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North Atlantic Wind Waves of 2005 Hurricane Season – Prediction vs. Observation[1]

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1. INTRODUCTION

The Atlantic hurricane season 2005 has been remarkable not only for its early beginning and late ending but also for the number of storms as well as the intensity of the hurricanes. According to National Climatic Data Center reports (NCDC, 2006), there was a record of 27 named tropical storms, of which 15 were hurricanes. Among them, 7 were major hurricane of category 3 or higher on the Saffir-Simpson Hurricane Scale (i.e., Dennis, Emily, Katrina, Maria, Rita, Wilma, and Alpha). An unprecedented three of them reached category 5 (Katrina, Rita, and Wilma), in which Hurricane Katrina was the most intense and destructing landfalling storm on record for the Atlantic. Another 6 named storms that made landfall were Arlene, Cindy, Dennis, Rita, Tammy, and Wilma. Many of these tropical cyclones have created enormous high waves disastrous to the coastal areas and marine related activities. The main purpose of present study is to evaluate accuracy of NCEP operational wave models predicted wave conditions caused by these tropical cyclones by comparing with buoy measurements reported by National Data Buoy Center (NDBC, 2005).

2. DATA

Model predictions are obtained from two regional wave models – WNA (the Western North Atlantic wave model) and NAH (the North Atlantic Hurricane wave model). They are parts of the NOAA's global wave forecasting system, NWW3 (NOAA WAVEWATCH III). The models run operationally four times a day to provide guidance forecasts for the North Atlantic Basin and the Gulf of Mexico including the Caribbean Sea. The 00 UTC forecast of each cycle run is based on analyzed wind fields. Theses two regional models use identical spatial grids and spectral discretization, but different wind forcing. The WNA and NWW3 models are driven solely with wind forecasts from NCEP GFS (Global Forecast System for the atmosphere) available at 3-h intervals. For the NAH wave model, high-resolution wind fields, generated hourly at NCEP by the GFDL (Geophysical Fluid Dynamics Laboratory) hurricane model, are blended with GFS wind fields. Detailed descriptions of these models can be found in Chao et al (2005) and Tolman et al (2005). Best available data for wave model validation were obtained from the web site of National Data Buoy Center (NDBC, 2005). In the present study, hourly hindcasts and measurements including winds (wind direction and wind speed at 10 m height) and waves (significant wave height and spectral peak period) at buoy stations were used. In addition, the significant wave steepness fields were constructed for NAH model predicted

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significant wave heights that were greater than 2 meter. The significant wave steepness is defined here as the ratio of the significant wave height to the wavelength associated with the spectral peak wave period. It is useful in identifying the storm that caused high waves at a particular buoy station.

3. THE PEAK WAVE HEIGHT

Based on monthly time series of buoy measured significant wave height at each buoy station in deep water, we determined the time of occurrence of wave heights that peak up to greater than 2 meter, which is an indication of high waves during the hurricane season. We then searched for the height and time of wave models (NAH/WNA) predicted peak wave heights closest to the time of buoy measured peaks. Furthermore, we identified storms whose extended life span covered these particular times of wave height peaks. If there were multiple storms whose life span all covered these particular hours, the sequential plots and animations of model derived significant wave steepness patterns for the significant wave height greater than 2 meter were used to determine which storm caused waves to reach that buoy location at that particular time. Occasionally, extra-tropical-cyclones (also known as mid-latitude storms or baroclinic storms) and tropical cyclones of interest co-existed, in addition to the sequence of significant wave steepness fields , wind fields also were examined so as to exclude those peaks that were fully or partially contributed by the mid-latitude storms. In what follows we will use time series of deep water buoys (Buoys located in a water depth greater than 200 meter) along the Atlantic coast for September 20005 to illustrate the stated procedure. The September monthly time series of the observed and predicted wave and wind for buoy stations 41010, 41002, 41001 and 44004 aligned from south to north off the U.S. Atlantic coastline is shown in Figure 1. The locations of these buoys can be found in the succeeding figures. The plots included spectral peak period, significant wave height, wind speed a 10 m above the mean sea level and wind direction. Tracks of tropical cyclones occurred in the North Atlantic basins during September 2005 are shown in Figure 2.

September 2005 was a busy month for the north Atlantic hurricane activities. Five named hurricanes occurred one after another: Hurricane Maria during September 1-10, Hurricane Nate during September 5-10, Hurricane Ophelia during September 6-18, Hurricane Philippe during September 17-24 and Hurricane Rita during September 18-26. Some of them co-existed in the same part of days. For each hurricane the NHC (National Hurricane Center) "best track" and GFDL nowcast track were plotted at 6 hour intervals. The dates of the best track at 00 UTC were also indicated along the path. The stages of intensity evolution along the track were indicated by segments of different colors and line types. They might involve tropical low/wave (LO/WV), subtropical depression (SD), subtropical storm (SS), extratropical system(EX), tropical depression(TD), tropical storm (TS) and hurricane (HU). Detailed definitions of these terms can be found in the NHC web site. The following brief description of the characteristics of these hurricanes relevant to the present study is based on a report prepared by the National Climatic Data Center (NCDC, 2006).

Hurricane Maria developed to a tropical storm on 2 September and became a hurricane on 4 September. The hurricane turned toward the northeast on 6 September, diminished to tropical storm strength and eventually became an extratropical storm on 10 September. Waves from Maria
unlikely would reach coastal areas. Hurricane Nate began as a tropical depression at 1800 UTC 5 September about 305 n mi south-southwest of Bermuda. The cyclone drifted northeastward and became a hurricane at 1200 UTC 7 September about 225 n mi south-southwest of Bermuda. It then moved eastward and remained well out at sea. By inspecting the time series plots shown in Figure 1, and wind and wave steepness patterns shown in Figure 3, it is inferred that Nate contributed to the rise of waves off the east coast before turned eastward.

Ophelia formed from one of two low pressure systems originated in the area extended from east of Bermuda to near the Florida Peninsula. The eastern low, south of Bermuda, eventually became Hurricane Nate. The western low, near the Bahamas, became Ophelia. It became a tropical depression on 6 September and became a tropical storm on 7 September. Ophelia continued strengthening and was briefly a hurricane on 8 September for just a short period of time and then weakened back to a tropical storm. A similarly short-lived hurricane phase occurred late on 9 September while Ophelia moved east-northeastward away from Florida. Ophelia became a hurricane for a third time on 10 September making a slow clockwise loop on 11-12 September, and weakened back to a tropical storm on 12 September. After completing the loop, the storm drifted northwestward on 13 September. Figure 4a shows wind fields and wave steepness patterns for September 9, 11, 13 00 UTC.

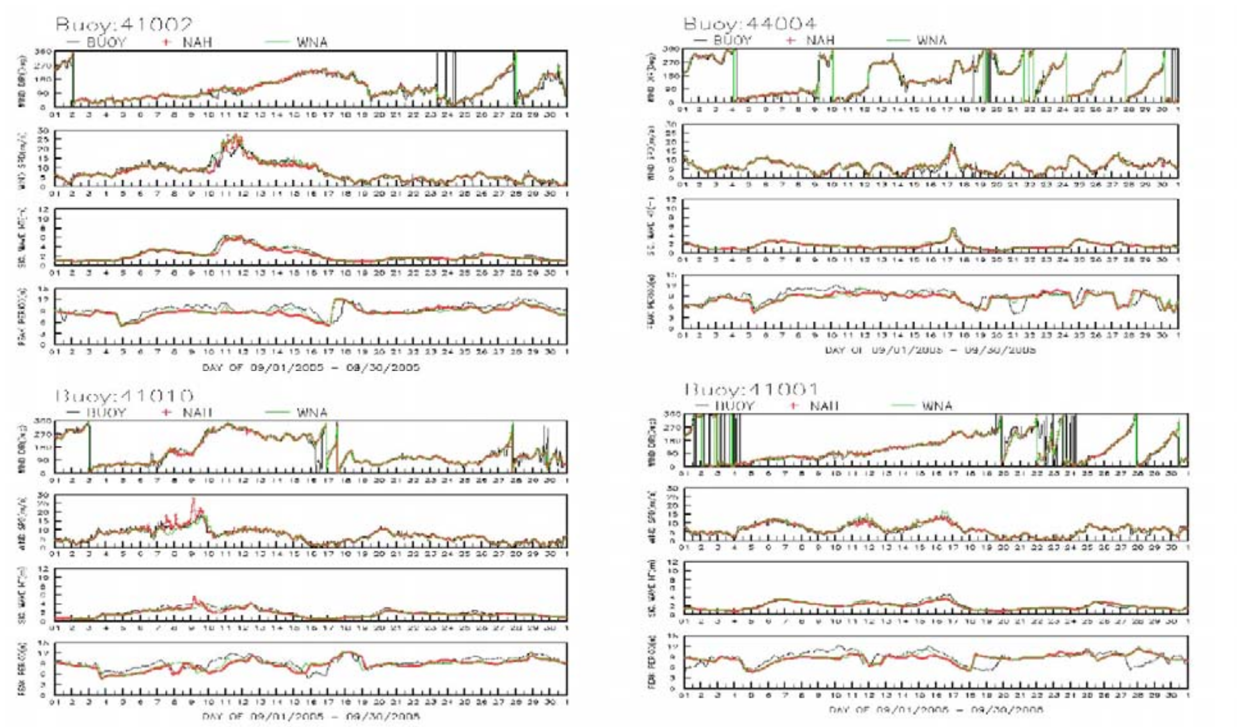

Fig. 1 September 2005 monthly time series of measured and predicted spectral peak period, significant wave height, wind speed and wind direction for four buoy stations.

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Ophelia moved slowly northward early on 14 September and became a hurricane for the fourth time. It moved parallel to the North Carolina coast and reached its peak intensity of 75 kt during 14-15 September. It became a tropical storm early on 16 September after passing south of Cape Hatteras. The storm turned northeastward and accelerated to reach near the southeast of the Massachusetts coast on 17 September and near the southern coast of Nova Scotia on 18 September. Figure 4b shows wind fields and wave steepness patterns for September 16, 17 and 18 00 UTC.

Hurricane Ophelia was a Category 1 hurricane and never made landfall along the U.S. coastlines, yet because of its slow movement along the coastline it produced substantial flooding and beach erosion. Ophelia undoubtedly has the dominating influence among these five hurricanes to the East coast wave environment during September 8 to 18. In Figure 1 double peaks were seen on the wave height occurred at Buoy 41010 between September 9 to 13 and at Buoy 41001 between September 11 to 18. In contrast, only single peak appeared at Buoys 41002 and 44004.between September 10 to 18. By inspecting representative wind fields and wave steepness patterns shown in Figure 4a for September 9, 11, 13 and Figure 4b for September 16, 17 and 18, respectively, it is clear that these wave height peaks were indeed produced by Ophelia.

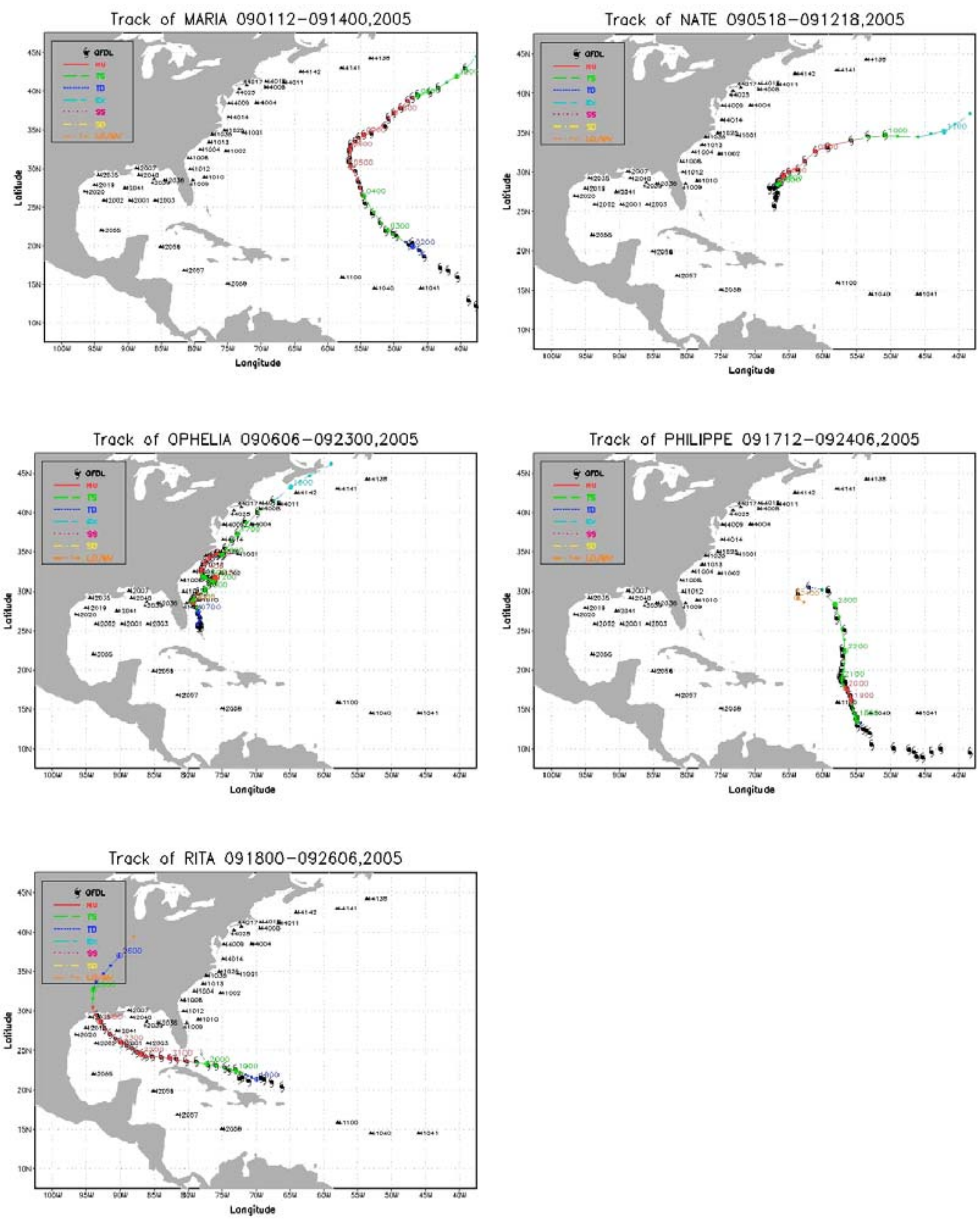

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Fig. 2 NCDC “Best tracks” and GFDL 00UTC storm positions

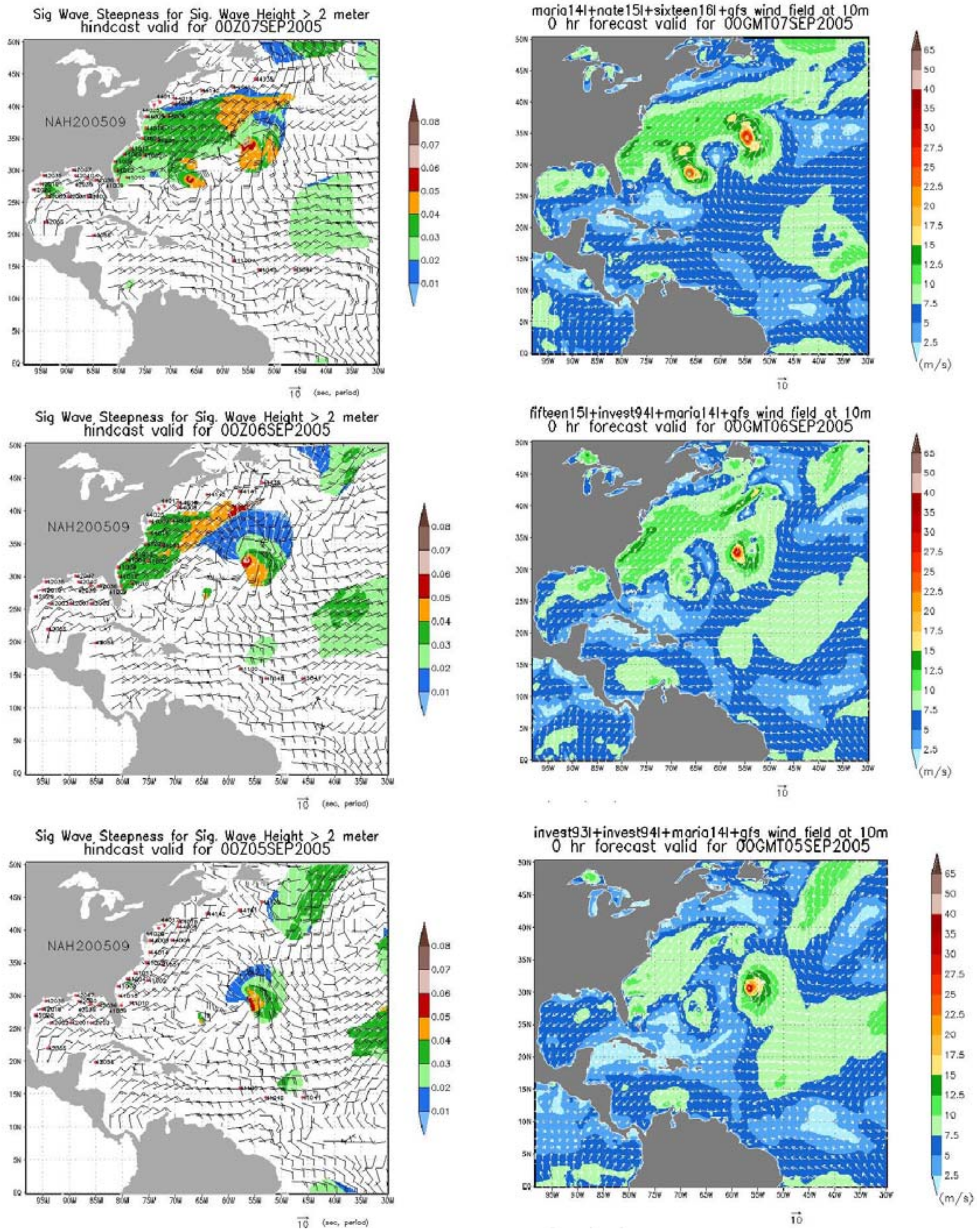

Fig. 3 Wave steepness and blended wind fields, September 5-7 (Hurricane Nate).

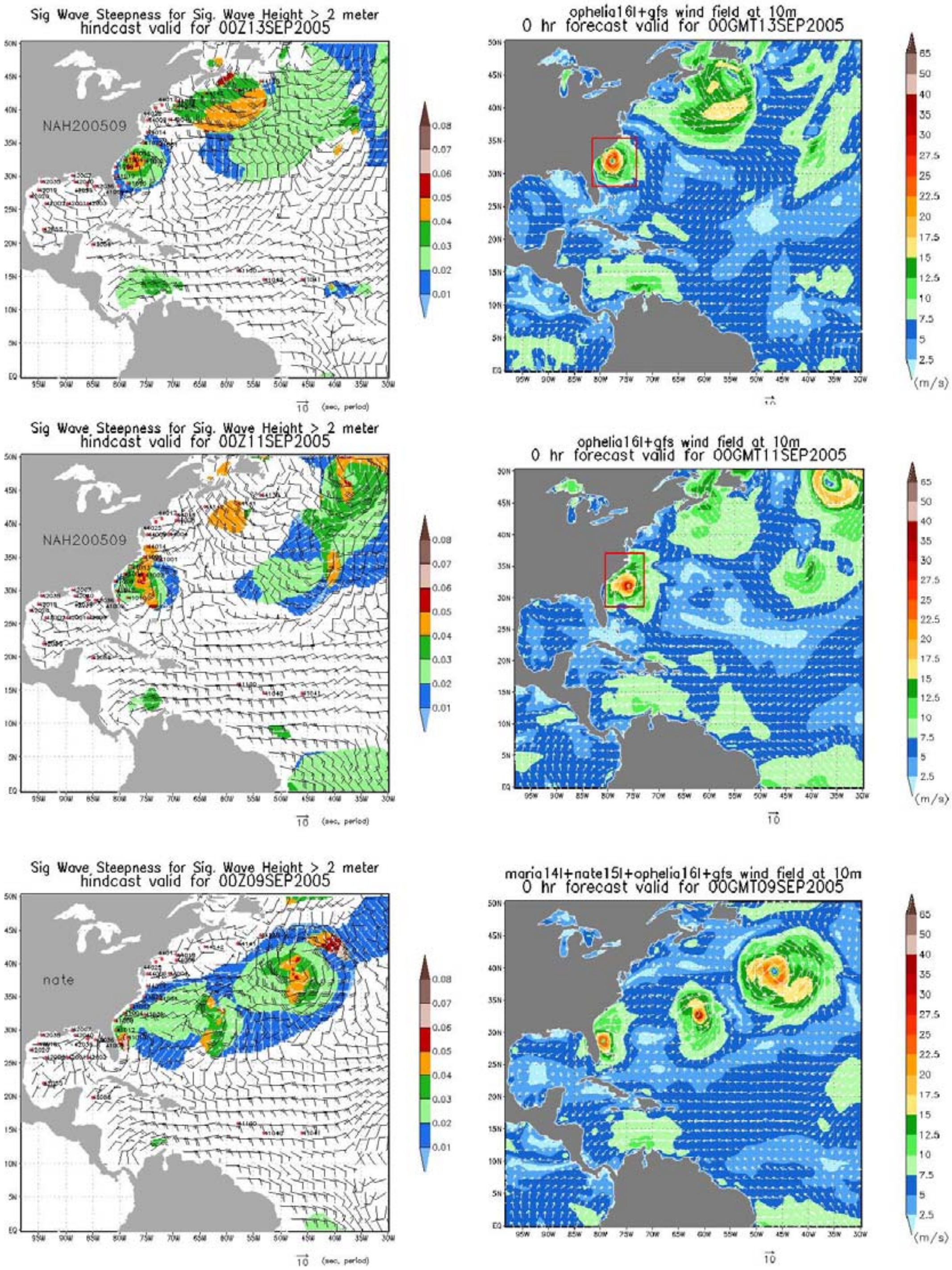

Fig. 4a Wave steepness and blended wind fields. September 9,11, and 13 (Hurricane Ophelia).

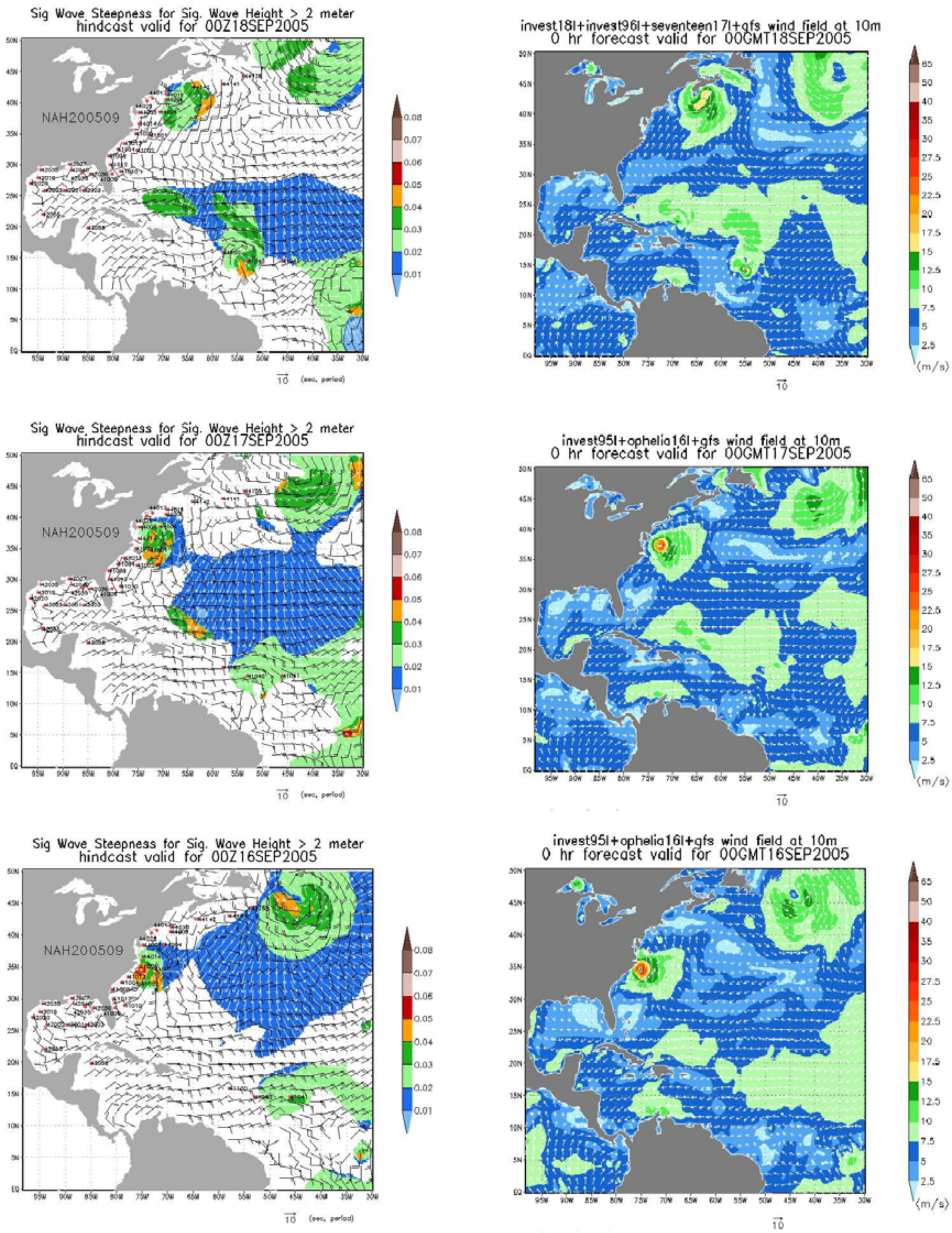

Fig. 4b Wave steepness and blended wind fields, September 16-18 (Hurricane Ophelia).

Hurricane Philippe had developed from a tropical depression near 1200UTC 17 September. The depression moved northwestward becoming a hurricane at 0000 UTC 19 September. While Philippe was strengthening, Tropical Storm Rita had formed in the Bahamas. It remained a tropical storm before swept over the Florida Straits on 20 September (and eventually became a Category 5 hurricane over the central Gulf of Mexico). Rita's contribution to the east coast wave environment was a minimum. However, it had some impact to Philippe, which weakened to a tropical storm by 1200 UTC 20 September. While Philippe was weakening, it continued to move northward and eventually moved into a deep extratropical cold low and produced a complicated synoptic environment, which in turn affected the northern portion of east coast wave

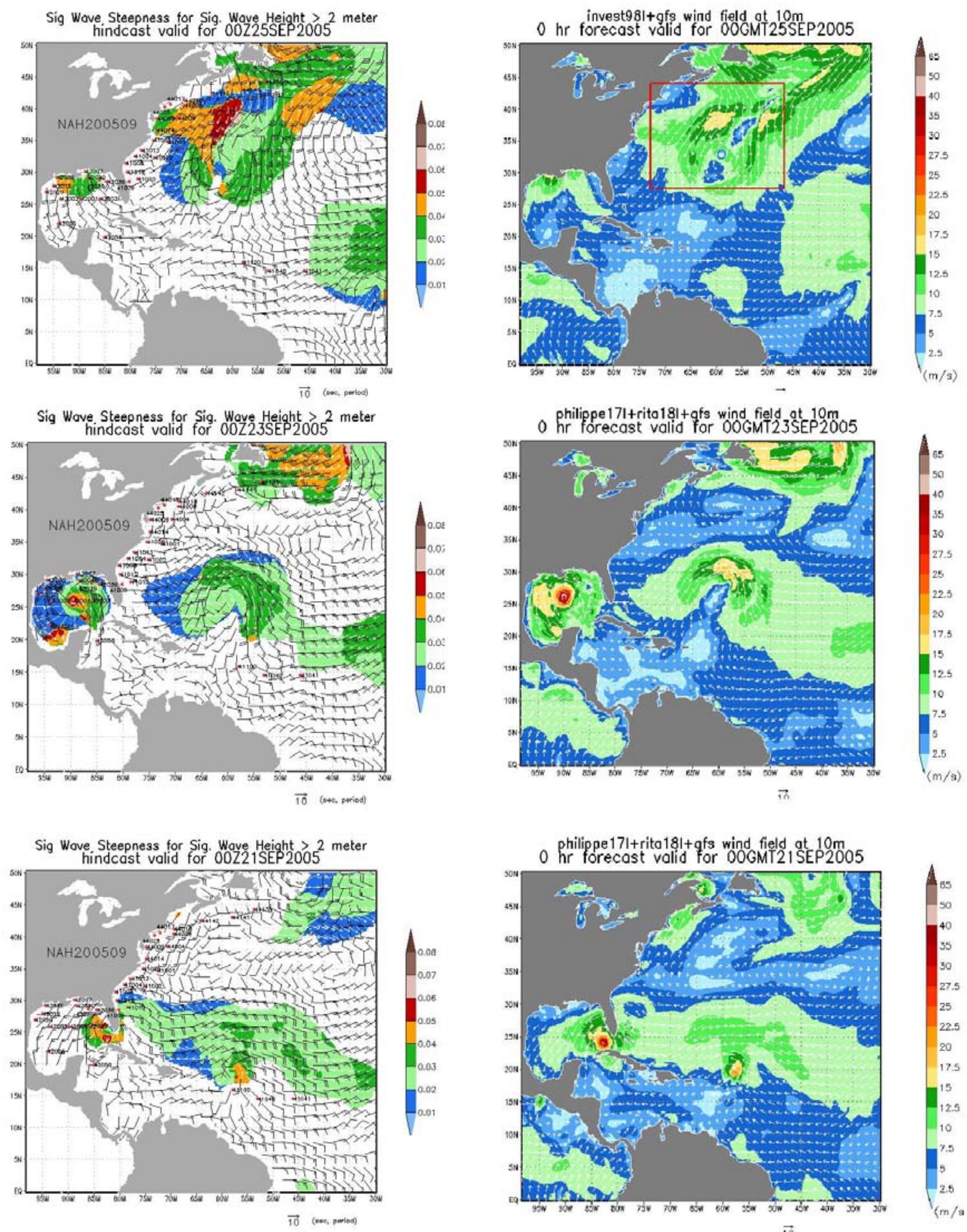

Fig. 5 Wave steepness and blended wind fields, September 21,23 and 25 (Hurricane Philippe).

environment to some extent. The representative wind fields and wave steepness patterns are shown in Figure 5. The slight rise of wave height to a peak after 20 September as can be seen in the time series plot at each buoy station (Figure 1), however, can no longer be considered as the contribution of Philippe alone. Therefore these peaks were excluded from further consideration.

Based on the above described consideration, and hourly data of buoy measurements and NAH and WNA wave models predictions (hindcasts), peak significant wave heights, their times of occurrence, simultaneous spectral peak period, and inferred storm are determined as list in Table 1 for the Atlantic deep water buoys for September 2005.

Table 1 Peak significant wave height (Hs), time of occurrence(month-day-hour), simultaneous Spectral peak period (Tp) and related storm name

Buoy ID	Buoy Peak Hs(m)	Buoy Time mmddhh	NAH Peak Hs(m)	NAH Time mmddhh	WNA Peak Hs(m)	WNA Time mmddhh	Name Of Storm	Buoy Tp (sec)	NAH Tp (sec)	WNA Tp (sec)
41001	3.7	90621	3.58	90619	3.59	90617	Nate	10	8.4	8.3
	3.6	91111	2.63	91113	3.13	91109	Ophelia	7.1	9.6	11.0
	5.4	91610	3.72	91613	4.44	91613	Ophelia	10	8.3	8.6
	3.2	92508	3.00	92511	3.12	92511	Philippe	9.1	8.0	8.0
41002	3.6	90613	3.48	90616	3.15	90615	Nate	10	8.1	8.3
	7.1	91023	5.92	91108	6.41	91110	Ophelia	11.1	8.6	9.3
	3.0	92520	2.45	92611	2.47	92608	Philippe	10	9.3	9.1
41010	4.9	90909	5.58	90905	3.58	90913	Ophelia	8.3	8.4	7.2
	4.7	91208	4.18	91211	4.16	91210	Ophelia	12.1	10.9	11.1
	3.3	92009	2.59	92013	2.76	92015	Philippe	8.3	9.1	9.1
	2.7	92508	1.72	92514	1.68	92515	Philippe	11.4	9.6	9.5
44004	2.7	90600	2.73	90605	2.76	90605	Nate	7.7	7.1	7.1
	6.9	91706	5.30	91708	5.87	91707	Ophelia	10.8	9.7	10.1
	3.5	92500	3.06	92423	3.03	92423	Philippe	10.8	6.9	6.9

The same procedure was applied to other tropical cyclones occurred in 2005 for available deep water buoy stations. For a buoy station in shoaling waters (Buoy stations in a water depth of less or equal to 200 meter), its connection to a specific storm was made simply by inferring from the nearby deep water buoy station.

4. MODEL PERFORMANCE

Our major interest in this study is to find out how well the regional wave model WNA and the hurricane specific wave model NAH made their predictions for the North Atlantic basin and for the Gulf of Mexico and the Caribbean Sea during the 2005 hurricane season. The reason for considering these two regions separately is that the Gulf of Mexico and the Caribbean Sea is a semi-enclosed basin while the Atlantic basin is an open ocean. The accuracy of prediction for the two regions might differ due to different geographic constrains on the characteristics of tropical cyclone induced wind wave. Figure 6a depicted the scatter plots of the peak wave height (denoted as HS), and the associated spectral peak wave period (denoted as TP), predicted by NAH for the North Atlantic basin and the Gulf basin including the Caribbean Sea. It can be seen from the scatter plots shown that NAH provided better predictions for the Gulf region although the wave height is under-predicted and the wave period has considerable scattering from the linear relationship between measurement and prediction. Figure 6b shows statistical information for model errors on the time of occurrence (labeled as (Hr) m – (Hr)o, in hour), the peak wave height (labeled as (Hm - Ho) / Ho) and the spectral peak wave period (labeled as (Tm – To) / To). Here, "m" and "o" denote model prediction and buoy measurement, respectively. The central line on each graph represents the mean values of labeled quantity while the outer two lines represent the standard deviation from the mean. It can be seen that the errors of NAH on the wave height and period predictions are concentrated within ±20% range but errors on

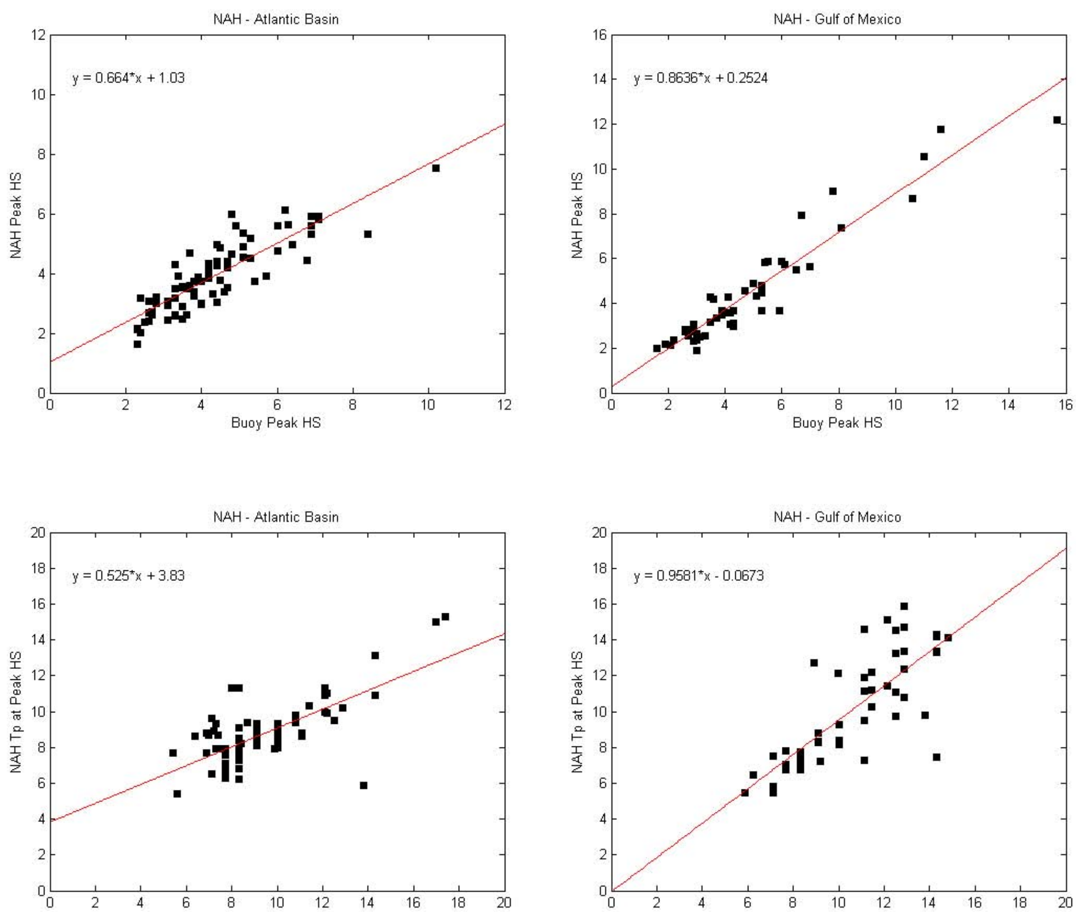

Fig. 6a Comparisons of NAH model predicted significant wave height and spectral peak period vs. buoy measurement for the Atlantic basin and the Gulf of Mexico-Caribbean Sea .

the wave height might extend up to 30% and up to 40% on the wave period. The time lag is mostly within ±5 hours range but some appeared to extend to ±10 hours which might indicate that the effects of swell generated by distant sources might not been completely filtered out during the processes of connecting the peak wave height with a storm. Another source that causes large scattering of predictions might be due to imperfection in specifying wind field near the hurricane center. Nevertheless, the "near zero" mean value of model deviation from observation indicate relatively small biases of model predictions. It is of interest to see that NAH tends to predict slightly later in time as shown by the positive values of the mean (Hr)m – (Hr)o for the Atlantic basin and earlier for the Gulf as indicated by the lines showing the negative mean values of (Hr)m – (Hr)o.

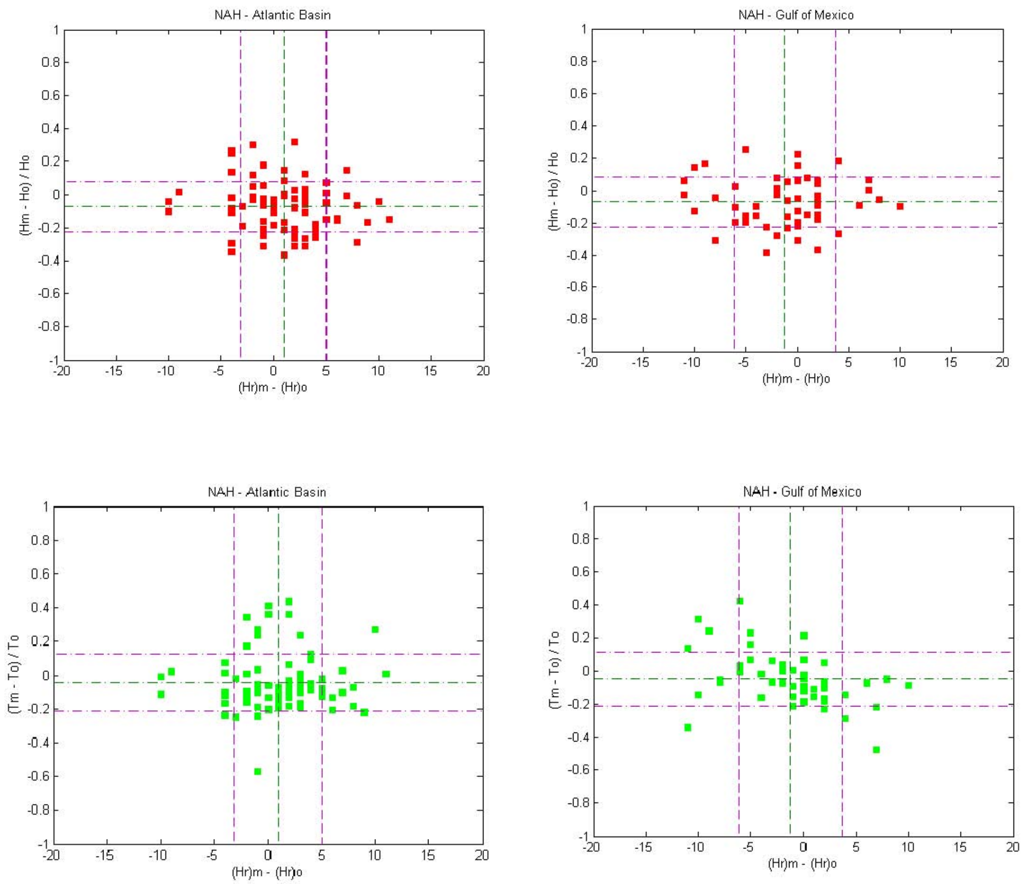

Fig. 6b Deviations of NAH model predictions from buoy measurements on the peak significant wave height, time of occurrence, and spectral peak wave period for the Atlantic basin and the Gulf of Mexico-Caribbean Sea.

Similar figures for WNA model is depicted in Figure 7a and 7b. By a comparison of Figure 7a with Figure 6a, it is found surprisingly that the overall performance of WNA using GFS winds only provides no worse if not better prediction than NAH using the blended winds as indicated by the linear best fit lines. The model still under-predict the peak wave height and associated period for the Atlantic basin but the values are higher than those predicted by NAH. As for the Gulf basin, the wave height is only slightly lower than measured while the wave period tends to have 1:1 relation with measurements even though data scattered considerably. By a comparison of Figure 7b with Figure 6b, it is found that similar to NAH predictions, the time lag is mostly within ±5 hours range but some of them appeared to extend to ±10 hours for both basins. WNA as

NAH tends to predict slightly later in time. On the other hand, unlike NAH, WNA predictions tend to be close to the time of observation for the Gulf basin.

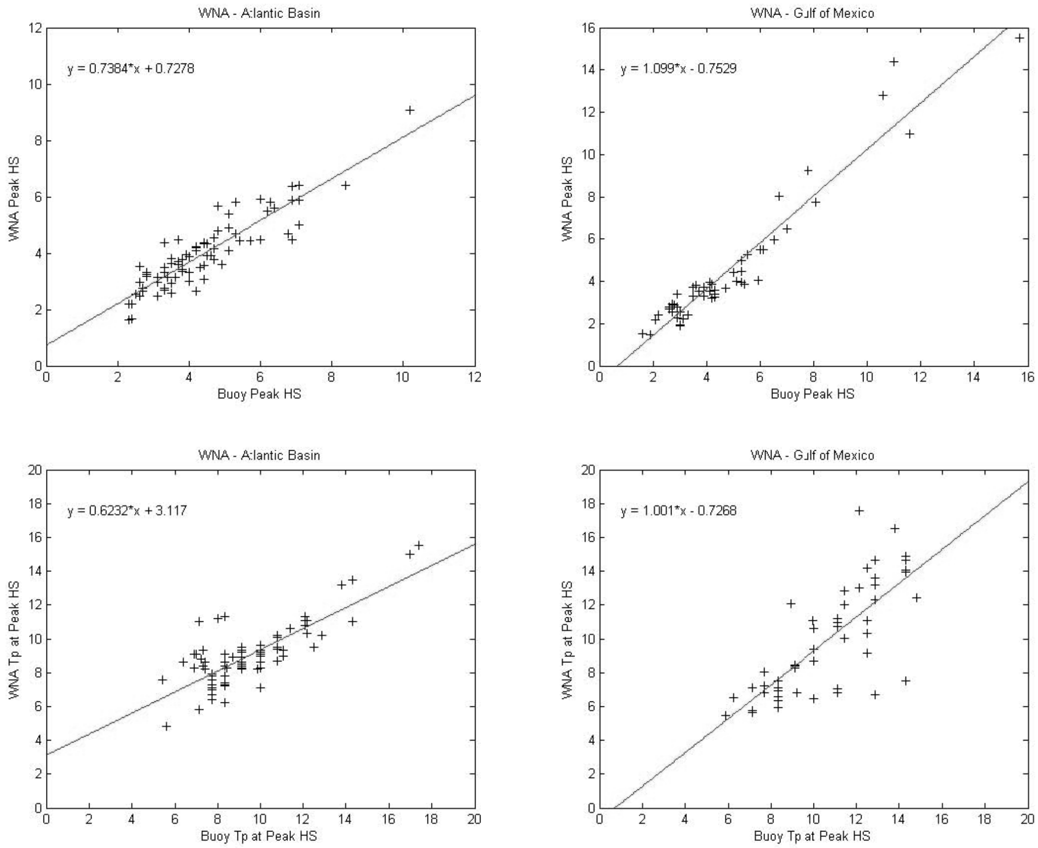

Fig. 7a Comparisons of WNA model predicted significant wave height and spectral peak period vs. buoy measurement for the Atlantic basin and the Gulf of Mexico-Caribbean Sea.

5. WAVES OF CATEGORY 5 HURRICANES

Three Category 5 hurricanes formed during the 2005 season (Katrina, Rita, and Wilma). According to National Climatic Data Center (NCDC, 2006), this is the most Category 5 hurricanes recorded in a single season, breaking the old record of two category 5 hurricanes set in 1960 and 1961. Hurricane Katrina was an extraordinarily powerful and deadly hurricane that caused catastrophic damage. After reaching Category 5 intensity over the central Gulf of Mexico, Katrina weakened to Category 3 landfall on the northern Gulf coast on August 29. Hurricane Rita became the second Category 5 hurricane after Katrina and was the third strongest hurricane ever recorded in the Atlantic Basin. Rita made its final landfall along the Texas-Louisiana border coastal region as Category 3 on September 24. Hurricane Wilma was the third Category 5 hurricane of the season. Wilma formed and became an extremely intense hurricane over the northwestern Caribbean Sea and it devastated the northeastern Yucatan Peninsula. It had the all-time lowest central pressure for an Atlantic basin hurricane at 882 mb. Wilma struck southern Florida on October 24 as a Category 3, creating extensive damages.

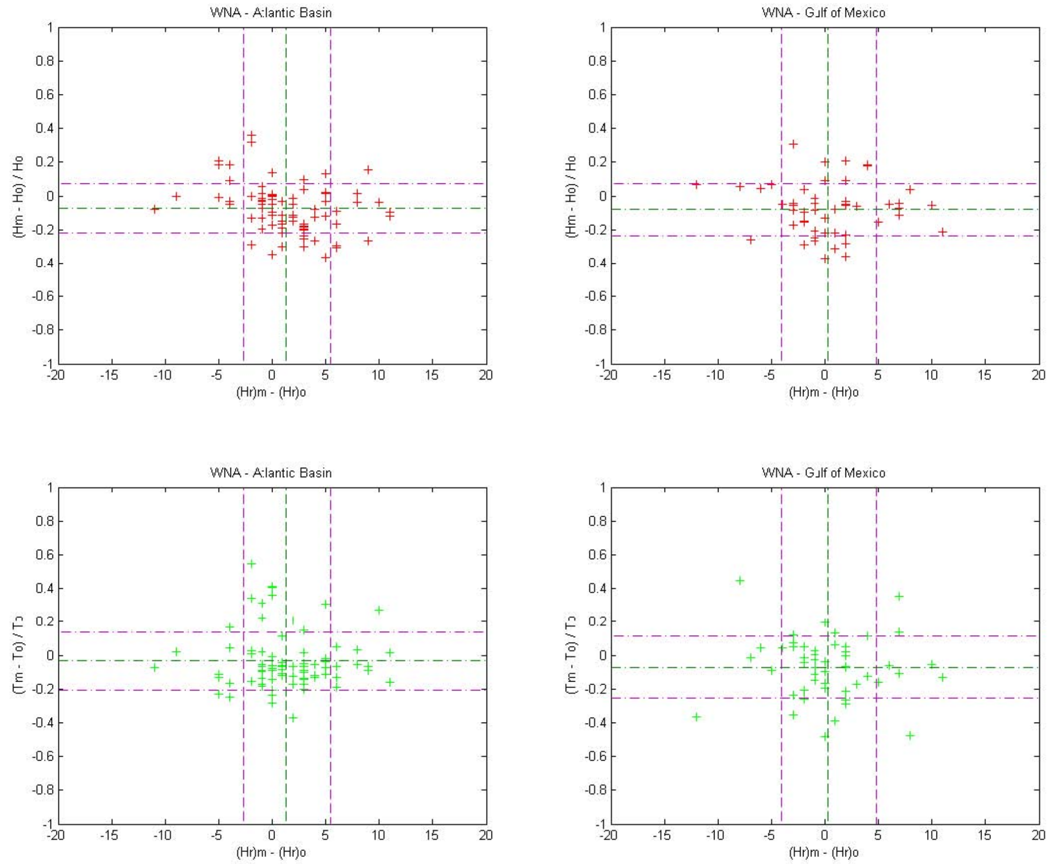

Fig. 7b Deviations of WNA model predictions from buoy measurements on the peak significant wave height, time of occurrence, and spectral peak wave period for the Atlantic basin and the Gulf of Mexico-Caribbean Sea.

In order to examine wave behavior associated with each hurricane, we selected four deep water buoy stations closest to the hurricane path. Ideal stations would be two on the left and two on the right of the hurricane path and all have measured and predicted wind and wave information available. Unfortunately as will be seen in the following figures, the conditions are not always satisfied. Figures 8, 9 and 10 show the hurricane tracks, positions of buoy stations and the evolution of wind and wave conditions at selected stations for Katrina, Rita and Wilma, respectively. For Katrina (Figure 8), buoys 42001 and 42041 are on the left side of the path while 42003 and 42040 are on the right. Despite closeness of 42001 and 42041 to the hurricane path in comparison with the other two on the right, i.e., 42003 and 42040, their maximum significant wave heights are much smaller. Northerly to westerly winds were blowing at 42001 and 42041 after the wave height reached the maximum. In contrast, easterly to southerly winds were blowing at 42003 and 42040 near the peak of wave height rise. It should be noted that buoy data for 42041 was not available and buoy data for 42003 was terminated because the buoy was capsized in the middle of high winds and high waves.

For Hurricane Rita (Figure 9) buoys 42003 and 42041 were on the right side of the track, 42002 on the left, while 42001 was right on the track. Buoy 42002 and 42003 were about the same distance away from the track where 42001 located. The maximum wave height at 42002, however, is much smaller than that of

42003. The wind direction changed from easterly to southerly at 42003 and 42041 after the wave height reached the maximum in contrast to 42002 whose wind direction rotated from northerly to westerly. The wind direction at 42001 changed from northerly to westerly to southerly in a very short period of time. The hourly winds to drive NAH and WNA were not adequately given for that short period of time. Fortunately, it did not affect wave model predictions substantially. It should be mentioned that buoy data were not available for 42041 and 42003. For Hurricane Wilma (Figure 10), buoys 42003, 41012, 41002 all are located on the left of the path. The local wind direction rotated from northerly to westerly after reaching the maximum wave height. Only buoy 42056 was on the right of the path and was close to the path. At 42056 the wave height roused in response to local winds rotating from northeasterly to easterly to southeasterly, typical for the observation location on the right of hurricane path. Substantial discrepancy between model predicted and buoy measured spectral peak wave periods was found at 41010 and 41002 off the Atlantic coast.

A major issue with validating hurricane wave forecasts is the sparsity of data. This is illustrated in Figure 11 with results for Katrina near landfall on September 29, 1200UTC. The upper panels in this figure show the wind fields of the WNA and NAH models. Both model have near identical tracks, with the track erroneously shifted to the west by 10 to 20 km. The NAH winds are more intense with reasonable spatial scales, but are shifted too much to the shallow waters. The WNA winds have a lower speed but larges spatial scale. This happens to give good wind at the only relevant observation location (buoy 42040), although the wind fields as a whole are less realistic than the NAH wind fields. The corresponding wave heights fields (lower panels in Figure 11) are also shifted between the models, due to the similar track but different spatial scales of the wind fields. If only buoy data at buoy 42040 are considered, one could easily come to the conclusion that the WNA model is far superior (Figure 8, buoy 42040 panel). With only three buoys in the view of Figure 8. there is clearly insufficient data to rigorously validate hurricane wave models.

Note that the model resolution in 2005 was insufficient to resolve this coastline, and therefore results at buoy 42007 cannot be expected to be very accurate. Furthermore, wave heights in the shallow waters behind the Chandeleur Islands are obviously unrealistic due to the lack of shallow water physics in the model, and due to the fact that the spatial resolution is even too poor to introduce these islands as obstructions. For the 2007 model implementation, the coastal resolution in this area is greatly improved, and surf-zone physics greatly improve model behavior (Chawla et al. 2007, in this conference).

5. CONCLUSION

Unprecedented number and intensity of tropical cyclones occurred in the North Atlantic basin and the Gulf of Mexico-Caribbean Sea in 2005. It provides an excellent opportunity to examine the performance of the operational wave forecast model under such conditions in detail. In this study, we validate NCEP operational Western North Atlantic regional wave model (WNA) and North Atlantic Hurricane wave model (NAH) against NDBC buoy measurements on more than 20 tropical cyclones, including three category 5 hurricanes. The parameters evaluated include the peak significant wave height, corresponding spectral peak period and the time of occurrence induced by each individual tropical cyclone. The result shows that the deviation of model predicted wave heights and periods from buoy measurements is essentially within 20% for both models. And the time lag on the occurrence of peak wave height is within 5 hour range. NAH does not yield better agreement with measurements than WNA as it should be. For the North Atlantic basin, both models under-predict wave height and wave period but WNA tend to predict higher values than NAH. For the Gulf of Mexico-Caribbean Sea, WNA predictions agree well with measurements while NAH still tend to be slightly lower than measurements. The predicted spectral peak wave period does not agree well with buoy measured. Perhaps, the spectral peak wave period is not a good indicator representing the over all wave condition. Additional elements such as the spectral component wave periods may need to be presented.

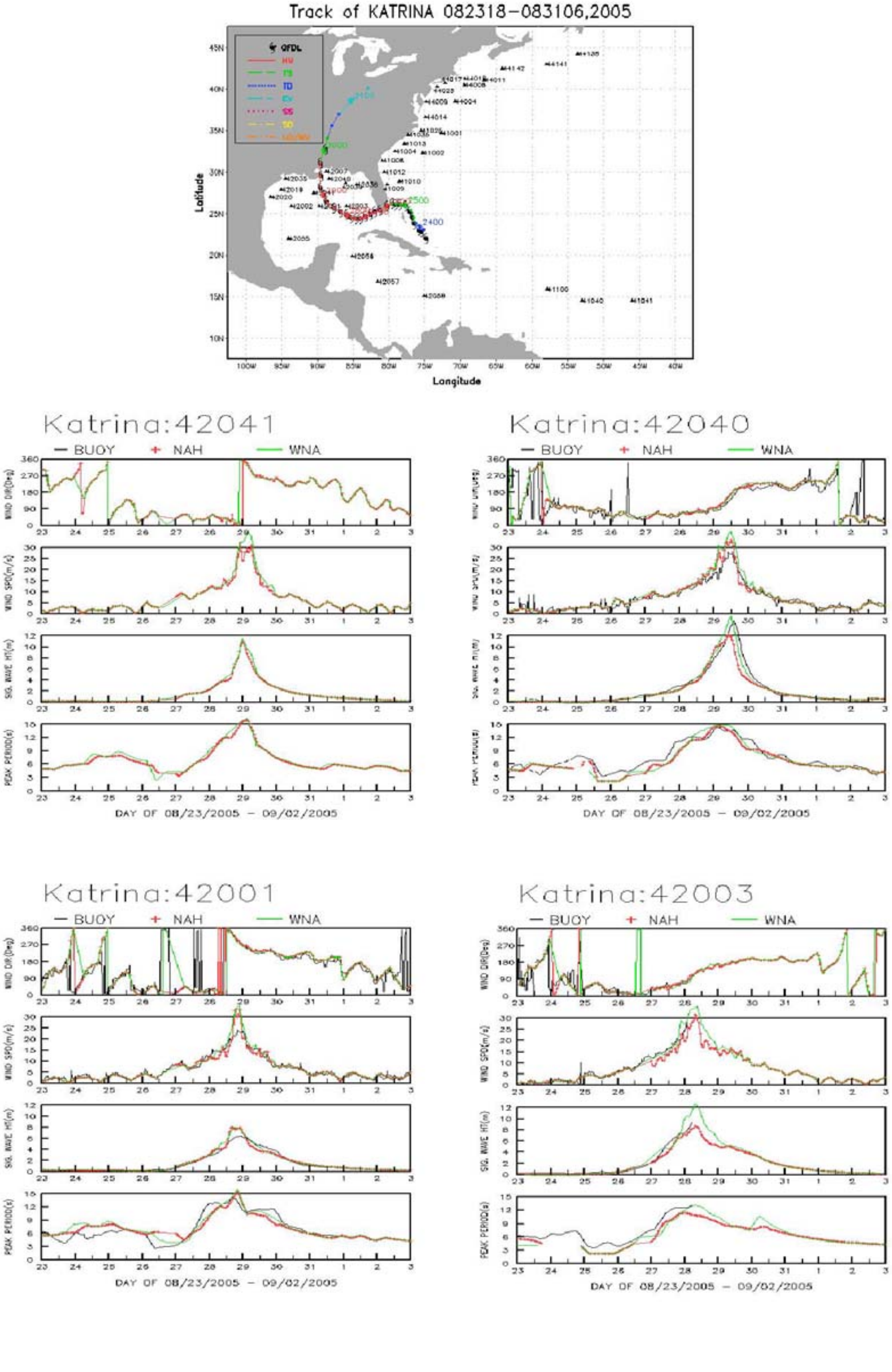

Fig. 8 Time series of wind and wave at buoy stations near Hurricane Katrina track.

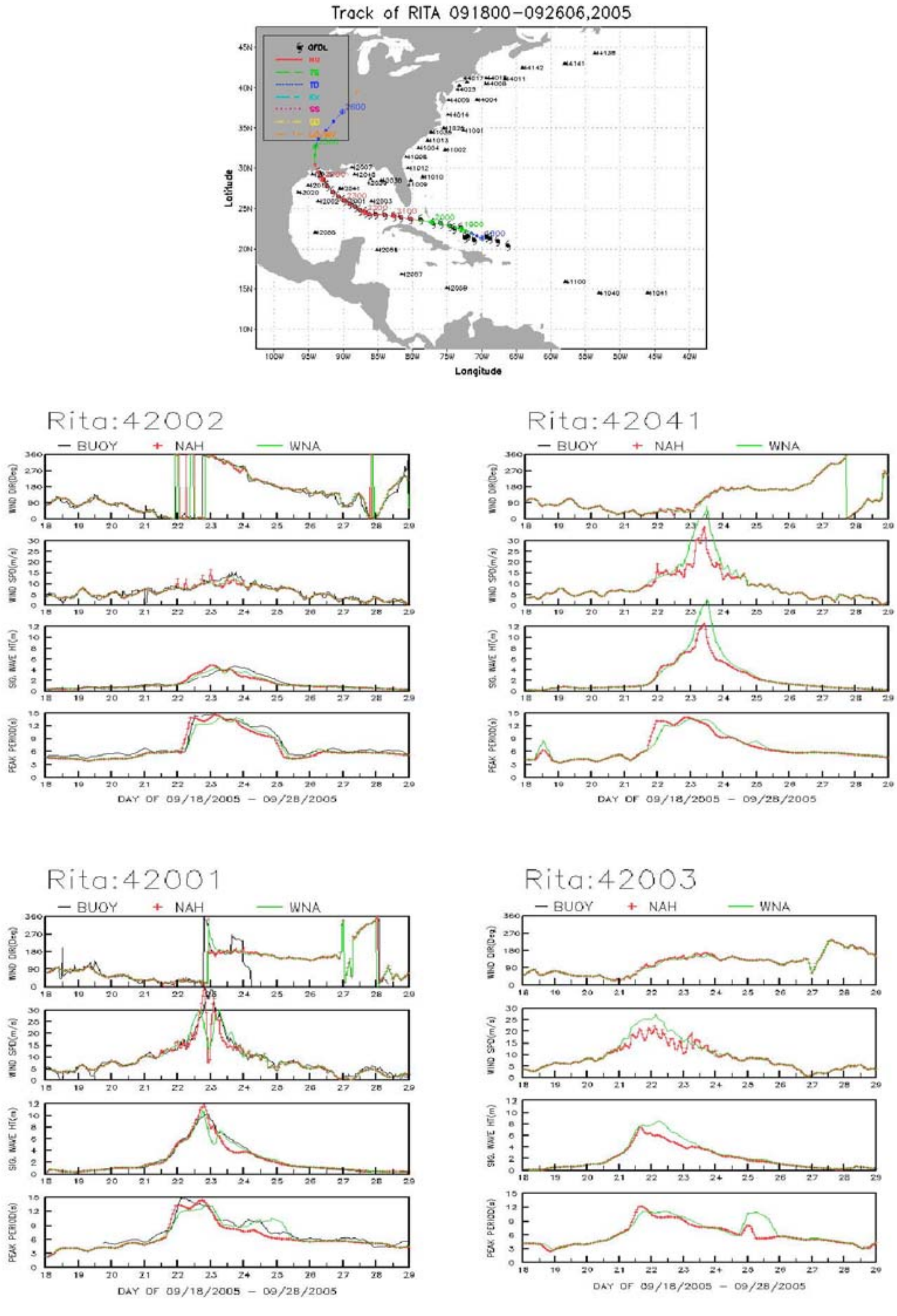

Fig. 9 Time series of wind and wave at buoy stations near
Hurricane Rita track.

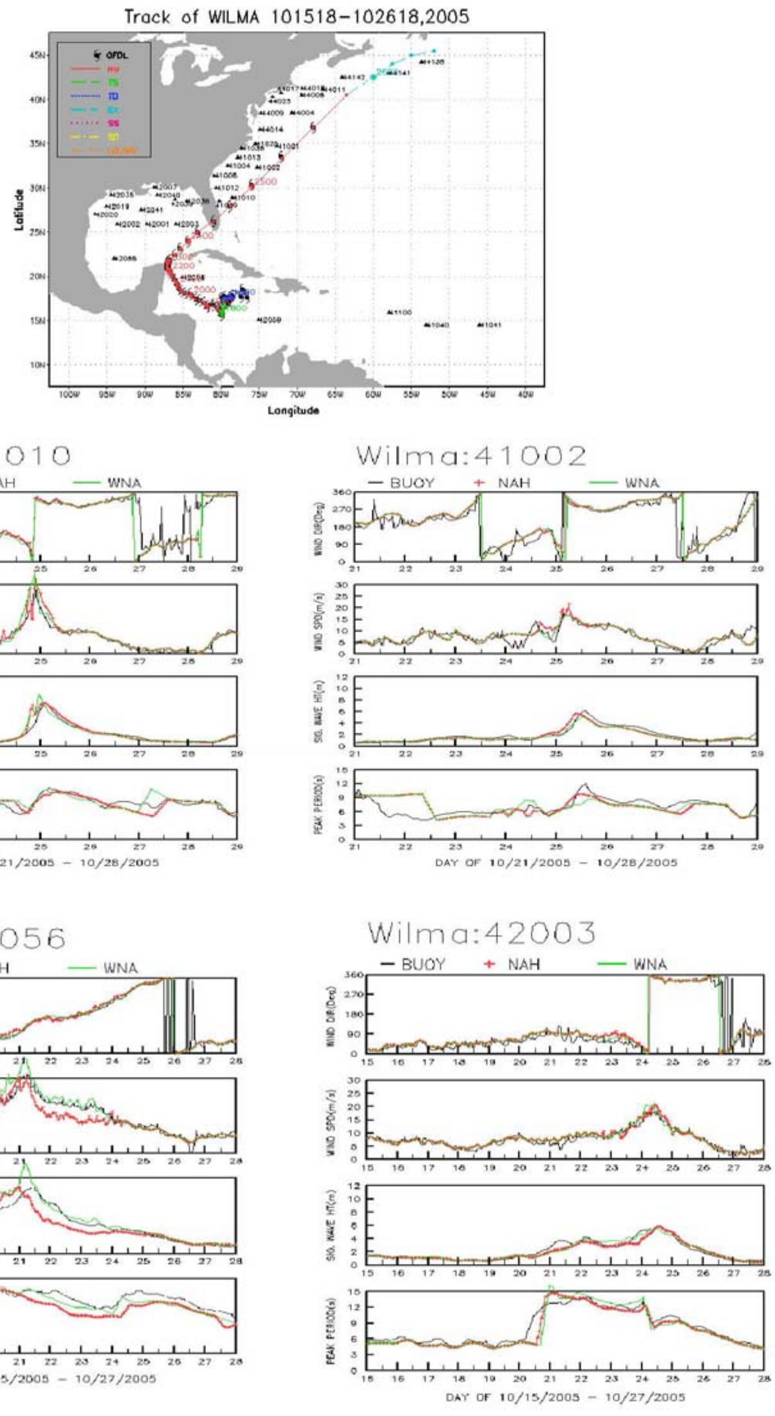

Fig. 10 Time series of wind and wave at buoy stations most close to Hurricane Wilma track.

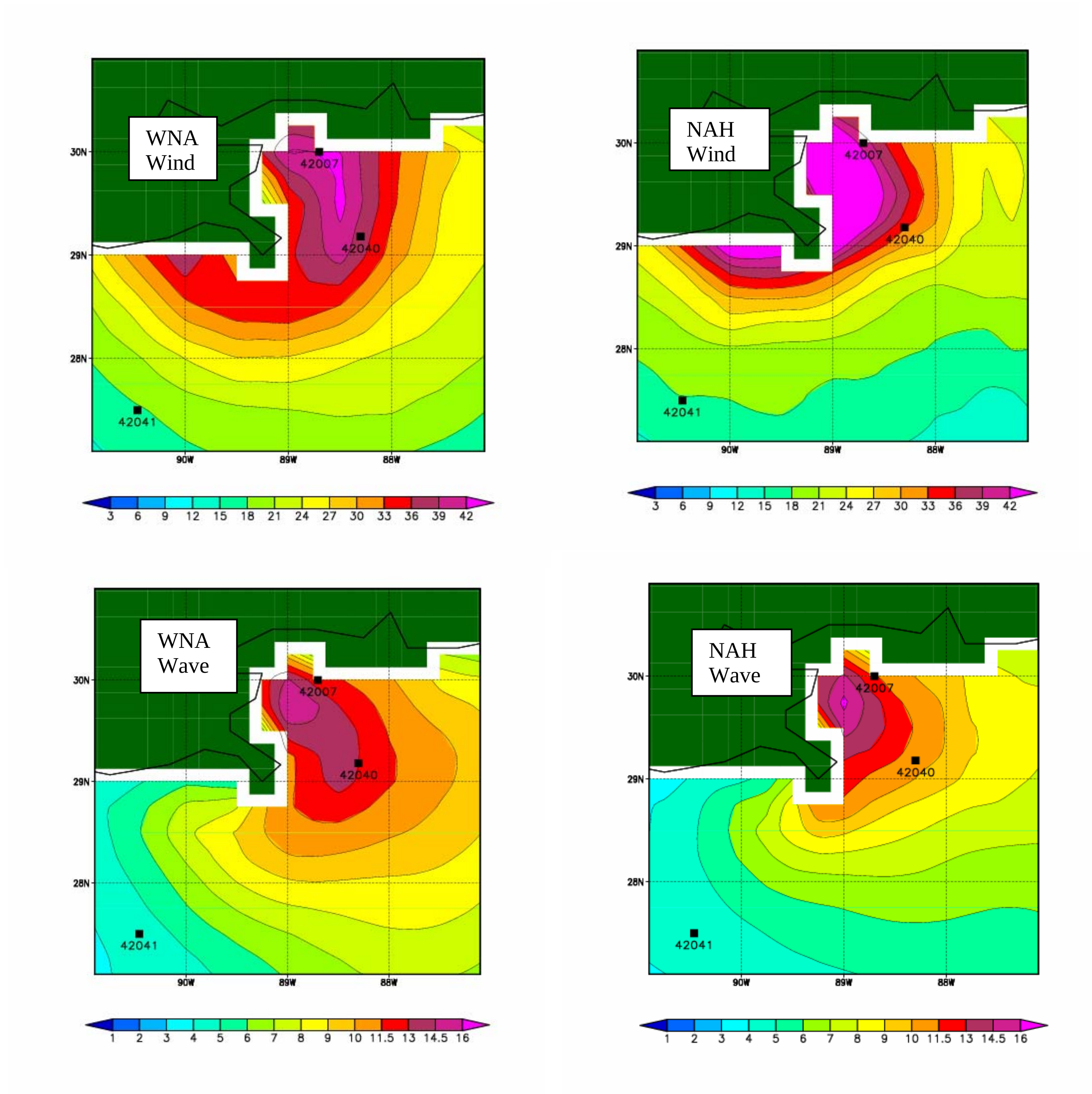

Fig. 11 A comparison of wind and wave fields of WNA and NAH,
September 29, 1200UTC

It can be concluded that the present wave models provide adequate and consistent but not necessarily accurate predictions. Improvements on the accuracy of hurricane wave prediction can be made only after the hurricane wind field can be specified correctly. As mentioned previously, NAH wave model which is driven by blended winds based on GFS atmospheric model and GFDL hurricane model winds does not provide better prediction than WNA model which is solely driven by the GFS. It might be to mention that the wind blending algorithm was developed almost a decade ago. At that time GFS, previously known as Medium-Range (MRF) and Aviation (AVN) models had a grid resolution of about 50 km which was too coarse to resolve the wind field structure associated with a relatively small hurricane vortex. Thus, the blending algorithm was initiated to incorporate with GFDL hurricane model to take advantage of its high resolution inner mesh of about 15 km (Chao and Tolman, 2000; Chao and Tolman, 2001). Since then, GFS underwent various improvements; among them was the change of grid resolution to about 30 km in 2005. As a result, GFS was able to provide improved wind forecast near the hurricane core.

It should be noted that the buoy measurements can only provide simplest first order validation of model predictions. The buoy measurement alone cannot provide sufficient and adequate validation of model predictions. Because of the sparsity of buoy data, the measured winds and waves mostly do not reflect the actual conditions unless the hurricane track is just right on or very near the hurricane path (see Chao et al., 2005, Tolman et al., 2005 for case studies).

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