VINCENT J. CARDONE

THE PRESENT STATUS OF OPERATIONAL WAVE FORECASTING

Numerical spectral ocean-surface wave-prediction models are used increasingly for the preparation of operational wave forecasts, wave-climate assessments, and the specification of design data for coastal and offshore structures. Recently, an international group of wave modelers compared 10 first- and second-generation wave models in the Sea Wave Modeling Project and found surprisingly large differences in model behavior and performance. The activities of the project have been continued by the Wave Modelers group, which is engaged in the development of a third-generation model based on improved representations of physical processes of wave growth, wave–wave interactions, and wave dissipation. Third-generation models will probably be in widespread use by the end of the decade and promise, together with satellite-based ocean wind and wave measurement systems, to provide accurate and timely global-scale specifications of the directional wave spectrum, as well as forecasts whose accuracy will be limited only by errors in numerical weather forecast systems.

INTRODUCTION

Numerical spectral ocean-wave models were introduced in the mid-1950s, but only within the last decade has their use become widespread. In many countries (e.g., Australia, Great Britain, the Federal Republic of Germany, Japan, Malaysia, Netherlands, Norway, and the United States) spectral wave models are used operationally at national meteorological centers in the preparation of real-time wave forecasts. Wave models have also been used to derive long-term (20 to 30 years) wave series in northern hemisphere basins for estimating the normal wave climate. Extreme wave statistics needed for designing coastal and offshore structures are developed today mainly from wave data generated by wave model hindcasts of relevant populations of severe historical storms.

Further interest in wave models has been stimulated in recent years by the prospect of routine global remote sensing of ocean-surface wind and wave properties from polar-orbiting satellites such as the Navy Remote Ocean Sensing System (NROSS).* The scatterometer to be flown on that system can retrieve near-surface winds from radar backscatter measurements, but the relationship between backscatter and wind speed probably depends on sea state. In addition, there is increasing evidence that the relationship between the wind field near the sea surface and the surface stress also depends on sea state. The NROSS will also fly a radar altimeter, but that instrument provides estimates of significant wave height only along the subsatellite track. To use the remote ocean-sensing data most effectively, they will have to be assimilated into a global wave model in real time, in much the same way that remote atmosphere measurements are used in numerical weather prediction models.

Within the past few years, the international community of wave modelers has cooperated and collaborated to a remarkable degree in efforts to identify weaknesses in present models and to develop and implement improved models. In the Sea Wave Modeling Project (SWAMP), 10 different spectral wave predictions (see Table 1) were subjected to a set of seven tests and systematically compared.[1] Most of the SWAMP participants have continued to work as a group (the so-called Wave Modelers, or WAM) to develop, evaluate, and implement a third-generation wave model. A prototype version of the WAM model was tested in 1986 at the European Centre for Medium Range Weather Forecasting with promising results (see the article by Komen elsewhere in this issue).

In this article, we first describe the basic structure and behavior typical of first- and second-generation wave models, with particular reference to the SWAMP results. We then assess the capabilities of typical operational wave-prediction models. Finally, we describe the present status of third-generation models and the benefits of future applications of such models.

Vincent J. Cardone is president of Oceanweather, Inc., Cos Cob, CT 08807.

WAVE PREDICTION MODEL STRUCTURE

The directional wave spectrum, $F(f,\theta)$, is the spectral representation of the variance of the surface-wave dis-

---

*NROSS, a U.S. program for global wind-field monitoring, was cancelled in December 1986. The prognosis for its revival is unclear as this goes to press.

Table 1—Models used in SWAMP intercomparison study.

Model Name	*Source Institution*
MRI	Meteorological Research Institute, Japanese Meteorological Agency, Tsukuba
VENICE	Instituto Studio Dinamica, Grandi Masse, Venice
NOWAMO	Norwegian Meteorological Institute
GONO	Royal Netherlands Meteorological Institute, De Bilt
TOHOKU	Geophysical Institute, Tohoku University, Sendai
HYPA	Institut für Meereskunde, Hamburg
BMO	British Meteorological Office, Bracknell
SAIL	Sea Air Interaction Laboratory, National Oceanic and Atmospheric Administration, Miami
DNS	Scripps, La Jolla/Naval Ocean Research and Development Activity, Bay St. Louis
EXACT-NL	Max Planck Institute of Meteorology, Hamburg

placement in terms of component wave frequency, f, and direction, θ.

$$\bar{\zeta}^2 = \int_0^{2\pi} \int_0^{\infty} F(f,\theta) df d\theta \ .$$

From the spectrum, one can specify quantities of interest, such as the significant wave height (SWH), the dominant wave period, the direction of propagation of maximum wave energy, and even the expected value of the maximum individual wave height in a run of waves.

Most spectral wave models are of the discrete type in which the spectrum is completely described as an array of frequency–direction spectral components of finite bandwidth. Typical directional resolution is 15 degrees, and typical frequency resolution is 0.01 hertz. With several hundred discrete spectral components at each model grid point, computer storage requirements in a wave model are considerable, since there are about 7000 grid points in a global grid of reasonable spatial resolution of, say, 2.5 degrees latitude/longitude. Hybrid models attempt to reduce storage and computational demands by representing the wind–sea part of the spectrum in terms of a few spectral shape and scale parameters and retaining narrow-banded representation only for swell.

The basis of spectral wave-prediction models is the spectral energy-balance equation, which in deep water and in the absence of currents is

$$\frac{\partial F}{\partial t} + \mathbf{V}_g \cdot \nabla F = S \equiv S_{\text{in}} + S_{\text{nl}} + S_{\text{ds}} \ , \qquad (1)$$

where the two-dimensional spectrum, F, depends on space and time, as well as frequency and propagation direction; V_g is the group velocity; and the source function, S, is expressed as the sum of S_{in}, energy input from the atmosphere, S_{nl}, the nonlinear transfer of energy by resonant wave–wave interactions, and S_{ds}, energy losses to dissipative processes such as wave breaking.

The solution of Eq. 1 is approximated numerically in wave models by alternate steps of simulated propagation (the advective rate of change) and growth (local rate of change) caused by sources and sinks. In the propagation step, the frequency bands are uncoupled and the directional bands are weakly coupled by convergence of meridians on a spherical earth or in shallow water by bottom refraction. In the growth step, the grid points are totally uncoupled and the degree of coupling between the frequency and direction bins depends on the form for S.

Propagation

A wide range of propagation schemes has been used in wave models, including higher order advective-differencing schemes,[2] discontinuous schemes that jump energy from point to point,[3] and explicit representations of wave-range paths along characteristic curves.[4] Highly nondispersive numerical advective schemes are not necessarily advantageous in banded models because for typical bandwidths there is natural dispersion. As recognized rather early,[5] there is little point in selecting an advective scheme for a discrete wave model that minimizes dispersion. Advective operators that are consistent with the natural dispersion of finite bandwidth spectral components have not been developed, but the requirements of such an operator have been described by SWAMP.[1] As a result, many operational wave models perform rather well with simple schemes. For example, the prototype third-generation WAM global model uses a first-order advective scheme. The present Navy global spectral ocean-wave model (GSOWM) uses an interpolatory scheme,[5] which is basically first order and includes great-circle propagation effects. The scheme has also been used successfully in storm hindcasts in the Ocean Data Gathering Program (ODGP)/SAIL family of models.[6]

Source Terms

Following SWAMP,[1] spectral wave-prediction models are differentiated by their source-term treatment. In so-called first-generation treatments (Fig. 1a), the input source term is generally represented as

$$S_{\text{in}} = A + BF \ ,$$

where A represents an excitation mechanism such as the model proposed by Phillips[7] to describe the resonance of surface-wave components with atmospheric turbulent

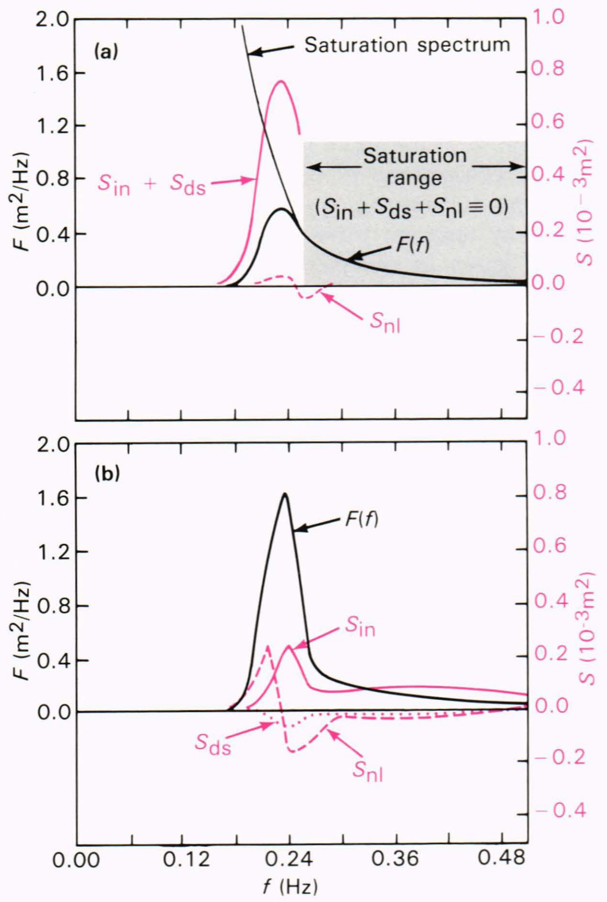

Figure 1—Relative energy balance for (a) first-generation and (b) second-generation models (after SWAMP[1]).

pressure fluctuations, and BF represents energy transfer to waves through coupling of the mean shear flow in the marine atmospheric boundary-layer-to-surface-wave components. In first-generation models, an equilibrium spectrum, usually the Pierson–Moskowitz, is used to limit the growth of the total wave energy and to shape the tail (high-frequency part) of the spectrum, thereby avoiding the need for a dissipation source term for wind waves. S_{nl} either is not considered or plays a minor role relative to S_{in}. Some first-generation models perform very well, as discussed below, because their linear and exponential growth rates are not taken directly from theory but have been refined based on observations of net wave growth in simple duration- or fetch-limited situations or on trial hindcasts of more complicated wave regimes. However, they do not model some features of wave generation, such as similarity of fetch and duration growth or spectral overshoot. Furthermore, these models may not be reliable if applied to wave regimes substantially different from those used for refining.

Second-generation source-term treatments are indicated schematically in Fig. 1b. The nonlinear source term plays the dominant role in the evolution of the spectrum because it greatly exceeds S_{in} in magnitude in the forward face of the spectrum. Since a rigorous representation of S_{nl} is not possible in a discrete model at current computer speeds, the S_{nl} source term in second-generation models is described in terms of only a few parameters and is valid only for a restricted class of spectral shapes. Most of such models have retained the simplified first-generation model treatment of the high-frequency part of the spectrum in terms of a saturation range rather than attempting an explicit balancing of source terms. The S_{in} term in second-generation models is usually taken from the Bight of Abaco field experiment,[8] which provides growth rates about a factor of 5 smaller than those used in first-generation models.

As demonstrated in SWAMP, second-generation models have not provided significant improvements over well-tuned first-generation models; this has led to the development of a third-generation model.[9] That model retains an empirical wind-input source function and a dissipation source function based on a general white-capping dissipation model.[10] The nonlinear source term is specified through the discrete-interaction operator parameterization,[11] which contains the same number of degrees of freedom as is used to specify the discretized spectrum and is structured in the same way as the exact Boltzmann integral. The computational efficiency of this form over the full integral is achieved by restricting the integration to only two elementary interaction configurations, as determined from a large number of tests with the exact integral, to describe the essential features of S_{nl}.

WAVE-MODEL PERFORMANCE

SWAMP

SWAMP consisted of the uniform application of 10 spectral models to seven hypothetical tests, each designed to reveal a particular property of the models. Model predictions were not compared with real data. The cases consisted of a pure advection test; fetch- and duration-limited wave growth in uniform stationary winds blowing orthogonal to a straight coast (case 2); slanting-fetch wave growth; wave growth in a basin with nonzero uniform winds in the half plane; wave growth on a plane with a 90-degree wind shift along a diagonal front; simulation of a stationary and translating hurricane (case 6); and local wave response to a 90-degree shift in wind. The SWAMP cases have provided a standard reference for the evaluation of present and future wave models. Figure 2 shows the results for case 2 for duration-limited seas. It also shows results for two first-generation models that were not included in SWAMP: the ODGP model[12] and the spectral growth/dissipation algorithms in GSOWM.[13] Incidentally, the previous Navy Northern Hemisphere spectral ocean-wave model (SOWM) and ODGP behaved similarly in the case 2 duration test but differed significantly in the fetch-limited test and in the test of duration-limited growth following a wind shift. The varied results of the SWAMP models in the simulated hurricane case (case 6) prompted SWAMP to conclude that

> ...reliable performance of the models in these situations, for which direct measurements are

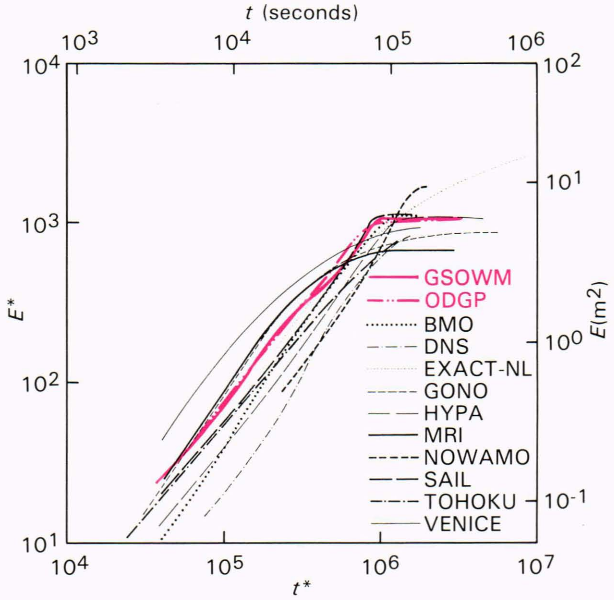

Figure 2—Duration-wise growth in case 2 (SWAMP[1]). The curves are for the 10 SWAMP models and the first-generation GSOWM and ODGP models.

> unfortunately sparse, must be regarded as highly questionable. A detailed analysis of the few existing hurricane wind and wave data sets in the light of the model intercomparison results for Case 6 would clearly be valuable.[1]

A number of such case studies are summarized below.

Storm Hindcasting

Most of the published data on model performance in situations of severe atmospheric forcing pertain to first-generation models. Reece and Cardone[14] evaluated the skill of ODGP model hindcasts of SWH and its associated peak period at a site in a storm, specified naturally as part of basin-wide simulations of complete storm histories. In over 60 individual comparisons in 19 different tropical and extratropical cyclones, the model hindcasts exhibited negligible bias and root-mean-square errors of less than 1 meter in height and 1 second in peak spectral period. Comparisons of measured and hindcast directional wave spectra in three of the hurricanes showed excellent agreement. The scatter index (100 times the root-mean-square error divided by the mean, over a sample of measured data) is frequently cited by wave modelers as a measure of forecasting quality. The scatter index in SWH was 11.9 percent in the comparisons cited above.

Several modelers have achieved comparable success with first- and second-generation models in hindcasts of historical storms after surface wind fields have been carefully reconstructed from source data. For example, the Shallow Water Intercomparison Model (SWIM)[15] produced scatter indexes of 19, 14, and 24 percent in deep-water hindcasts of two severe North Sea storms with the BMO, GONO, and HYPA models, respectively. Figure 3 compares those hindcasts with a blind hindcast of the same storm sequence carried out with the ODGP model on comparable spectral and grid resolutions. The wind fields used in the SWIM model hindcasts were identical; the ODGP model hindcast used a different wind field. Both wind fields, however, agreed well with measurements at the FULMAR (North Sea) verification site. Apparently, over the models shown, model performance depends more on subtle differences in the wind field and model tuning than on the rather different forms used for the source terms within the models.

So far, the third-generation model has undergone more limited evaluation in terms of storms. However, six extratropical storms that occurred in 1983 and 1984 on the western European continental shelf were hindcast and evaluated at several measurement sites.[9] Mean errors in SWH were generally less than 0.5 meter with scatter indexes between 10 and 20 percent. The third-generation WAM model has also been used to hindcast three Gulf of Mexico hurricanes, including the intense Hurricane Camille in 1969, with good results. A complete evaluation of these hindcasts is given in Ref. 9. Figure 4 compares the hindcast and measured frequency spectra associated with peak sea states in Camille at the measurement site directly in the path of the eye (the measurement system failed at the peak of the storm).

Wave Climate Assessment

There have been three applications of spectral wave models to provide basin-wide descriptions of the long-term wave climate. The Navy's 20-year hindcast study[16] used the first-generation SOWM model[13] to calculate the two-dimensional spectrum (180 components) at 6-hour intervals on a grid covering the entire northern hemisphere over the 20-year period 1956 to 1975. The Army performed a comparable study of the North Pacific and North Atlantic Oceans[17] with the second-generation model of Resio.[18] More recently, the Norwegian Meteorological Institute completed a 27-year hindcast of the eastern North Atlantic Ocean and Norwegian Sea with the second-generation SAIL model. Figure 5 (from Ref. 19) compares the hindcast and measured wave climate, expressed in terms of frequency distributions of SWH and peak spectral period, for a 5-year subset of the data at a measurement site in the northern Norwegian Sea. The results of these studies have been used extensively in engineering studies involving design and operation of coastal and offshore structures and in ship-response studies.

Real-Time Applications

The above-referenced studies were carried out with wind fields produced from historical meteorological data. The U.S. Navy and Norwegian wave models, among others, are used for real-time forecasting. Since the initial states for wave forecasts are generated in a hindcast mode from analyzed wind fields, the succession of wave analyses provided in the operational systems accumulates over time to provide a climatology. The accuracy of

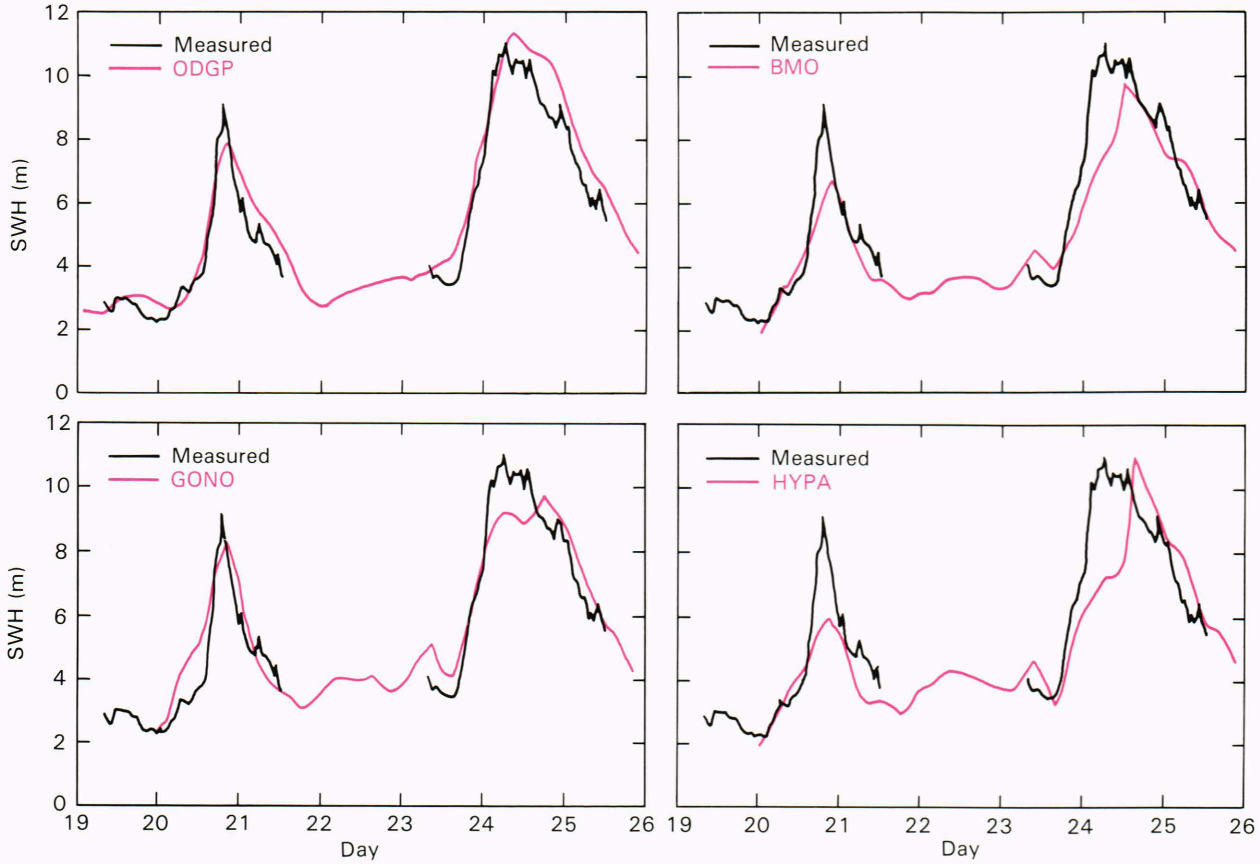

Figure 3—Validation of hindcast of North Sea storms at the FULMAR platform in the North Sea (BMO, GONO, and HYPA hindcasts), November 19-26, 1981 (after the Shallow Water Intercomparison Model Group[15]).

these real-time wave analyses appears to depend mainly on the accuracy of the wind fields used to drive the wave forecast system.[20] Figure 6 (from Ref. 20) compares errors in wind speed and SWH in predictions provided by the Navy SOWM system and a privately operated North Atlantic forecast system that uses the ODGP model.[21] The error statistics are derived from verification of twice-daily 48-hour forecasts over an 8-month period at six sites off the U.S. and Canadian east coasts. There appears to be an approximately linear growth of the SWH scatter index with the growth of the wind-speed scatter index. Forecast winds for the GSOWM at the sites are interpolated from objective forecast surface wind fields, while forecast wind fields for the ODGP are derived from surface-pressure-field forecasts from the National Oceanic and Atmospheric Administration after modifications have been applied in a real-time man-machine forecast system.

Basically, the same correlation has been demonstrated for GONO model forecasts in the North Sea.[22] It appears that current operations are limited mainly by the errors in input wind fields. This in itself should not be surprising. However, it is not generally realized that SWH and peak spectral frequency in deep water can be specified to an accuracy of 10 percent (scatter index) with present calibrated wave models, where winds are specified with random errors in speed and direction of about ±2 millimeters per second and ±20 degrees. The scatter of 25 to 35 percent in wave analyses derived from present operational model-based systems arises mainly because wind-field errors are about twice as large as those found in detailed hindcasts of case-study storms. The larger scatter in wave forecasts reflects the growth of errors in forecast wind fields derived from numerical weather prediction models.

FUTURE PROSPECTS

The present high level of activity in the international wave-modeling community portends continued rapid progress in the refinement and application of wave-prediction models. In addition to its wave-model work, WAM continues to address remaining basic questions involving the details of the spectral energy balance. Among these activities is a reanalysis of existing data sets on fetch-limited wave growth in order to develop a standard growth curve for deep-water wave generation. A related need is a more precise form of the atmospheric-input source term—one that includes the effects of atmospheric thermal stratification, the contribution of microscale and mesoscale gustiness, and possibly the effects of the sea state itself on the total air–sea momentum transfer. A second question concerns the directional properties of the wave spectrum in both equilibrium conditions and in situations of wave growth

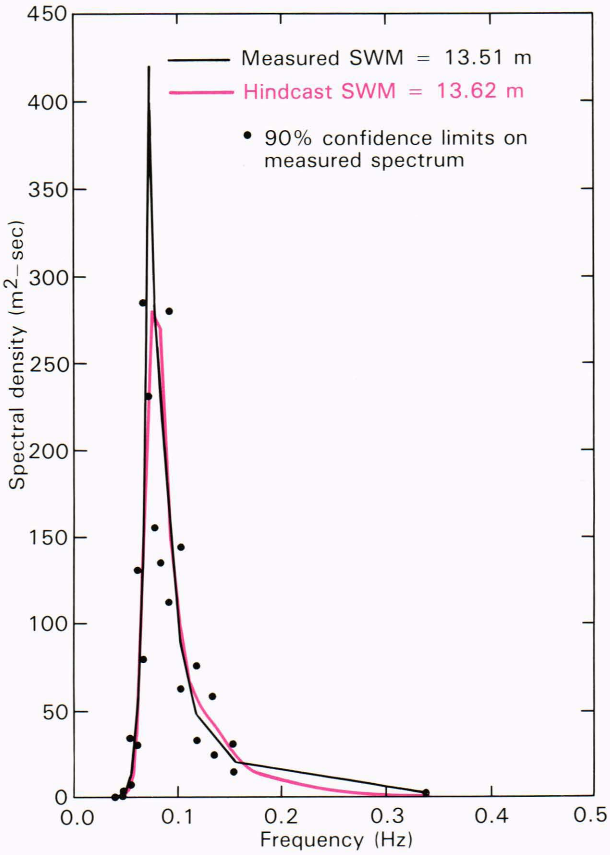

Figure 4—Measured and hindcast SWH in Hurricane Camile, August 17, 1969, 2100 GMT (after Hasselmann et al.[9]).

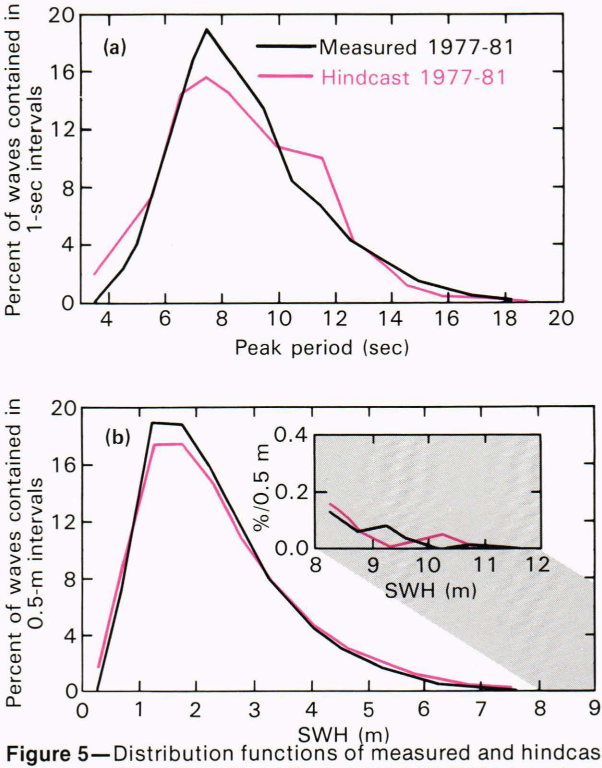

Figure 5—Distribution functions of measured and hindcast values at grid point 1032. (a) Peak period. (b) SWH; Insert: enlargement of distribution tail of SWH (after Eide et al.[19]).

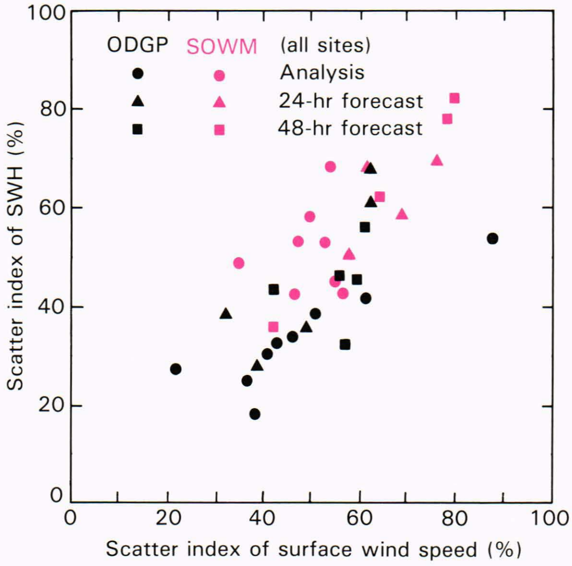

Figure 6—Correlation of wind speed and SWH scatter indexes (after Cardone and Szabo[20]).

in a turning wind. The research will be aided by the large increase in the quality and volume of directional wave-measurement data sets that have become available within the past few years. Finally, the details of the spectral energy balance in shallow water need to be better understood, particularly the form of the bottom-dissipation source term. This area of research is currently hindered by a lack of high-quality wave measurements in shallow water, though several new field programs are currently under way.

In wave model applications, the third-generation WAM model will likely become operational within a year or so at the European Centre for Medium Range Weather Forecasting in the form of a global model with a nested regional model covering the European continental shelf. Since third-generation models require about an order of magnitude greater computer time than second- or first-generation models, the latter two will continue to remain in widespread use on medium-speed mainframes, minicomputers, and supermicrocomputers. Indeed, as third-generation models are validated against measured data sets of the highest quality and as detailed features of the spectral energy balance are revealed, it is probable that some further improvements in the parametric source term representations of first- and second-generation models may be implemented in operational models.

In the near term (say 1 to 5 years) at least, more refined wave models may contribute little to improving skill in operational wave analyses and forecasts unless the accuracy of marine-wind analyses and forecasts is also improved. Such improvements are not likely to occur on a global scale until the early 1990s, when present programs to place remote microwave-sensing satellite systems in orbit are realized.

Cardone[20] has reported a case study of the severe North Atlantic storm of September 9 through 11, 1978, that damaged the ocean liner *Queen Elizabeth 2* and in which remotely sensed marine surface-wind data were obtained by Seasat. In that study, alternate representations of the surface wind field were produced in order to compare the specifications possible from the Seasat enhanced database with wind fields derived solely from operational pressure analyses based on conventional data. Over a three-day period during which the Seasat scatterometer viewed the developing storm at 12-hour intervals, the conventional operational analyses were found to be very poor despite the fact that the storm formed and moved through the active North Atlantic shipping lanes (Fig. 7).

The six-hour wind fields produced from combined conventional and Seasat wind data were used to drive a high-resolution, calibrated spectral ocean-wave model (the ODGP model) to hindcast the evolution of the sea state over the North Atlantic Ocean during the lifetime of the storm. This base-case hindcast was compared to a control wave hindcast driven by surface wind fields derived from an operational 6-hour pressure analysis. The large differences between the base-case and the control hindcasts (Fig. 8) are indicative of the very large errors that occasionally characterize real-time wave analysis.

The impact study also included a number of simulated 24-hour wave forecasts for which initial wave states

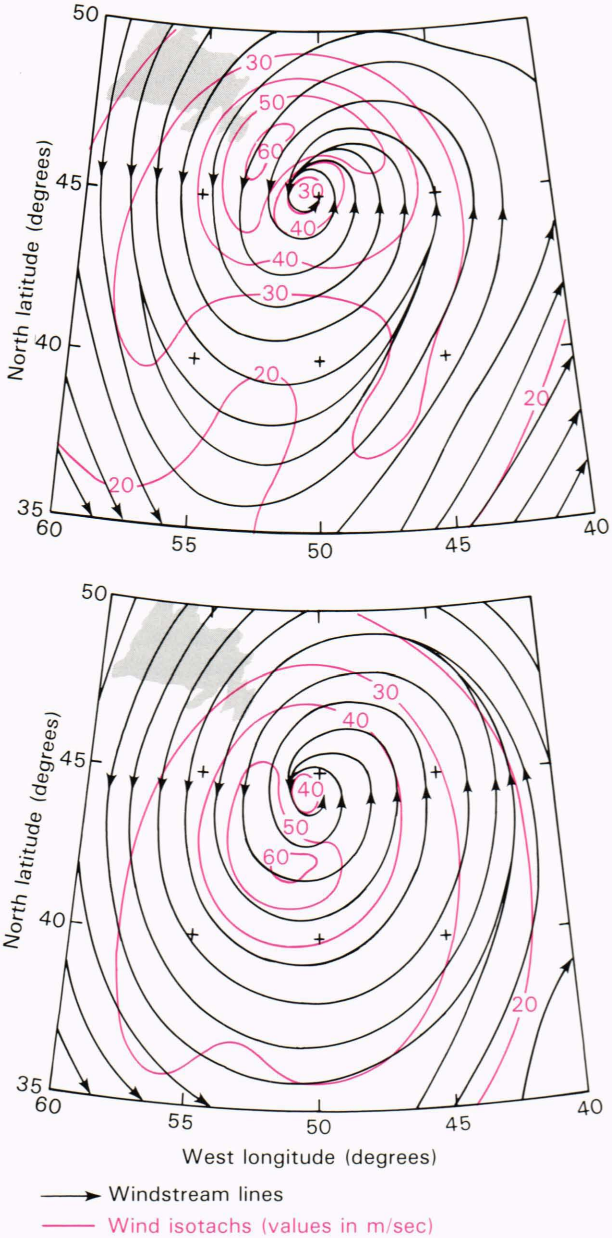

Figure 7—Comparison of an operational surface-wind field derived from the National Meteorological Center final analysis pressure field (top) and a base-case wind field from combined Seasat-A scatterometer system and conventional data (bottom) for 1200 GMT, September 10, 1978.

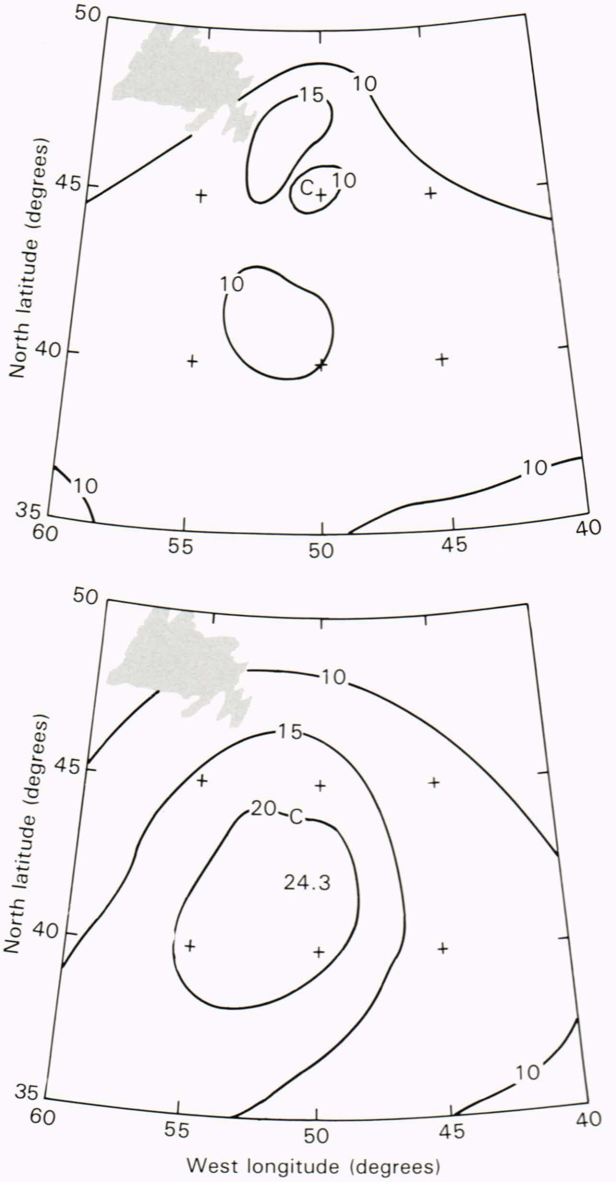

Figure 8—Comparison of hindcast SWH (at 5-foot contour intervals) from a simulated operational wind field (top) and the wind field derived from Seasat-A scatterometer system data (bottom) at 1200 GMT, September 10, 1978. The locations of the storm center are indicated as C. The maximum hindcast SWHs are also indicated.

were taken from either a base-case or a control hindcast run and in which forecast wind fields were derived from various forecast pressure fields. Table 2 (from Ref. 23) gives simulated verifications of these forecasts against sea states specified in the base-case hindcast for several runs, in terms of peak hindcast SWH and mean and root-mean-square errors in wind speed and SWH. In forecast run F1, the forecast pressure fields produced operationally at the Fleet Numerical Oceanography Center (FNOC) were used to provide forecast winds in the 24-hour period beginning 1200 GMT, September 9. In that period, the *Queen Elizabeth 2* storm central pressure deepened to 950 millibars, while FNOC specified only 999 millibars. The peak SWH was forecast to be 10.3 feet versus 24.3 feet in the base-case hindcast. In run F2, which used the same control initial state as F1, the experimental NWP model run of Anthes et al.[24] was used to provide wind fields. Their model captured about 30 percent of the explosive deepening observed in this 24-hour period, and peak sea states were closer to the base-case value, though still significantly lower (18.5 versus 24.3 feet).

Two 24-hour forecast experiments addressed the 24-hour period following 1200 GMT, September 10, during which the storm central pressure filled to 976 millibars, but peak SWH continued to build as the area of high winds about the storm expanded. It was at the end of this period that the *Queen Elizabeth 2* storm encountered peak SWHs estimated to be in the range of 35 to 40 feet. The base-case hindcast specified 37.2 feet. A 24-hour forecast run (F3) using the control run initial state and the NMC forecast model pressure fields from the National Oceanic and Atmospheric Administration predicted peak sea states to be less than half that observed (17.4 feet). The same forecast winds were used for run F4, but initial states were taken from the base-case hindcast. This run is intended to simulate the idealized situation in which spacecraft-derived wind and/or wave measurements together with a wave model provide a "perfect" specification of the directional spectrum. However, F4 produced a peak SWH only marginally greater than that provided by run F3.

These simulation experiments suggest that much of the benefit of spacecraft-monitoring of marine winds and sea states is lost in the first 12 to 24 hours of forecast horizon unless skill in numerical weather forecasts of intensity changes in marine cyclones is significantly improved from current levels. Until actual spacecraft data become available in the early 1990s, spectral wave models should be used in observing system-simulation experiments to assess the potential benefits of proposed remote-sensing systems, to develop and test algorithms for the assimilation of wind and wave data into wave models, and to help define the attributes of a future operational remote earth-observation system.

REFERENCES

[1] SWAMP (Sea Wave Modeling Project) Group (24 authors), *Ocean Wave Modeling,* Plenum Press, New York (1985).

[2] J. A. Ewing, "A Numerical Wave Prediction Method for the North Atlantic Ocean," *Dtsch. Hydrogr. Z.* **24,** 241–261 (1971).

[3] L. Bear, *An Experiment in Numerical Forecasting of Deep Water Ocean Waves,* Report LMSC-801296, Lockheed Missile and Space Co., San Diego (1962).

[4] T. P. Barnett, "On the Generation, Dissipation and Prediction of Ocean Wind Waves," *J. Geophys. Res.* **73,** 513–529 (1968).

[5] J. A. Greenwood and V. J. Cardone, *Development of a Global Ocean Wave Propagation Algorithm,* final report to Navy Fleet Numerical Weather Central, Monterey, CA, Contract N-00228-76-C-3081 (1977).

[6] J. A. Greenwood, V. J. Cardone, and L. M. Lawson, "Intercomparison Test Version of the SAIL Wave Model," in *Ocean Wave Modeling,* The SWAMP Group, Plenum Press, New York (1985).

[7] O. M. Phillips, "On the Generation of Waves by Turbulent Wind," *J. Fluid Mech.* **2,** 417–445 (1957).

[8] R. L. Snyder, R. W. Dobson, J. A. Elliot, and R. B. Long, "Array Measurements of Atmospheric Pressure Fluctuations above Surface Gravity Waves," *J. Fluid Mech.* **102,** 1–59 (1981).

Table 2—*Queen Elizabeth 2* storm wave-model impact experiments.[23]

			1200 GMT, September 10, 1978						*1200 GMT, September 11, 1978*					
					Field errors relative to base run*						*Field errors relative to base run*			
		Wind Field	P_0**	SWH_{pk}†	$WS^{††}$ *(m/s)*		*SWH (m)*		P_0	SWH_{pk}	*WS (m/s)*		*SWH (m)*	
Run	*Type*	*Source*	*(mb)*	*(ft)*	*Mean*	*rms*	*Mean*	*rms*	*(mb)*	*(ft)*	*Mean*	*rms*	*Mean*	*rms*
Base case	Hindcast	Seasat-A scatterometer system/ conventional analysis	950	24.3	–	–	–	–	976	37.2	–	–	–	–
Control	Hindcast	NMC 6-hr SLP***	980	10.0	−1.3	5.0	−0.8	1.5	978	26.6	−1.4	4.0	−0.3	0.9
F1	Forecast	Control + FNOC	999	10.3	−4.8	6.8	−1.6	2.2						
F2	Forecast	Control + Anthes[24]	984	18.5	−2.3	5.5	−0.4	1.3						
F3	Forecast	Control + NMC							996	17.4	−3.9	6.0	−1.5	2.2
F4	Forecast	Base + NMC							996	19.0	−3.9	6.0	−1.3	2.0

*Mean and rms errors computed relative to the base-case-run grid fields of SWH over the domain covering the storm circulation only.

**P_0 = minimum central pressure.

†SWH_{pk} = peak SWH.

††WS = wind speed at 20 m.

***NOAA National Meteorological Center sea-level pressure analyses.

[9] S. Hasselmann, K. Hasselmann, P. A. E. M. Janssen, G. J. Komen, L. Bertotti, A. Guillaume, V. J. Cardone, J. A. Greenwood, M. Reistad, and J. A. Ewing, "The WAM Model, a Third Generation Ocean Wave Prediction Model" (in preparation, 1986).

[10] K. Hasselmann, "On the Spectral Dissipation of Ocean Waves due to White Capping," *Bound.-Layer Meteorol.* **6,** 107–127 (1974).

[11] S. Hasselmann, K. Hasselmann, J. H. Allender, and T. P. Barnett, "Computations and Parameterizations of the Nonlinear Energy Transfer in a Gravity-Wave Spectrum, Part II: Parameterization of the Nonlinear Energy Transfer for Application in Wave Models," *J. Phys. Oceanog.* **15,** 1378–1391 (1985).

[12] V. J. Cardone, W. J. Pierson, and E. G. Ward, "Hindcasting the Directional Spectrum of Hurricane Generated Waves," *J. Petrol. Tech.* **28,** 385–394 (1976).

[13] R. M. Clancy, J. E. Kaitala, and L. F. Zambresky, "The Fleet Numerical Oceanography Center Global Spectral Ocean Wave Model, *Bull. Am. Meteorol. Soc.* **67,** 498–512 (1986).

[14] A. M. Reece and V. J. Cardone, "Test of Wave Hindcast Model Results against Measurements during Four Different Meteorological Systems," Offshore Technology Conference Paper No. 4323, 14th Annual OTC Conference (1982).

[15] SWIM Group (9 authors), "A Shallow Water Intercomparison of Three Numerical Wave Prediction Models," *Q. J. R. Meteorol. Soc.* **111,** 1087–1112 (1985).

[16] S. M. Lazanoff and N. Stevenson, "Preliminary Verification of the FNWC Twenty-Year Northern Hemisphere Wave Spectral Climatology," in *Proc. NATO Symp. Turbulent Fluxes through the Sea Surface—Wave Dynamics and Prediction,* Plenum Press, New York (1978).

[17] W. D. Corson and D. T. Resio, *Wave Information Study for Coastlines, Report II: Comparisons of Hindcast and Measured Significant Wave Heights,* Army Corps of Engineers Waterways Experiment Station, Vicksburg, Miss. (1981).

[18] D. T. Resio, "The Estimation of Wind-Wave Generation in a Discrete Spectral Model, *J. Phys. Oceanog.* **11,** 510–525 (1981).

[19] L. I. Eide, M. Reistad, and J. Guddal, *Data Base of Computed Wind and Wave Parameters for the North Sea, the Norwegian Sea and the Barents Sea, Every 6 Hours for the Years 1955–1981* (in Norwegian), Det Norske Meteorologiske Institutt, Oslo (1985).

[20] V. J. Cardone and D. Szabo, "Impact of Uncertainty in Specification of Offshore Wind Accuracy of Wave Hindcasts and Forecasts," in *Proc. Workshop on Offshore Winds and Icing* (1985).

[21] B. M. Eid, V. J. Cardone, and J. A. Greenwood, "Evaluation of Two Operational Spectral Ocean Wave Models: SOWM and ODGP," 19th Annual Canadian Meteorological and Oceanographic Society Congress, Montreal (Jun 1985).

[22] P. A. E. M. Janssen, G. J. Komen, and W. J. P. de Voogt, "An Operational Coupled Hybrid Wave Prediction Model," *J. Geophys. Res.* **89,** 3635–3654 (1984).

[23] V. J. Cardone, "Potential Impact of Remote Sensing Data on Sea-State Analysis and Prediction," final report to Contract No. NAS5-26890. (NASA/Goddard Space Flight Center), Oceanweather Inc. (1983).

[24] R. A. Anthes, Y. H. Kuo, and J. R. Gyakum, "Numerical Simulations of a Case of Explosive Marine Cyclogenesis," *Mon. Weather Rev.* **111,** 1174–1188 (1983).