P4.3 FORECAST CHALLENGES AND LESSONS FROM THE 2008 SAINT PATRICK'S DAY SUPER SWELL

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1. INTRODUCTION

The Outer Banks of North Carolina has a very complex near shore wave climate due to multiple changes in beach direction and the adjacent bathymetry. The area is also very prone to erosion and ocean over-wash as the topography consists mainly of mobile sand dunes. Additionally, the Outer Banks is susceptible to large wave action since it is both directly and indirectly affected by a wide variety and high frequency of coastal storms (Bosserman and Dolan 1968, Davis et al. 1993, and Mather et al. 1964). The National Weather Service (NWS) forecast office in Newport/Morehead City, North Carolina (WFO MHX) is responsible for the official wave forecasts in the waters out to 20 nautical miles (37 km) off the Outer Banks. Dependable wave forecasts are crucial to the local economy given the high volume of commercial and recreational fishing that takes place in the area. In addition, the area is famous for other marine related activities including surfing, kite surfing, sailing, and beach tourism. Because of this, forecasters at WFO MHX field thousands of calls yearly from those interested in marine weather observations and forecasts.

During the period 15-16 March 2008, a complex frontal system (Fig. 1) and attendant low pressure moved through the Southeastern states that led to a major severe weather outbreak resulting in at least 5 deaths and 60 injuries (NCDC 2008). The parent surface low pressure area then moved offshore later on 16 March and rapidly intensified into a hurricane force, extratropical low by early 17 March approximately 630 km SE of Halifax, Nova Scotia. Numerical Weather Prediction (NWP) models did a fair job at representing the intensity of the cyclone but did a poor job at depicting its wind field. Specifically, the operational models significantly underestimated the magnitude, length, and duration of the fetch of E and NE winds in the north semicircle of the storm.

The storm to hurricane force E and NE winds aimed at the Outer Banks produced seas upwards of 30-40 ft. (10-12 m) near the storm. After these waves propagated away from their originating fetch, it resulted in a significant long period swell event for east exposed beaches in the Outer Banks. The swell was much larger than forecasters expected due to the under prediction of the available wave model guidance. The swell event produced surf in excess of 10-15 ft. (3-4.6 m) for the beaches between Buxton and Duck, NC, dangerous rip currents, minor beach erosion and ocean over-wash.

The ocean over-wash problem is both significant and common in the Outer Banks as it often results in road closures and has condemned countless water front homes (i.e. King 2008). The ocean over-wash from this swell event led to the temporary closure of Highway 12 on Pea Island National Wildlife Refuge and near Mirlo Beach. Mirlo Beach is notorious for ocean over-wash and in fact, the Dare County Department of Emergency Management has a web camera there to help monitor the problem. WFO MHX will issue a coastal flood advisory, or warning, when water level rises of 2 to 3 ft. (.6-.9 m), or 4 ft. (1.2 m) or greater, are anticipated, respectively. However, very little physical guidance is available to the forecasters for this phenomenon aside from dated rules of thumb.

The effects associated with the large swells generated by this storm system were not limited to the Outer Banks. While this paper focuses on Eastern North Carolina, it is of note that the swell affected a wide area in the western Atlantic ranging from Canada to the Caribbean. Puerto Rico reported that the high surf and coastal flooding from this event resulted in approximately 2.5 million dollars in damage (NCDC 2008). The 35-40 ft. (10.7-12.2 m) surf generated in Puerto Rico during 19-20 March 2008 from this storm is accepted to be the largest the island has seen from an extratropical system since the "Perfect Storm" in November 1991 (Sanders and Willis 2002).

The aim of this paper is to provide a reference for forecasters that documents new technologies useful in operational wave forecasting, and that suggests a methodology for gaining Situational Awareness (SA) during swell events. Only a brief description of the meteorology and wave model verification is discussed in Section 3. A detailed analysis of key signs in buoy data, satellite altimeter wave height data, and satellite

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derived swell wavelengths and directions measured by the advanced synthetic aperture radar (ASAR) aboard the ENVISAT satellite (ESA 2008) are discussed in Section 4. A review of relevant SA research from various social scientists and its application to distant swell events is presented in Section 5. A summary and future work, including current projects underway at WFO MHX to improve the ocean over-wash and coastal flood program, are discussed in Section 6.

2. DATA

Various observed and modeled wind fields were analyzed around the deep low SE of Nova Scotia during 16-18 March 2008 in order to gain an understanding for the processes that resulted in the wave heights being much higher than predicted off the coast of North Carolina. The graphics and discussion presented in section 3 focus on the Global Forecast System (GFS) atmospheric model (i.e. Rhome 2007) since its 10m winds are used to drive the NOAA Wavewatch III (WW3) model (Tolman 2002), which presently is the only wave model guidance available directly at WFO MHX. The surface analyses shown are from the National Centers for Environmental Prediction (NCEP) Unified Surface Analysis. This analysis is a joint, human generated product that is collectively done by NCEP's Ocean Prediction Center, Hydrometeorological Prediction Center, Hawaii Forecast Office, and the National Hurricane Center (Berg 2007).

In-situ wind observations (ship and buoys) were used in this study in addition to QuikSCAT data (i.e. Von Ahn et al. 2006) in order to locate problems in the GFS wind forcing. Archived buoy data obtained from the National Data Buoy Center (NDBC) website were compared to output from the WW3 model. Satellite derived wave observations were also analyzed in this study and compared to WW3. Significant wave height retrievals from the altimeter aboard the Jason-1 satellite (NASA/JPL 2008) and peak wave periods and directions observed by the ASAR aboard the European Space Agency's (ESA) ENVISAT satellite (ESA 2005 and Collard 2005) are discussed in Section 4.

The case presented in this paper marks the first time the ENVISAT wave period retrievals are documented to be successful in improving wave forecasting at WFO MHX and to our knowledge the NWS as a whole. Peak wave periods and directions are obtained from a small portion of the ASAR dataset. Essentially the ASAR radar echoes take a small "movie" of the ocean of an area approximately 5X9 km, and 1s duration. From this movie and well-known responses of radar echoes to swell slopes and velocities, the signal is converted into 2D wave spectra (Fabrice Collard, personal communication, March 23, 2008). Collecte Localisation Satellite (CLS), a subsidiary of the Central National d'Etudes Spatiales (CNES), is a French group that uses this dataset to create a product that takes the peak period and direction of each swell partition of the 2D spectra and propagates it in time using the deep water dispersion relationship.

3. METEOROLOGY AND WAVE VERIFICATION

Surface low pressure associated with a robust upper short wave trough moved from the Tennessee River Valley through the Carolinas during 15 March 2008 (Fig. 1) and then pushed offshore the Outer Banks of North Carolina around 0600 UTC 16 March 2008. The combination of high instability, shear, and both surface and upper level support from this system led to a deadly severe weather outbreak across the Southeast United States. The NCEP Storm Prediction Center (SPC) in Norman, Oklahoma issued a rare high risk of severe thunderstorms in their Day 1 convective outlook for this event, which ultimately led to 51 tornado reports, 163 severe hail reports, and 83 reports of wind damage (Fig. 2).

The parent surface low pressure area intensified rapidly to hurricane force by 0000 UTC 17 March approximately 630 km SE of Nova Scotia following a 24hr pressure drop of 27 hPa (999 hPa to 972 hPa). The low deepened further by 1200 UTC 17 March to 965 hPa. At this point, the low contained a warm front extending almost due east from the center as analyzed by the NCEP Ocean Prediction Center in Washington, DC (Fig. 3). A QuikSCAT pass at 0800 UTC 17 March showed a fetch of E and NE winds north of this warm front ranging from gale to low end hurricane force (Fig. 4). This fetch was approximately from 41N-46N between 49W-60W, or just south of Newfoundland, and pointed directly at the east facing beaches of the Outer Banks and Mid Atlantic States (the so called "swell window").

The GFS did not adequately represent the fetch of E and NE winds north of the warm front, but seemed to have a good handle on the strong N and NW winds in the west semicircle of the low. The GFS was depicting the winds in the Outer Banks swell window mostly in the strong to low end gale range on the Beaufort Scale (Met Office 2008) where observations suggested winds were some 20-30 kt (10-15 m/s) higher (Fig. 5). This undoubtedly led to the problems in the operational wave model guidance available at WFO MHX. In fact, WW3 underestimated the wave heights during the peak of the swell by nearly 7 ft (2.1 m) when compared to observations from Diamond Shoals buoy 41025 early on March 19 (Fig. 6). WW3 peak wave periods were also several seconds too low when compared to buoy 41025 (Fig. 7). The underestimation of wave period was most likely due to the errors in the GFS wind forcing. However, wave period underestimation by WW3 has been shown to be more of a systematic problem with long period swell events, possibly attributed to wave model physics or parameterizations (Quilfen et al. 2004).

4. BEATING THE WAVE MODEL GUIDANCE

Forecasters readily have access to satellite derived winds such as QuikSCAT, buoy, ship, and CMAN data which help locate problems in the GFS wind forcing. This in turn can be used in conjunction with various local tools and nomograms to predict a more realistic wave field than WW3. The deep water dispersion relationship and decay tables can then be used to get an estimate of when a swell event may arrive at a beach of interest and at what fraction of its original height. This process is clearly demonstrated with statistical wave tables in Morris and Nelson (1977) and also in the Shore Protection Manual (Jachowski 1973).

However, the QuikSCAT instrument is on its backup science data transmitter and aging bearings are leading to an increase in motor torque. Either of these issues could easily lead to the loss of QuikSCAT data at any time, though the NASA Jet Propulsion Laboratory estimates up to 4 more years of operations are possible from the satellite (Robert Gaston, QuikSCAT program manager, personal communication, Dec. 10, 2008). While there are plans to fly a QuikSCAT operational follow on mission, forecasters should not depend on this data. Furthermore, gaps in the QuikSCAT coverage often miss a fetch of interest. Buoy, ship, and CMAN wind data are also invaluable to marine forecasting but also often do not lie in a specific area of interest. These reasons dictate the need for forecasters to utilize satellite wave data for marine forecasting.

Several studies suggest wave height data obtained by satellite altimeters is as good as buoy data and thus has merit for operational purposes (Hwang et al. 1998 and Tolman et al. 2002). Like buoy and QuikSCAT data, gaps in the satellite's footprint often make it easy to miss an area of interest. That was not the case in this event though as the Jason-1 (JPL 2008) satellite passed directly over the high seas of interest at approximately 2200 UTC 18 March 2008. This pass revealed a large area of 30-40 ft (9.1-12.2 m) seas over the NW Atlantic waters SE of Nova Scotia (Fig. 8) where the WW3 model was depicting seas several feet lower. Upstream data such as this provide a crucial clue to forecasters that downstream wave forecasts need to be adjusted appropriately.

Marine forecasters at WFO MHX started using the CLS satellite derived wave period and direction product during 2008 primarily in an effort to get a feel for how WW3 handles approaching swell events. This observational product also provided a key clue to forecasters during this event that WW3 was several seconds too low in its wave period forecast. Figure 9 depicts an example image from this product, which in its original form is an animation of several days that shows swells dispersing through the ocean, showing an area of 16-17 s swell energy observed by the ASAR instrument approaching the Outer Banks of North Carolina on 18-19 March from the NE. WW3 spectral bulletins did show longer period NE swell approaching the Outer Banks during this time frame, but was mainly in the 11-15 s band (Fig. 7). Wave period underestimations such as this can significantly impact shoaling coefficients (Monk 1950) which in turn affects NWS rip current forecasts and coastal flood advisories and warnings.

While buoy data is not always found in a location of interest, it was in this event. Upstream buoy data can often provide forecasters insight to when approaching swell events may be under or over forecast by WW3. This information can then be used to increase lead time in warning mariners of approaching large seas. Georges Bank buoy 44011 and the Hotel buoy 44004 250nm E of Cape May, NJ can provide this type of information for NE swell events approaching the Outer Banks associated with storm systems in the North Atlantic. For example, during this event the observed wave heights at buoy 44011 were several feet (2-2.7 m) higher than what WW3 was depicting during 17-18 March 2008 (Fig. 10). Observed peak wave periods at buoy 44011 were also several seconds higher than what WW3 was predicting during this time frame. This discrepancy was greatest approximately 24 hours before the swell peaked offshore the Outer Banks, which is almost exactly the swell travel time along the great circle route between buoys 44011 and 41025 for 15 second energy (Table 1). Similar to the observations in the satellite data, discrepancies between the upstream buoy data and WW3 can easily be applied to the downstream wave forecasts issues by WFO MHX for the coastal waters offshore the Outer Banks.

5. MAINTAINING SITUATIONAL AWARENESS

The study of SA has increased dramatically since the 1980's. Multiple definitions for SA have been offered in these studies, but in a broad sense, SA provides "the primary basis for subsequent decision making and performance in the operation of complex, dynamic systems" (Endsley, 1995). Klein (2000) discussed four reasons why SA is important: 1) It has been shown to be linked to performance, 2) Limitations in SA are related to errors, 3) SA may be related to expertise, and 4) SA is the basis for decision making in most cases. Much of the research in SA has attempted to understand how professionals acquire and maintain SA. Early work in SA focused on a pilot's cockpit, but has since expanded to fields such as air traffic control, medicine, space travel, education, and weather forecasting (Endsley and Garland, 2000).

Endsley described three main levels of SA: The detection of the environment's relevant elements (Level 1 SA), the comprehension of the elements' meaning (Level 2 SA), and the projection of the elements' status into the future (Level 3 SA). These levels can be applied to marine forecasting where

Level 1 SA is related to the meteorologist viewing wind and wave observations and model initialization fields within various computer platforms or hand drawn analyses. Level 2 SA is the pattern recognition process of these data, while Level 3 SA is applying that recognition to the forecast process. The remainder of this section attempts to use the large swell event in this case as a basis for forecasters to acquire and maintain all 3 Levels of SA during similar events.

As described in sections 1 and 2, before this frontal system moved offshore it led to a deadly severe weather outbreak across the Southeast United States. This led to forecaster fatigue and mental and physical stress through multiple warnings, media interviews, exhausting long shifts, etc. It could be easy for forecasters to let their guards down after such a weather system and the associated severe threat moved offshore. However, it is of paramount importance that forecasters be cognizant of all threats of a particular weather system, including those that occur indirectly from distant sources such as those described in this paper associated with swell events. A similar potential situational awareness struggle was discussed in Willis (2007) associated with the deadly swell event that followed the recurvature of Hurricane Florence (2006) well off the United States Eastern Seaboard. The unusually large swell event that affected the East Coast came days after it was evident that Hurricane Florence was not going to be a direct threat to the U.S., and peaked on pleasant weather days that led to large beach populations. This combination led to hundreds of ocean rescues, two deaths in Florida, minor coastal flooding, and beach erosion along portions of the East Coast. Both cases present the need for continuous analysis of distant storm systems for potential swell events and the associated threats. This cannot be done without SA.

It is important to recognize that many weather forecasters that enter the NWS come from different backgrounds, many of whom have very little formal training in wave forecasting. We feel it is safe to say that the majority of academic programs in meteorology from which most of the forecasters come from offer very little background on the science and rudiments of wave forecasting. Thus, it is important for forecasters to take advantage of the many training modules available from the NWS on marine forecasting. This, and experience, are large steps in gaining expertise in wave forecasting and the ability to obtain and maintain SA.

It is possible that wave forecasters could benefit from taking the following steps and asking a few general questions while attempting to gain the 3 levels of SA when dealing with distant swell events (after a basic understanding of wave forecasting principles is gained):

Obtaining Level 1 SA for swell events, viewing the following relevant wind and wave elements:

- Local and distant observed surface wind fields from both in-situ and satellite derived sources.
- Local and distant buoy wave observations including spectral density plots and individual wave system heights, periods, and directions.
- Satellite observed wave heights and wave periods.
- Atmospheric and wave model initializations, including local and distant WW3 spectral bulletins.

Obtaining Level 2 SA for swell events, comprehending the data's meaning by asking the following questions:

- What weather systems are creating each wave system being observed and depicted in the WW3 spectral bulletins?
- Are the atmospheric models handling the current conditions appropriately, especially the winds pointed at your location along great circle routes from distant weather systems?
- Are there any signs in the upstream buoy or satellite observations that suggest the wave models are performing poorly regardless of what the observed vs. modeled winds suggest?
- What could these questions mean for my location?

Obtaining Level 3 SA for swell events, making the wave forecast:

- Use information gained with Level 1 and 2 SA to determine how and if to apply the wave model guidance. Examples: 1) If wave periods of an approaching wave system are observed to be much higher (lower) than WW3 is depicting, the forecaster will need to forecast a quicker (slower) arrival time based on the deep water dispersion relationship. 2) If wave heights of an approaching wave system are observed to be higher or lower than WW3, the forecaster will need to use decay coefficients or other studies to determine the height of the swell upon arrival of their location. This could be done by using the statistical tables provided in Morris and Nelson (1977). 3) If the winds going into the wave model are different from those being observed, ideally the forecaster would have the wave model rerun using a more realistic wind field. Since this ability is currently limited in forecast offices, an alternative could be to use fetch tables that provide wave heights and periods based on different wind strengths, durations, and fetch lengths, such as those provided in the Shore Protection Manual (Jachowski 1973) or other computer programs that offer similar results.

- Describe how the differences in the wave heights, periods, and directions being forecast will impact local conditions in the forecast. This requires additional SA of how different wave systems affect your location of interest. For example, very long period NE swells such as the one in this study can cause very hazardous conditions near Oregon Inlet, lead to a higher rip current threat, and also will refract into south facing beaches more than shorter period NE swells.
- Disseminate forecasts, advisories, and warnings accordingly.

6. CONCLUSIONS AND FUTURE WORK

The large swell event that affected the Outer Banks 18-20 March 2008 provided an opportunity to review wave forecasting methodology in addition to adapting satellite observation tools into the forecast process. The event was significantly under forecast by WW3 due to problems in the GFS wind forcing, and led to high surf, dangerous rip currents, and high wave setup leading to ocean over-wash and the closure of Highway 12. These threats affected the Outer Banks 2-3 days after the same weather system produced deadly severe weather across the Southeast States. This reminded forecasters the need of always maintaining SA for all weather and marine hazards, especially those associated with distant swell events. SA during swell events can only be obtained after proper training is completed, though the need for continuous analysis of distant weather systems through in-situ and satellite observations combined with their application to computer models and wave forecasting is presented.

WFO MHX is currently working with the University of North Carolina at Chapel Hill (UNC) and the U.S. Army Corps of Engineers Field Research Facility in Duck, North Carolina to implement the high resolution near shore wave model, SWAN (Simulating WAves Nearshore), into operations in an effort to improve near shore wave analysis and forecasting. SWAN will provide a superior depiction of the hazards near the coast compared to WW3 since it includes near shore physics, while WW3 is a deep water wave model not designed for shallow water waves. This will increase forecaster SA of wave conditions near shore where much of the marine traffic near the Outer Banks occurs, thus providing forecasters more confidence when communicating with mariners about waves in the near shore zone.

WFO MHX is also working with UNC and the Renaissance Computing Institute (RENCI) to improve coastal flood forecasts, advisories, and warnings. RENCI is currently running the ADCIRC (Leuttich et al, 1993) coastal circulation and storm surge model with wind input from the North American Mesoscale model (NAM). This is providing forecasters high resolution water level guidance for extratropical storm systems, and preliminary results (not shown) have been favorable. Future plans are to use forecaster created, value added wind fields from the NWS National Digital Forecast Database to drive both SWAN and ADCIRC to produce a wave and water level forecast consistent with the wind forecast. Ultimately there are aspirations to couple SWAN and ADCIRC in real time to help forecast water level rise due to both wind and wave setup in addition to tides. This holds promise to provide guidance for the frequent ocean over-wash problem observed in the Outer Banks. The modeling efforts to improve the WFO MHX coastal flood program are being complemented by an office initiative to improve water level observations. This consists of staff gauges being deployed and a growing human spotter network focused on reporting water levels in locations across Eastern North Carolina prone to coastal flooding.

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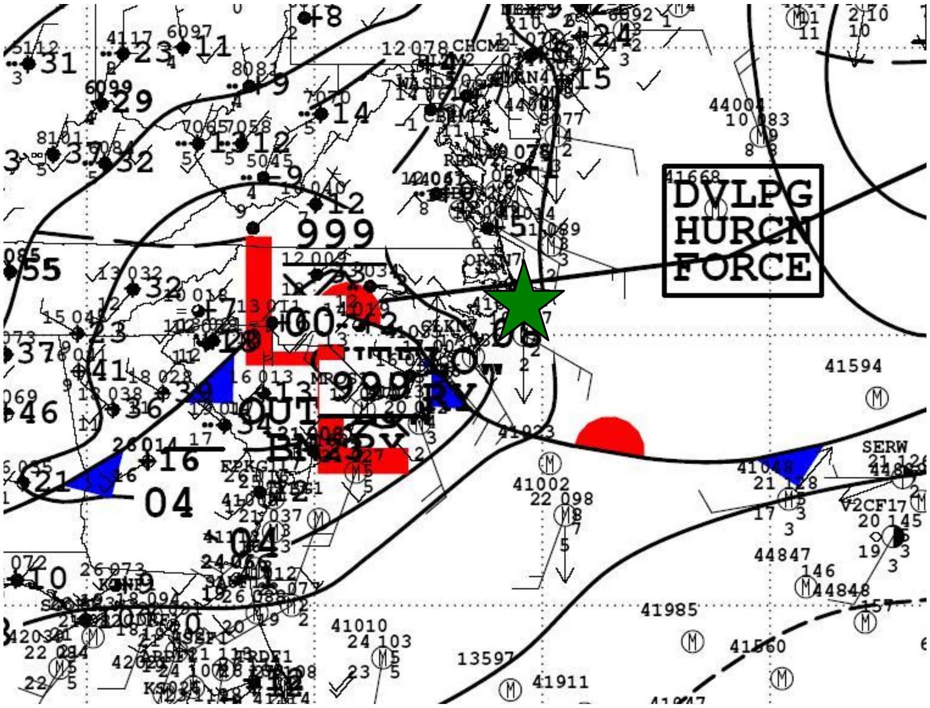

Figure 1. NCEP Unified Surface Analysis from 1800 UTC 15 March 2008. Green star denotes location of Outer Banks, North Carolina.

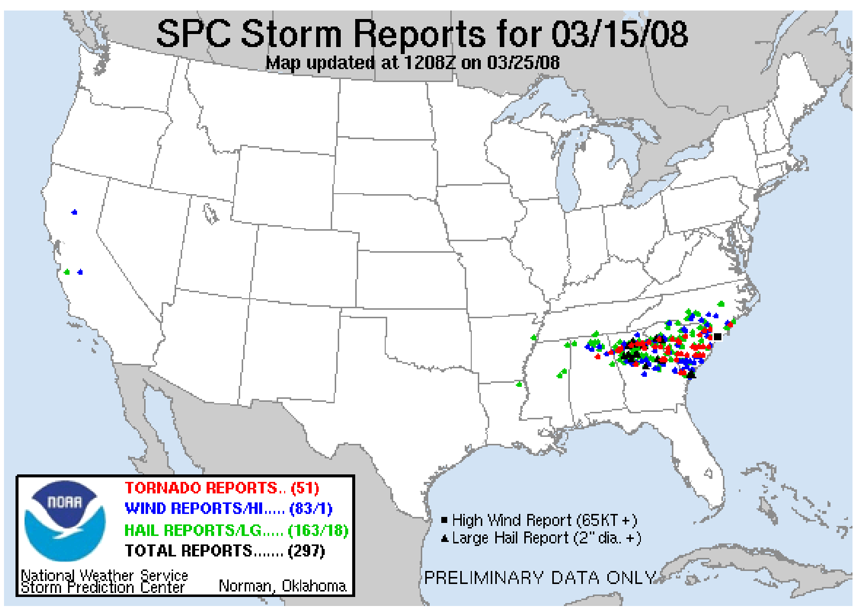

Figure 2. Preliminary severe weather reports from SPC from 15 March 2008, prior to the swell event.

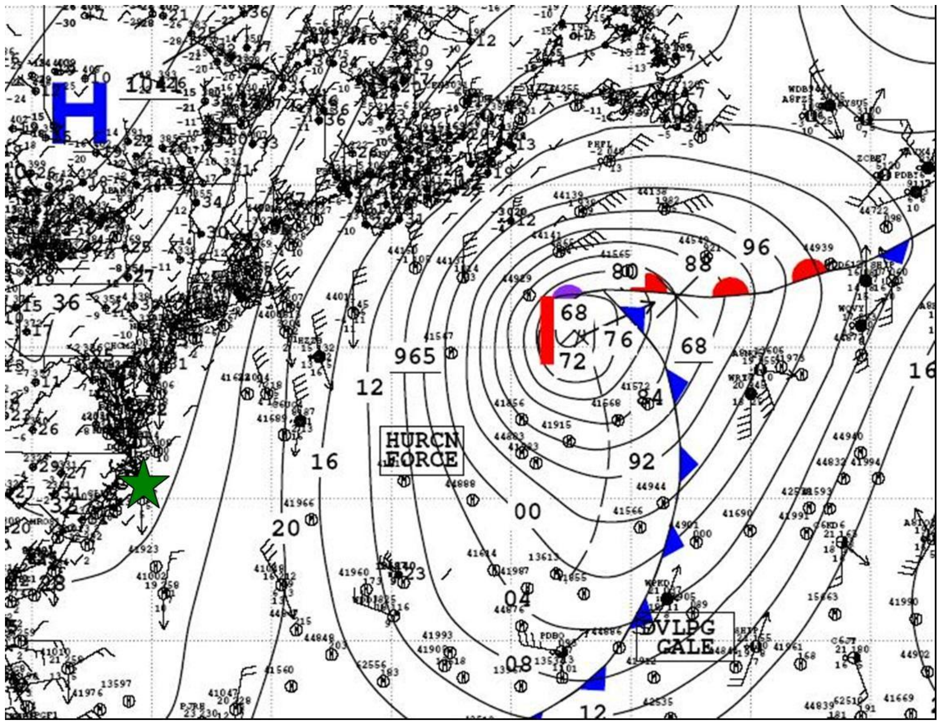

Figure 3. NCEP Unified Surface Analysis from 1200 UTC 17 March 2008. Green star denotes location of Outer Banks, NC.

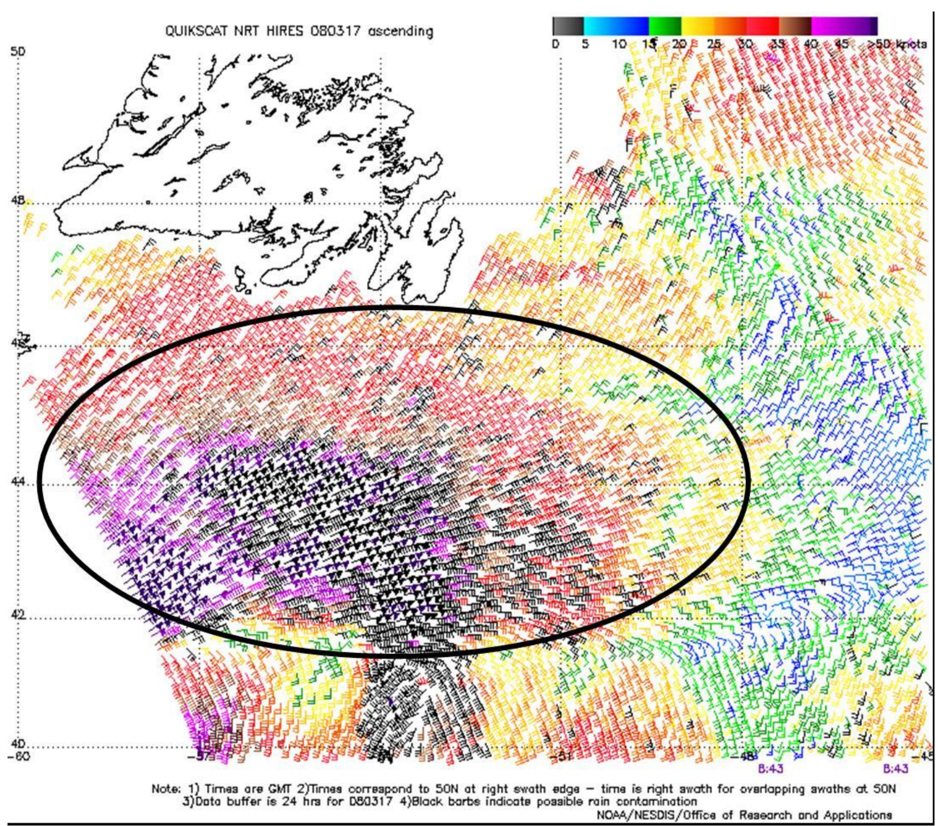

Figure 4. QuikSCAT pass from 0843 UTC 17 March 2008 showing large fetch of strong to hurricane force winds S of Newfoundland aimed at the Outer Banks (circled).

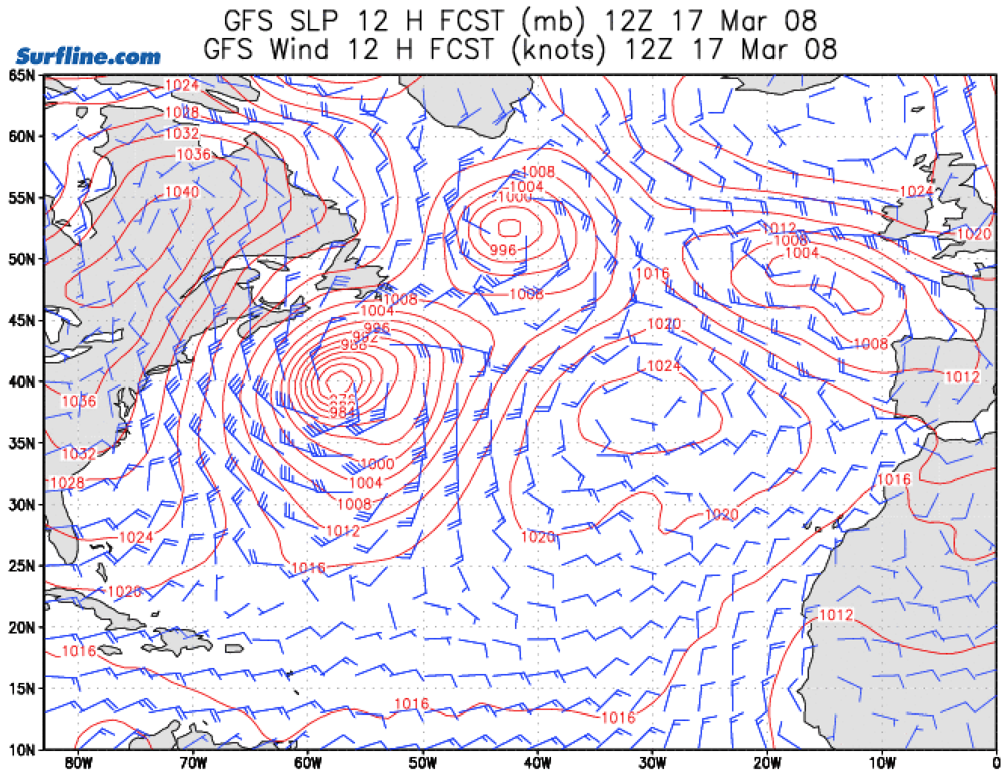

Figure 5. GFS surface winds 1200 UTC 17 March 2008.

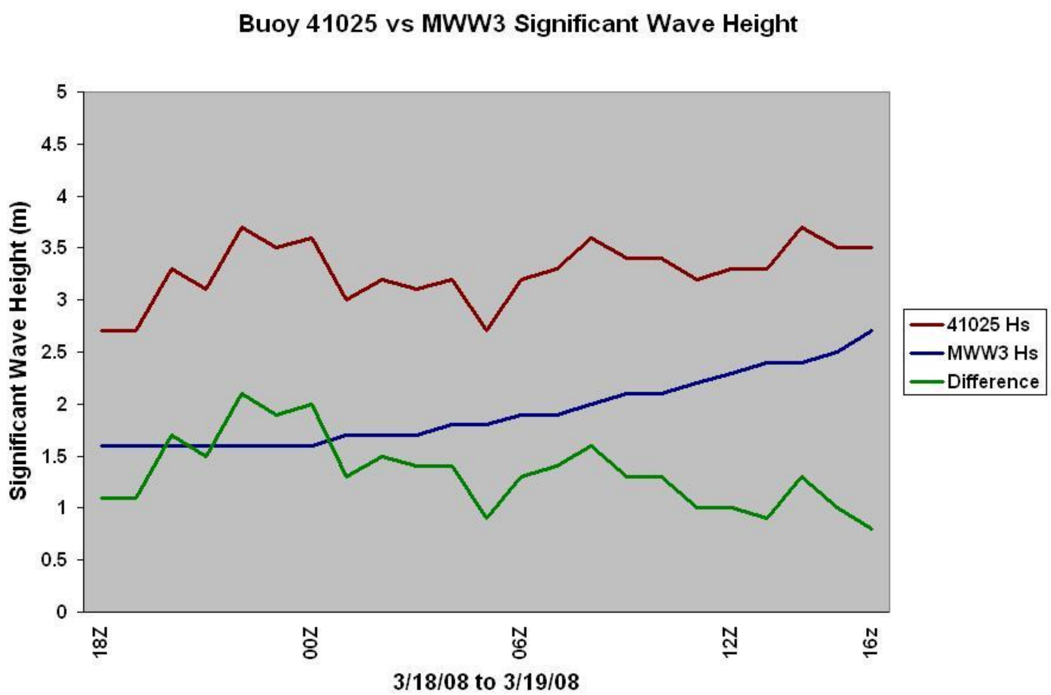

Figure 6. Significant wave heights (Hs in meters) from buoy 41025 (red) and WW3 (blue) from 18-19 March 2008. Difference between observed and modeled wave heights shown in green.

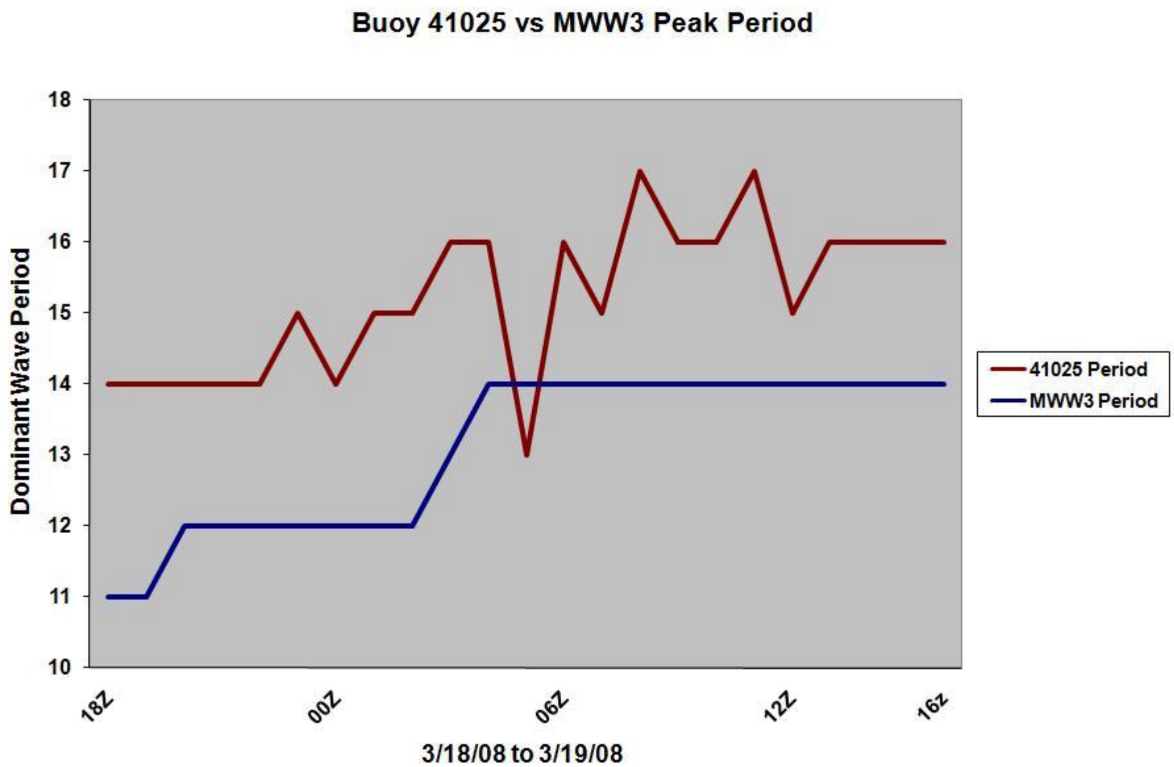

Figure 7. Peak wave periods (s) from buoy 41025 (red) and WW3 (blue) during 18-19 March 2008.

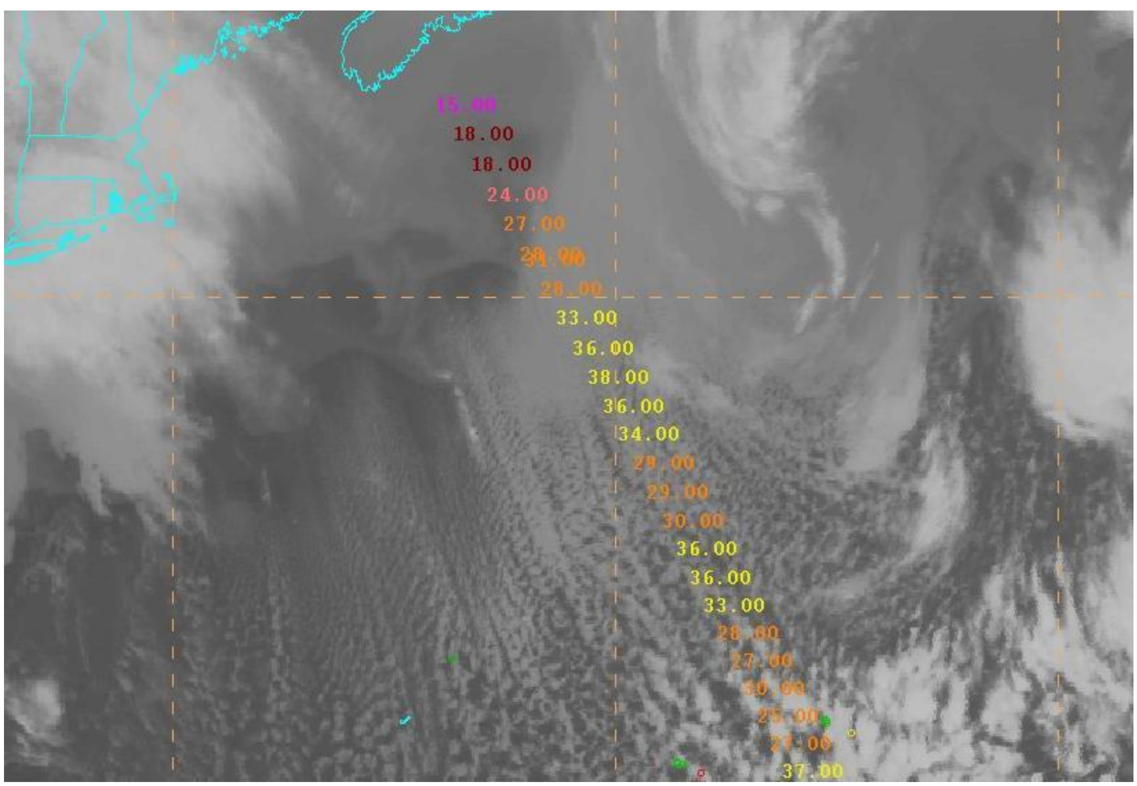

Figure 8. Jason-1 altimeter significant wave heights (colored numbers in feet) overlaid on infrared satellite imagery from 2215 UTC 18 March 2008, showing large area of 30-40ft (9.1-12.2m) seas SE of Nova Scotia.

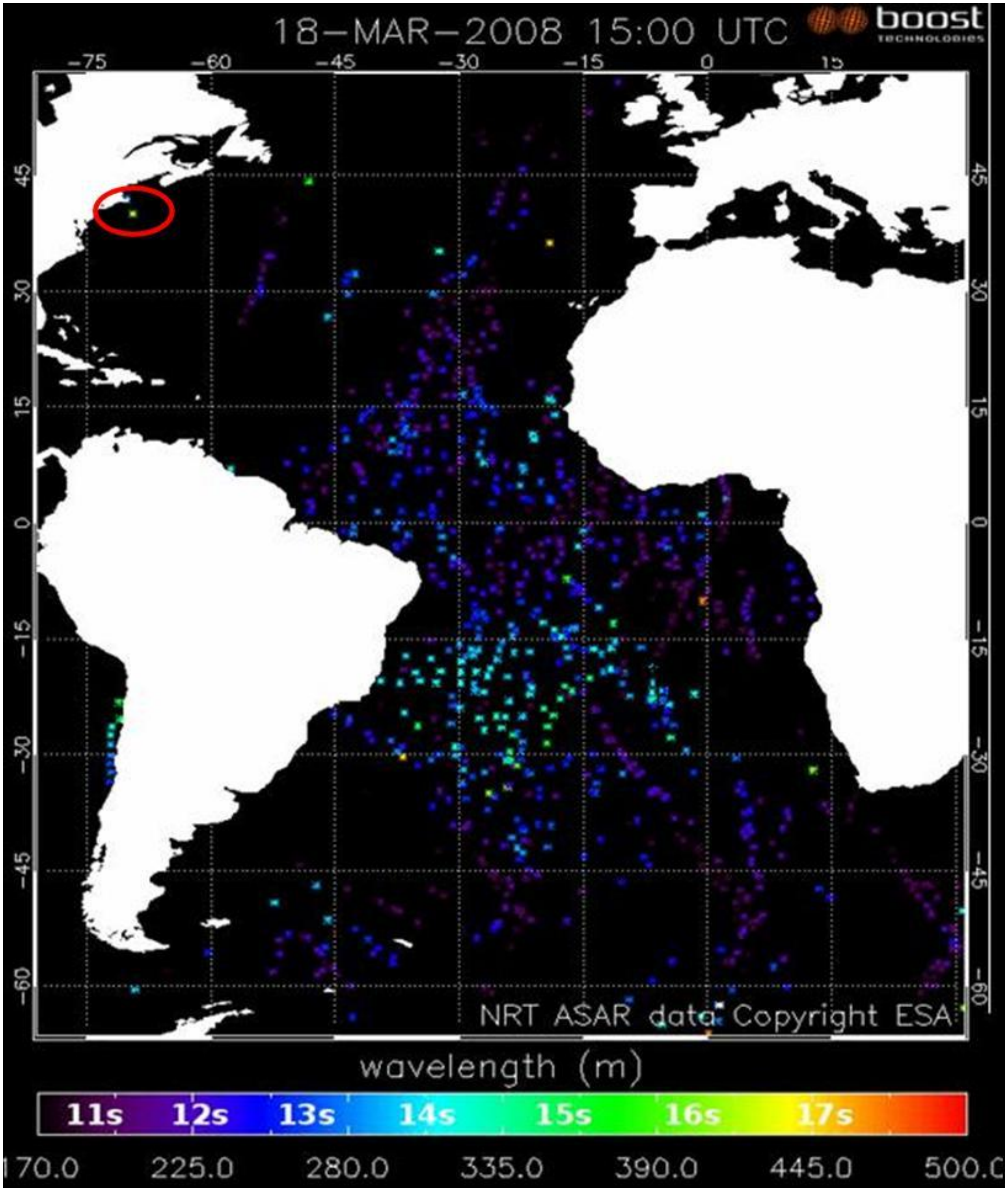

Figure 9. ASAR data from ESA processed by CLS showing peak wave periods in Atlantic Basin. The image represents one frame of animation that shows area of 16-17s swell energy S of Cape Cod (circled in red) on 18 March 2008 approaching the Outer Banks from the NE.

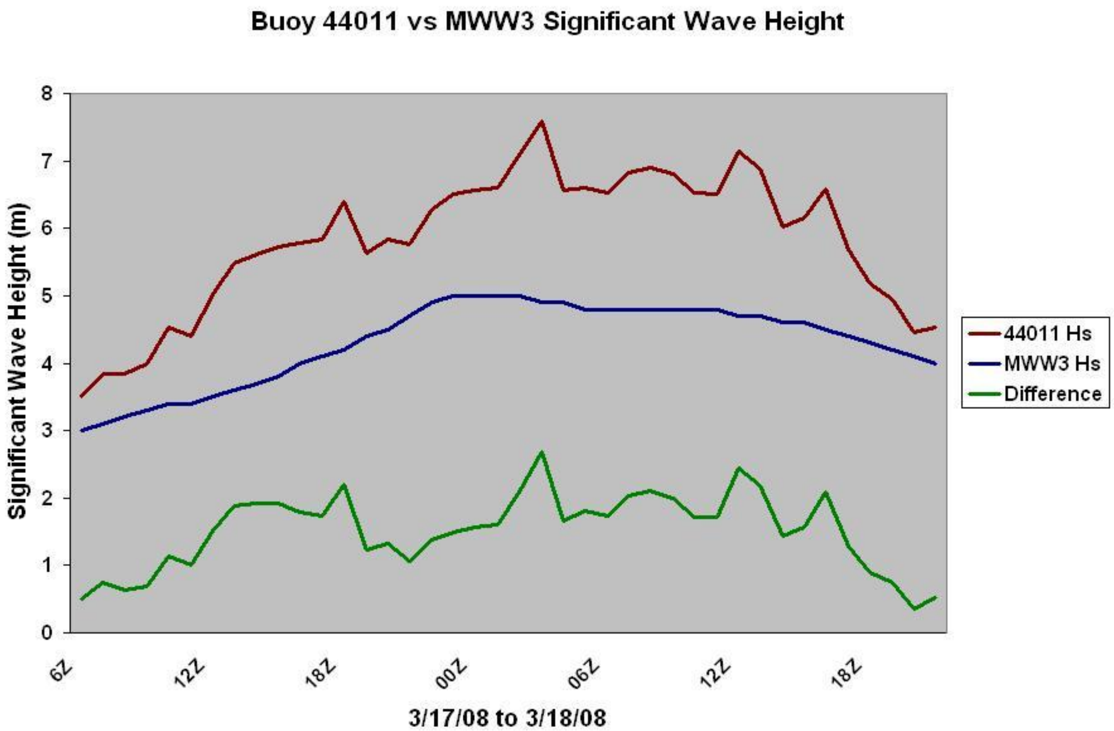

Figure 10. Significant wave heights (Hs in meters) from buoy 44011 (red) and WW3 (blue) from 18-19 March 2008. Difference between observed and modeled wave heights shown in green.

Period	Buoy 44011	Buoy 44004
10	36.9	21.1
11	33.5	19.2
12	30.7	17.6
13	28.4	16.3
14	26.3	15.1
15	24.6	14.1
16	23.0	13.2
17	21.7	12.4
18	20.1	11.7
19	19.4	11.1
20	18.4	10.6

Table 1. Swell travel time in hours between Diamond Shoals Buoy 41025 and Georges Bank Buoy 44011 (red) and between 41025 and Hotel Buoy 44044 (blue) for various wave periods.