93). Longshore current and wave height mod-
.de the surf zone. *J. Geophys. Res.*, 98(C9),

ıdsen (1997). Quasi-3D modeling of nearshore
tation), Res. Report CACR-97-04, Center for
ıv. of Delaware.

A New Global Wave Forecast System at NCEP [1]

Hendrik L. Tolman [2]

Abstract

This paper describes a new ocean wave prediction system which is presently being developed at the National Centers for Environmental Prediction (NCEP). The wave model is briefly described together with its global application in the forecast system. The validation of the wind fields and the wave model are discussed. NCEP's wind fields include a moderate systematic bias, which has reduced significantly with recent upgrades of NCEP's model suite. The new wave model (WAVEWATCH-III) required some modifications in its first practical application. With these modifications, the new model outperforms the WAM model in the tropics, and gives similar results at higher latitudes in a three-month hindcast study. A parallel comparison with NCEP's present operational WAM model has recently started.

1. Introduction

In the past five years a new wave model has been developed at Ocean Modeling Branch (OMB) of he National Centers for Environmental Prediction (NCEP). This model is called WAVEWATCH-III and is based on the WAM model (WAMDIG 1988, Komen et al. 1994) and on previous versions of WAVEWATCH (Tolman 1989, 1991, 1992). It nevertheless differs from its predecessors in all important aspects, i.e., the governing equations, model structure, numerical approaches and physics parameterizations. This model is extensively described in Tolman (1997), and a brief description presented here in section 2.

To test this model in practical conditions, a global application has been made, using NCEP's operational products as input. This global application is described

---

[1] OMB Contribution Nr. 152.

[2] UCAR Visiting Scientist, Ocean Modeling Branch, National Centers for Environmental Prediction, NOAA/NWS, 5200 Auth Road Room 209, Camp Springs, MD 21746, USA. E-mail: Hendrik.Tolman@NOAA.gov

in section 3. Validation of this forecast system is performed in three stages. (i) Validation of wind fields. (ii) Validation of the wave model in hindcast mode using the best possible winds. (iii) Validation of the entire system (wind and wave models) in forecast mode and parallel comparison with NCEP's operational WAM model. Stages (i) and (ii) consider hindcasts for the period of December 1994 through February 1995.

Presently (December 1997), the first two stages of the validation study are completed or nearing completion. The results of the wind validation are described briefly in section 4. The wind speeds show moderate systematic biases both against buoy data and satellite data. Because the operational weather models are continually being updated and improved, the wind speed biases also have to be monitored continuously, and bias corrections have to be updated when necessary. The validation of the wave model in hindcast mode is nearing completion and the results are briefly described in section 5. It is shown that the model required some modification to the parameterizations of the physics regarding aspects not covered by the previous testing in idealized conditions (e.g., Tolman and Chalikov, 1996). With these modification, WAVEWATCH-III shows similar model behavior as WAM at high latitudes, but better behavior at low latitudes. The parallel forecast model comparison has started December 1, 1997, and its results will be presented elsewhere. Results of the parallel model runs can be inspected on the OMB home page at http://polar.wwb.noaa.gov under the experimental products section (NOAA Experimental Wave model).

2. Model description

A detailed description of version 1.15 of WAVEWATCH-III as used in NCEP's new wave forecast system can be found in its manual (Tolman 1997)[3]. Here, only a brief description will be presented.

WAVEWATCH-III solves the spectral balance equation for the action density spectrum N as a function of the wavenumber k and the direction θ

$$\frac{D\,N(k,\theta)}{D\,t} = \frac{S}{\sigma} \ , \tag{1}$$

where S represent the net source term for the conventional variance ('energy') spectrum $F = N\,\sigma$, and σ represents the intrinsic frequency

$$\sigma = \sqrt{gk\ \tanh(kd)} \ , \tag{2}$$

and where d represents the mean water depth.

The left side of Eq. (1) describes linear propagation, including shoaling, depth refraction, and wave-current interactions. For the present global application, wave-current interactions are not considered, and shallow water effects are fairly irrelevant (although the model is formally run as a shallow water model). Effects of propagation are calculated using the third-order accurate ULTIMATE QUICKEST scheme (Leonard 1979, 1991; Tolman 1995), using time steps that scale with the frequency or wavenumber of the spectral component considered. To avoid reduced resolution in shallow water implicit to the use of the wavenumber spectrum for the description of the wave field, a variable wavenumber grid corresponding to an invariant frequency grid is used (Tolman and Booij, 1998).

The right side of Eq. (1) represents sources and sinks in the balance equation, including relevant nonlinear propagation effects. The net source S is generally considered to consist of several constituents,

$$S = S_{wind} + S_{nl} + S_{ds} + S_{bot} \ , \tag{3}$$

where the terms on the right side represent wind-wave interactions, resonant wave-wave interactions, dissipation ('whitecapping') and wave-bottom interactions. In WAVEWATCH-III these terms are modelled according to Chalikov and Belevich (1993), Hasselmann et al. (1985), Tolman and Chalikov (1996) and JONSWAP (1973), respectively. The source terms are integrated in time using a semi-implicit numerical scheme (WAMDIG, 1988), with a dynamically adjusted time step (Tolman 1992, 1997), which concentrates computation effort in locations where spectra are subject to rapid changes.

3. A global application

For testing purposes, WAVEWATCH-III has been run on a global grid with a longitude-latitude resolution of 1.25°×1°. The grid covers an area from 78° S to 78° N. The spectrum is discretized using 24 equally spaced directions and 25 logarithmically distributed frequencies ranging from 0.041 Hz to 0.42 Hz. This model runs twice daily, performing a 12h hindcast and a 72h forecast.

The wind fields driving the wave model are obtained from NCEP's operational Global Data Assimilation Scheme (GDAS) and the aviation cycle of the Medium Range Forecast model (AVN) (Kanamitsu 1989, Kanamitsu et al. 1991, Derber et al., 1991, Caplan et al., 1997). The winds are converted from the lowest model level to 10m height assuming neutral stability. These wind fields are available at 6h intervals for the hindcast studies of stages (i) and (ii) of the validation, and at 3h intervals for the parallel forecast comparison (using analyses and 3h forecasts in the hindcast part of the wave model run). The wind speeds are corrected statistically as described in section 4.

As is described in section 5, WAVEWATCH-III accounts for effects of atmospheric stability on wave growth. The wave model therefore also requires stability information. This information is obtained from the lowest level air temperatures of the above wind models, and sea surface temperatures from the 50km SST analysis provided by NESDIS (updated two times per week).

Finally, the wave model incorporates a dynamically updated ice coverage in polar regions. These data are obtained from NCEP's operational automated passive microwave sea ice concentration analysis (Grumbine 1996) (updated daily).

---

[3] Available as a postscript file on http://polar.wwb.noaa.gov (OMB home page) .

4. Wind fields

In the first stage of the validation study the wind fields driving the wave model are validated using buoys and satellite data for the period of December 1994 through February 1995. Observations at deep-ocean buoys and satellite data from the ERS-1 altimeter and scatterometer are considered. This part of the validation has been completed, and the results will be published in full in Tolman (1998a). Here, only the main findings will be presented.

Wind observations from buoy data are considered to be free of biases. Using these data, the analyzed GDAS wind speeds are shown to have a moderate but systematic bias, for which the following statistical correction is obtained

$$U_c = -1.26 \text{ ms}^{-1} + 1.12\, U_o \ , \qquad (4)$$

where U_o and U_c represents the original and corrected wind speeds, respectively. Although this correction is fairly moderate, it can have a noticeable impact on a wave model because the wave height scales approximately with the square of the wind speed. Biases for the forecast AVN wind speeds against buoy observations are larger, but appear to be related to random rather than systematic errors, and can therefore not be corrected statistically (Tolman 1998a).

Unfortunately, buoy observations cover only a small part of the worlds oceans, and a validation using these data can therefore not be considered as truly global. A truly global validation can only be performed with satellite data. Unfortunately, satellite data are generally inferred rather than direct observations, and are known to be prone to systematic errors. To minimize the latter errors, satellite data have been collocated with buoy observations and systematic errors are corrected statistically (see Tolman 1998a). Below, the error corrected satellite observations are simply denoted as the satellite observations.

Of particular interest is the altimeter data, as it provides collocated wind and wave observations. The altimeter wind data, however, are systematically contaminated by the local wave conditions, and should therefore not be used when validating a wave forecast system. Scatterometer wind observations do not appear to be influenced by the local wave conditions, and will therefore be used here. The GDAS wind speeds show a similar bias against the scatterometer data as derived from the buoy data [Eq. (4)], and the corresponding subjective correction (mostly based on northern hemisphere data) is given as

$$U_c = -1.50 \text{ ms}^{-1} + 1.10\, U_o \ . \qquad (5)$$

For the forecast AVN wind fields, systematic biases change somewhat in the tropics, but again most changes in biases appear to be related to random rather than systematic forecast errors. From Eqs. (4) and (5) a blended bias correction is constructed, where Eq. (4) is used near the coast and near buoy locations (note that most 'deep-ocean' buoys are still fairly close to the coast), and where Eq. (5) is used in the deep ocean.

The GDAS and AVN are in a continuous state of development. For instance, major changes were implemented late 1995 (Caplan et al. 1997), and the amount of marine satellite data ingested by the GDAS changed significantly in November 1997. The above bias correction can therefore only be considered as a snapshot. Within the wave forecast system, the systematic errors of the wind fields have to be monitored continuously. This systematic monitoring has started in February 1997 using buoy and ERS-2 data. For the period of February through October 1997, the following bias correction based on buoy data was found

$$U_c = -0.30 \text{ ms}^{-1} + U_o \ , \qquad (6)$$

whereas the GDAS biases against buoy data since November 1997 appear to be even smaller (based on the limited data collected since then). The difference between Eqs. (4) and (6) illustrate the need for continuous monitoring of wind speed errors. These more recent bias corrections will be published in more detail elsewhere, and will eventually be posted on the OMB home page.

5. Wave model validation

In the second stage of the validation study WAVEWATCH-III is tested in hindcast mode for the period of December 1994 through February 1995. After some modifications to the wave model have been defined, it is compared to the WAM model. This part of the validation study nears completion, and results will be published in full in Tolman (1998b). As with the first stage of the validation study, only a brief summary of results will be given here.

5.a WAVEWATCH validation

Up to the present application, WAVEWATCH-III has only been tested in idealized conditions (Tolman and Chalikov 1996, Tolman 1995). These idealized tests do not cover the following three points, which all have to be addressed in a practical application.

- In Tolman and Chalikov (1996), WAVEWATCH-III is tuned to data for either a stable or unstable atmospheric boundary layer. For a practical application a tuning has to be selected, and possibly the effects of stability have to be accounted for explicitly.
- Swell propagation has been tested only as a pure propagation problem without source terms. The input term of Chalikov and Belevich (1993), however, includes a mechanism where swell looses momentum to the atmosphere in low or adverse wind conditions. This mechanism has not been the subject in any of the above idealized tests.
- Wave growth tests in Tolman and Chalikov consider fetch-limited growth, but the saturation behavior for unlimited fetch is touched upon only briefly and might need to be reconsidered in a practical application.

Testing WAVEWATCH-III for the above hindcast period has shown that both the model tuning and swell propagation needed some attention and require modifications to the wave model. Saturation behavior did not require modifications.

Waves grow more rapidly under conditions of unstable atmospheric stratification than in stable conditions. The increased growth rate is much larger than can be explained from the corresponding increase in surface stress / momentum transfer (Kahma and Calkoen 1992, 1994). Because the atmospheric stratification over the open ocean is mostly neutral, it is expected that a model tuned to the corresponding growth curves would render good results over a large part of the global ocean. Such a version of WAVEWATCH-III, however, proved to result in a systematic negative bias throughout the world's oceans when compared to the altimeter wave height data. This bias is effectively removed if the model is retuned to represent growth curves for unstable stratification conditions. This appears to be a deficiency in the model physics which appears to be shared by the WAM model; WAM also gives good results in the open ocean but simultaneously reproduces growth curves for unstable stratification conditions. This deficiency might well be related to errors in the Discrete Interaction Approximation used to estimate nonlinear interactions, as will be discussed in detail in Tolman (1998b).

It should be noted that there are several ways to retune the wave model. Intuitively, the tuning strategy outlined in Tolman and Chalikov (1996) should be used. This is a cumbersome method, and does not solve the underlying problems with the parameterization of the physics. An alternative and simple method used here is to retune the model by defining an effective wind speed internal to the model. This allows for easy tuning and keeps the balance between source terms intact. It is also allows for simple way of incorporating additional effects of instability as will be discussed below.

After the general retuning as outlined above, negative biases remain in systematically unstable regions like the Gulf Stream and the Kuroshio. The potential effects of stability on wave growth within the model is assessed by considering model errors against buoy data as a function of the stability parameter *ST*

$$ST = \frac{gh}{U_h^2}\,\frac{T_a - T_s}{T_o} \quad , \qquad (7)$$

where h is the observation height and T_a, T_s and T_o are the air, sea and reference temperature. Such an analysis indeed suggests that wave growth is systematically underestimated in areas with unstable conditions. Ideally, effects of stability would be included in the physics of the model. Designing such physics parameterizations, however, would require an effort well outside the scope of the present validation study. As a simple ad-hoc solution, an effective wind speed is used inside the model. Details of the effective wind speed will be published in Tolman (1998b).

Even with the above corrected tuning of the model, it was found that wave heights in the tropics where severely underestimated. This behavior can be attributed to the decay of swells by winds in the Chalikov and Belevich (1993) input source term, which apparently was modelled too strong. The corresponding part of this input source term is based on a part of a numerical model of the air flow over waves that was poorly resolved and included large interpolation errors (Chalikov, personal communication), Recalculation with a more efficient model suggested that the swell momentum loss due to winds might have been overestimated by up to an order of magnitude. In WAVEWATCH-III, this error is corrected by reducing the negative swell 'input'. Based on repeated model runs and the altimeter wave height data, the negative input for swell was reduced to 15% of its original strength. With this correction, remaining wave height biases against the altimeter data are small and more or less randomly distributed over the global domain. Remaining areas with larger biases all appear to be related to island chains that significantly inhibit swell propagation but that are not resolved by the model grid. The most prominent examples are the Aleutian Islands and the Bismarck and Solomon Islands.

5.b Comparison to WAM

With the above corrections WAVEWATCH-III appears to give reasonable results. To compare it with the state-of-the-art, cycle 4 of the WAM model has been run on the same grid and with the same input[4]. Details of this comparison will again be published in Tolman (1998b). The following are some of the findings:

- Compared to the altimeter wave height data WAM shows moderate negative biases in storm tracks at higher latitudes, and moderate positive biases in the tropics (particularly in the Pacific Ocean). The biases are generally larger than in WAVEWATCH-III and could be considered to support the theory that swell looses energy to the atmosphere (contrary to the assumptions in WAM).
- Overall rms errors of WAM and WAVEWATCH-III at high latitude (altimeter and buoy data) are similar, with WAM generally showing slightly better results.
- Overall rms errors of WAM in the tropics, particular in the Pacific Ocean, are up to a factor of two larger than in WAVEWATCH-III. Both biases and random errors contribute to this difference.
- In the deep ocean away from unresolved geographical features, the rms error of WAVEWATCH is roughly 10-15% of the mean observed wave height. For WAM such errors range from 10% in the storm tracks to up to 25% in the eastern tropical Pacific Ocean.

Apart form the model performance, its economics are of importance. The new model might be expected to be significantly more expensive due to is higher-order accurate numerical schemes. This is offset, however, by the generally more economical time step management. Furthermore, grid points covered with ice are taken out of the computation in WAVEWATCH-III, whereas the wave energy at such points is set to zero after the calculations in WAM.

---

[4] WAM was run without a dynamically updated ice edge. Experience with parallel versions of WAM at NCEP suggest that effects of the ice edge are confined to a relatively narrow margin around polar ice fields.

Table 1 : Numerical economy of WAM and WAVEWATCH-III for the present global application on a Cray C90.

	blocks and blocksize	CPU's	memory required (Mw)	CPU and IO wait time (s/day)
WAVEWATCH-III	1 / 30030	1	24	830 / 25
		12	31	835 / 25
WAM	1 / 30030	1	57	740 / 5
	20 / 2048	1	7.5	850 / 190

In Table 1, the numerical economy of several applications of WAVEWATCH-III and WAM is compared. Several remarks need to be made regarding this table

- WAM has the option to divide the computational domain in several 'blocks' in order to reduce the memory requirements of the model. WAVEWATCH-III does not have such an option.
- WAM has been parallelized elsewhere, but not for this study. All IO was performed to conventional 'slow' disks and WAM produced considerably less output than WAVEWATCH-III.
- CPU time needs for WAM do not vary much from day to day, but requirements for WAVEWATCH-III depend on both weather conditions and ice coverage and are therefore estimates. In particular during the southern hemisphere winter the CPU time requirements generally drop by more than 10%.

Table 1 shows that resource requirements for both model are fairly similar. WAM can be run using less memory than WAVEWATCH-III if small blocks are used. WAM is somewhat faster than WAVEWATCH-III when a 1-block version is used, but then requires more than double the memory.

6. Discussion and conclusions

The validation of a new wave forecast system at NCEP is under way. The validation of the wind and wave models comprising this system is (largely) finished, and the entire system is presently being compared in forecast mode with the operational implementation of WAM at NCEP. For this purpose, a parallel forecast is performed with the new system since December 1997.

The first part of the validation study shows that the wind fields produced by NCEP include moderate but noticeable systematic biases, for which statistical corrections can be defined. The magnitude of these biases has significantly decreased with recent updates to NCEP's global analysis and models.

The second part of the validation study shows that the wave model used in the new forecast system (WAVEWATCH-III) compares favorably against the well known WAM model. At high latitudes, the new model shows slightly poorer results than WAM, but at low latitudes, the new model preforms much better. Two remarks need to be made regarding this comparison of wave models. First, this is the first attempt to use radically different parameterizations of the physics in a practical application. The fact that this new model performs at least similar to the well-established and fine-tuned WAM model is promising. Secondly, WAVEWATCH-III and WAM have been tuned or developed in systematically different ways. Following conventional procedures, WAM has been developed almost entirely depending on buoy data. The modifications to WAVEWATCH-III as described here, on the other hand, lean heavily upon mean biases from global altimeter data, ignoring buoy data. It is therefore not surprising that WAM show excellent behavior when compared to buoy data, and that WAVEWATCH-III shows small biases throughout the domain. The fact that the latter model shows similar results than WAM when compared to the buoy data in spite of the fact that this was not the target of the latest modifications of the model strongly support its new parameterizations of the physics.

The new forecast system is presently being compared to the operational WAM model at NCEP. These two systems differ not only in wind fields and wave model, but also in numerical model resolution. Particularly, the operational WAM model is implemented with a spatial resolution of 2.5° in longitude and latitude, and with a spectrum containing 12 directions. Results of both forecast systems can be found on the OMB home page at http://polar.wwb.noaa.gov under the operational and experimental sections, respectively.

References

Caplan, P. J., Derber, W. Gemmill, S.-Y. Hong, H.-L. Pan and D. Parish, 1997, Changes to the 1995 NCEP operational medium-range forecast model analysis/forecast system. *Wea. Forecasting*., **12**, 581-594.

Chalikov, D.V., and M.Y. Belevich, 1993, One-dimensional theory of the wave boundary layer. *Bound.-Layer Meteor*., **63**, 65-96.

Derber, J.C., D.F. Parish, and S.J. Lord, 1991, The new global operational analysis system at the National Meteorological *Center. Wea. Forecasting* , **6**, 538-547.

Grumbine, R.W., 1996, Automated passive microwave sea ice concentration analysis at NCEP. NWS/NCEP/OMB technical note **120**, 13pp.

Hasselmann, S., K. Hasselmann, J.H. Allender and T.P. Barnett, 1985, Computations and parameterizations of the nonlinear energy transfer in a gravity-wave spectrum, Part II: Parameterizations of the nonlinear energy transfer for application in wave models. *J. Phys. Oceanogr*., **15**, 1378-1391.

Kahma, K.K. and C.J. Calkoen, 1992, Reconcilingdiscrepancies in the observed growth rates of wind waves. *J. Phys. Oceanogr*., **22**, 1389-1405.

Kahma, K.K. and C.J. Calkoen, 1994, Growth curve observations. In: Komen et al., 1994, 174-182.

Kanamitsu, M., 1989, Description of the NMC global data assimilation and forecast system. *Wea. Forecasting*, **4**, 335-243.

Kanamitsu, M., J.C. Alpert, K.A. Campana, M.P. Caplan, D.G. Deaven, M. Iredell, B. Katz, H.-L. Pan, J. Sela, and G.H. White, 1991, Recent changes implemented into the global forecast system at NMC. *Wea. Forecasting* , **6**, 425-435.

JONSWAP Group, 1973: Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). *Ergänzungsheft zur Deutschen Hydrographischen Zeitschrift*, Reihe A (8) Nr. **12**, 95 pp.

Komen, G.J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann and P.E.A.M. Janssen, 1994, *Dynamics and modelling of ocean waves*. Cambridge university press, 532 pp.

Leonard, B.P., 1979, A stable and accurate convective modelling procedure based on quadratic upstream interpolation. *Comput. Methods Appl. Mech. Engng.*, **19**, 59-98.

Leonard, B.P., 1991, The ULTIMATE conservative difference scheme applied to unsteady one-dimensional advection. *Comput. Methods Appl. Mech. Engng.*, **88**, 17-74.

Tolman, H. L., 1989, The numerical model WAVEWATCH: a third generation model for the hindcasting of wind waves on tides in shelf seas. *Communications on Hydraulic and Geotechnical Engineering*, Delft Univ. of Techn., ISSN 0169-6548, Rep. no. 89-2, 72 pp.

Tolman, H. L., 1991, A third-generation model for wind waves on slowly varying, unsteady and inhomogeneous depths and currents. *J. Phys. Oceanogr.*, **21**, 782-797.

Tolman, H. L., 1992, Effects of numerics on the physics in a third-generation wind-wave model. *J. Phys. Oceanogr.*, **22**, 1095-1111.

Tolman, H. L., 1995, On the selection of propagation schemes for a spectral wind wave model. NWS/NCEP Office Note 411, 30 pp. + figures.

Tolman, H. L., 1997, User manual and system documentation of WAVEWATCH-III version 1.15. NOAA/NWS/NCEP OMB Technical Note Nr. **151**, 97 pp.

Tolman, H. L., 1998a, Validation of NCEP's ocean winds for the use in wind wave models. Submitted.

Tolman, H.L., 1998b, Validation of a global application of NCEP's new ocean wave model. In preparation.

Tolman, H.L., and D.V. Chalikov, 1996, Source terms in a third-generation wind wave model. *J. Phys. Oceanogr.*, **26**, 2497-2518.

Tolman, H. L., and N. Booij, 1998: Modeling wind waves using wavenumber-direction spectra and a variable wavenumber grid. Submitted.

WAMDIG, 1988, The WAM model - a third generation ocean wave prediction model. *J. Phys. Oceanogr.*, **18**, 1775-1810.