Appeared in the Fifth Conference on Coastal Atmospheric and Oceanic prediction and Processes, pp. 62-64, 2003

3.5 TROPICAL CYCLONE FORCING OF OCEAN SURFACE WAVES

Chung-Sheng Wu*, Arthur A. Taylor, Jye Chen, and Wilson A. Shaffer
National Weather Service/NOAA, Silver Spring, Maryland

1. INTRODUCTION

Hurricanes pose a major threat to coastal life and marine property. On the U.S. east coast, hurricane-generated storm surges generally dominate waves over a gently sloping shelf. For islands or coastal areas where the shelf is narrow, hurricane waves approach the coast ahead of landfall and dominate surges. In tropical and subtropical regions, storm waves and their statistical properties play a significant role in design requirements for coastal and marine structures.

During 1950-1977, parametric wave models based on significant wave height and period were developed (e.g. Bretschneider, 1957; Ross, 1976) for marine weather prediction and offshore oil industry design. Cardone (1976) employed a spectral wave model for diagnostic studies with the known hurricane track. In the 1990's, advances in computer power and in the physics of numerical spectrum ocean wave modeling have enabled the development of global ocean wind wave prediction models.

Due to grid size limitations and the complexity of wind model simulation, the global ocean wave models are not generally used for operational hurricane wave forecasting. Hsu (2000) developed a simple wave height-central pressure drop relationship and demonstrated that the U.S. Army's hurricane wave prediction method is still adequate in coastal areas for the oil industry. The merit of an ocean wave model is that it can be used to learn tropical cyclone wave behavior. Based on a numerical solution of the radiative transfer balance equation and limited field data collected during tropical cyclones on Australia's Northwest Shelf, Young (1988) proposed a parametric hurricane wave model. The model captures the physics of tropical cyclone waves via the JONSWAP formulation of wave spectrum. The model is forced by the surface wind beneath the moving storm and prescribes maximum wave height and period, which is the severe swell wave generated by the storm. The U.S. Army has adopted his formulation and a monogram in the new Coastal Engineering manual. In the present approach, we integrated existing maximum surface winds with Young's wave model and compared wave heights and periods with ocean wave observations .

2. MODEL FORMULATION

The hurricane surface wind field has been extensively studied for storm surge prediction. Atkinson and Holliday (1977) developed a simple formula relating the cyclone's pressure drop to maximum sustained wind for the Western Pacific. A more general form was proposed by Holland (1980). The merit of these models is that they are analytical models for the surface wind profile in a hurricane. A similar formulation was applied to the wave model in the present work. The framework of the hurricane wind and wave model is described below.

*Chung-Sheng Wu, Meteorological Development Laboratory, Office of Science and Technology, National Weather Service, Silver Spring, MD 20910; email: cs.wu@noaa.gov

2.1 HURRICANE WIND MODEL

Holland (1980) employed a standard pressure profile for a tropical cyclone and obtained the popular gradient wind profile. Jelesnianski and Taylor (1976) assumed a surface wind profile in the pressure equation. Their wind profile is normalized by the maximum wind speed in a concentric circular pattern. The radius to the maximum wind, R_{max}, defines the location of the maximum wind speed V_{max}. The maximum wind speed is a function of the radius of maximum winds, pressure drop, and forward speed. The solution procedure starts with an initial guess of V_{max}, then iterates the pressure profile until a maximum wind speed corresponds to the center pressure drop. This model has been applied to the U.S. National Weather Service's tropical storm surge model. It is conveniently named as the SLOSH wind. The radius of maximum wind, R_{max}, can be estimated from aircraft reconnaissance or the satellite image as suggested by Hsu and Yan (1998). The surface analysis wind developed by Hurricane Research Division of NOAA can also be used for determining the size after the hurricane track is determined. R_{max} is a crucial parameter for the hurricane wind field. In many tropical cyclones, it was found that the radius of the maximum wind reduces as the central pressure drops.

The determination of tropical cyclone wind is a topic of research. Hsu (2000) adopted the maximum sustained wind as used by the U.S. Army Corps of Engineers (USACE) and obtained good results for hurricane Georges. While Holland wind varies with a free parameter B ranging from 1.0 to 2.5, the USACE and SLOSH winds solely depend on the values of the storm intensity and forward storm speed. The latter two winds can reproduce Holland's wind. For real applications, we included the USACE and SLOSH winds in the present parametric wind wave model to cater various storm conditions. The accuracy of the maximum wind speed is still improving. In addition to the analytic and empirical formulae, wind speeds can also be obtained from radar and satellite observations as well as global numerical model output.

2.2 HURRICANE WAVE MODEL

Young (1988) developed the wave model based on the 2^{nd} generation of WAM model using nested grids with a finest resolution of 15-km. The model produced data and then calibrated with field measurement of storm waves. The model analysis focuses on the maximum wave height and period. By satisfying wave growth and wave dispersion criteria, fifteen empirical coefficients are determined. The parametric wave model calculates an equivalent fetch based on the radius of maximum wind and the forward storm speed. The method of solution applies well to a range of tropical cyclone conditions in Australia, providing that there are no secondary weather systems present in the local field.

The wave solution is strongly affected by the maximum wind speed and the forward storm speed. If the hurricane winds are specified, the maximum significant wave height is then obtained as well as the corresponding wave period.

2.3 MODIFIED JONSWAP SPECTRUM

For coastal and marine weather forecast warning and advisories, it may be acceptable to use the prediction of maximum significant waves. For design and safe operation of ships in the harbor and offshore structures, it is necessary to consider wave spectra loading during tropical cyclones. Ochi (1993) proposed a modified JONSWAP spectrum for hurricane seas as a function of the predicted significant wave height and the peak frequency. This spectrum is served as the incoming wave from the ocean for shallow water wave modeling to determine the coastal seas in coastal areas.

3. MODELING RESULTS

To verify the validity of the formulation introduced in Section 2, we applied the parametric model to hurricane cases that occurred along the U.S. east coast and the Gulf of Mexico. The hurricanes were chosen such that the NOAA buoys were close to the hurricane track, then the wind and wave data were collected for model comparison. Through the 1990's, only six hurricanes (Table 1) were selected. The parametric wave model effectively calculated the significant wave heights and periods at the buoy sites.

Hurricane Floyd cost billion's of dollars of damage to the state's heavily developed coast, though emergency response services were in action long before the hurricane made landfall. Buoy station 41010 captured increasing wave heights as Floyd made a northward turn parallel to the northeast coast of Florida as influenced by the presence of Gulf Stream.

Table 1 summarizes the comparisons of predicted waves and observed wave data. For Hurricane Bonnie, the input data are from the NOAA research aircraft by Wright et. al (2001), in which the maximum wave height was 10.70 m with a period of 13.89 sec (based on wavelength of 300 meters). The model calculates a significant wave height of 10.46 m and wave period of 13.78 sec. The overall accuracy of wave period prediction is better that of the wave heights. The mean relative error (MRE) for the six cases is less than 5 percent of the corresponding cases.

The parametric wave model is simple to use but limited to slowly varying tropical cyclone paths. It is meant to complement the operational ocean hurricane wave model. An ocean spectral wave model with highly nested grids (to capture the maximum peak wind) may yield a solution with the same degree of accuracy as the parametric model at the expense of extensive computer calculations. Using the same hurricane information, the present model can effectively estimate the probable peak wave during the storm. We tested many other hurricane seas and found that the simple formula by Hsu (1991) does represent a good estimate of the maximum wave with about 20-50% error. However, the present approach can give specific values for various storm cases, when more input data are provided.

Table 1. Comparisons of significant wave heights and periods to observed values for recent hurricanes.

Hurricanes track time		Fran 09/05/96 21Z	Lili 10/02/02 2030Z	Georges 09/27/98 16Z	Floyd 09/15/99 08Z	Bonnie 08/24/98 21Z	Iniki 09/11/92 18Z
Wave Height (m)	Model	11.50	11.12	10.48	14.24	10.46	4.95
	Data	11.64	11.20	10.88	14.20	10.70	5.05
Period (s)	Model	14.22	13.28	13.8	14.95	13.8	9.0
	Data	14.29	13.25	13.2	15.4	13.9	8.4
Relative Error (%) for wave height		-1.2	4.5	3.6	.28	-2.2	-2.0

This approach is currently being tested in operations by the NWS's Tropical Prediction Center.

4. CONCLUSION AND REMARKS

Wave prediction within a hurricane is still a challenge for a contemporary ocean spectrum wave model, such as the 4th generation model WAM. The complexity of high winds near the eye center requires a numerical model with high resolution both in time (hourly) and in space (1 km). A parametric wave model based on the available solutions of a nested grid ocean wave model and field data is applied, and the modeling results are summarized as follows:

(1) For six major hurricanes in the U.S. East Coast and the Gulf of Mexico where a wave buoy is close to the storm center, the parametric model gives wave height predictions within 5% error compared with the measured buoy wave data. The swell period and thus wave steepness are also favorably verified with the wave data offshore and inshore, which is essential for shipping.

(2) The parametric model was tested for a series of wind and storm conditions. It covers more than the formula in Hsu (2000), which simply relates the wave height to the central pressure drop. For a wide variety of applications, the present model can work with a hurricane track model to make real-time high wave forecasts.

(3) Field observations over the ocean are extremely sparse during a hurricane. NOAA scientists recently installed a radar on an aircraft to measure the wave spectrum field during hurricane Bonnie. They developed an empirical method of predicting dominate swell wave direction. This information can be used with a coastal wave model for providing forerunner coastal flooding.

However, the parametric model is limited to slowly changing hurricane motion. For monitoring the entire wave pattern, a two-dimensional multiple-nested ocean wave model driven by a nested ocean wind field is the solution as developed by the National Center of Environmental Prediction of NOAA.

ACKNOWLEDGEMENTS

The writer wishes to thank Prof. S. A. Hsu for his motivation and numerous discussions during the study. Appreciation is also extended to Dr. H. R. Glahn for his support of the Coastal Storm Surge and Wave program.

5. REFERENCES

Atkinson, G. P. and Holliday, C. R.,1977: "Tropical cyclone minimum sea level pressure maximum sustained wind relationship for the Western Pacific", Mon. Wea. Rev., 105, 421-427.

Bretschneider, C. L., 1957: "Hurricane design wave practices", J. Waterway and Harbor Div., ASCE, 83 (ww2), 1238-1--1238-33

Cardone, V. J., W. J. Pierson and E. G. Ward, 1976: "Hindcasting the directional spectra of hurricane-generated seas", J. Petroleum Tech., 28, 385-395.

Hsu, S. A., 1991: "Forecasting hurricane waves", Marine Weather Log, 35 (2), 57-58.

Hsu, S. A., M. F. Martin, Jr., and Blanchard, B. W. 2000: "An evaluation of the USACEs deep water wave prediction techniques under hurricane conditions during Georges in 1998", J. Coastal Research, 16 (3), 823-829.

Hsu, S. A. and Yan Z., 1998: "A note on the radius of maximum wind for hurricane", J. Coastal Research, 14, 667-668.

Holland, G. J., 1988: "An analytic model of the wind and pressure profiles in hurricanes", Mon. Wea. Rev., 108, 1212-1218.

Jelesnianski, C. P. and Taylor, A. D.,1973: "A preliminary review of storm surges before and after storm modification", NOAA Tech Memorandum, ERL, WMPO-3, NOAA, Dept. of Commerce, 20-28.

Li, C. W. and Mao, M. 1992: "Spectral modeling of typhoon generated waves in shallow water", J. Hydr. Res., 30, 5, 611-622.

Ochi, M. K., 1993: "On hurricane-generated seas", Proceeding of the 2nd Symposium on Ocean Wave Measurement and Analysis, ASCE, 374-387.

Ross, D., 1976: "A simplified model for forecasting hurricane generated waves", Bul. Am. Meteo. Soc., 57(1), 113-114

Wright, C. W., E. J. Walsh, D. Vandemark, and W. B. Krabill, 2001: "Hurricane directional wave spectrum spatial variation in the open ocean", J. Phys. Oceanogr., 31, 2472-2488.

Young, I. R., 1988: "Parametric hurricane wave prediction model", J. Waterway, Port, Coastal and Ocean Eng., 114, 5,639-652.

Young, I. R. 2003: "A Review of the Sea State Generated by Hurricanes ", Marine Structures. 16, 201-218