CHAPTER 62

Observed and Modeled Wave Results From Near-Stationary Hurricanes

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Abstract

Wave conditions in hurricanes have been difficult to study because of a lack of high-quality wave data and poor descriptions of the wind field. In the 1994 and 1995 hurricane seasons, two Category 1 hurricanes (Gordon and Felix) approached the North Carolina coast and stalled for a period of about 2 days. Although the storms were minimal hurricanes they produced large swell that persisted for several days. A wave gauging network of two to five directional instruments in water depths ranging from 8 to 50 m operated throughout the storms. Because of their proximity to land, both storms were extensively observed by radar and aircraft so that the wind fields are well described. The data set offers an opportunity to evaluate two prediction methods to examine the wave field during these most unusual hurricanes.

Introduction

In 1994 and 1995, Hurricanes Gordon and Felix approached the U. S. Army Engineer Waterways Experiment Station's Field Research Facility (FRF) at Duck, NC (Figure 1), stalled, and then eventually moved away. Of the two, Felix was by traditional meteorological measures the stronger (Categories 1 and 2) on the Saffir-Simspon scale but produced lower wave heights in the vicinity of the FRF than Gordon (tropical storm to brief Category 1) which produced some of the largest wave heights recorded at National Data Buoy Center (NDBC) Buoy 44014 located 90 km to the northeast of the FRF.

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This paper investigates the wave fields in the two storms by comparing simple and complex simulation models of the wind and wave fields to observations in order to determine if the wave field in Gordon was indeed anomalous. Most engineering models of hurricane wind fields assume a symmetric vortex that is uniformly propagated at a forward speed, so that when a vector is added to the vortex, the asymmetric wind field of a moving storm is produced. Thus, when hurricanes became nearly stationary, they would be expected to be similar to the simple vortex. Observations provide an opportunity to understand how well the simulation technology can estimate the stationary case, as well as the approaching and receding storm cases. Waves in each storm were estimated by (1) using the procedure described in the *Shore Protection Manual* (1984) termed SPM84, and (2) simulation with Cycle 4 of the wave model WAM (Komen et al. 1995) driven by an analyzed wind field provided by Oceanweather, Inc.

The concept of the paper is to apply two types of simulation approaches to wave estimation in the two storms using routine approaches for obtaining input meteorologic information. These are used with fairly standard wave estimation procedures to obtain an estimate of the waves. In this study the wind and wave models were not iteratively run to obtain a best estimate of the wave field by providing feedback corrections to the wind field model. The goal is to understand results obtained using routine approaches, because this is closer to a case where extensive wave data would not be available for hindcast or forecast, which is typical of many design situations.

Wave Observations

Locations of the wave buoys and arrays used in the study are shown in Figure 1. All except the Waverider buoy and Linear Array at the FRF are NDBC buoys emplaced for routine measurements or in the case of Gordon for the DUCK94 experiment (e.g. Birkemeier 1994, Jensen 1994). Table 1 provides a summary of the location and water depths of the buoys and gauges. The height, period, direction, and spectral data used in the study were produced by the routine analysis procedures of NDBC (Steele et al. 1992) or the FRF reported in Leffler et al. (1993) and Long and Oltman-Shay (1991).

Wind-Field Simulations

The wind field required for SPM84 is an internal element of the wave field parameterization of the wave estimates and requires central pressure,

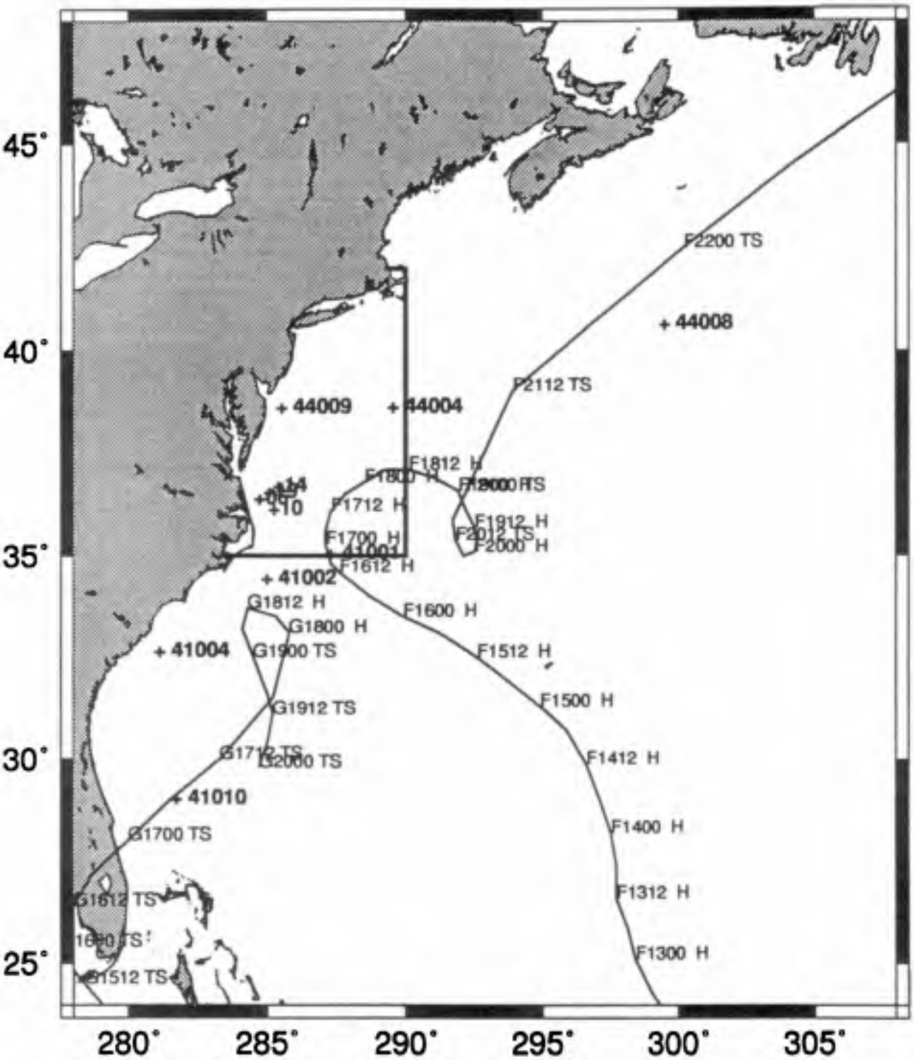

Figure 1. Position of NDBC buoys, and storm tracks for Gordon (G) and Felix (F) Nested grid domain indicated by box.

far field pressure, radius to maximum winds, and forward speed of the storm. These parameters were obtained from the National Hurricane Center (Samuel Houston, personnel communication, 1996).

The wind fields required for the WAM simulations consist of wind speed and direction at every grid point in the simulation interpolated to every time-step for

Table 1. Measurement Sites for 3GWAM Comparisons

BUOY #	GORDON	FELIX	LONGITUDE	LATITUDE	DEP.
41001	X	X	72° 39' 46"	34° 42' 06"	4444
41002	X		75° 14' 26"	32° 17' 42"	3658
44004	X	X	70° 43' 16"	38° 32' 14"	3231
44009		X	74° 42' 07"	38° 27' 49"	28
44014	X	X	74° 50' 01"	36° 34' 59"	48
44006	X		75° 30' 00"	36° 16' 00"	30
44019	X		75° 10' 00"	36° 25' 00"	40
44010	X		74° 59' 00"	36° 01' 00"	52
FRF-WR	X	X	75° 41' 59"	36° 10' 05"	18
FRR-LA	X	X	75° 44' 43"	36° 11' 16"	8.5

which the wave model equations are integrated. The method used by Oceanweather, Inc. (e.g. Cardone, Greenwood, and Greenwood 1992; Cox et al. 1994) assumes that the hurricane wind field can be simulated by a vortex embedded in an overall large-scale pressure gradient field. The wind field is estimated from the gradient wind approximations. An interactive optimal kinematic analysis (IOKA) procedure is then applied to modify the estimated winds so that they better match observed winds in the vicinity of the wave field. This solution was obtained at snapshots of the storm's history and then interpolated in time and space to give the required input to the wave model. For these simulations, the snapshots were taken evèry 3 hours (interpolated to 1 hour using a moving center algorithm preserving the storm's center), and data were output on a 0.5-deg grid. The NDBC buoys and FRF have wind field records for the storms. However these data have been used in the IOKA as an essential ingredient of the windfield analysis. Since they cannot provide independent validation of the wind field, they will not be presented here.

SPM84 Procedure

The method for producing hurricane wave estimates in deep water is relatively straightforward. The method has an equation of significant wave height H_S and period T_S

$$H_s = 5.03 \exp(R\Delta p/4700)[1 + 0.29\alpha V_F/(U_R)^{0.5}]$$

$$T_s = 8.6\exp(R\Delta p/9400)[1 + 0.145\alpha V_F/U_R^{0.5}]$$

where R is radius of maximum winds (km), Δp is the pressure drop, α is the forward speed coefficient (about 1 for a slow-moving storm), V_F is the forward speed (m/s), and U_R is the maximum sustained wind speed at the 10-m elevation. Once these values are obtained, the SPM84 provides a generalized nomogram (in terms of r/R: radius of the local r relative to the eye over the radius to maximum winds) that displays the wave height pattern in reference to the eye and the direction of movement.

WAM Model Set-up

WAM Cycle 4 was set up on a 0.25-deg grid for the entire region shown in Figure 1 using 25 frequencies ($f_{i+1} = 1.1 \cdot f_i$) and 24 directions (15 degree bins). The refraction and shoaling routines were turned on. The model received wind input every hour and was interpolated to the 0.25-deg grid in space and 600 s in time (WAM propagation time-step). Both hurricane fields were generated 3 days prior to the test period for spin-up of the wave model domain.

Hurricane Gordon

Gordon formed in the Caribbean and moved into the Gulf of Mexico across Florida into the Atlantic. Our analysis begins with the movement of the storm into the Atlantic near Cape Canaveral, FL at which point it was a tropical storm. The tropical storm moved northeastward from November 17, 1994, until early on the 18th when it slowed its movement and began to drift to the west approximately 200 km to the south of Cape Hatteras. As the storm was blocked from further northward movement, it intensified to a minimal hurricane for about 1 day, and then rapidly moved southward towards the Bahamas and lost strength.

SPM Method: The SPM84 calculations were made at a point when the storm was nearly stationary and had peak winds of 35-38 m/s. In the region of maximum winds, SPM84 (Table 2) indicates a maximum wave height of 7.7 m with a period of 12 s. The height and period at buoy 41002 - just north of the eye of the storm (r/R of 1.6) were estimated to be 5.7 m at 12 s compared to a buoy observation of 5-5.7 m and 10 -12 s for the times bracketing the analysis (eight buoy observations are missing). At buoy 41001 at an r/R of 2.4 northeast of the eye, the estimate via SPM84 is a height of 5.7 m with a period of 12 s. The buoy observations are significantly larger, 11 m and 13 s.

Table 2. Wave Height Results, SPM84 and WAM

STORM	LOC	SPM84	WAM	NDBC Obs.
GORDON	Max. Wind	7.7m / 12s*	10m / 13s*	---
	41001	5.7m / 12s*	7m / 11s*	11m / 13s
	41002	5.7m / 12s*	6.9m / 11s*	5m / 11s
	44014	3.8m / 12s*	6m / 12s*	9m / 15s
FELIX	Max. Wind	9m / 12s*	10m / 13s*	---
	44004	5.4m / 12s* 7.2m / 12s**	6.0m / 12s* 5m / 12s**	6.0m / 12s* 8.0m / 12s**
	44009	3.6m / 12s*	4.0m / 12s	3.8m / 12s*
	44014	5.4m / 12s* 7.6m / 12s**	4.0m / 12s* 6.2m / 14s**	4.0m / 12s* 6.8m / 15s**
	41001	6.3m / 12s* 7m / 12s**	5.2m / 9s* 8.0m / 14s**	5.8m / 9s* 7.8m / 15s**

* Stationary
** Closest Approach

At buoy 44014, 90 km northeast of the FRF and at an r/R of 5.4, the estimate was 3.8 m with a 12-s period, compared to the buoy observations of 9 m and 15 s.

Thus the SPM84 provided an estimate consistent with the observations near the center of the storm if the missing observations were similar to the ones bracketing it. However, the SPM84 technique dramatically missed the wave heights at 41001 and 44014, which were more to the east and northeast of 41002 and much further from the storm. Orientation of the nomogram was varied relative to the storm motion, but no significant improvement was obtained. The only way to achieve the size answers at 41001 and 44014, given the SPM84 method, would be to greatly increase the wind speed (and pressure drop) which was unsupported by the meteorological estimates.

WAM Simulations: The WAM simulations provide a detailed history of the waves over the entire region with hourly output. The input wind field has far more detail and asymmetry than is possible with the SPM approach. Figure 2 provides the wave height traces for 41002, 41001, and 44014. Results at the peak times are also provided in Table 2. Estimated peak wave conditions for the storm on the 18th were 10 m with a peak period of 13 s - substantially larger than the SPM84 estimate. The trace at 41002 indicates that the simulation and observations were fairly close on the 17th and the latter half of the 18th. On the morning of the 18th, the simulation suggests waves of 7 m, but the buoy failed

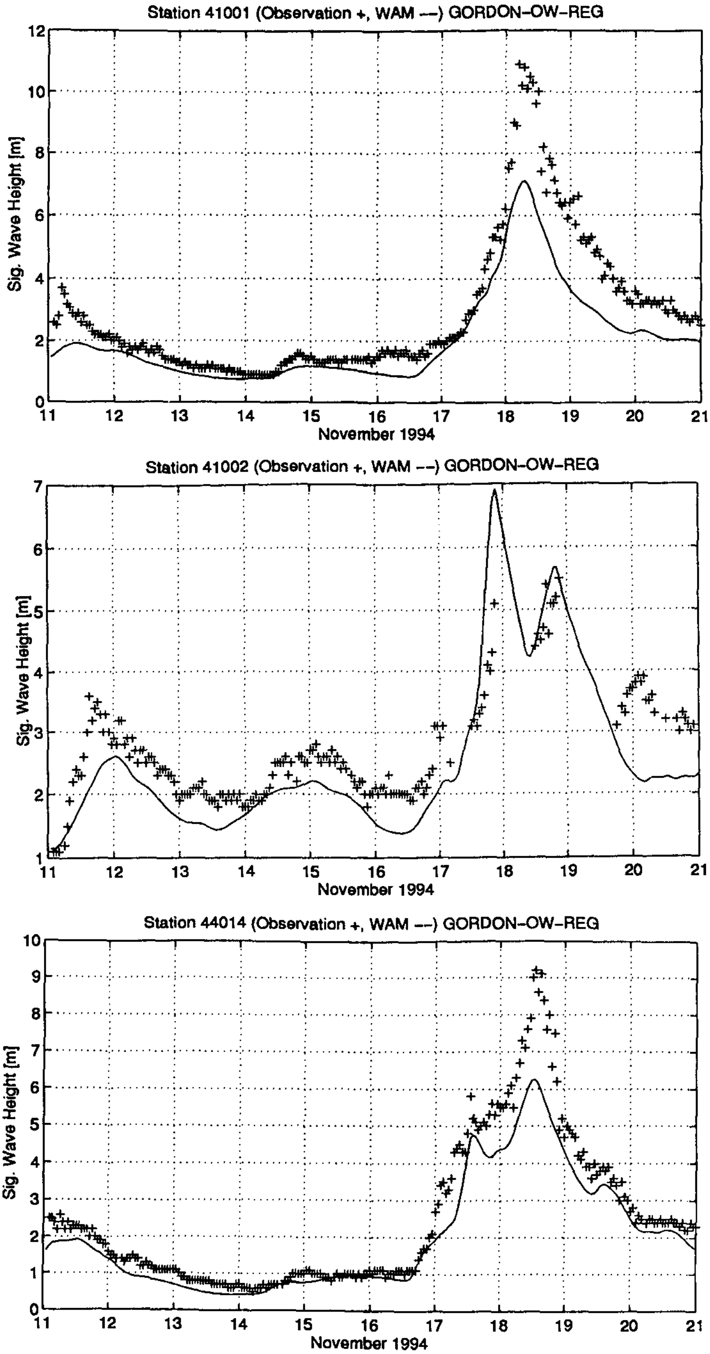

Figure 2. Comparison of WAM (solid line) versus measurements (+) at Buoys 41001 (top), 41002 (middle), and 44014 (bottom).

to collect data. At 41001, the simulation trace is fairly close to the observations until the morning of the 18th, at which time the model peaks at 7 m, but the observations continue to climb to 11 m and 13 s. The trace comparison at 44014 is fairly similar in that the simulation significantly underestimates the peak wave conditions (6 m predicted versus 9 m observed).

The WAM simulations provide larger wave heights than the SPM84 simulations, but it is clear that although the observations near the center of the storm (41002) are not poorly predicted, those to the east and northeast were badly underpredicted. If just the observations at 41002 and 41001 are compared (the buoys are about 150 km apart), the waves at 1200 on the 18th are about 4.5 m at 41002 versus 11 m at 41001. So there is a very rapid variation in conditions depending upon location with respect to the eye (both radial distance and quadrant), as is generalized in SPM84.

Hurricane Felix

Felix originated in the eastern Atlantic and moved steadily towards the United States. Our interest begins on the August 13, 1995 as the storm enters the computational grid some 4 days before closest approach to Cape Hatteras, NC. The storm moved steadily to the northwest towards Cape Hatteras as a Category 2-3 hurricane. By the 17th, the storm's northwest movement has been greatly reduced and the storm moves slowly to the north, then recurves to the east, looping on the 19th and 20th offshore of the Outer Banks of NC. Finally, on the 21st, the storm moves rapidly to the northeast as it becomes a tropical storm. In the region of Cape Hatteras, the storm remained a medium Category 1.

SPM Method: The SPM84 was applied several times. The first was when the storm was nearly stationary, and additional estimates were made when the storm was at closest approach 41001 and 44014 to the buoy (Table 2). The estimated maximum wave was 9 m at 12 s for the stationary case. SPM84 and buoy observations were fairly close - normally within a meter. Wave periods were low for the closest approaches at 41001 and 44014. Based on this very simple approach, the SPM method appeared to give a satisfactory estimate for this storm.

WAM Simulations: Results of the WAM simulations are given in Table 2. The simulated wave heights and periods based on stationary and closest approach times compare favorably with the observations. Comparisons of the wave height traces to the observations provides more mixed results (Figures 3 and 4). At 41001 (Figure 3), where the hurricane passed right over, the simulations are quite reasonable until 1200 on the 16th. After that time the observed heights fall more quickly than the simulated. From the 18th on, the simulations are 1-2 m

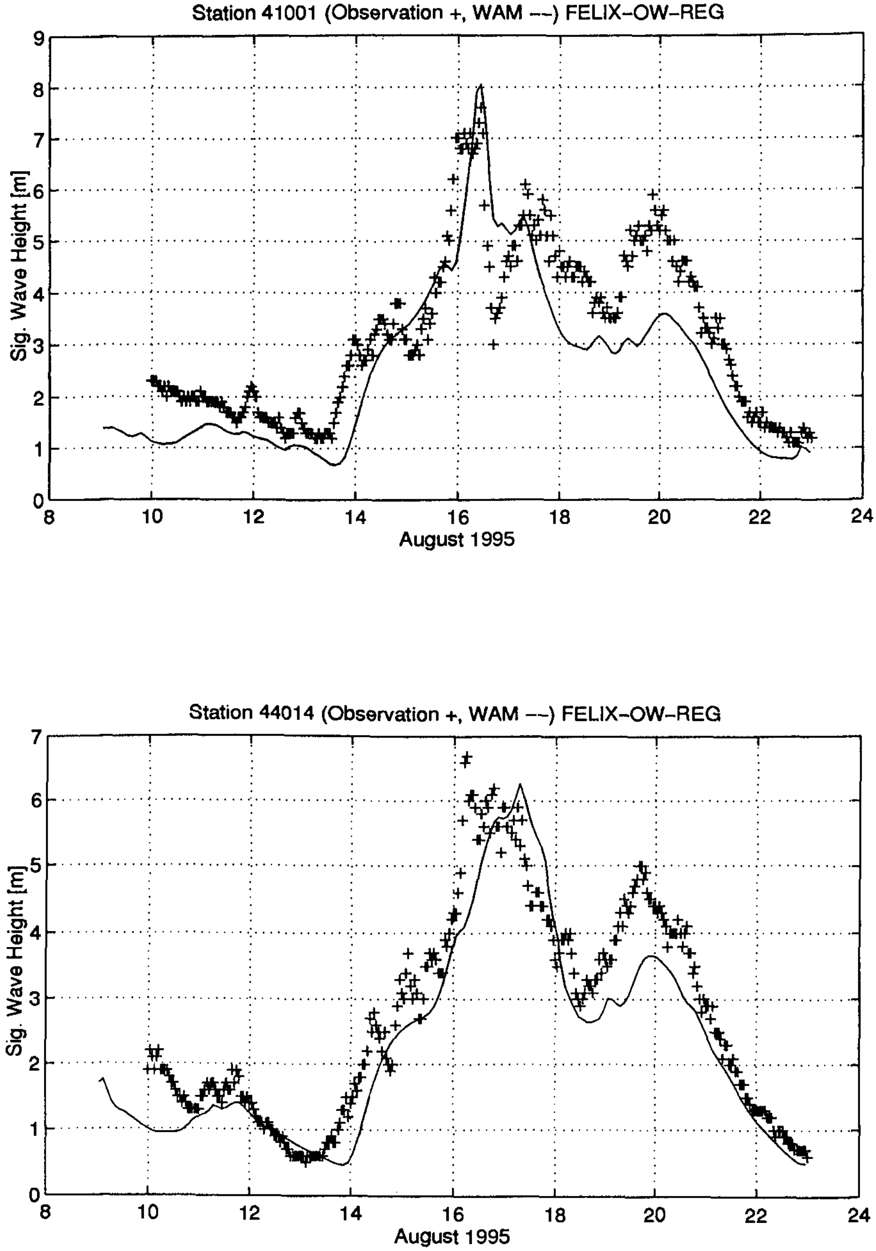

Figure 3. Comparison of WAM (solid line), and measurements (+), at 41001 (top), and 44014 (bottom) panel.

lower than the observed. At this time, the hurricane is in the looping process. At 44014 (Figure 3), the pattern is fairly similar. The simulations produce a similar peak height though the largest waves appear to arrive earlier than indicated by the simulation. The simulated decay of the storm is excellent until the 18th, when the observations rise more than the simulated values with a difference of 1 to 2 m seen. At 44009 (Figure 4), which lies in fairly shallow water off of Delaware bay, the pattern is similar to 44014, although the waves do not get as large as at 44014. Comparison of the simulation results to observations at 44004 (Figure 4), which is several hundred kilometers off of Delaware Bay and just to the north of the storm path, is by far the worst. The simulations completely underestimate large waves on the 16th and underestimate waves by nearly 3 m on the 18th-21st. Ship observations near 44004 recorded during the time of Felix were on the order of 2 to 4 m lower than the buoy wave heights. This suggests the potential of other factors such as the Gulf Stream influencing the measurements at 44004.

Thus, even though comparison of the WAM and SPM84 results to the observations at closest approach and when the storm was stationary are fairly good, comparison of the simulated history of wave heights shows that the WAM results underestimated (as much as 4 m) the storm when it was in the looping phase.

Discussion

Objectives of this paper were to understand (1) if Gordon was in some sense anomalous, and (2) how well two wave estimation approaches (one very simple, one very complex) performed with the typical level of information available for many forecasts and hindcasts. In judging the prediction approaches, it must be stated that any error is an integrated error for both wind field specification/modeling and wave model physics and numerics.

In considering Hurricane Gordon, it is best to contrast results to Hurricane Felix. In Felix application of both prediction methods gave fairly satisfactory results for peak quantities in the storm at most locations. Felix had consistently stronger winds and a somewhat smaller physical size. Felix at most produced 8 m waves at the buoys it passed by. Gordon, although generally weaker, produced waves larger than Felix by 3 m at 41001 and 2 m at 44014. At 41002, the simulation results from WAM and the observations were in reasonable agreement. Thus, although some systematic error in WAM or SPM84 cannot be ruled out, the authors hypothesize that Gordon must have been highly asymmetric with a region of larger winds to the east of the storm that is not caught in the current meteorological specification of the storm.

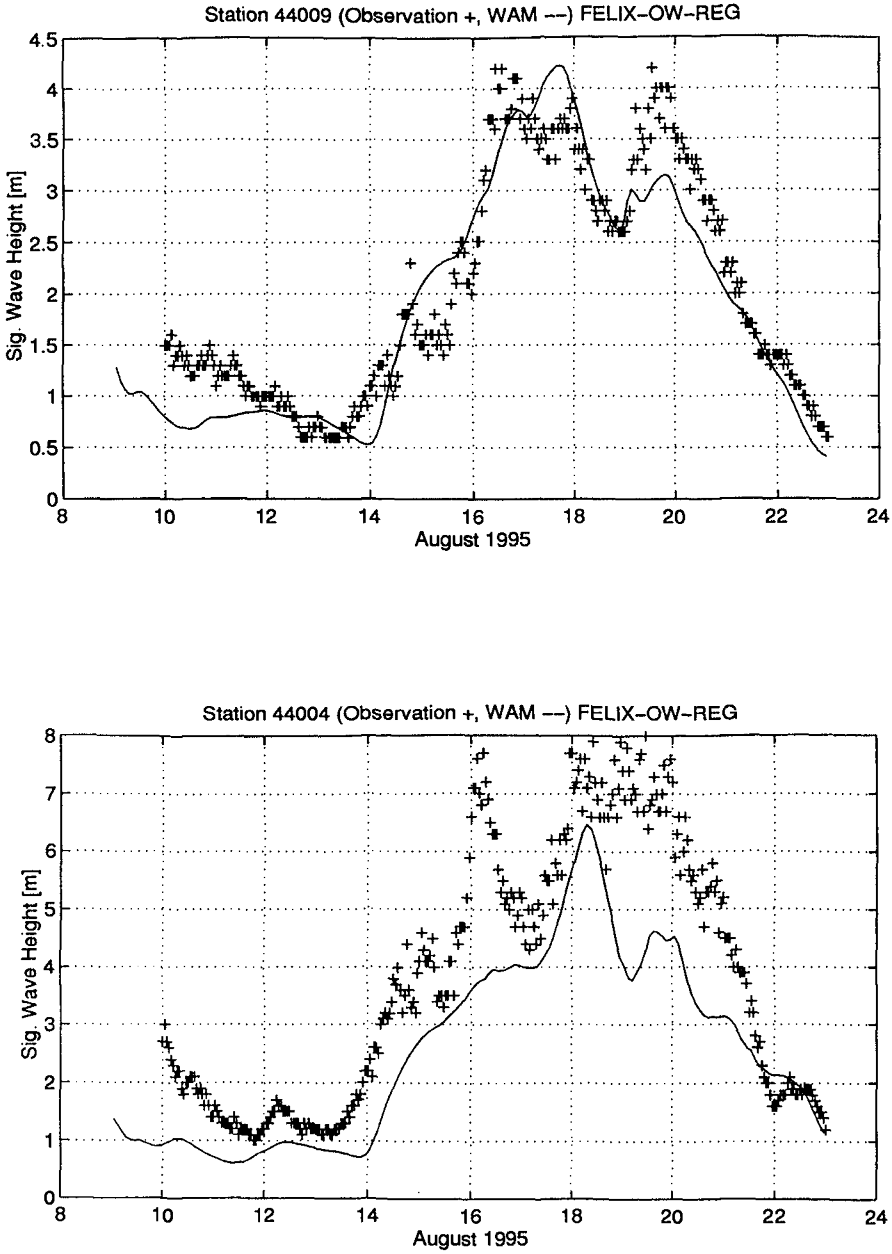

Figure 4. Comparison of WAM (solid line), and measurements (+), at 44009 (top) and 44004 (bottom) panel.

With regard to Felix, it appears that simulation methods do reasonably well when the storm is moving in a more or less straight line, but that the combination in wind field and WAM does not replicate what happened in the turning and looping situation. One can postulate two reasons for the problem. First, the simple vortex model approach may not be adequate when the storm is wobbling in a loop. Second, the ability of a model such as WAM to handle such radically turning winds and mixed sea-swell conditions has never been proven.

The principal lesson learned of engineering consequence is that fairly weak-appearing storms can produce unexpected high wave heights if the storm stalls or loops, with the error for a weak hurricane/strong tropical storm approaching 3-4 m in significant wave height. Moreover, forecast/hindcast of the wave height trace in the stalling/looping storms may produce errors of 1-2 m.

Acknowledgements

The research conducted here was performed under the Navigation Hydrodynamics Research and Development Program, Modelling the Evolution of Wave Spectra in Shallow Water work unit. The authors acknowledge Headquarters, U.S. Army Corps of Engineers, for authorizing publication of this paper. Special thanks are extended to Ms. Claudette Doiron for compiling, and Ms. Janean Shirley for editing this manuscript.

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