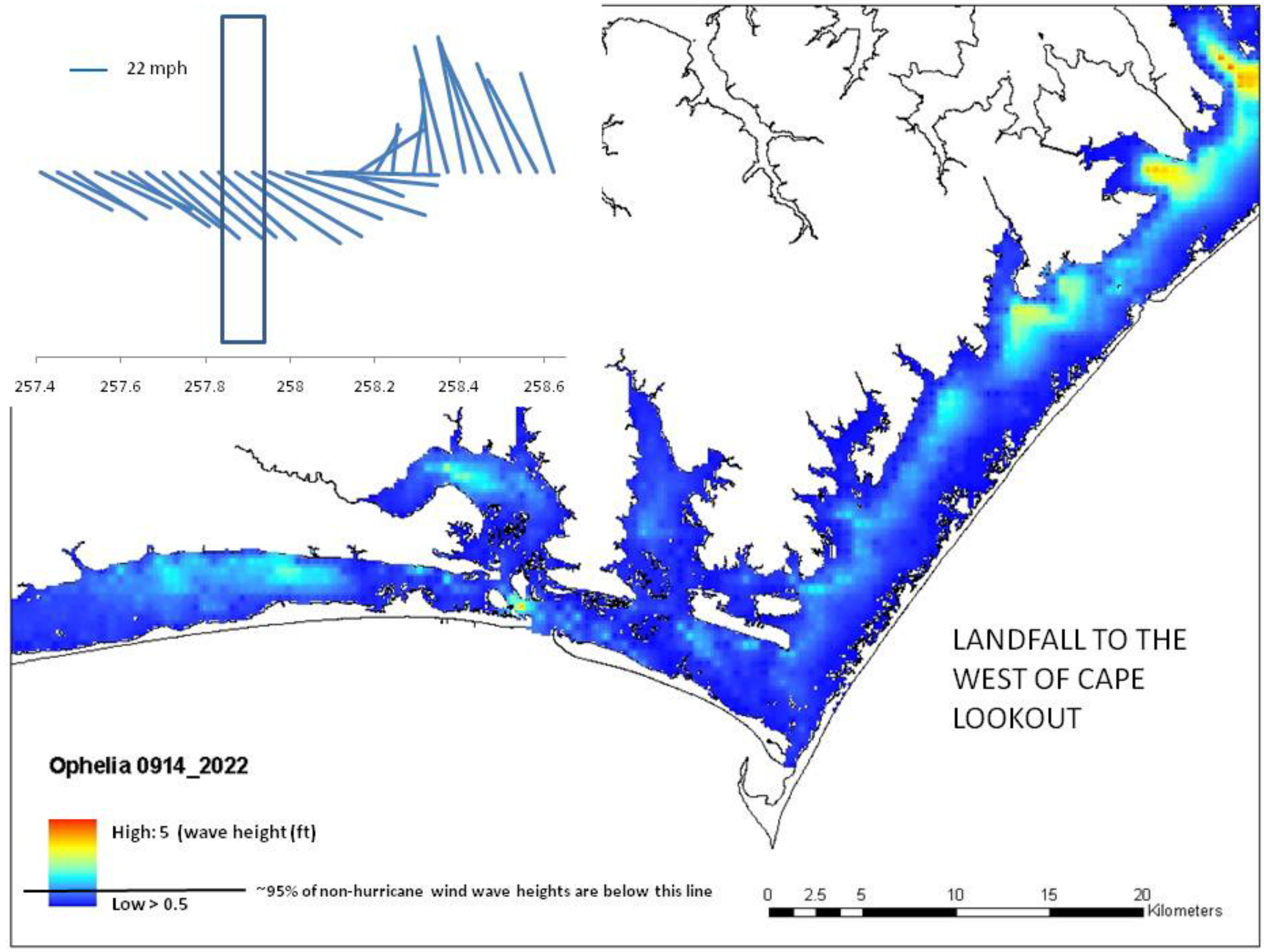

Figure 23. Simulation for hurricane Ophelia with west landfall, September 14, 2005: 2022h.

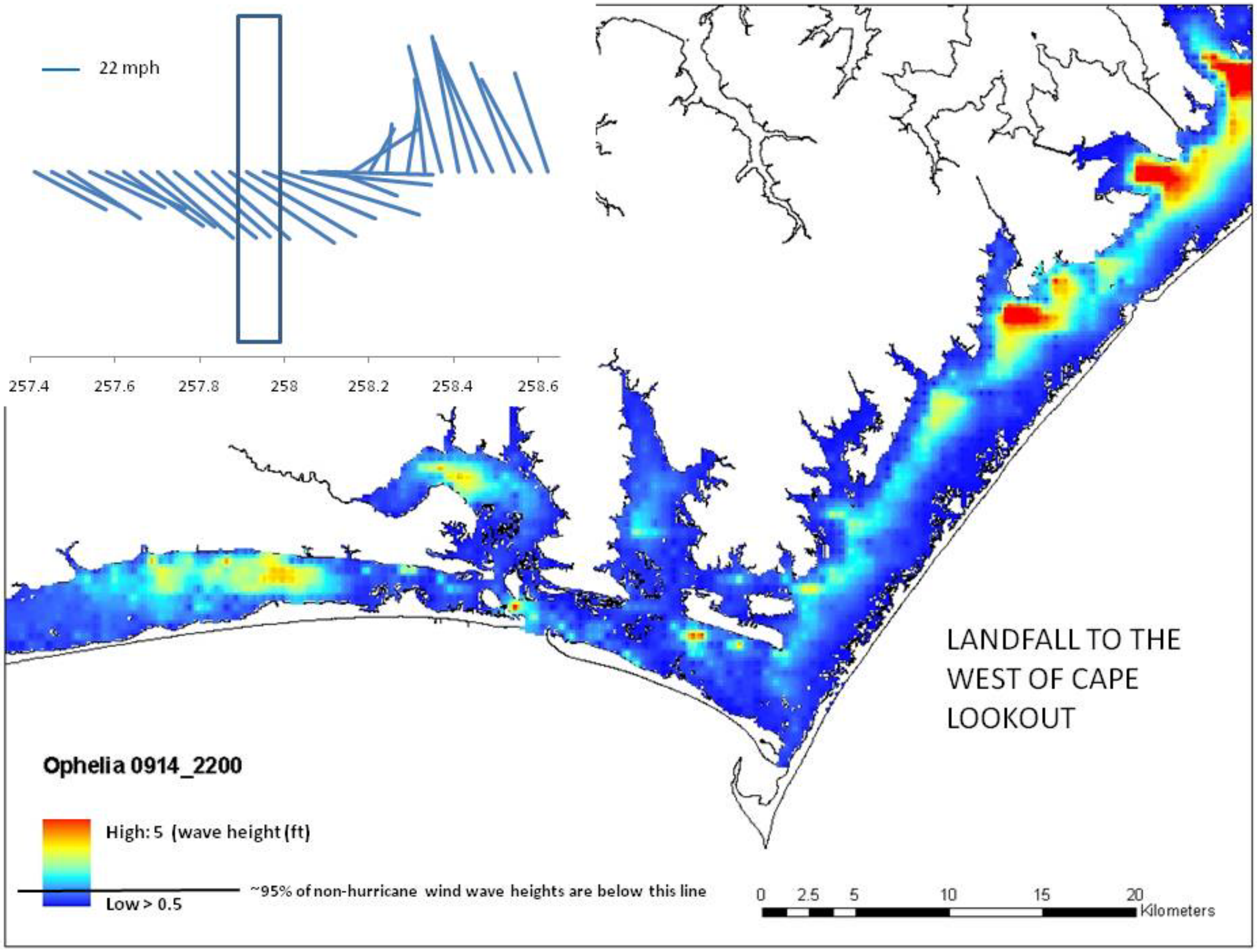

Figure 24. Simulation for hurricane Ophelia with west landfall, September 14, 2005: 2200h.

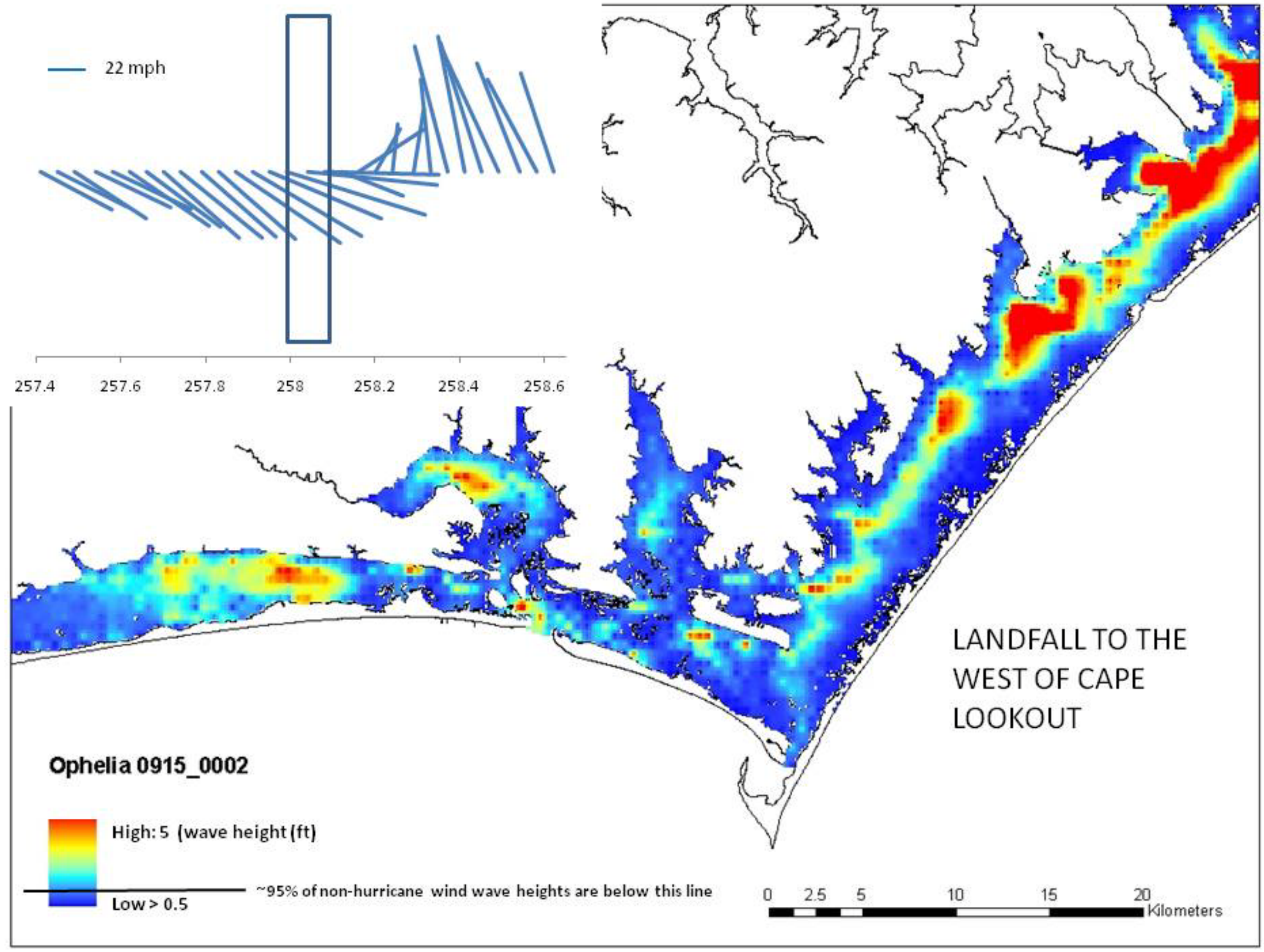

Figure 25. Simulation for hurricane Ophelia with west landfall, September 15, 2005: 0002h.

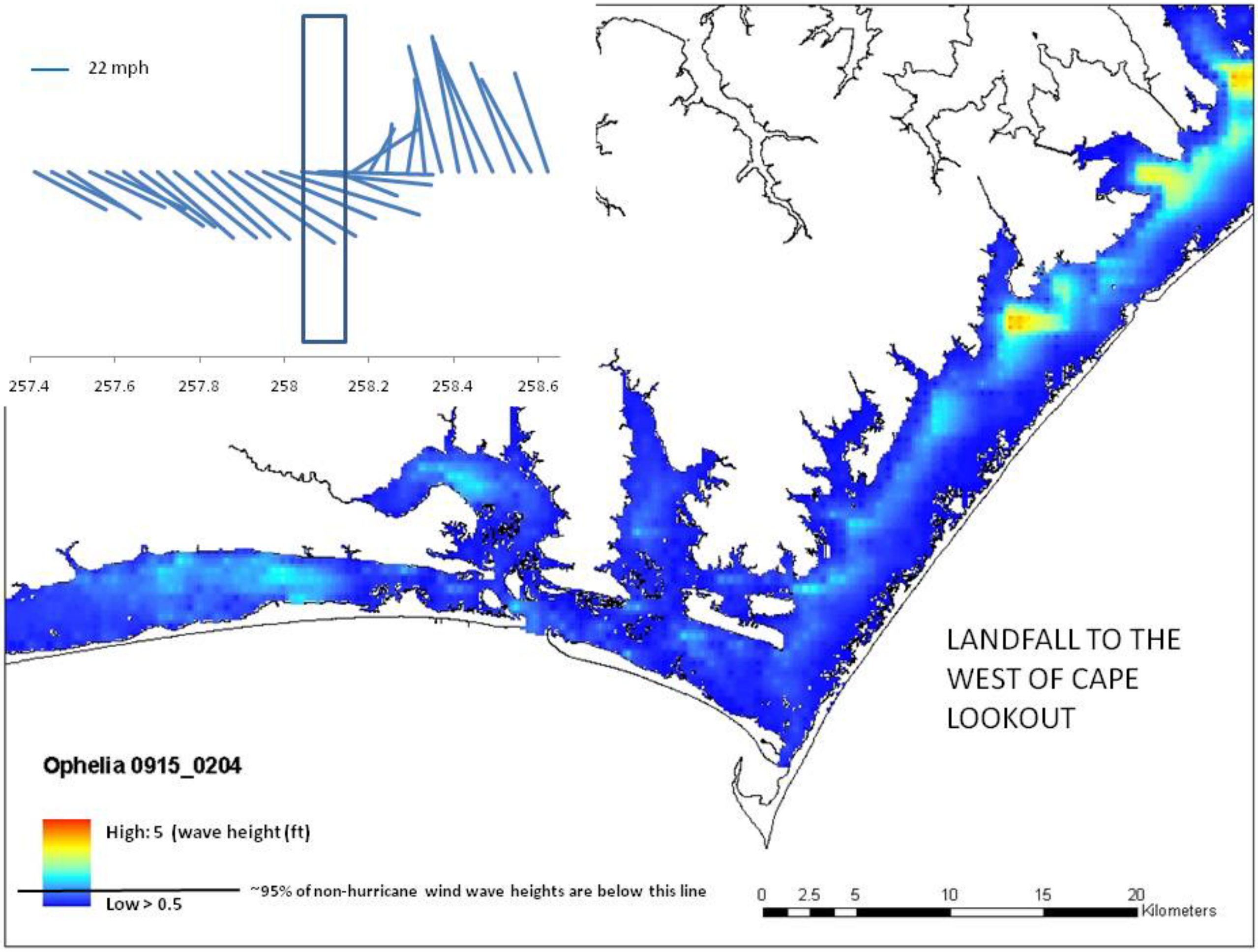

Figure 26. Simulation for hurricane Ophelia with west landfall, September 15, 2005: 0204h.

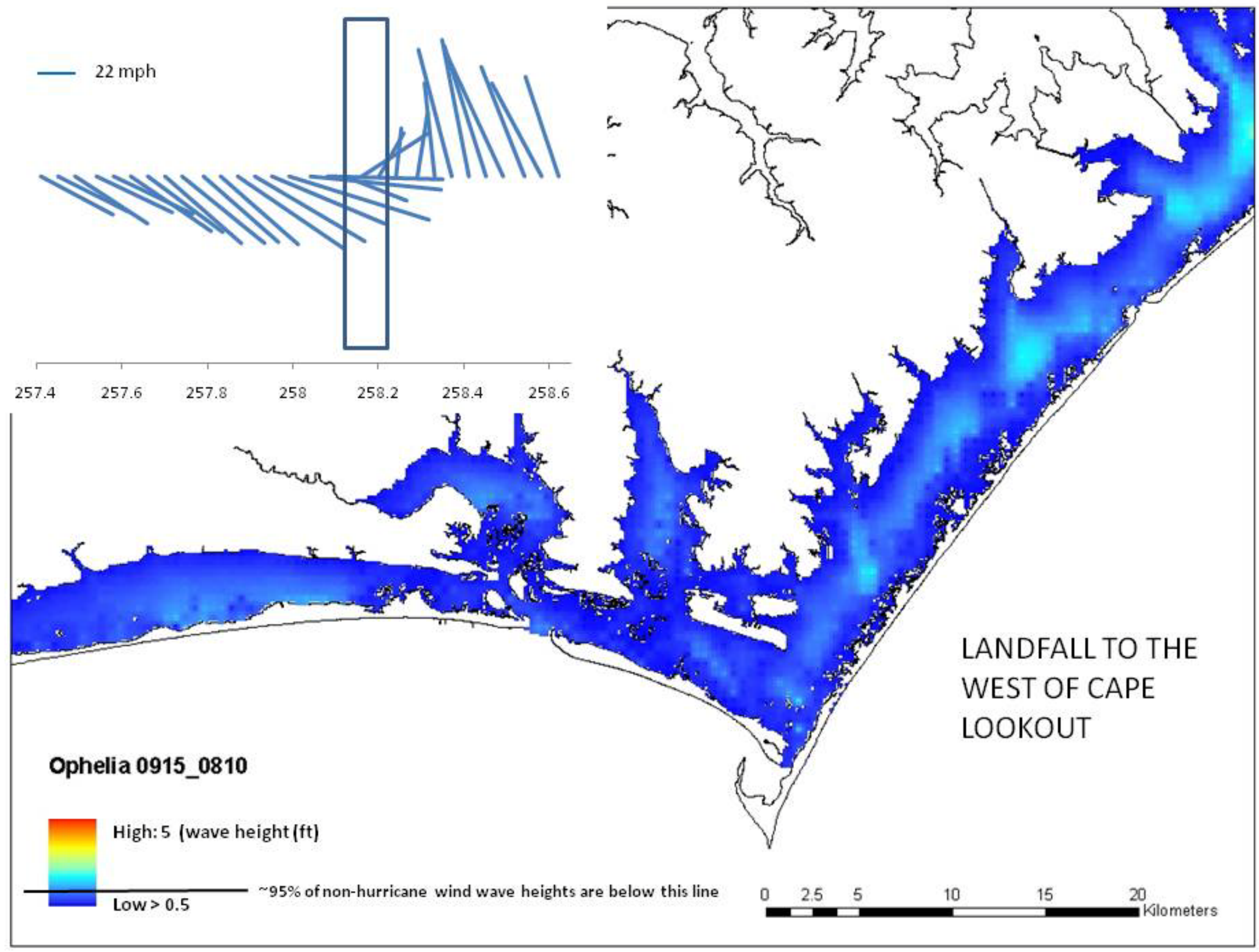

Figure 27. Simulation for hurricane Ophelia with west landfall, September 15, 2005: 0810h.

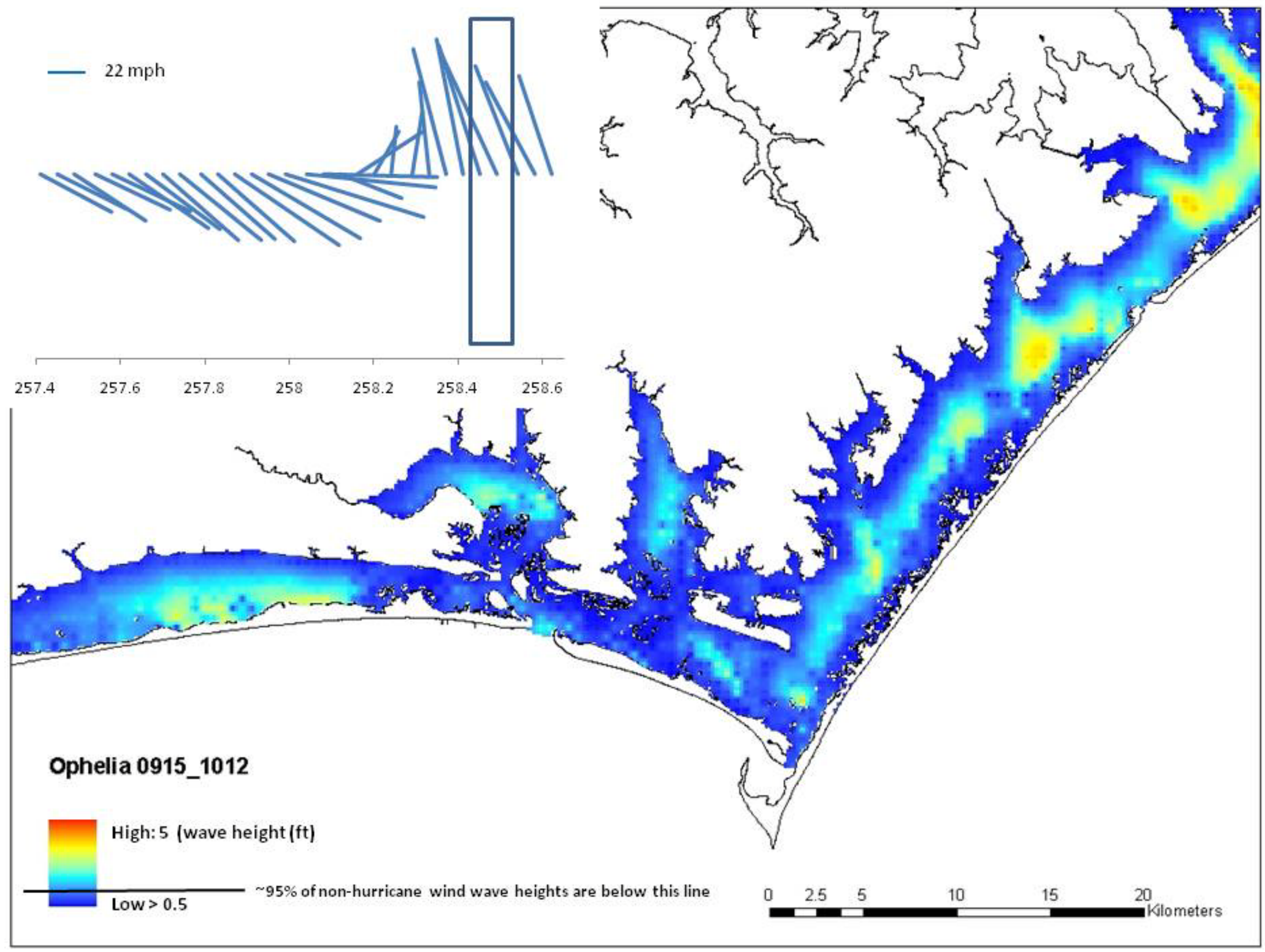

Figure 28. Simulation for hurricane Ophelia with west landfall, September 15, 2005: 1012h.