5B.7 Implementing the SWAN Wave Model at Three East Coast National Weather Service Offices

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1. INTRODUCTION

Part of the National Weather Service (NWS) mission is to provide watches and warnings for ocean areas to protect life and property and to enhance the economy. Accurate wave forecasts are crucial to meeting this mission. While large strides have been made to improve the overall ocean wave modeling and forecasting capabilities in the NWS over the last several years (i.e. the implementation of the NOAA WAVEWATCH III model and extensive training materials), very little in the way of reliable, high resolution wave model guidance has been developed for forecasters for the *coastal zone* prior to 2005. It is a fact that the majority of marine traffic must navigate coastal waters through the basic requirement of leaving and entering ports, harbors, and inlets. The NWS Weather Forecast Office in Eureka, CA (WFO EKA) recognized this and implemented the Simulating WAves Nearshore (SWAN) model into their daily marine forecast operations during 2005 in conjunction with the United States Army Corp of Engineers Field Research Facility (USACE-FRF) and Humboldt State University (Nicolini and Crawford, 2005). The NWS offices in Wakefield, VA, Newport/Morehead City, NC, and Wilmington, NC (WFO's AKQ/MHX/ILM) transitioned this effort to the East Coast during 2007-2009 through a collaborative project with USACE and the University of North Carolina (UNC) at Chapel Hill (Devaliere et al., 2008). SWAN has greatly improved the ability for forecasters to depict wave regimes near complex coastlines, bays, sounds, and other shallow water areas where coarser, deep water wave models such as the current version of WAVEWATCH III (WW3) are not applicable. It should be noted that the National Centers for Environmental Prediction (NCEP) is working to implement significant improvements to near shore wave modeling capabilities in WW3.

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Another major improvement the NWS SWAN effort has brought to operations is that it produces wave forecasts that are physically consistent with official NWS wind forecasts. This is done by utilizing gridded wind fields created by forecasters via the Graphical Forecast Editor (GFE) for the National Digital Forecast Database (NDFD) (NWS, 2008) as input for the SWAN model. Since the SWAN domain extends beyond the wind forecast area of the NWS East Coast offices, the current method for filling this gap is to blend the forecaster created winds with those from the Global Forecast System (GFS) atmospheric model. This presents a potential source of error that is discussed in this paper.

Shortly after SWAN was installed at the three East Coast Offices, major Hurricane Bill tracked north well offshore the East Coast in the western North Atlantic. Hurricane Bill was never a direct threat to land areas of the United States, but it did produce one of the most significant long period swells along the Eastern Seaboard in recent history. The swells generated deadly rip currents and surf in excess of 20 feet (6m). This case allowed forecasters to assess SWAN output during a unique event that had significant coastal impacts.

A brief technical description of SWAN is presented in section 2. This will include recent enhancements to the model such as the ability to use boundary conditions from the North Atlantic Hurricane WW3 model, new spectral output, and a new spatial tracking scheme. Operational examples focusing on the swell event from Hurricane Bill and a case where SWAN built waves too quickly in the Onslow Bay of North Carolina are presented in section 3. Limitations of the model, a summary, and future work are presented in sections 4 and 5.

2. The Mid Atlantic NWS SWAN Model

SWAN is a third generation wave model that is designed to produce accurate wave analyses and forecasts in coastal areas based on the input of wind, bathymetry, and current conditions. The model simulates phenomena such as waves generated by winds, wave propagation in time and space, refraction, shoaling, nonlinear interactions, white-capping, and bottom friction. A detailed description of the physics included in SWAN in addition to setup information are provided in the SWAN users manual (The SWAN Team, 2009).

The USACE FRF in Duck, NC and UNC set up a web based SWAN wave model application for the Mid Atlantic Coast during the first phase of this project (Figure 1). Careful calibration and validation of the model was performed prior to the transition to NWS operations (Devaliere et al., 2007). A spectral partitioning and spiral search algorithm for the identification and tracking of wave systems was also developed prior to the model becoming fully operational (Hanson and Phillips, 2001; Devaliere et al., 2009). This system identifies individual wind sea and swell wave components and searches through the domain to find similar wave characteristics in neighboring grid points to identify homogeneous wave system fields that evolve through space and time.

Operational implementation of the SWAN model was then performed at NWS WFO's MHX, AKQ, and ILM during the spring and summer of 2009. Each office developed its own domain as show in Figure 2. Both the X and Y resolutions were initially setup at 5 km, but WFO MHX found that increasing the resolution to 2.5 km better depicted wave conditions around the complex coastline near the Outer Banks of North Carolina. Boundary conditions are routinely provided by the NCEP Multi-Grid WW3 model (Tolman, 2007) which is driven solely by GFS winds. However, a recent enhancement was to allow for the use of boundary conditions from the North Atlantic Hurricane (NAH) WW3 model which uses winds from the GFDL Hurricane Model nested within the GFS wind field (Alves et al., 2005). The NAH WW3 model has proven to often produce more accurate wave forecasts associated with tropical cyclones because the GFDL model typically resolves the wind field better during these events compared to the coarser GFS model. The majority of the winds used to run the NWS SWAN model come from the official NDFD wind forecast from that office. These winds are value added by the forecasters using the NWS GFE software. The NDFD wind forecasts are typically derived from various computer models or a blend of computer models. Subjective adjustments can then be made by the forecaster as desired. The winds utilized in the outer periphery of each NWS SWAN domain are a blend of that office's winds with their neighbor's NDFD winds to the north and south, and with the GFS model winds to the east.

An important thing to note is that the NWS offices in this project are currently running SWAN in stationary mode. Stationary mode assumes instantaneous wave propagation, growth, and decay in a domain. This is a safe assumption in very small domains, but can lead to significant errors in larger domains (Rogers et al., 2006). Careful sensitivity tests need to be done to optimize a good balance of temporal resolution, domain size, and whether to run the model in stationary or unstationary mode. An example of a forecast error caused by this assumption is discussed in section 3.

NWS forecasters can run the SWAN model "on the fly" after they have finished creating their wind forecasts. Output is received at 6 hour time steps in two increments: first non partitioned data including significant wave height, peak wave period, and peak wave direction, and then partitioned output that includes the wave systems present at each grid point. Each wave system is given a number in GFE that is tracked in space and time via the spiral search algorithm.

Spectral output at select points is also available through vector (Figure 3) and time series (Figure 4) formats. The wave vector plot, referred to by the NWS as the 'Hanson Plot', is useful for both visual validation and forecast guidance through graphical representation of the forecasted wave systems. The wave vector plot displays evolution of wave systems for particular points through the forecast period. If this point coincides with a buoy, the plot starts with a day of observations, allowing the forecaster to see at a glance how well the model matches observed data. The length of the arrows are proportional to the wave height, the arrow direction indicates the direction of wave propagation ('toward' true north), and the base of the arrows identify the wave period. Differing wave systems are coded with different colors. The wind speed is plotted in the lower panel. Observed buoy data is positioned left of the pink vertical line, while model data is located to the right of the line. The 'TDY', 'TNT', etc. nomenclatures at the top of the plot designates 'Today', 'Tonight', etc. matching the nomenclatures used in the GFE.

The time-series plots show spectral wave data in a similar fashion as the WW3 text bulletins that forecasters are familiar with. The observed data however are not available in the time-series plots. The wave system color codes are the same in both products and the wave system numbers correspond to the wave system numbers found in the GFE grids.

The partitioned wave data in GFE and the spectral point output in vector and time series formats have proven especially useful in producing rip current and surf forecasts, as it allows forecasters to gauge wave systems that will have a direct impact on the shore. This is very useful for locations that have beaches that face different directions, such as along the Outer Banks of North Carolina. For example, these products provided assistance to forecasters in issuing high surf advisories and a high threat of rip currents during the SE swell associated with Hurricane Bill. This is discussed in greater detail in the next section.

3. OPERATIONAL EXAMPLES

Hurricane Bill was a Category 4 storm that was never a direct threat to the United States (Figure 5). However, the unique combination of Bill's track, size, and intensity sent a significant long period swell to the East Coast during 21-24 August 2009. This led to high surf and dangerous rip currents that ultimately claimed two lives and injured at least 16 people along the Eastern Seaboard (NCDC, 2009).

Hurricane Bill occurred just after all three NWS offices had transitioned SWAN into their forecast operations. This event was the first time forecasters got a feel for the model's capabilities and performance during a rare event that had significant impacts. As a whole, SWAN verified favorably during this event as shown in Figure 6. In addition, the long period swell event provided opportunities beyond verification. It allowed forecasters to visualize in plan view the capabilities of a near shore wave model to depict swell propagation around complex bathymetry and coastlines. For example, human spotter reports have suggested that wave heights are often largest around Rodanthe, NC during a homogeneous swell event across the Outer Banks. However, it is easy for forecasters to think that the area just east of Cape Hatteras would have the highest wave heights as that area is the most exposed to different wind and wave directions. Furthermore, there is an in-situ observation site east of Cape Hatteras at Diamond Shoals which often has the highest observed wave heights around given its exposure. SWAN depicted that the long period southeast swell event from Hurricane Bill produced the highest waves just east of Rodanthe (Figure 7). This is the kind of information we can now communicate to our customers which ultimately helps save lives.

An interesting finding from WFO ILM during the Hurricane Bill swell was that SWAN performed well at the Frying Pan Shoals buoy 41013 but overestimated wave heights at the Masonboro Inlet buoy 41110 by 0.4 m (Figure 8). It is impossible to determine if this is a systematic problem during long period swell events with only one documented case. However, the fact that both of these buoys are in the WFO ILM SWAN domain and have similar exposure to SE swell makes the case worth documenting. This potential issue may be related to the fact that buoy 41110 is very close to the shore and thus long period swells are significantly impacted by the local bathymetry. Buoy 41013 is much further offshore in deeper water, and thus may not experience such issues. Initial hypothesis are that SWAN may not have resolved shoaling of the long period swell before it reached buoy 41110, or that refractive processes may have allowed some of the swell energy to miss the buoy. Both of these phenomena could have occurred on a sub-grid scale level that would require SWAN to be run at a resolution higher than the 2.5km used in this project. Additional sensitivity tests can be performed to help determine the exact cause and identify potential solutions.

Since the transition of SWAN to operations during the summer of 2009, forecasters have noted a tendency for the model to grow and decay waves too quickly during changing wind conditions. This was documented during October 28, 2009 when a warm front pushed north through eastern North Carolina and the adjacent coastal waters. Very light E to SE winds rapidly increased from the S/SW south of the front. SWAN was several hours too early in building the seas in this case compared to observations at buoy 41036 located offshore New River Inlet, NC (Figure 9). Rogers et al. (2006) discussed this potential problem when running SWAN in stationary mode. This problem seems to have played at least a partial role in this case. A sensitivity test was performed that revealed a more accurate wave growth and decay during this event when run in unstationary mode for some locations (Figure 9). However, model run time was 10 times as long in unstationary mode compared to stationary mode, which has significant operational impacts.

4. LIMITATIONS

SWAN has brought several positive impacts to marine forecasting operations that are described in this paper. However, as with any model, there are limitations which forecasters need to be aware of:

- If the inherent WW3 boundary conditions are not handling a particular wave system well, SWAN will not either as those wave systems from WW3 are propagated through the SWAN domain. This is often due to problems with the GFS wind forcing of the WW3 boundary conditions.
- The WFO's involved in this project are using simple smoothing functions in GFE to blend winds with neighbor forecast offices along their north and south borders, and with the GFS model to the east. These winds are then used to drive SWAN. Inconsistencies in wind fields between forecast offices or the GFS model can have negative impacts on the SWAN wave output.
- Running in stationary mode can lead to SWAN growing and decaying waves too quickly. Unstationary mode can improve this but significantly increases model run time.
- Increasing model run length and/or resolution can also significantly increase model run time.

5. SUMMARY AND FUTURE WORK

The NWS Offices in Wakefield, VA, Newport, NC, and Wilmington NC partnered with UNC and the USACE to implement the SWAN wave model into operations during 2009. The model is producing high resolution wave forecasts that are physically consistent with NWS wind forecasts in addition to providing accurate depictions of wave regimes around complex coastlines. The model has helped build confidence in wave forecasting in coastal areas where other techniques and models have performed poorly. Given that the majority of marine traffic occurs within five miles of the coastline, SWAN is providing NWS forecasters with information that is crucial to ensuring their mission of protecting life and property.

The NWS offices involved in this project are currently collaborating with the WFO's in Miami and Tallahassee, FL who are also running SWAN in an effort to investigate instances of the unrealistic wave growth and decay that can occur with running in stationary mode. Initial sensitivity tests suggest that running the model in non-stationary mode can improve this problem, but increases the run time significantly which is not ideal in an operational setting. One potential compromise would be to run a lower resolution outer domain in non stationary mode with higher resolution inner domains in stationary mode, since the stationary assumptions are more valid in small domains.

Efforts are currently being made at WFO MHX to improve observations and forecasts for area inlets. There is potential in using SWAN wave spectra derived from this project coupled with current and tide information to develop a high resolution simulation around inlets in North Carolina. This would provide mariners timely information on when and where hazardous conditions such as shoaling or dangerous wave/current interactions may exist in or around an inlet.

7. ACKNOWLEDGMENTS

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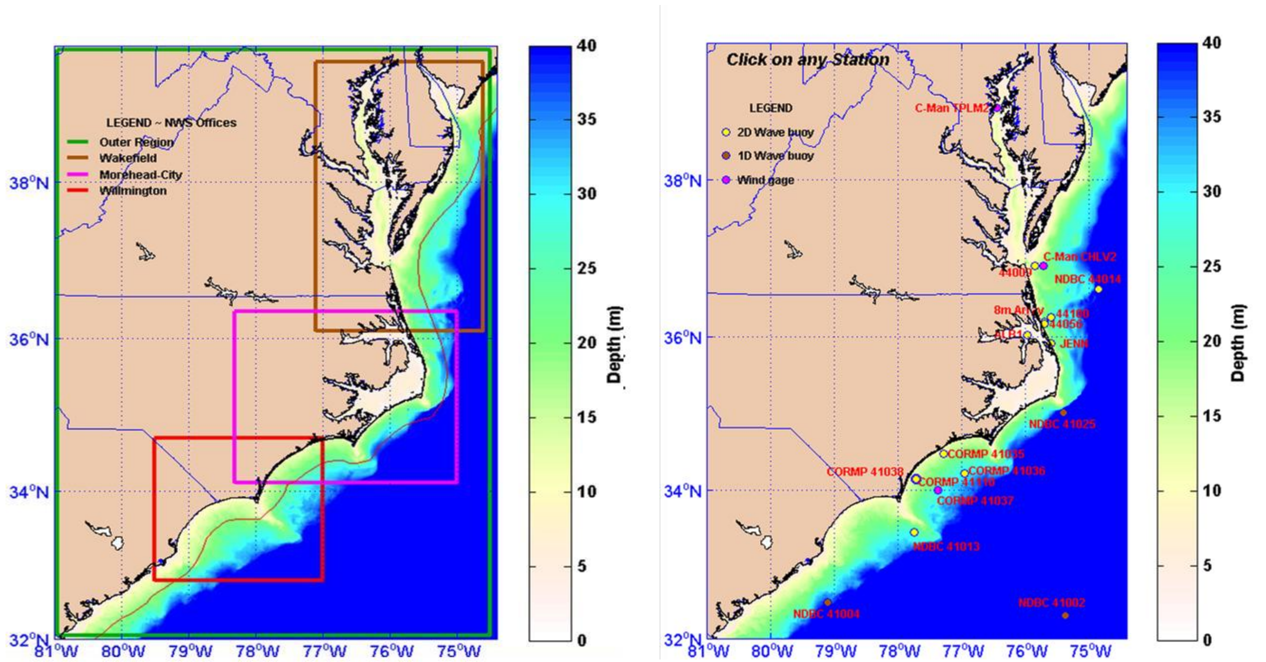

Figure 1. SWAN domains set up by USACE for NWS AKQ, MHX, and ILM (left) and location of buoys used for validation studies in this project (right).

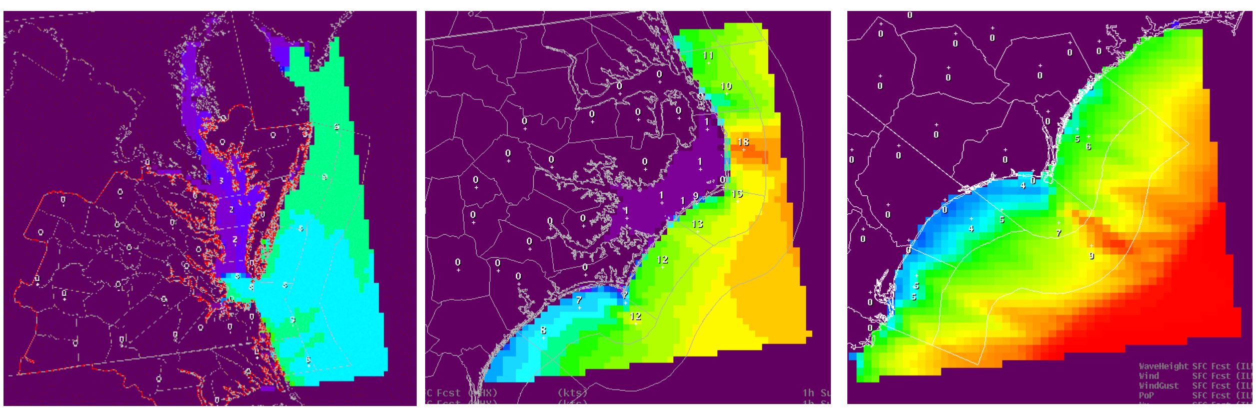

Figure 2. SWAN domains as seen in GFE for AKQ, MHX, and ILM.

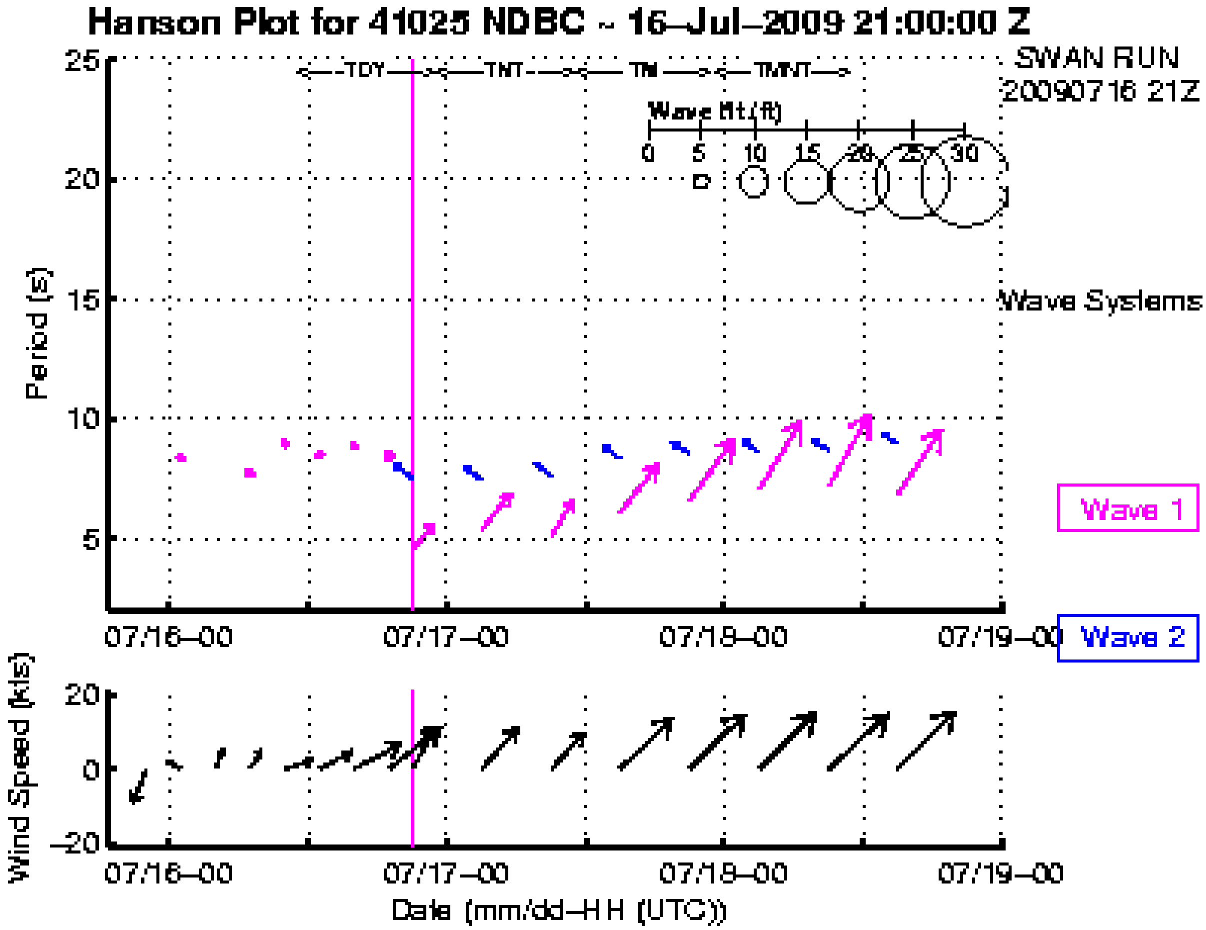

Figure 3. Hanson plot example from buoy 41025 showing dominant SSW wind waves (pink) and smaller SE trade wind swell (purple).

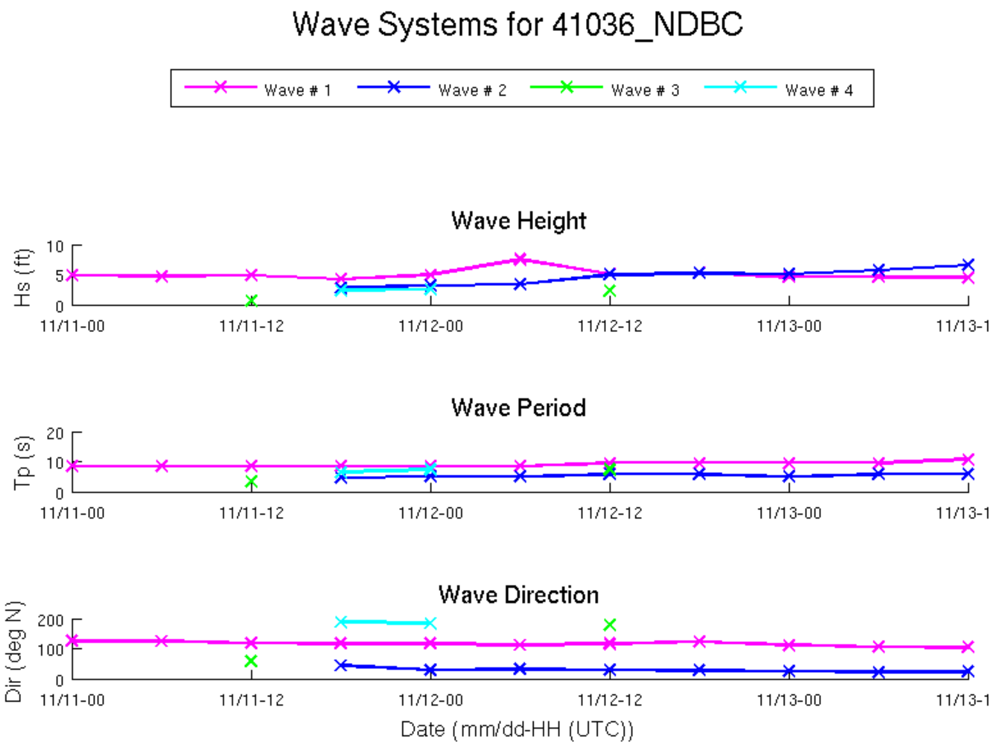

Figure 4. Time series example from buoy 41036.

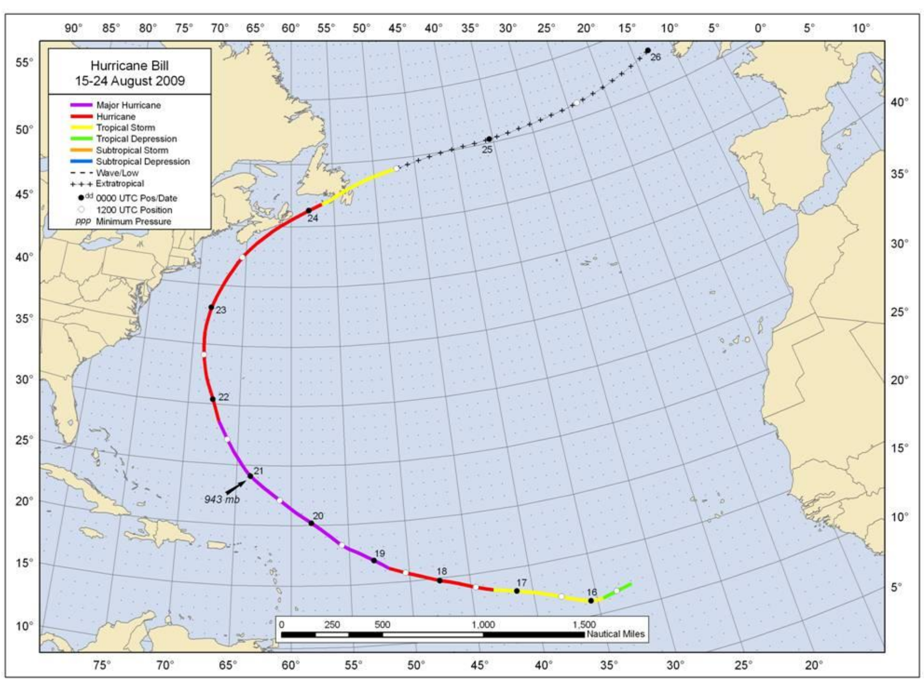

Figure 5. NHC best track of Hurricane Bill.

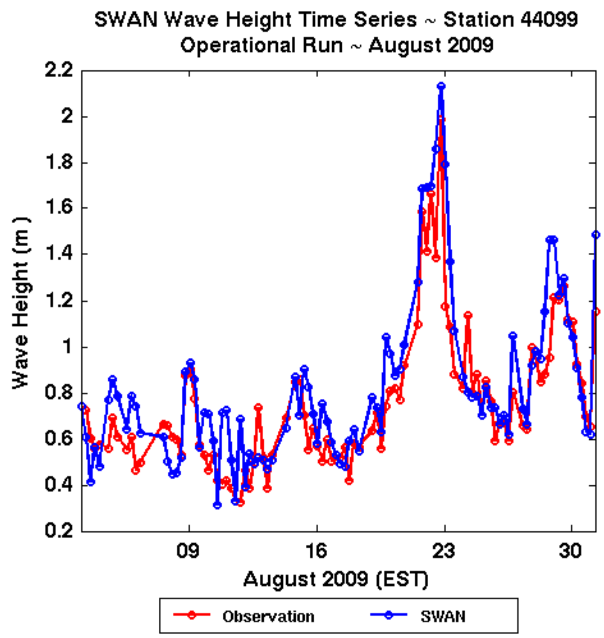

Figure 6. SWAN verification for August 2009 at buoy 44099 (Wakefield CWA).

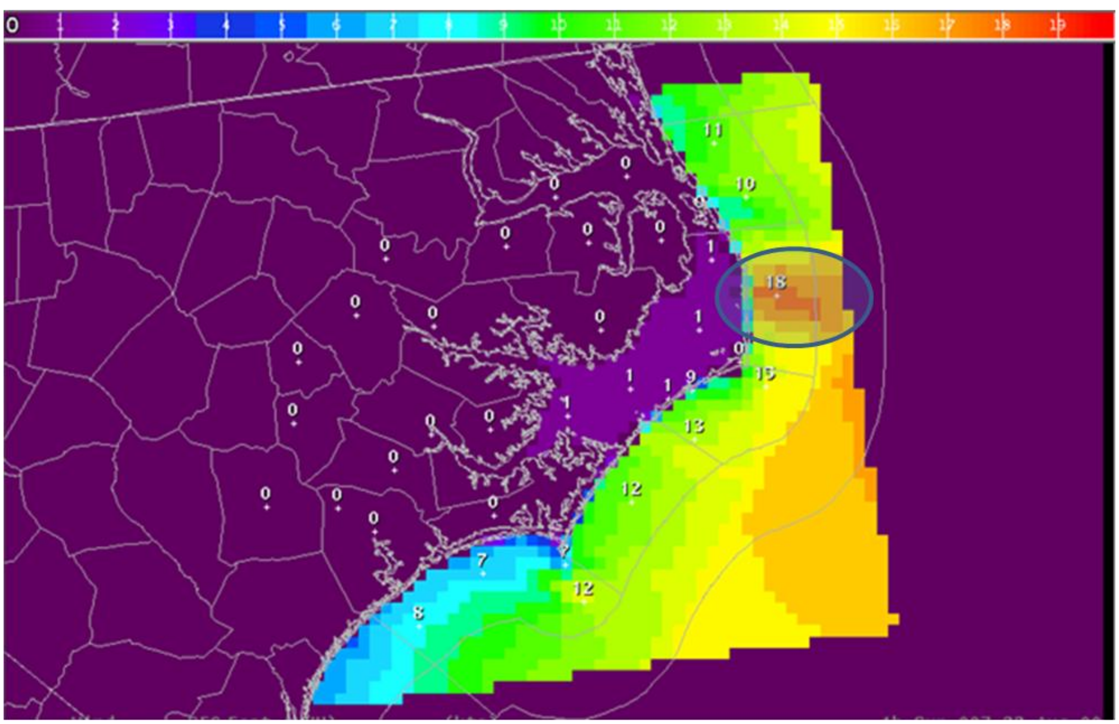

Figure 7. SWAN significant wave height at 12Z 22 August 2009 as seen from WFO MHX GFE during peak of the SE swell from Hurricane Bill. Maximum (~18ft/6m) circled just east of Rodanthe.

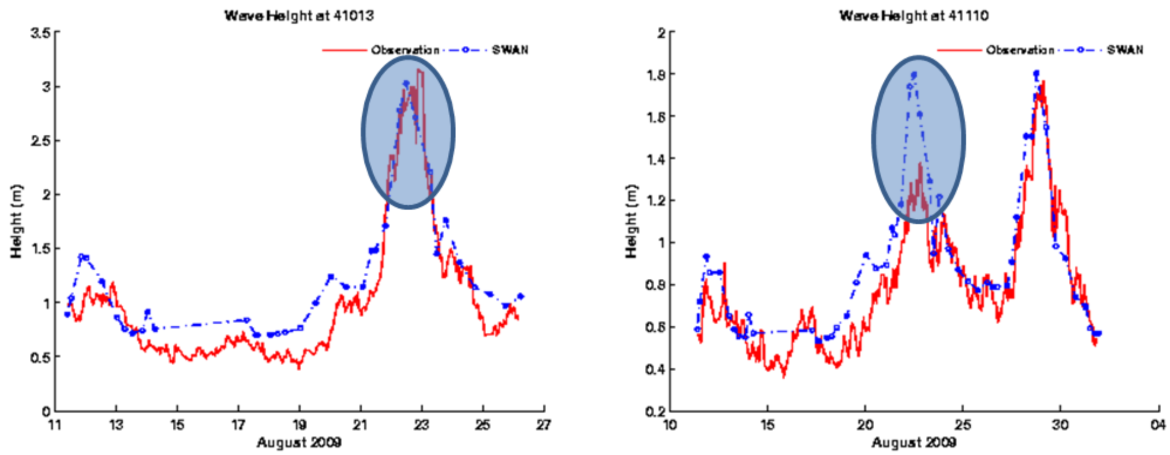

Figure 8. SWAN verification for buoys 41013 (left) and 41110 (right) which are in the WFO ILM forecast area. Blue shaded area represents peak of Hurricane Bill swell around 22-23 August 2009. Red line is observation and blue line is SWAN. See Figure 1 for buoy locations.

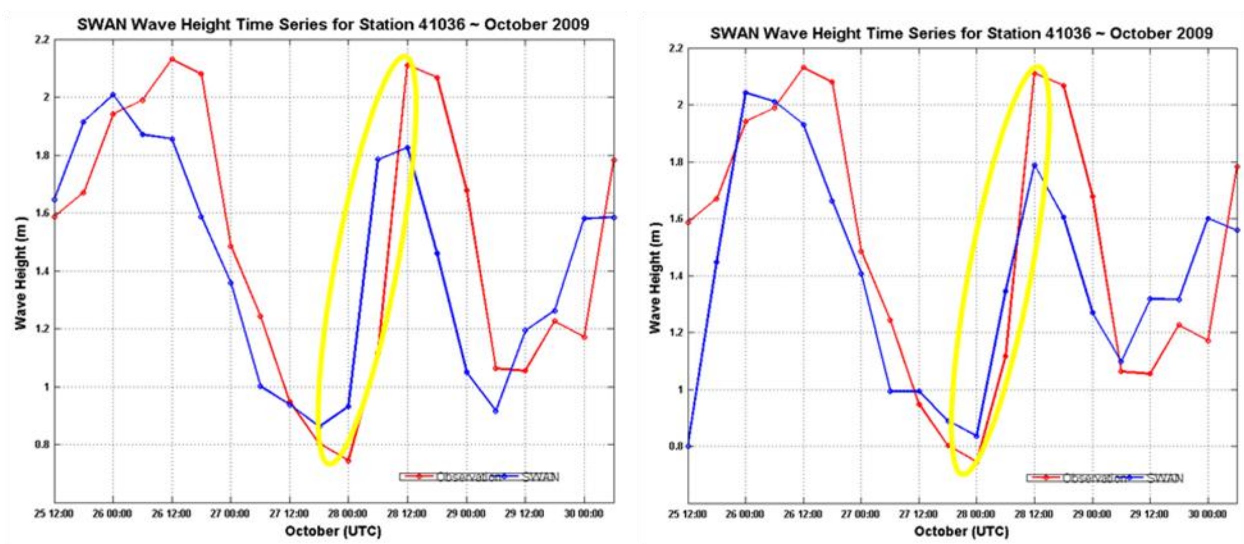

Figure 9. SWAN verification for buoy 41036 in stationary mode (left) and unstationary mode (right) during 25-30 October 2009. Red line is observation and blue line is SWAN. Area highlighted in yellow represents building seas associated with a warm front progressing north through the area.