Diagnosing the Large Swell Event Associated with the Extratropical Transition of Hurricane Florence (2006)

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1. INTRODUCTION

Category one Hurricane Florence was a classic Cape Verde tropical cyclone that recurved over the western North Atlantic during September 2006. The storm produced an unusually large swell event for the East Coast of the United States that broke typical conceptual models of tropical cyclone wave forecasting. The significant long period swell event affected the East Coast well after the storm had recurved and moved east of the Canadian Maritimes as an extratropical cyclone (figures 1 and 2). The operational wave model guidance used at the National Hurricane Center's Tropical Analysis and Forecast Branch (NHC TAFB) did not represent the peak of this swell event very well.

The swell event peaked in Florida early on 14 September 2006 (figure 2) and led to two deaths in Central Florida -- one on 14 September and the other on 16 September. Hundreds of beach rescues were also reported along the East Coast during this time in addition to minor coastal flooding and beach erosion (NCDC 2006). Both deaths and many of the rescues were reported after advisories on Florence had been ceased by the National Hurricane Center. This presents a challenging task to operational forecasters to inform the public of potential indirect dangers of tropical cyclones beyond the time the storm itself can be classified as a tropical cyclone.

Typical East Coast swell events associated with recurving tropical cyclones are first characterized by a rise in long period swell energy that outruns the storm. These types of swell events normally subside (in both height and period) steadily as the storm moves north of the latitude of a beach of interest. For example, powerful category four Hurricane Luis (1995) had a similar track as Hurricane Florence and followed this conceptual model well (figure 1). The swell associated with Luis that affected Florida rose steadily up until the storm was near the latitude of the state and then dropped rapidly as Luis headed towards the Canadian Maritimes (figure 3). Category four Luis produced almost exactly the same peak wave heights offshore Florida as category one Florence. This also produces a socially challenging task to forecasters and media outlets to inform the public of potential dangers beyond the scope and ability of the Saffir-Simpson scale (Simpson and Riehl 1981).

The meteorology associated with the swell event from Hurricane Florence is discussed in section 3 while the operational wave model verification is discussed in section 4. The challenging social impacts presented with this event, conclusions, and potential future work are discussed in section 5.

2. DATA AND METHODS

Various versions of the Wavewatch III model (WW3) were used for this study. The

National Centers for Environmental Prediction's (NCEP) Western North Atlantic regional (WNA) WW3 is compared to the North Atlantic Hurricane (NAH) WW3. The WNA version of WW3 uses 10 m wind forcing every 3 hours from the Global Forecast System (GFS) atmospheric model to produce a wave field on a .25 X .25 degree grid. The NAH WW3 has the same spatial resolution as the WNA WW3 but blends the above GFS winds with hourly hurricane GFDL winds when available. The coarser resolution, global NCEP WW3 and FNMOC WW3 models were also used in this study but the results are not presented in detail due to their poorer performance. Details of the WW3 model can be found in Tolman (2002). Information on the GFS and GFDL models can be found in Rhome (2007). It should be noted that 35 m GFDL model winds were used in this study since that is the level closest to the surface that is available operationally.

Several observed and modeled wind fields at times prior to the peak of the swell event were analyzed in order to obtain an understanding of why the waves got so large offshore Florida and why the wave models performed poorly. The comparison in sections 3 and 4 represent only the times where the atmospheric models and observations were identified to have the largest differences and thus the greatest impact on the swell forecast. The wind observations presented are a collection of all buoy, ship, and CMAN stations that were available in real time to TAFB marine forecasters. QuikSCAT data (Von Ahn et al. 2006) was also used in this study to locate problems in the wind forcing of the GFS and GFDL models.

The wave data used in this study was provided by the archives on the National Data Buoy Center's (NDBC) website. The tracks for Hurricanes Luis and Florence presented in figure 1 were generated using the official NHC best track data.

3. METEOROLOGY

The swell event associated with Hurricane Florence was so large due to the interaction between the storm itself and a strong 1035 mb high pressure center that built into eastern Canada during 11-12 September (figure 4). This set up a significant fetch of NE winds offshore the East Coast as Florence was recurving over the western North Atlantic. Florence was a large tropical cyclone from its origin off the African Coast (Beven 2007). As is typical with extratropical transitions (i.e. Jones 2003), the area of gale to storm force winds associated with the already large Hurricane Florence expanded even further from 11-13 September until the storm eventually became extratropical early on the 13^{th}.

Additionally, the high pressure area over eastern Canada built southward over the Mid-Atlantic United States from 12-13 September. This allowed the strong NE winds off the East Coast and Canadian Maritimes to build south-southwestward, promoting a "captured fetch" (i.e. Morris and Nelson 1977) aimed at Florida and the Bahamas. This combination of factors led to the uniquely large and dangerous swell event for Florida and much of the East Coast in general.

Neither the GFDL nor GFS models adequately represented the wind field associated with Hurricane Florence's extratropical transition during 12-13 September when compared to the surrounding surface observations and QuikSCAT (figures 5-7). However, both models had their perks. The GFDL model seemed to represent the strongest winds near the center of Florence better than the GFS model. On the contrary, the GFS model proved superior in representing the long fetch of NE winds well to the north and northeast of the center. The GFDL model badly missed the high NE winds north of the center as shown in figure 5, which appears to be the by-product of the model misrepresenting a developing frontal structure as the storm gained baroclinicity. The GFDL model showed winds of less than 25 kt where the actual observations from Environment Canada's buoys 44138, 44141, and 44139 reported 35-40 kt winds. The GFS model had a better handle on the developing frontal structure but again did not resolve the high winds near the core, which were estimated to be up to 70 kt based on the official NHC best track (Beven 2007). Both the GFDL and GFS solutions resulted in an underestimated NE fetch aimed at Florida around 00Z on 13 September.

4. WAVE MODEL VERIFICATION AND SWELL EVENT DISCUSSION

The problems with the GFDL and GFS wind forcing undoubtedly led to the problems in the wave fields predicted by the WNA and NAH WW3 models. Both versions of WW3 well represented the beginning and end of the swell event for buoy 41010 offshore Central Florida, but did not well represent the wave heights during the peak of the event (figure 2). Both versions of WW3 also underestimated the dominant wave period during the peak of the swell event by several seconds (figure 8).

The peak of the swell event at buoy 41010 occurred between 00Z-12Z 14 September (figure 2). At 00Z 13 September, both the GFS and GFDL had problems representing the wind field around the transitioning Hurricane Florence as discussed in section 3. At this time, the leading edge of the long fetch of NE winds off the East Coast was approximately 700 NM from buoy 41010 (figure 6). Buoy 41010 reported dominant wave periods of 15-16s during the peak of the swell event early on 14 September. A basic swell travel time calculation was performed to back trace the 15-16s swell energy that arrived at buoy 41010 to its origin. This long period energy takes approximately 30 hours to travel 700 NM. Thirty hours from 00Z 13 September coincides with when the swell was peaking at buoy 41010. Therefore, it is suspected the wave models missed the peak of the swell event offshore Florida early on 14 September due to the problems in the modeled wind fields around 00Z 13 September.

Somewhat different results were noted when comparing the operational wave models to the observations from buoy 41001 located 150 NM east of Cape Hatteras, North Carolina. Both the WNA and NAH wave models overestimated the significant wave heights during the swell event at buoy 41001 (figure 9). The WNA model did not overestimate the waves by as much as the NAH model did. The higher than observed wave heights are likely the result of the overestimation of the N/NE winds near the buoy. The winds in the immediate vicinity of buoy 41001 were only 10 kt at 00Z 13 September. The GFDL model had the 20 kt isotach very close to buoy 41001 at this time. In general, the GFDL overestimated the N winds by 10-20 kt over much of the area from 32N-45N between 65W-75W (figure 5). The GFS did a little better in this aspect and thus the WNA outperformed the NAH model in predicted wave heights. However, both models similarly underestimated the dominant period during the entire event at buoy 41001 (figure 10). The underestimation of the period of the NE swell offshore Cape Hatteras could have been used by marine forecasters as an indication that the models may have also underestimated the period offshore Florida.

5. SOCIAL IMPACTS, CONCLUSIONS AND FUTURE WORK

Hurricane Florence produced a dangerous wave event both near shore and offshore the United States East Coast. The event caused at least two deaths in Florida and hundreds of ocean rescues. The wave heights observed offshore Florida during this event were comparable to the swells and surf generated by the deadly "Perfect Storm" in 1991 (Sanders and Willis 2004). The operational wave model guidance used at TAFB underestimated the peak wave heights offshore Florida early 14 September due to problems in the wind forcing of the GFDL and GFS models around 00Z 13 September. Problems in the wind forcing also led to an overestimation of the modeled wave heights offshore Cape Hatteras. Wave periods were underestimated during the entire event offshore both Florida and Cape Hatteras.

An accurate wave period forecast is imperative to producing an accurate surf forecast since breaking waves are directly related to wave period (i.e. Monk 1950). In addition, wave period has significant impacts on the safety of offshore mariners since it is directly related to wave steepness and wavelength. Unfortunately, wave period is not a parameter routinely forecast in the text products provided by the Ocean Prediction Center (OPC) or NHC TAFB at this time. Graphical 48 and 72 hour wave period forecasts are provided via fax charts valid at 00Z and 12Z daily. Inclusion of period into the OPC/TAFB text products and production of more frequent graphical period charts are possible in the future, but no current plan is in place.

Surf and offshore deaths combined account for 22% of all tropical cyclone related deaths – second only to inland flooding (Rappaport 2000). This statistic clearly shows the motivation for this study in addition to the need for improving wave forecast services within the National Weather Service (NWS). Public awareness of dangerous swell events is also vital to the NWS mission.

The public perception of a swell event similar to that produced by Hurricane Florence leads to a potentially very dangerous situation. The swell event peaked in Florida well after the NHC had stopped issuing advisories on the storm. It could be easy for the American public to assume safety after the NHC forecasts that a tropical cyclone will recurve away from the United States. It would be even easier to assume safety after a storm has already recurved, moving out to sea near the Canadian Maritimes, and after it has been officially classified as an extratropical cyclone by the NHC. This is the situation that arose during the extratropical transition of Hurricane Florence -- a scenario that potentially caused a false sense of security. This false sense of security can lead to increased public activities in and near the ocean.

The large swell event that affected Florida associated with the extratropical transition of category 1 Hurricane Florence (2006) was of the same caliber as the swell event produced by category 4 Hurricane Luis (1995). This presents another potentially dangerous public misperception. Swell events are dependent on the size, movement, and winds of a storm. The Saffir-Simpson scale (1981) does not account for all of these factors and thus should not be used to estimate the hazards associated with ocean waves. Further public outreach may be needed to communicate this misperception of wave events associated with tropical cyclones.

In addition to informing the public of impending dangerous wave events, National Weather Service marine forecasters are required to evaluate numerous atmospheric and ocean wave models to produce the best possible forecast. Marine forecasters often have to decide which wave model guidance to use under tight time constraints. Forecasters often assume that the NAH WW3 model will outperform WNA WW3 model during tropical cyclone wave events, since that is what the NAH model was designed to do. However, as this study shows, both models should be evaluated as either can perform better, or both may have problems. Or, as noted with Hurricane Florence's extratropical transition, both the GFDL and GFS models may represent pieces of the storm more accurately than the other. Since TAFB and OPC marine forecasters are required to look at the overall picture of large oceanic areas, they may notice these large scale differences in the models more readily than a local marine forecaster at a Weather Forecast Office (WFO). On the contrary, a WFO forecaster may notice local details that could be of importance to OPC/TAFB forecasters. This presents the need for continued and improved coordination of swell events between NCEP and WFO marine forecasters. One possible improvement would be where the marine forecasters from both the WFO and NCEP environments produce a seamless suite of value added wind grids which in turn were used to drive WW3. Something of this nature may be feasible by using software such as the Graphical Forecast Editor (GFE) currently operational at the WFO's.

6. ACKNOWLEDGEMENTS

The author would like to thank Ethan Gibney for producing figure 1. Invaluable input was also provided by Jack Beven, Jamie Rhome, Robbie Berg, and John Cangialosi. Finally, this research would not have been possible without the support from Christopher Burr and Ed Rappaport.

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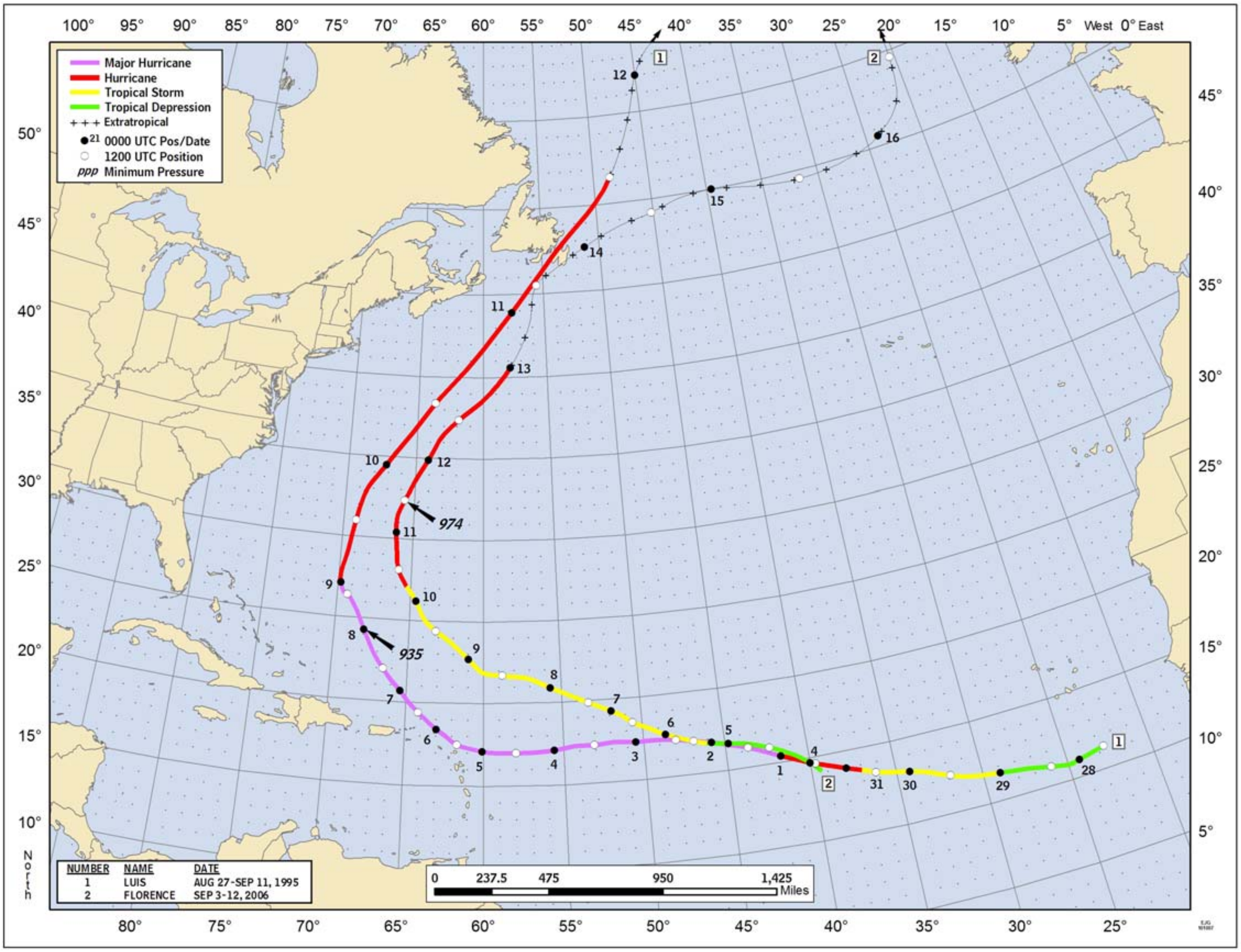

Figure 1. Official NHC best track for Hurricanes Luis (1) and Florence (2). Track during extratropical stage is based on analyses from the Ocean Prediction Center.

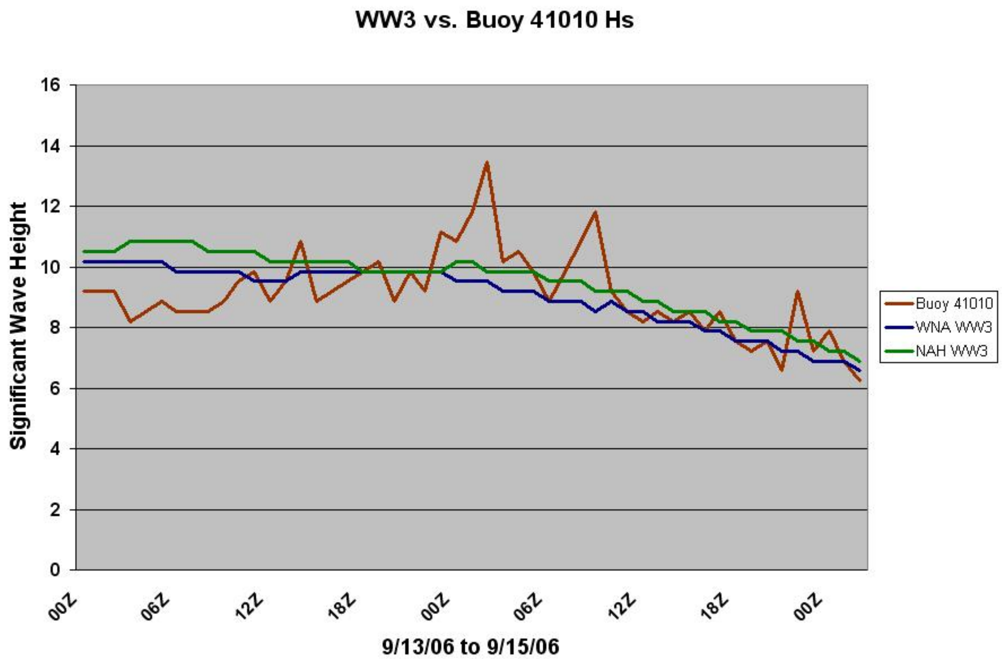

Figure 2. Observed and modeled significant wave heights (ft) at buoy 41010 offshore Cape Canaveral, Florida from 13-15 September 2006.

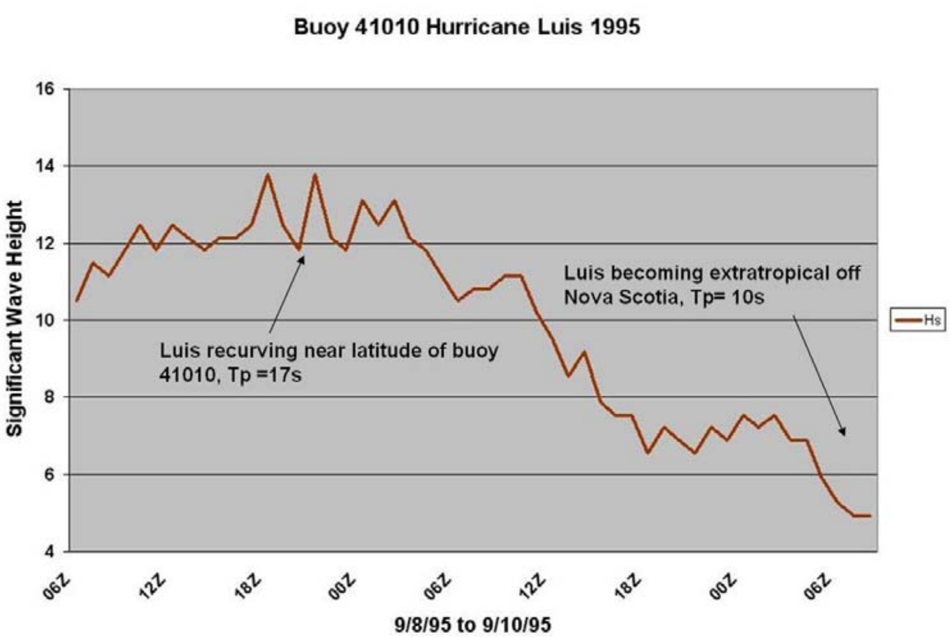

Figure 3. The swell event associated with Category 4 Hurricane Luis at Outer Canaveral buoy 41010, showing a peak in long period energy when the storm was near the latitude of the buoy, and then a steady drop as the storm recurved towards the Canadian Maritimes. This demonstrates a typical long period swell event for Florida associated with a tropical cyclone. Significant wave height (ft) plotted from 8-10 September 1995.

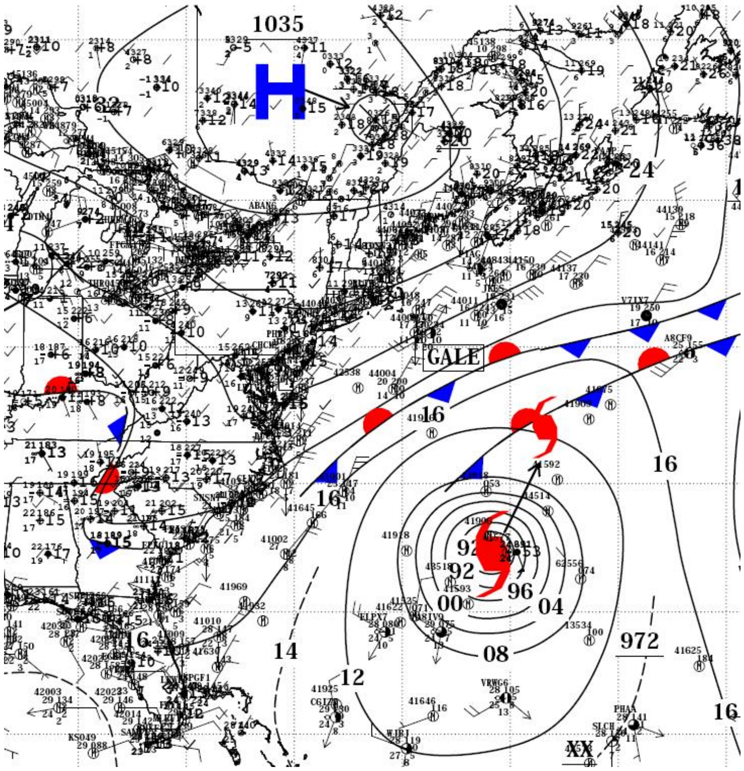

Figure 4. NWS Unified Surface Analysis from 12Z September 11, 2006 showing strong high pressure over Eastern Canada interacting with recurving Hurricane Florence.

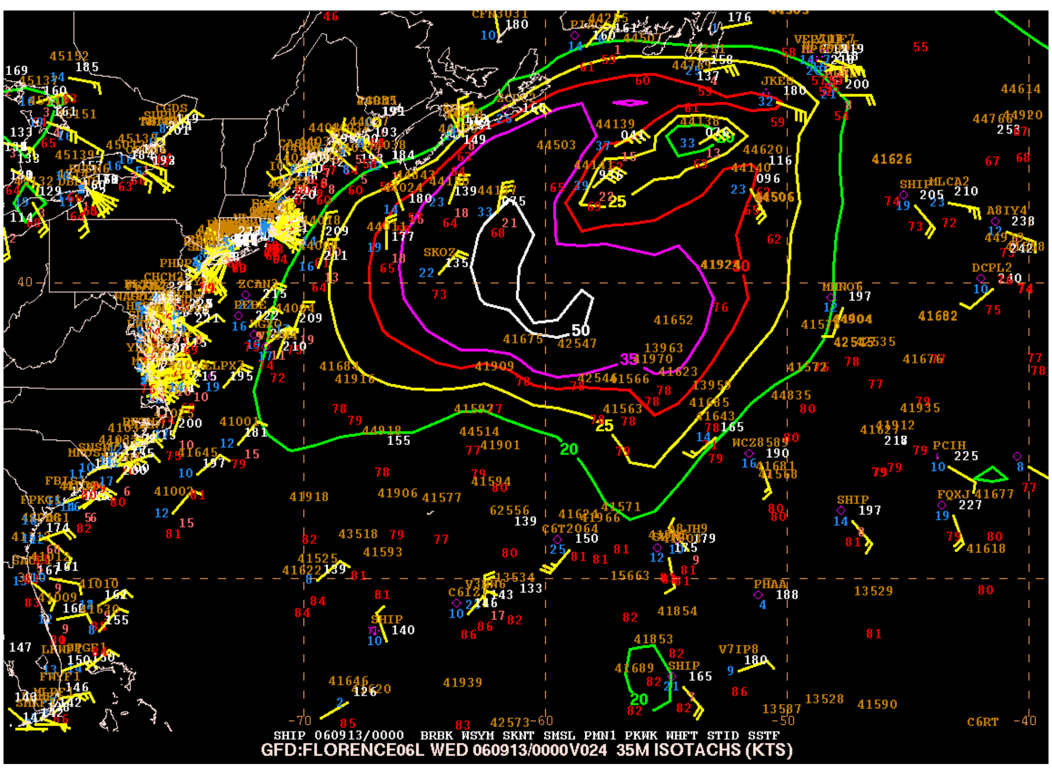

Figure 5. GFDL 35m isotachs (colored lines) and available buoy, ship, and CMAN observations from 00Z 13 September 2006.

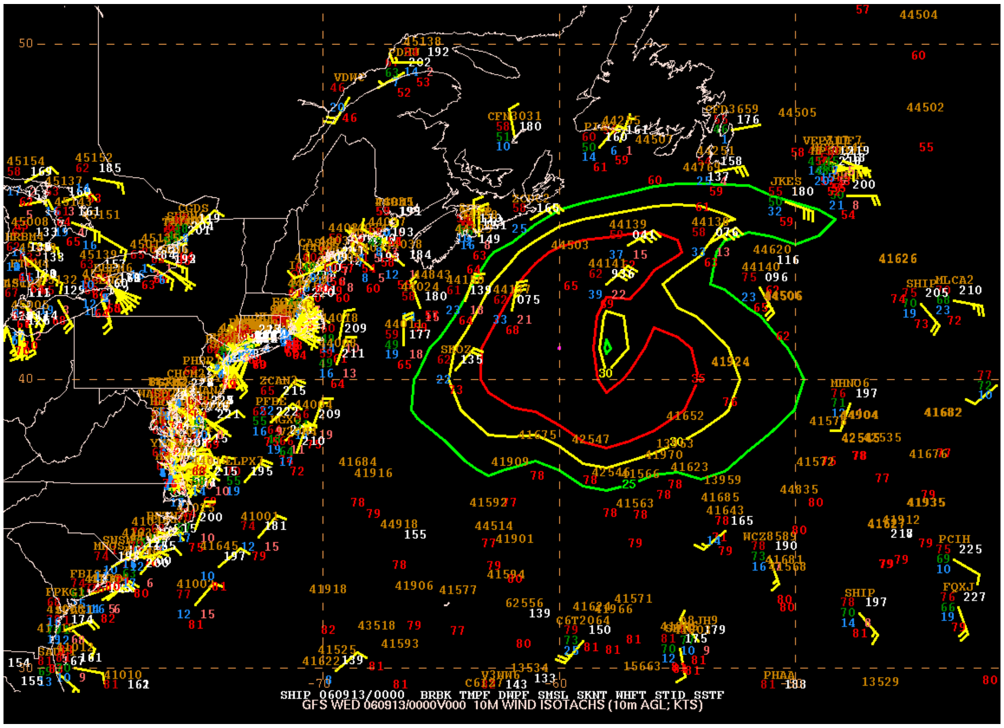

Figure 6. GFS 10m isotachs (colored lines) and available buoy, ship, and CMAN observations from 00Z 13 September 2006.

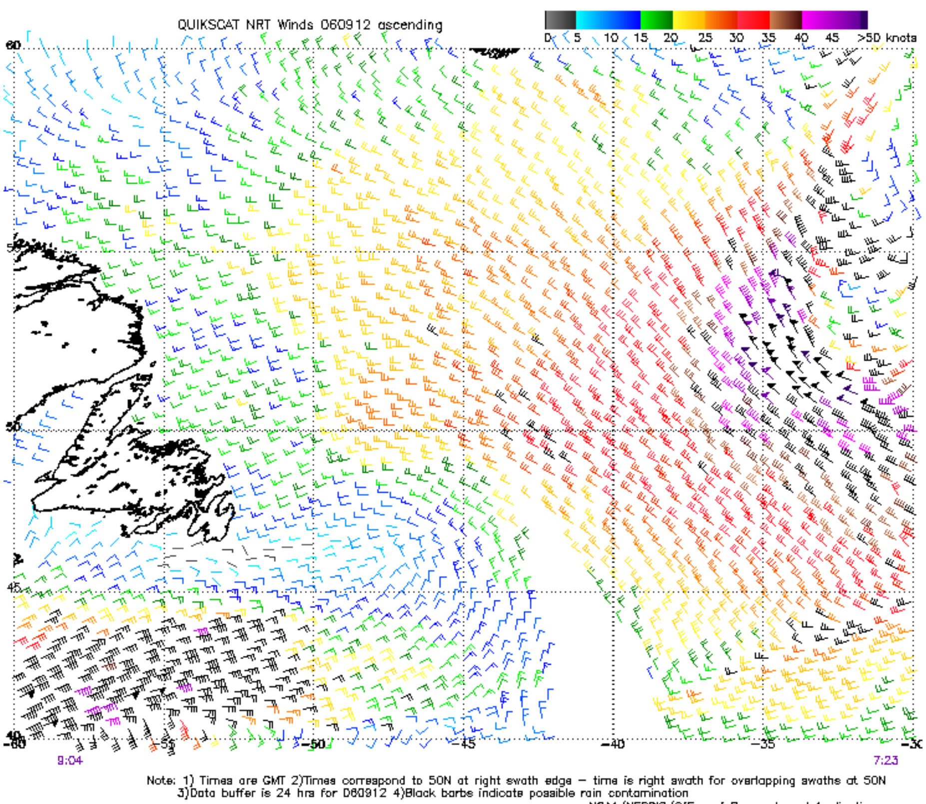

Figure 7. QuikSCAT pass from 12 September 2006 showing long fetch of gale to storm force NE/ENE winds S of Newfoundland where model data showed a minimum.

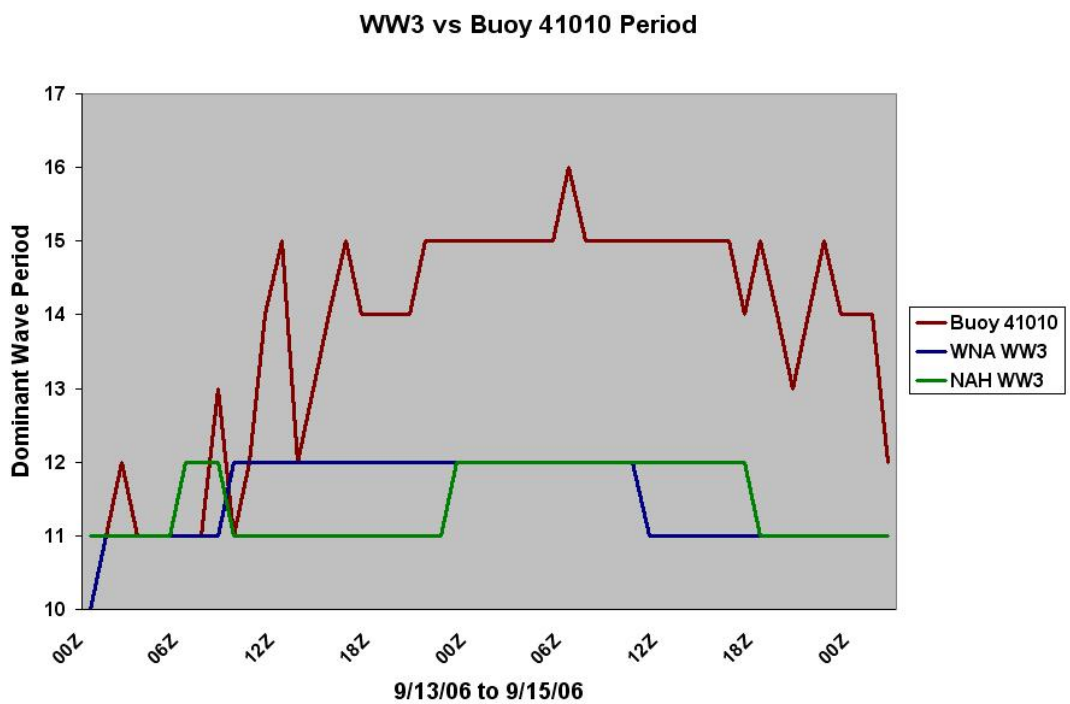

Figure 8. Observed and modeled dominant wave period (s) at buoy 41010 from 13-15 September 2006.

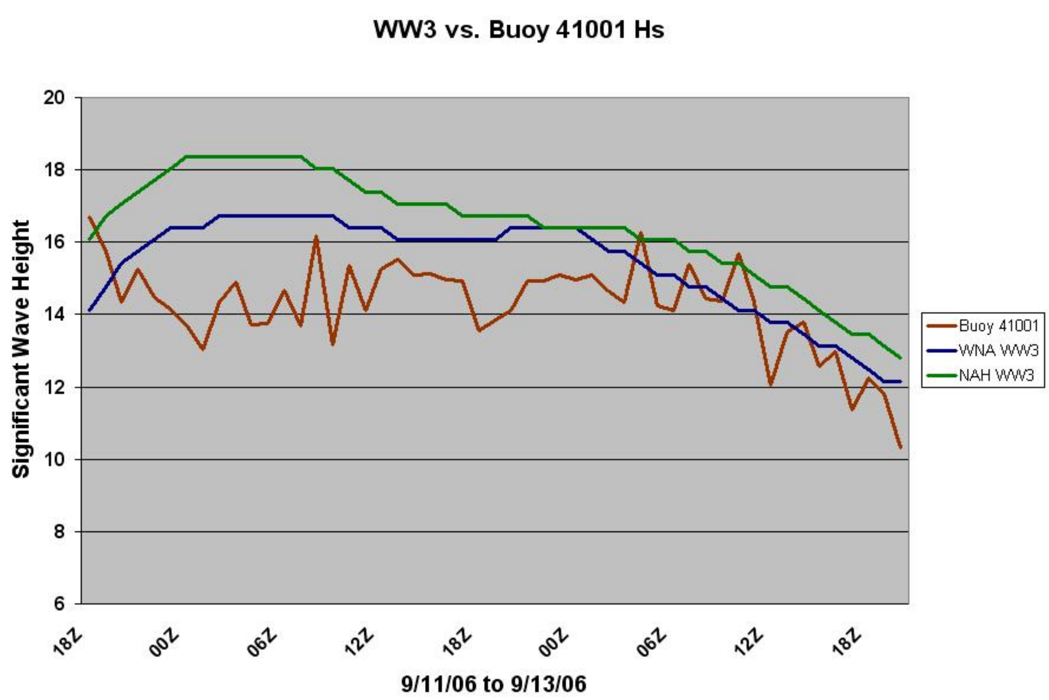

Figure 9. Observed and modeled significant wave heights (ft) at buoy 41001 offshore Cape Hatteras, North Carolina from 11-13 September 2006.

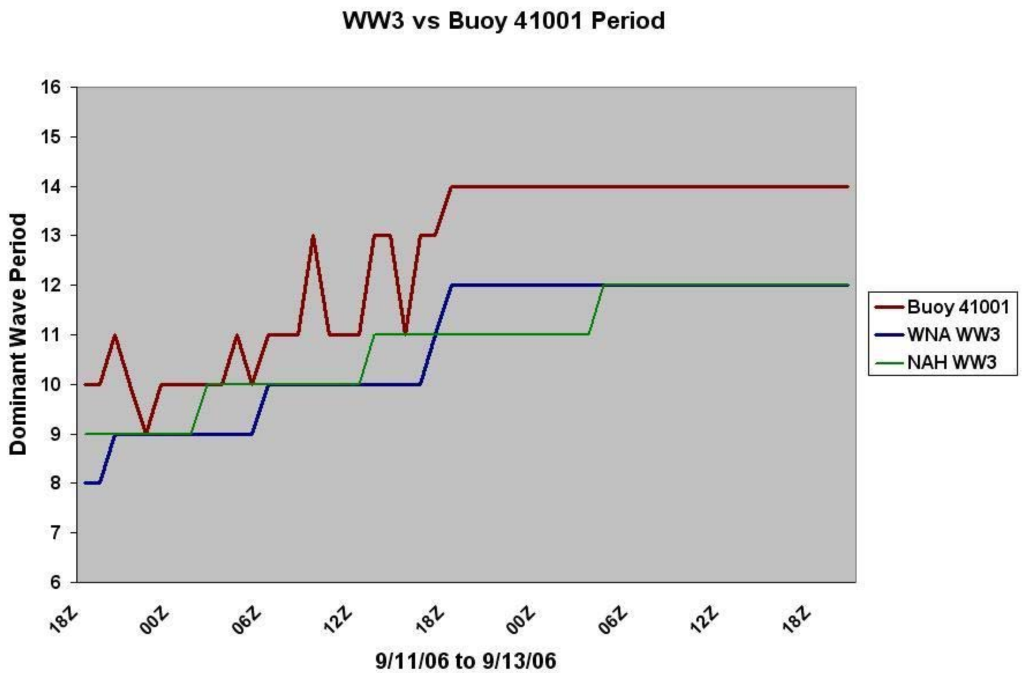

Figure 10. Observed and modeled dominant wave period (s) at buoy 41001 from 11-13 September 2006.