



**INTERNATIONAL SYMPOSIUM: WAVES -  
PHYSICAL AND NUMERICAL MODELLING**

UNIVERSITY OF BRITISH COLUMBIA,  
VANCOUVER, CANADA

AUGUST 21 - 24, 1994

**DEVELOPMENT OF A THIRD-GENERATION  
OCEAN WAVE MODEL AT NOAA/NMCC.<sup>1</sup>**

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**ABSTRACT**

A new third generation wave model (WAVEWATCH III) is presently being developed at NOAA/NMCC. The present paper gives a general description of the model and focusses on (i) the functional design, (ii) the governing balance equation and a new variable-grid approach developed for this equation, and (iii) on the development of a new source term package. The new source terms are shown to improve fetch-limited model behavior significantly. Our approach to dissipation, considering high and low frequency dissipation separately, potentially simplifies the systematic investigation of the effects of whitecapping within the wave energy balance.

**INTRODUCTION**

Wave prediction has been an integral part of the activities of the Marine Prediction Branch of the Development Division of NOAA/NMCC for several years. Until recently, all forecasts were made using a locally customized implementation of the second-generation SAIL model [Greenwood et al., 1985], the so-called NOW (NOAA Operational Wave) model. More recently, several versions of the third generation WAM model [WAMDIG (1988)] have been implemented. A third-generation wave model integrates the spectral energy balance equation using first principles only, i.e., without assuming a spectral

<sup>1</sup> OPC contribution Nr. 88.

shape. Such models are significantly more expensive than previous models, but are generally assumed to be superior as they (by design) are universally applicable without the need of re-tuning, and as they allow for direct implementation of new parameterizations of the actual physical processes.

In spite of the apparent success of the WAM model, there is room for improvement in third generation wave modelling. WAM uses simple first order propagation schemes, and the source terms of WAM result in inaccurate growth behavior for short fetches (as will be shown below). Optimization considerations have furthermore influenced the transparency of the source code of WAM, which somewhat hampers experiments to improve WAM. Considering the above, development of a new third-generation wave model has been initiated at NOAA/NMCC. This model (WAVEWATCH III) is a further development of WAM and WAVEWATCH (Tolman, 1991). Its application is intended for global and regional scales, with grid resolutions of typically 10 km or larger, and depths of typically 10 m and larger.

Presently (march 1994), the general system design for WAVEWATCH III has been finished, and a test version of the new model using simple first order propagation schemes and the source terms of WAM cycles 1-3 has been coded, tested and optimized. Meanwhile, a new source term package is being developed independently (using WAVEWATCH II, Tolman 1991, 1992). The search for a new propagation schemes is still ongoing, although several proven higher order scheme are readily available [e.g., Neu and Won (1990), Tolman (1991, 1992)]. As the model is still under development, a complete description cannot be given here. The present paper will consider the following subjects. First, the functional design of the model will be discussed briefly, together with the computational economy of the model. Secondly, the selected balance equation will be discussed, together with a new variable-grid approach used to solve this equation. Thirdly we will outline the new physics package and present some initial results for standard fetch-limited wave growth tests.

**MODEL DESIGN**

The intended range of application of the new model as described above implies that effects of finite depths and currents are potentially important. The bathymetric scales, however, are generally much larger than the scale of individual waves. Diffraction is therefore ignored and depths and currents are assumed to vary slowly compared to the scales of a single wave. The corresponding balance equation will be discussed in the following section. The intended applications dictate functional requirements such as (i) accounting for dynamically adjusted ice coverage, (ii) data transfer between nested implementations, (iii) full plug compatibility and (iv) a transparent code. The latter two requirements are desirable to simplify experiments with new source term parameterizations and new numerical approaches, and to facilitate later inclusion in larger model systems (coupled models and data assimilation).

To assure maximum transparency, propagation and source terms are numerically

decoupled, as are propagation in physical and spectral space. This splitting technique leaves sufficient options for vectorization and strongly promotes parallelization. This is illustrated in Table 1, in which the CPU and wallclock times of a global implementation of the test version of WAVEWATCH III and the semi-operational global implementation of WAM at NOAA/NMC are compared. Both models use a  $2.5^\circ \times 2.5^\circ$  longitude-latitude resolution with 5655 sea points and 25 discrete spectral frequencies. WAVEWATCH III uses 24 directions and WAM uses 12 directions. Although WAVEWATCH III thus incorporates twice the number of degrees of freedom compared to WAM, it proved only slightly more expensive, and is efficiently parallelized (see Table 1).

Two remarks need to be made on the comparison in Table 1. First, we compare WAM cycle 4 with a model including the physics of WAM cycle 3. The upgrading of WAM from cycle 3 to cycle 4 increases computation effort by approximately 10%. Secondly, a significant part of the gain in efficiency of WAVEWATCH III over WAM is due to the fact that the dynamic source term integration scheme of WAVEWATCH III (as described below) increases the effective source term time step from 20 min. in WAM to approximately 27 min. in WAVEWATCH III. This gain is possible because of the propagation time step of 40 min used for this spatial resolution. For higher spatial resolutions time steps in both models will be dictated by the CFL criterion, in which case the CPU time required for WAVEWATCH III will be closer to that of WAM.

## THE BALANCE EQUATION

Wind waves on slowly varying depths ( $d$ ) and currents ( $\mathbf{U}$ ) are most elegantly described with a spectral action balance equation (e.g., Bretherton and Garrett, 1968; Whitham, 1974). In the linear approach the action spectrum is two-dimensional and can be described as a function of the spectral direction  $\theta$  and either the wavenumber  $k$ , the relative or intrinsic frequency  $\sigma$  (as observed when moving with  $\mathbf{U}$ ) or the absolute frequency  $\omega$  (as observed in a fixed frame of reference). For slowly varying currents, the latter three 'phase' parameters are interrelated through the dispersion relation and a Doppler equation.

$$\sigma^2 = gk \tanh kd, \quad (1)$$

$$\omega = \sigma + \mathbf{k} \cdot \mathbf{U}. \quad (2)$$

Traditionally, wind waves are described with the variance spectrum as a function of the frequency  $f = \omega/2\pi$  and the direction  $\theta$ ,  $F(f, \theta)$ , or the corresponding wave action spectrum  $N(f, \theta) = F(f, \theta)/\sigma$ . From a theoretical point of view, however, the wavenumber spectrum  $N(k, \theta)$  has been considered more appropriate for modeling wind waves due to its invariance properties with respect to the water depth for the physics of wave growth and decay (e.g., Kitaigorodskii, 1962, 1983; Kitaigorodskii et al., 1975; Bouws et al., 1985). The governing equations for the evolution of this spectrum can

be written as (e.g., Hasselmann et al., 1973; Willebrand, 1974)

$$\frac{\partial N}{\partial t} + \nabla_x \cdot \dot{\mathbf{x}}N + \frac{\partial}{\partial \theta} \dot{\theta}N + \frac{\partial}{\partial k} \dot{k}N = \frac{S}{\sigma}, \quad (3)$$

$$\dot{\mathbf{x}} = \mathbf{c}_g + \mathbf{U}, \quad (4)$$

$$\dot{\theta} = -\frac{1}{k} \left[ \frac{\partial \sigma}{\partial d} \frac{\partial d}{\partial t} - \mathbf{k} \cdot \frac{\partial \mathbf{U}}{\partial t} \right], \quad (5)$$

$$\dot{k} = -\frac{\partial \sigma}{\partial d} \frac{\partial d}{\partial t} - \mathbf{k} \cdot \frac{\partial \mathbf{U}}{\partial t}, \quad (6)$$

where the group velocity  $\mathbf{c}_g$  is given by  $\mathbf{c}_g \equiv \partial \sigma / \partial \mathbf{k}$  and  $\theta$ ,  $s$  is a coordinate in the direction  $\theta$ ,  $m$  is a coordinate perpendicular to  $s$  and  $S$  represents the net source term for wave generation and dissipation. For convenience of notation, the dependency of  $N$  and  $S$  on  $k$  and  $\theta$  has been neglected.

The use of these equations for the wavenumber spectrum has a (numerical) disadvantage for waves propagating from deep to shallow water. In such conditions, long waves are significantly shortened (i.e.,  $k$  increases significantly), as is illustrated in Fig. 1. If the  $k$ -space of the spectrum is discretized with an invariant wavenumber grid, as is common practice in wave models, this leads to a loss of resolution in shallow water. However, this 'shoaling' is a reversible process, which suggest that its effects can be incorporated in a variable wavenumber grid. The potential of such a grid to eliminate numerical disadvantages for limited depths and mean currents will be discussed in detail elsewhere. In WAVEWATCH III a spatially and temporally invariant  $\sigma$ -grid is used. The corresponding wavenumber grid is a function of the instantaneous depth only (see Fig. 1). Transformed to this grid, the governing equations (3) and (6) become

$$\frac{\partial N}{\partial t} + \mathbf{c}_g \cdot \nabla_x \cdot \left( \frac{\dot{\mathbf{x}}N}{\mathbf{c}_g} \right) + \frac{\partial}{\partial \theta} \dot{\theta}N + \frac{\partial}{\partial k} \dot{k}N = \frac{S}{\sigma} + \mathbf{c}_g^{-1} \frac{\partial \sigma}{\partial d} \frac{\partial d}{\partial t} \frac{\partial N}{\partial k}, \quad (7)$$

$$\dot{k}_g = \frac{\mathbf{U} \cdot \nabla_x d \frac{\partial \sigma}{\partial t} - \mathbf{k} \cdot \frac{\partial \mathbf{U}}{\partial t}}{\mathbf{c}_g}. \quad (8)$$

whereas Eqs. (4) and (5) remain unchanged. The equation for the variable grid differs from the original balance equation (3) on three points.

First, an additional term arises at the right side of the equation. This term represents a change of grid due to temporal variations of the depth, without changing the actual spectrum  $N(k, \theta)$ . The numerically non-conservative nature of this term is potentially disadvantageous. However, it can be shown that this term is generally small, and that water levels can generally be updated sparsely. Without loss of generality, the corresponding part of Eq. (7) can then be replaced with a conservative interpolation between the new and the old grid. The remaining balance equation is quasi-steady with respect to the depth.