Numerical Simulation of Sea Surface Directional Wave Spectra under Hurricane Wind Forcing

IL-JU MOON, ISAAC GINIS, AND TETSU HARA

Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island

HENDRIK L. TOLMAN

SAIC-GSO at NOAA/NCEP Environmental Modeling Center, Camp Springs, Maryland

C. W. WRIGHT AND EDWARD J. WALSH*

NASA Goddard Space Flight Center Wallops Flight Facility, Wallops Island, Virginia

(Manuscript received 15 August 2002, in final form 30 January 2003)

ABSTRACT

Numerical simulation of sea surface directional wave spectra under hurricane wind forcing was carried out using a high-resolution wave model. The simulation was run for four days as Hurricane Bonnie (1998) approached the U.S. East Coast. The results are compared with buoy observations and NASA Scanning Radar Altimeter (SRA) data, which were obtained on 24 August 1998 in the open ocean and on 26 August when the storm was approaching the shore. The simulated significant wave height in the open ocean reached 14 m, agreeing well with the SRA and buoy observations. It gradually decreased as the hurricane approached the shore. In the open ocean, the dominant wavelength and wave direction in all four quadrants relative to the storm center were simulated very accurately. For the landfall case, however, the simulated dominant wavelength displays noticeable overestimation because the wave model cannot properly simulate shoaling processes. Direct comparison of the model and SRA directional spectra in all four quadrants of the hurricane shows excellent agreement in general. In some cases, the model produces smoother spectra with narrower directional spreading than do the observations. The spatial characteristics of the spectra depend on the relative position from the hurricane center, the hurricane translation speed, and bathymetry. Attempts are made to provide simple explanations for the misalignment between local wind and wave directions and for the effect of hurricane translation speed on wave spectra.

1. Introduction

Hurricane-generated wave fields are of interest both scientifically for understanding wind–wave interaction physics and operationally for predicting potentially hazardous conditions for ship navigation and coastal regions. A hurricane with intense and fast-varying winds produces a severe and complex ocean wave field that can propagate for thousands of kilometers away from the storm center, resulting in dramatic variation of the wave field in space and time (Barber and Ursell 1948).

In recent years there have been considerable efforts made to measure the directional spectra of hurricane-generated surface waves and to investigate its spectral characteristics. Wyatt (1995) described measurements of the directional spectra of storm waves using high-frequency radar to explain the effect of fetch on the directional spectrum of Celtic Sea storm waves. Holt et al. (1998) examined the capability of synthetic aperture radar imagery from *ERS-1* satellite to track the wave fields emanating from an intense storm over a several day period. Wright et al. (2001) and Walsh et al. (2002) studied the spatial variation of hurricane directional wave spectra for both open ocean and landfall cases using the National Aeronautics and Space Administration (NASA) Scanning Radar Altimeter (SRA) for the first time. These measurements have provided detailed wave characteristics only at a specific space and time.

Ocean wave modeling is a very useful and convenient way to obtain the spatial and temporal distribution of directional spectra without the limitations associated with measurements, although the model output may differ from observations because of uncer-

* Current affiliation: NOAA/Environmental Technology Laboratory, Boulder, Colorado.

Corresponding author address: Il-Ju Moon, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882.
E-mail: mij@gso.uri.edu

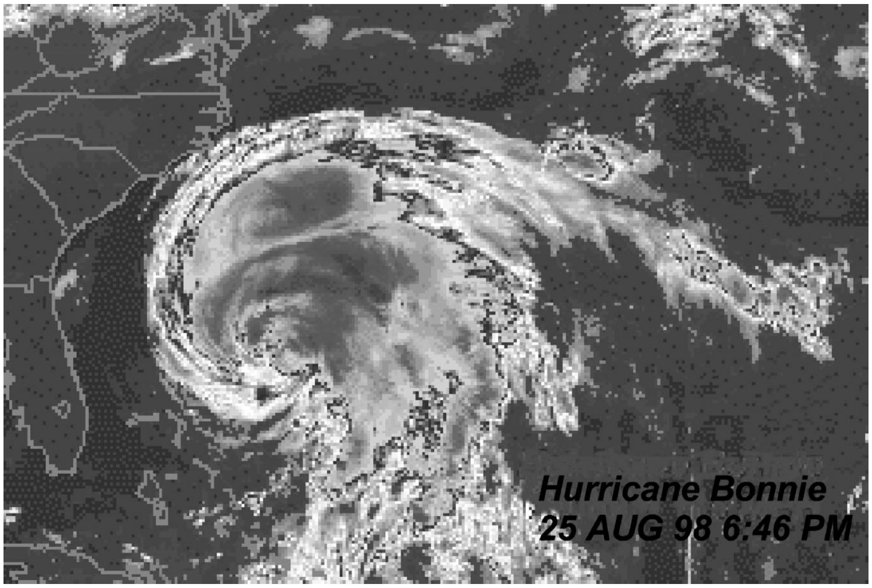

FIG. 1. Hurricane Bonnie from satellite image at 1846 UTC 25 Aug 1998.

tainties in wind input, model physics, and numerics. Recently, considerable improvements have been made in predicting ocean wave directional spectra. Until the late 1980s, many models were developed using simple nonlinear interaction approximations and assumptions on spectral shape (first- and second-generation models). After the Sea Wave Model Project (SWAMP) study in the mid-1980s, through community efforts, the Wave Model (WAM) was developed with explicit treatment of nonlinear interactions (third-generation models), essentially replacing all previous models (WAMDI Group 1988; Komen et al. 1994). The WAM has been verified and applied to wave hindcast and forecast, air–sea coupling, and data assimilation over many seas of the world (Dell'Osso et al. 1992; Bauer et al. 1992; Monaldo and Beal 1998; Prasadkumar et al. 2000). Recently, a new ocean surface wave model, WAVEWATCH III (Tolman 1999), was developed at the National Oceanic and Atmospheric Administration–National Centers for Environmental Prediction (NOAA–NCEP) in the spirit of the WAM. It is designed with more general governing transport equations that permit full coupling with ocean models, improved propagation schemes (third order), improved physics integration scheme, and improved physics of wave growth and decay. The WAVEWATCH III (WW3) has been validated over a global-scale wave forecast and a regional wave forecast (Tolman 1998, 2002; Tolman et al. 2002; Wingeart et al. 2001).

5. Summary and conclusions

Hurricane Bonnie was one of the most powerful hurricanes to directly hit the coast of North Carolina during recent decades, and its translation speed varied from 2 to 8 m s^{-1}. In this study, the Hurricane Bonnie directional wave spectra obtained from NASA Scanning Radar Altimeter are compared with ocean wave model results. The wave model, a version of the WAVEWATCH III, uses a high-resolution grid ($\frac{1}{12}° \times \frac{1}{12}°$) to simulate the sea surface spectra of hurricane-generated wind waves. This is the first detailed comparison between model simulations and observations of the spatial distribution of hurricane directional wave spectra in both open ocean and landfall cases.

The modeling results show that, excluding shallow areas near the shore, the model yields an excellent simulation of directional spectrum as well as significant wave height, dominant wavelength, and wave direction under hurricane wind forcing. The present simulation allows more complete analyses of the hurricane-generated wave field than do observations at limited time and space.

From the results of observation and numerical modeling, we have found that the hurricane-generated wave field is mostly determined by two factors: the distance from the hurricane center or the radius of maximum wind and hurricane translation speed. For the case of a hurricane with low translation speed, the dominant wave direction is mainly determined by the distance from the hurricane center. For the case of a fast-moving hurricane, the dominant waves are mostly determined by resonance. When the group velocity of dominant waves is close to the hurricane translation speed, their growth may be significantly enhanced due to the resonance effect, and the swell produced by the resonance dominates wave systems over its propagating areas.

We have suggested simple analytical models for estimating the swell directions for both slow- and fast-moving storms. The swell directions derived from these models demonstrate excellent agreement with those of SRA observation and numerical simulation.

The present study clearly demonstrates that using realistic wind forcing and a high-resolution WAVEWATCH III model may yield successful simulations of surface wave fields in hurricane conditions.