l. (1988) "Ripple generation under
dian continental shelf." Continental

ween growth and dissipation in an
North Sea." Journal of Physical

(1985) "Similarity of the wind wave
rnal of Geophysical Research, Vol

ırnal of Geophysical Research, Vol

wind-wave model. Part I: Model
8, pp. 1465-1483.
hness in unsteady oscillatory flow."

wright, D.E., Enke, K., Ewing, J.A.,
rburg, A., Muller, P., Olbers, D.J.,
rements of wind-wave growth and
(JONSWAP)." Erganzungsheft zur
Nr. 12, 95 pp.
ectral wave attenuation by bottom
nference on Coastal Engineering,

)) "Movable bed friction factors for
nference on Coastal Engineering,

ted ripples." Journal of Geophysical

, K. (1978) "Nonlinear and linear
ılent fluxes through the sea surface,
Vol 1, pp. 347-365.
H: a third generation model for the
Communications on Hydraulic and
N 0169-6548, Rep. No. 89-2, 72 pp.
aves on slowly varying, unsteady and
ysical Oceanography, Vol. 21, pp.

l bottom-friction" Submitted for

or random ocean wave dissipation."

d swell in extreme depth-limited
1, pp. 149-172.
uced by saltating sediment." Journal

v." Coastal engineering, Vol.13, pp.

Advances in Hydro-Science and -Engineering, Volume I
Sam S.Y. Wang (ed.) *ISBN 0-937099-02-3 (2-Part Set)*

GLOBAL WAVE PREDICTION, USING THE WAM MODEL AND NMC WINDS[1]

H. S. Chen[2]

ABSTRACT

We employ the Cycle 3 version of the WAM (Wave Model) model (hereafter referred to as WAM3) and use forcing by the NMC (National Meteorological Center) winds to calculate global ocean wave spectra during the period from November 1991 to May 1992. The calculations have been conducted for wave hindcasts and forecasts using the analysis winds and forecast winds, respectively. The results of the WAM3 waves and the NMC winds have been compared with the NDBC (National Data Buoy Center) buoy data and with results from other models. The comparisons indicate that the WAM waves in general predict a good estimate of the significant wave height, but often underpredict the extreme waves when compared with the buoy data. Nevertheless, its accuracy and quantitative measures are shown to be slightly better than those from the other global models. The CPU time for a 24-hour prediction run on the NMC Cray YMP computer is about 150 seconds.

INTRODUCTION

Accurate understanding and prediction of wind waves is of considerable interest to marine forecasters, oceanographers, meteorologists, ocean engineers and coastal engineers. During the last five decades, the state-of-the-art in wind wave modeling and prediction has improved significantly from the empirical approaches of Sverdrup and Munk (1947) and Bretschneider (1958) (for example see the Shore Protection Manual 1984), to spectral approaches including directionality using the radiative transport equation (e.g. SWAMP Group 1985). At present, the most advanced directional spectral model is the so-called third generation wave model of which the WAM model is an example (WAMDI Group 1988). Although these computationally complex directionally spectral models have achieved significant improvements in wind wave prediction, many uncertainties still remain. Wind waves result from air-sea interaction as well as several other physical processes; specifically, wave propagation, refraction, and source functions. The source functions include atmospheric generation, wave-wave interaction, wave-current interaction, and wave dissipation. Some of these physical processes can be described with adequate precision, but others like atmospheric generation and wave dissipation are still incompletely understood and remain a challenge for both research and development. Despite this incomplete

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understanding of the source functions, many wind wave models are being used not only for marine forecasting and rational engineering design but also for understanding and verifying the mechanisms involved in wave evolution.

In this study we employed the WAM3 wave model and used the NMC winds as the driving force to calculate the global wave field. The calculated (WAM3) waves are compared with field data from the NDBC buoys and the results from other wave models. Quantitative measurements of the performance of the WAM3 waves are also included.

WAVE MODEL

The WAM model has been recently used for wind wave prediction as well as for the study of wind wave evolution. The model was originally developed by Hasselmann (1987) and has been continuously improved by the WAM Development and Implementation (WAMDI) group (The WAMDI Group 1988). The model is a third generation directional spectral model. It is based on a field solution of the radiative transport equation which, in the absence of currents, can be simply written as

$$\frac{\partial F}{\partial t} + \frac{\partial c_\phi F}{\partial \phi} + \frac{\partial c_\lambda F}{\partial \lambda} + \frac{\partial c_\theta F}{\partial \theta} = S_{in} + S_{nl} + S_{dis} \tag{1}$$

where $F(\phi, \lambda, t, f, \theta)$ is the wave energy density spectrum, (ϕ, λ) are latitude and longitude, t is time, f is the wave frequency, θ is the wave direction, $(c_\phi, c_\lambda, c_\theta)$ are the propagation velocities in the corresponding (ϕ, λ, θ) coordinates, S_{in} is the atmospheric source function, S_{nl} the source function for nonlinear energy transfer due to the resonant quartet-wave interactions, and S_{dis} the source function for wave dissipation due to whitecapping and bottom friction. In WAM3, S_{in} uses Snyder's empirical formulation (Snyder et al. 1981), replacing the wind velocity by the friction velocity based on Komen's scaling (Komen et al. 1984), while in the Cycle 4 version of the WAM model (hereafter referred to as WAM4) S_{in} uses Janssen's formulation based on a quasi-linear theory of wind-wave generation (Janssen 1989, 1991). The major difference between WAM3 and WAM4 relates to S_{in}; in the WAM3 model the wave growth rate depends only on wind velocity, while in the WAM4 model it depends on both wind velocity and wave age.

The WAM model uses a finite difference numerical scheme; a first-order upwind scheme is used for the advection term and an implicit second-order centered difference scheme for the source terms. The WAM model is also being continually improved with better wave physics and enhanced computational efficiency; therefore, the WAM computer code has several versions. The latest version is WAM4 and has been available since last summer. The reader is referred to Hasselmann (1987), The WAMDI (1988), and Günther, et al (1992) for a detailed description of the WAM model.

NMC WINDS

In the WAM model, surface wind is the only driving force used to generate wind waves. There are acknowledged difficulties in obtaining accurate surface wind fields, primarily due to low spatial and temporal resolution of the observational data. Nevertheless, the presently available wind models for wind analysis and forecasting are sufficient to provide reasonably accurate surface winds for this study. The NMC analysis and forecast winds have been selected for use in the wave hindcast and forecast, respectively. The analysis winds at 10 meters above the sea

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surface are derived from the analysis winds from the lowest sigma layer of the GDAS (Global Data Assimilation System) through a logarithmic profile adjustment and a correction due to air-sea temperature difference. The lowest sigma layer is within the atmospheric boundary layer just above the sea surface. For the forecast winds, the 10-meter winds are derived from the NMC Aviation Winds, with a similar adjustment and correction applied for the analysis winds. Quantitative measurements of the NMC analysis winds for this study are shown in Table 1. The reader is referred to Burroughs (1989) for more information on the NMC analysis and forecast 10-meter winds.

Table 1. Quantitative Measures of Analysis Wind

Mo/Yr	n	$\overline{o}$	$\overline{m}$	σ_o	σ_m	mae	$bias$	$rmse$	ia	cor
11/91	7657	7.24	7.54	3.38	3.36	1.90	0.30	2.54	0.85	0.72
12/91	4047	7.61	8.47	4.02	4.21	2.02	0.86	2.77	0.88	0.80
01/92	5863	6.98	7.64	3.97	4.10	2.02	0.67	2.75	0.88	0.78
02/92	4931	6.68	6.98	3.52	3.34	2.08	0.30	2.80	0.82	0.67
03/92	8564	6.94	7.48	3.57	3.51	2.05	0.54	2.82	0.83	0.70

n = number of data; o = obs data; m = model data; overline '-'= mean;
σ = standard deviation; mae = mean absolute error;
$rmse$ = root mean square error; ia = index of agreement; cor = correlation.
length unit = meter.

NUMERICAL CALCULATIONS

We use the NMC three-hourly analysis winds as input to the WAM3 model to hindcast 24-hour global ocean wave spectra and the NMC three-hourly forecast winds to forecast 72-hour global ocean wave spectra. Daily calculations were conducted during November 1991 through May 1992. The computational grid covers the global ocean region from 75S to 75N with a resolution of 3 degrees in both latitude and longitude. The wave spectrum is represented by 25 logarithmically spaced frequencies with the ratio of frequency increment to the frequency, being equal to 0.1 and the minimum frequency of 0.042 hz, and the wave directionality is resolved into 12 directions (i.e., 30 degrees per angular bin). The integration time step is 30 minutes for both propagation and source terms. The calculations were conducted on the Cray YMP computer at NMC. The CPU time for a 24-hour hindcast/forecast run is about 3 minutes which is about 7 times faster than a similar run on a Cyber 205 computer (Chen 1991).

RESULTS of HINDCAST and FORECAST

The calculated results for the WAM3 hindcast and forecast waves indicate that the synoptic patterns of the global waves in terms of the significant wave height, H_s, and mean wave direction, in general, respond closely to the global winds. The WAM3 waves are compared with the buoy data from 24 NBDC moored deep-water buoys. These buoy stations are 21004 and 22001 in the southern seaboard of Japan, 32302 in the western seaboard of Chile, 46001, 46002, 46003, 46005, and 46006 in the Gulf of Alaska and the western seaboard of Canada, 46035 in the Bering Sea, 46025 and 46042 in the western seaboard of California, 51001 and 51004 near the Hawaiian Islands, 17001 near the Antarctic Circle, 41001, 41002, 41006, 41008, 44004, 44008, 44011, and 44014 in the eastern seaboard of the United States, 42001 in the Gulf of Mexico, and 62108 in the western sea board of Ireland.

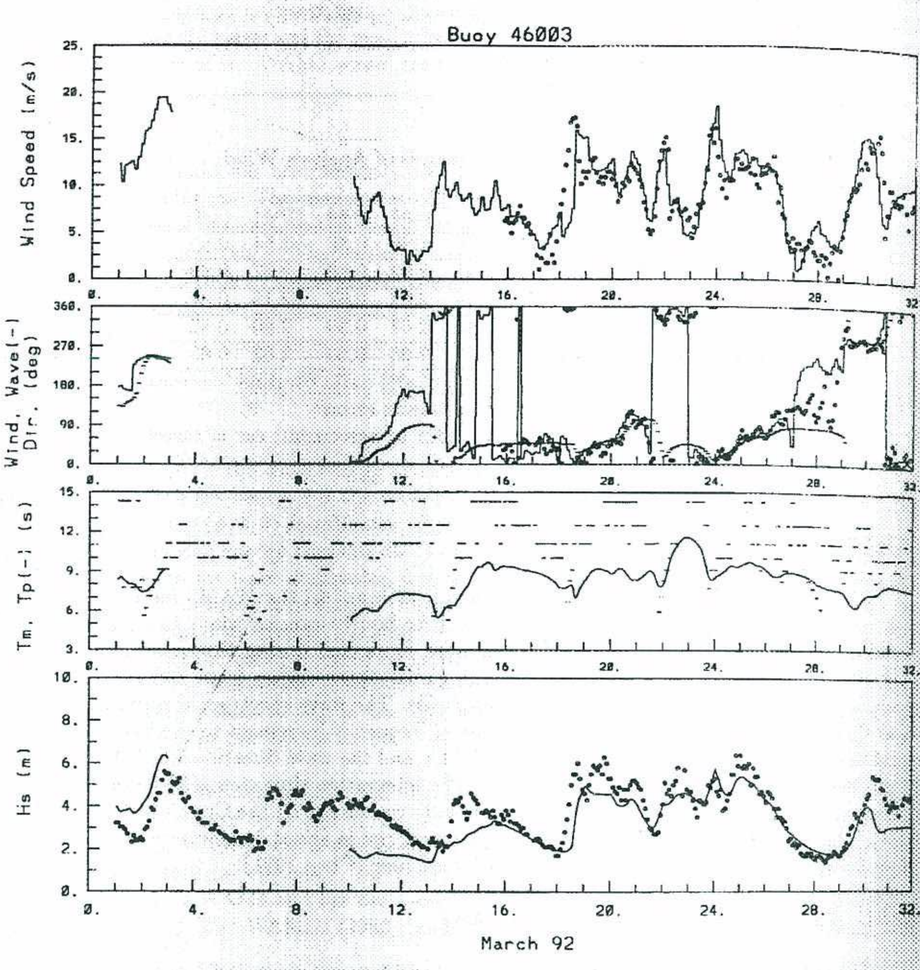

Figure 1. Time Series of Waves and Winds, where o o o buoy and — NMC wind or WAM3. In the second figure from top, - - - mean (WAM3) wave direction and the others for the NMC winds; in the third figure, T_p, - - -, peak (buoy) wave period and T_m, —, mean (WAM3) wave period.

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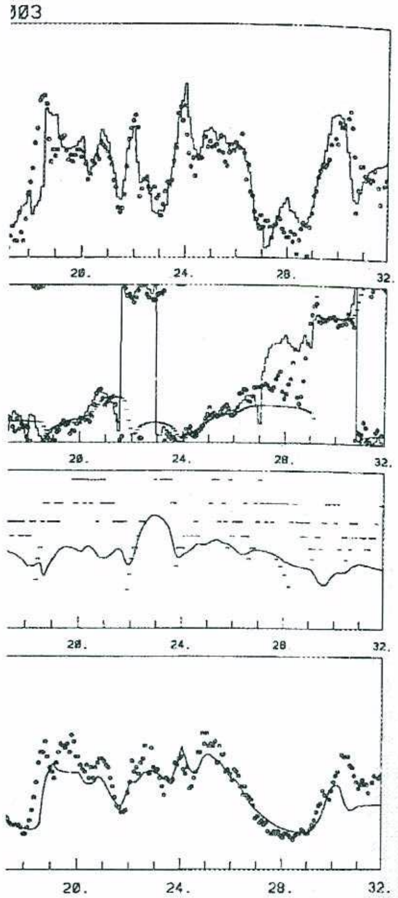
Comparison of H_s time series at the buoy stations indicate that the WAM3 waves generally agree closely with the buoy data, but often underestimate the extreme waves as typically illustrated in Figure 1. We note that from Figure 1 the model warm-up period may last 6 days from March 10 through 16. During this period, the wave fields have little memory of the past, therefore, the WAM3 waves would predict rather lower H_s waves. Quantitative measurements of the WAM3 24-hour hindcast waves are shown in Table 2. The average bias is $-0.6m$ and the average root mean square error is $1.55m$. Notably, the quantitative measurements could come up much better if all the WAM3 waves from the model warm-up periods had been excluded in performing the statistics. Quantitative measurements of the WAM3 72-hour forecast waves are shown in Table 3, where the NOW (NOAA Ocean Wave) model is another NMC operational global wave model. The WAM3 waves are clearly superior to the NOW waves.



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- - -, peak (buoy) wave period and T_m,

Table 2. Quantitative Measures of WAM3 Hindcast Waves

Mo/Yr	n	$\overline{o}$	$\overline{m}$	σ_o	σ_m	mae	$bias$	$rmse$	ia	cor
11/91	7657	2.43	1.93	1.53	1.11	0.64	-0.50	1.08	0.83	0.78
12/91	4047	3.17	2.37	2.38	1.40	1.03	-0.80	1.97	0.71	0.66
01/92	6649	2.90	2.35	1.91	1.31	0.75	-0.56	1.50	0.77	0.68
02/92	5504	2.45	1.85	1.60	0.89	0.77	-0.60	1.42	0.66	0.60
03/92	8697	2.67	2.09	2.02	0.99	0.83	-0.58	1.80	0.60	0.54

see Table 1 for notations

Table 3. Quantitative Measures of WAM3 Forecast Waves

Global — *Nov* 91

Model	n	$\overline{m}$	$\overline{o}$	σ_m	σ_o	cor	$bias$	$rmse$
24h forecast								
NOW	338	3.03	2.65	1.55	1.62	0.91	0.38	0.78
WAM3	203	2.27	2.47	1.39	1.53	0.88	-0.20	0.74
48h forecast								
NOW	338	3.11	2.65	1.59	1.62	0.89	0.46	0.89
WAM3	190	2.31	2.49	1.32	1.51	0.87	-0.18	0.76
72h forecast								
NOW	338	3.23	2.65	1.68	1.62	0.87	0.58	1.03
WAM3	176	2.46	2.50	1.37	1.47	0.85	-0.04	0.78

Global — *Dec* 91

Model	n	$\overline{m}$	$\overline{o}$	σ_m	σ_o	cor	$bias$	$rmse$
24h forecast								
NOW	751	3.25	2.88	1.57	1.61	0.88	0.37	0.87
WAM3	226	2.63	2.83	1.41	1.47	0.84	-0.20	0.83
48h forecast								
NOW	751	3.37	2.88	1.65	1.61	0.87	0.49	0.98
WAM3	240	2.69	2.81	1.49	1.56	0.85	-0.12	0.86
72h forecast								
NOW	751	3.47	2.88	1.68	1.61	0.84	0.59	1.11
WAM3	255	2.65	2.70	1.54	1.54	0.81	-0.05	0.95

Table 3. (continue)

Global *Jan 92*

Model	*n*	$\overline{m}$	$\overline{o}$	σ_m	σ_o	*cor*	*bias*	*rmse*
24h forecast								
NOW	738	3.39	2.89	1.55	1.49	0.86	0.50	0.96
WAM3	345	2.54	2.81	1.38	1.46	0.83	-0.27	0.88
48h forecast								
NOW	738	3.48	2.89	1.65	1.49	0.84	0.59	1.07
WAM3	325	2.60	2.82	1.42	1.48	0.84	-0.21	0.84
72h forecast								
NOW	738	3.55	2.89	1.80	1.49	0.81	0.65	1.24
WAM3	294	2.65	2.83	1.54	1.52	0.75	-0.18	1.10

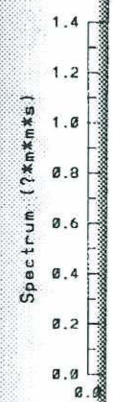
Global *Feb 92*

Model	*n*	$\overline{m}$	$\overline{o}$	σ_m	σ_o	*cor*	*bias*	*rmse*
24h forecast								
NOW	672	2.96	2.51	1.33	1.22	0.82	0.45	0.89
WAM3	246	2.08	2.44	1.06	1.25	0.85	-0.35	0.76
48h forecast								
NOW	672	3.04	2.51	1.38	1.22	0.80	0.53	0.99
WAM3	234	2.14	2.45	1.08	1.30	0.82	-0.31	0.80
72h forecast								
NOW	672	3.13	2.51	1.42	1.22	0.78	0.62	1.10
WAM3	247	2.35	2.52	1.24	1.33	0.76	-0.17	0.90

Global *Mar 92*

Model	*n*	$\overline{m}$	$\overline{o}$	σ_m	σ_o	*cor*	*bias*	*rmse*
24h forecast								
NOW	702	2.79	2.35	1.15	1.14	0.78	0.45	0.88
WAM3	298	2.26	2.46	1.11	1.20	0.81	-0.21	0.74
48h forecast								
NOW	702	2.89	2.35	1.21	1.14	0.78	0.54	0.95
WAM3	299	2.30	2.43	1.17	1.22	0.79	-0.13	0.78
72h forecast								
NOW	702	2.98	2.35	1.22	1.14	0.75	0.63	1.05
WAM3	302	2.41	2.48	1.14	1.24	0.77	-0.06	0.81

see Table 1 for notations



Figure

		Jan 92
cor	*bias*	*rmse*
.86	0.50	0.96
.83	-0.27	0.88
.84	0.59	1.07
.84	-0.21	0.84
.81	0.65	1.24
.75	-0.18	1.10

		Feb 92
cor	*bias*	*rmse*
.82	0.45	0.89
.85	-0.35	0.76
.80	0.53	0.99
.82	-0.31	0.80
.78	0.62	1.10
.76	-0.17	0.90

		Mar 92
cor	*bias*	*rmse*
.78	0.45	0.88
.81	-0.21	0.74
.78	0.54	0.95
.79	-0.13	0.78
.75	0.63	1.05
.77	-0.06	0.81

Table 3. (continue)

Global — *Apr 92*

Model	n	$\overline{m}$	$\overline{o}$	σ_m	σ_o	*cor*	*bias*	*rmse*
24*h forecast*								
NOW	754	2.39	1.92	1.04	1.01	0.76	0.46	0.85
WAM3	380	1.74	1.95	0.82	0.98	0.74	-0.21	0.70
48*h forecast*								
NOW	754	2.51	1.92	1.09	1.01	0.74	0.59	0.96
WAM3	381	1.86	1.96	0.89	0.98	0.72	-0.10	0.72
72*h forecast*								
NOW	754	2.60	1.92	1.13	1.01	0.69	0.68	1.08
WAM3	380	1.93	1.96	0.87	0.98	0.69	-0.04	0.73

Global — *May 92*

Model	n	$\overline{m}$	$\overline{o}$	σ_m	σ_o	*cor*	*bias*	*rmse*
24*h forecast*								
NOW	789	2.20	1.66	0.83	0.77	0.76	0.54	0.77
WAM3	349	1.54	1.81	0.56	0.73	0.70	-0.27	0.59
48*h forecast*								
NOW	789	2.22	1.66	0.80	0.77	0.71	0.56	0.82
WAM3	363	1.55	1.81	0.56	0.73	0.57	-0.25	0.67
72*h forecast*								
NOW	789	2.26	1.66	0.79	0.77	0.64	0.60	0.90
WAM3	363	1.54	1.79	0.55	0.73	0.46	-0.26	0.72

see Table 1 for notations

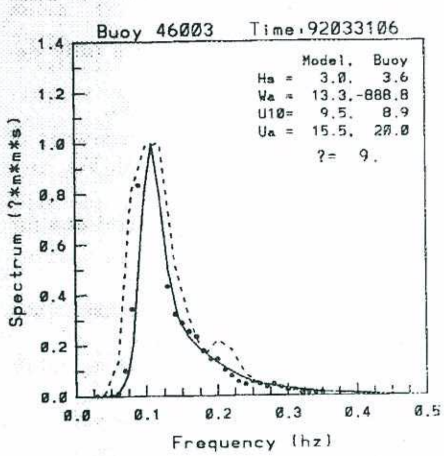


Figure 2. One Dimensional Wave Spectrum, where o o o buoy, — WAM3, and --- GMEX.

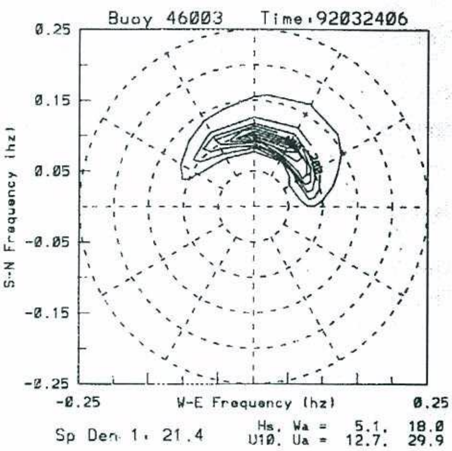


Figure 3. Two Dimensional (Directional) Wave Spectrum.

Comparison of one dimensional wave spectra shows that the spectral shapes of the WAM3 waves generally follows those of the buoy data, particularly they agree remarkably well at high frequencies, but the WAM3 spectra often underestimate near the peak frequency and low frequencies. For a relevant comparison, we have always selected cases where the model waves and buoy data have similar values of H_s; Figure 2 is a typical result. Note that in Figure 2 GMEX is the NMC Gulf of Mexico regional model using a grid resolution of 0.5 degree. Two dimensional wave spectra for the WAM3 waves, although observed data were not available for comparison, are generally reasonable since they correspond closely to the winds shown in Figure 3.

REFERENCES

Bretschneider, C.L., 1958: **Revisions in wave forecasting: Deep and shallow water**, Proc. Int. Conf. Coastal Eng. ASCE, 6th, pp 30-67.

Burroughs, L.D., 1989: **Ocean products center products review summary for 1988**, Technical Notes, OPC No.37, Ocean Products Center, NOAA.

Chen, H.S., 1991: **Wave calculation using WAM model and NMC winds**, Proceedings of 1991 ASCE Engineering Mechanics Conference;Mechanics Computing in 1990's and Beyond, Vol.1, pp 368-372.

Günther, H., Hasselmann, S., and Janssen, P.A.E.M., 1992: **The WAM model cycle 4**, DKRZ WAM Model Documentation Report No.4, Edited by Modellberatungsgruppe, Hamburg.ISSN 0940-9327.

Hasselmann, S., 1987: **Manual for The Use of The WAM Wave Model System**, Max-Plank-Institut für Meterologie, Hamburg.

Janssen, P.A.E.M., 1989: **Wave-induced stress and the drag of air flow over sea waves**, JPO, Vol. 19, pp 745-754.

Janssen, P.A.E.M., 1991: **Quasi-linear theory of wind-wave generation applied to wave forecasting**, JPO, Vol. 21, pp 1631-1642.

Komen, G.J., Hasselmann S. and Hasselmann K., 1984: **On the existence of a fully developed windsea spectrum**, JPO, Vol. 14, pp 1271-1285.

Shore Protection Manual, Vol.I, CERC, WES, U.S. Army Corps of Engineers, 1984.

Snyder, R.L., Dobson, F.W., Elliot, J.A. and Long, R.B., 1981: **Array measurements of atmospheric pressure fluctuations above surface gravity waves**, JFM, Vol. 102, pp1-59.

Sverdrup, H.U. and Munk, W.H., 1947: **Wind, sea and swell: Theory of relations for forecasting**, US Navy Hydrographic Office Publication 601.

The SWAMP Group, 1985: **Ocean wave Modeling**, Plenum Press, New York.

The WAMDI Group, Dec. 1988: **The WAM model - A third generation ocean wave prediction model**, JPO, Vol.18, pp 1775-1810.