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RECENT DEVELOPMENTS IN WAVEWATCH III AT NCEP [1]

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Abstract Recent and ongoing developments of the WAVEWATCH III wind wave model at the National Centers for Environmental Prediction (NCEP) are presented. The attention is focused on the development of a multi-scale version of this model, featuring two-way nesting and dynamically relocatable nests, and on the development of more capable versions of the Discrete Interaction Approximation for the parameterization of nonlinear wave-wave interactions in wind wave models.

INTRODUCTION

The WAVEWATCH III model is a third generation wind wave model developed at the National Centers for Environmental Prediction (NCEP) for operational wind wave forecasting (Tolman et al., 2002). This model is freely available from the Marine Modeling and Analysis Branch (MMAB) web site[3]. Two releases of WAVEWATCH III have been made available to the public. The first is model version 1.18, released in April 1999, the second is model version 2.22, released in September of 2002. Since then, the development of WAVEWATCH III at NCEP has been ongoing. The following modifications have been incorporated in the experimental version of WAVEWATCH III at NCEP.

A) The exact nonlinear interaction package of Van Vledder (2002) has been upgraded to a more recent version.
B) In the version 2.22 setup of the model several model output files are direct access files that are simultaneously accessed by all processors on which the model runs. This requires a truly parallel file system on a distributed computer architecture, and is generally time consuming. The model output has been redesigned to have dedicated processors for each output file. This removes the need for a parallel file system, and is generally more economical (see Tolman, 2003b).

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[3]http://polar.ncep.noaa.gov/waves/wavewatch

C) A model version has been generated that allows for continuous grid movement, for instance to follow a hurricane. This modification is described in detail in Tolman and Alves (2005). It is intended for research only, and requires deep water without land masses.

These three modifications are present in model version 3.04. This model version is not released, but can be made available for distributed computing without parallel file systems. Furthermore, three main lines of development are presently undertaken in WAVEWATCH III:

1) A multi-scale version of the wave model is being developed, with full two-way nesting and with the capability of relocating nests during the computation.
2) The centerpiece of a third generation wind wave model is the direct parameterization of the nonlinear interactions source term. In all practical wave models, this is achieved by using the Discrete Interaction Approximation (DIA, Hasselmann et al., 1985). More advanced version of the DIA are being developed for WAVEWATCH III.
3) Similarly, a Neural Network Interaction Approximation (NNIA) is being developed with the intent to replace or supplement the DIA.

In the present manuscript, a progress report will be on the status of the multi-scale wave model, and the DIA studies. For a review of recent progress on the NNIA development, reference is made to Tolman and Krasnopolsky (2004), whereas early results can be found in Krasnopolsky et al. (2002) and Tolman et al. (2005).

A MULTI SCALE WAVE MODEL

Traditionally, wind wave models consider one-way nesting only, that is, coarse resolution models provide boundary conditions for fine resolution models, but the fine resolution models do not return data to the coarse resolution models. This is acceptable in conventional coastal applications, where deep ocean conditions can have a large impact on the coastal wave conditions, but where detailed coastal wave conditions usually have little or no impact on deep ocean conditions.

An exception is the prediction of waves generated by hurricanes. In the generation area, wind fields display variability on an extremely small spatial (and temporal) scales. Hence, high spatial resolution is required for a wave model near the hurricane. In contrast, swell fields radiating away from the hurricane have increasingly large spatial scales, and hence require lower spatial resolution in a wave model. Efficient modeling of wind waves generated by hurricanes therefore requires information transfer from high resolutions near the hurricane to lower resolutions away from the hurricane (two-way nesting).

NCEP has provided specialized guidance for wind waves generated by hurricanes since the 2000 Atlantic hurricane season (see Chao et al., 2005). This system became fully operational in June 2001. In the corresponding wave models, the need for two-way nesting is avoided by applying a relatively high spatial resolution over large areas. Whereas the resulting forecast guidance has been generally of good quality, this is obviously not an economical way of running the wave model, and in fact, the required large area of high resolution has limited the attainable spatial resolution. In contrast, relocatable, telescoping nests have been used for hurricane forecasting for over a decade (e.g. Kurihara et al., 1995). The need for two-way nesting and relocatable nests in operational wave models has thus become apparent. This need is further highlighted by the apparent need for coupled atmosphere-wave-ocean modeling (e.g., Bender and Ginis, 2000; Bao et al., 2000). Such coupling is greatly simplified if (some of) the models share identical grid systems.

Wave models with variable grid spacing have been used before. Gomez and Carretero (1997) developed a version of the WAM model with two way nesting of grids with different resolution. Benoit et al. (1996) present a third generation wave model on an unstructured grid, with typically high coastal resolution and low deep ocean resolution. Such a model would be a natural match with similar atmospheric models for hurricanes as presented by, for instance, Gopalakrishnan et al. (2002). In the NCEP operational environment, it is important that the multi scale wave model is compatible with the ocean and atmosphere model with which it will be coupled. Unstructured grids are therefore not considered here. Instead, multi-scale technology will be introduced in the existing operational WAVEWATCH III model using structured grids.

The basic design concept of the multi-scale version of WAVEWATCH III is to run multiple Cartesian or longitude-latitude grids as independent models in a single program. Two-way data transfer between grids is performed internally in the program for each time step. Three major tasks can be identified in the development of such a model.

i) WAVEWATCH III version 2.22 has a static data structure for a single model grid. This single, static data structure has to be replaced by a multiple, dynamic data structure to allow for the storage of data for multiple grids in a single program.
ii) A new model 'driver' has to be developed to manage the computations for all the individual grids, as well as the data flow between them.
iii) Actual nesting strategies have to be developed, implemented and tested.

Whereas the last task represents the actual goal of the development, the first two task represent the main effort in the development. Task (i) requires the re-writing of most of the wave model code, without allowing for changes in the model results. This task has been completed. The replacement of the static data structure by a dynamic data structure adds a moderate overhead to the run time of the model of typically 5%, depending on the harware and compilers. Details of the dynamic data structure will be published elsewhere.

Task (ii) can be sub-divided in the design of the algorithm to manage the computation for individual grids, development of effective I/O functionality, and efficient and transparent application to parallel computer architectures. The basic algorithm has been designed and implemented in a new driver, which is presently being developed further with regards to I/O and parallel implementation.

Task (iii) considers the expansion of the one-way nesting techniques presently available in WAVEWATCH III. We hope to have a first version of the two-way nesting techniques available for internal use at NCEP in the summer of 2006.

EXPANDING THE DIA

Following Hasselmann (1960), wind wave models are generally based on the energy or action balance equation

$$\frac{DF}{Dt} = S = S_{in} + S_{nl} + S_{ds} \quad , \tag{1}$$

Where F represents the wave spectrum, and S the source terms for wind input, nonlinear interactions, and dissipation, respectively. In this equation, the nonlinear interactions S_{nl} are crucial, as they result in the lengthening of the waves during wave growth, and as they stabilize the spectral shape. These interactions describe the resonant and conservative exchange of action, energy and momentum between so-called quadruplets of four wave components with frequency σ_n and wavenumber $\boldsymbol{k}_n$ (n = 1-4), which satisfy the resonance conditions

$$\boldsymbol{k}_1 + \boldsymbol{k}_2 = \boldsymbol{k}_3 + \boldsymbol{k}_4 \quad , \tag{2}$$

$$\sigma_1 + \sigma_2 = \sigma_3 + \sigma_4 \quad . \tag{3}$$

The strength of the interactions is governed by a six-dimensional Boltzmann integral, including moving singularities. In the present study, the Webb-Resio-Tracy (WRT) method is used to evaluate these 'exact' interactions (Webb, 1978; Tracy and Resio, 1982; Resio and Perrie, 1991), using the portable package developed by Van Vledder (2002)[4]. Even with present day computing power, these exact interaction are too expensive to use in practical wave models. Instead, third-generation wave models have used the Discrete Interaction Approximation (DIA, Hasselmann et al., 1985) for the last two decades. The DIA is developed for the energy spectrum $F(f,\theta)$ as a function of the frequency $f = \sigma/2\pi$ and the direction θ, discretized with a logarithmic frequency grid with a constant increment factor for discrete frequencies f. For each discrete spectral grid point $\boldsymbol{k}_d$, only two quadruplets are considered, defined by Eq. (2) and (3) and

$$\left.\begin{array}{rcl} \boldsymbol{k}_2 = \boldsymbol{k}_1 & = & \boldsymbol{k}_d \\ \sigma_3 & = & (1+\lambda)\sigma_1 \end{array}\right\} \quad , \tag{4}$$

where λ is a constant, originally set to $\lambda = 0.25$. Furthermore, the Boltzmann

[4] Model version 5.04 used here.

integral for the interaction strength is replaced by

$$\begin{pmatrix} \delta S_{nl,1} \\ \delta S_{nl,3} \\ \delta S_{nl,4} \end{pmatrix} = \begin{pmatrix} -2 \\ 1 \\ 1 \end{pmatrix} C g^{-4} f_1^{11} \times \left[F_1^2 \left(\frac{F_3}{(1+\lambda)^4} + \frac{F_4}{(1-\lambda)^4} \right) - \frac{2F_1F_3F_4}{(1-\lambda^2)^4} \right] . \qquad (5)$$

where F_n is the spectral energy density at component n of the quadruplet, $\delta S_{nl,n}$ is the corresponding contribution to the interaction, and C is a proportionality constant, originally set to $C = 3\,10^7$.

The DIA is by and large responsible for the success of third-generation wave models. However its limitations were already recognized by Hasselmann et al. (1985). Since then many studies have sought to improve upon the DIA. As a first part of a similar effort at NCEP, an inventory was made of previously suggested improvements to the DIA, as reported in Tolman (2003a, 2004). It was found that it is essential to expand the definition of the quadruplet as given by Eq. (4), and to allow for the use of multiple quadruplet definitions for each discrete spectral component. The maximum versatility can be introduced in a quadruplet by defining it in terms of three free parameters λ, μ and $\Delta\theta$ (see Tolman, 2005)

$$\left. \begin{array}{lllll} \boldsymbol{k}_d & = & \frac{||\boldsymbol{k}_1||}{||\boldsymbol{k}_1+\boldsymbol{k}_2||} (\boldsymbol{k}_1 + \boldsymbol{k}_2) & & \\ \sigma_1 & = & a_1\sigma_d & = & (1+\mu)\sigma_d \\ \sigma_2 & = & a_2\sigma_d & = & (1-\mu)\sigma_d \\ \sigma_3 & = & a_3\sigma_d & = & (1+\lambda)\sigma_d \\ \sigma_4 & = & a_4\sigma_d & = & (1-\lambda)\sigma_d \\ \theta_2 & = & \theta_1 \pm \Delta\theta & & \end{array} \right\} , \qquad (6)$$

which represent a symmetric version of the quadruplet defined by Van Vledder (2001). The corresponding contributions to the interactions become

$$\begin{pmatrix} \delta S_{nl,1} \\ \delta S_{nl,2} \\ \delta S_{nl,3} \\ \delta S_{nl,4} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} -1 \\ -1 \\ 1 \\ 1 \end{pmatrix} C\, g^{-4} f_d^{11} \times \left[\frac{F_1F_2}{(a_1a_2)^4} \left(\frac{F_3}{a_3^4} + \frac{F_4}{a_4^4} \right) - \frac{F_3F_4}{(a_3a_4)^4} \left(\frac{F_1}{a_1^4} + \frac{F_2}{a_2^4} \right) \right] . \qquad (7)$$

Note that Eq. (6) results in four independent quadruplets, whereas Eq. (4) results in two quadruplets. To assure the Eq. (7) reduces to Eq. (5) for $\mu \equiv 0$ and $\Delta\theta \equiv 0$ the factor $\frac{1}{2}$ is needed in the former equation. A multiple DIA (MDIA) based on this expanded definition of the quadruplet can be constructed by defining N sets of parameters $(\lambda, \mu, \Delta\theta)$. If the interaction according to the quadruplet i defined as $S_{nl,i}$, the final MDIA is defined as

Table 1: Selected Optimum MDIA settings.

N	ζ (%)	λ (-)	μ (-)	$\Delta\theta$ (°)	C $\times 10^{-7}$
1	26.0	0.212	—	—	1.88
2	16.3	0.127	—	—	3.84
		0.278	—	—	1.83
3	11.6	0.063	0.009	—	12.1
		0.184	0.028	—	2.40
		0.284	0.128	—	5.33
4	9.6	0.065	0.167	82.2	8.32
		0.111	0.237	52.0	3.74
		0.127	0	4.0	5.14
		0.302	0.195	4.9	3.45

$$S_{nl} = \frac{1}{N} \sum_{i=1,N}^{N} S_{nl,i} \quad . \tag{8}$$

In the initial study at NCEP (Tolman, 2003a, 2004) it was found, consistent with other studies, that this MDIA indeed can result in a much more accurate representation of the exact interactions for test spectra than can be obtained with the original DIA. Unfortunately, it was also found that these more accurate descriptions of individual interactions do not necessarily result in more accurate results of the full WAVEWATCH III model, and in some cases do not even result in stable model integration. With this in mind, a second study was initiated, as reported in Tolman and Krasnopolsky (2004) and Tolman (2005).

This second study deals with many subjects, including the effects of sampling of spectral space, and reasons for unstable model integration. The most important subject, however, is the introduction of a holistic optimization approach for the MDIA. In this approach, the MDIA is not optimized by minimizing errors of S_{nl} for selected spectra, but by minimizing wave model errors of model integration with the MDIA. As a benchmark for this holistic optimization a conventional time and fetch limited test are performed with WAVEWATCH III using standard model settings, but replacing the DIA with the exact WRT method as described above. A wind speed of 20 ms^{-1} is used in both cases, and 48 hourly spectra from the time limited test case and 50 fetch limited spectra at 10 km intervals from the fetch limited test are used as the data to be reproduced by model integration using the MDIA. The optimum MDIA setting is obtained by minimizing errors ϵ_H for the wave height H_s,

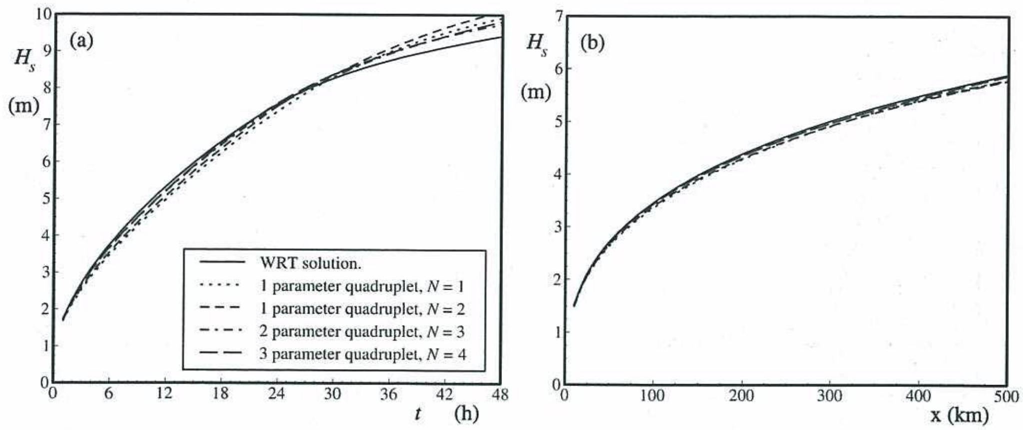

Fig. 1: Wave height H_s for (a) time limited test as a function of time t and (b) for fetch limited test as a function of fetch x for the WRT model solution and various MDIAs as identified in Table 1 (from Tolman, 2005).

$$\epsilon_H = \sqrt{\frac{1}{m}\sum_{1}^{m}\frac{(H_{s,x} - H_{s,a})^2}{H_{s,x}^2}} \quad , \quad H_s = 4\sqrt{\iint F(f,\theta)\, df\, d\theta} \quad , \tag{9}$$

where m is the number of benchmark spectra, where the suffices x and a denote the exact and approximated solutions. Similar errors ϵ_{e1}, ϵ_{e2}, ϵ_{s1} and ϵ_{s2} are defined for the one and two dimensional spectra $F(f,\theta)$ and $F(f)$ and the corresponding steepness spectra $k^2F(f)$ and $k^2F(f,\theta)$ (Tolman, 2005). These error measures are combined into a single cost function ζ

$$\zeta = \frac{a_H\epsilon_H + a_{e1}\epsilon_{e1} + a_{e2}\epsilon_{e2} + a_{s1}\epsilon_{s1} + a_{s2}\epsilon_{s2}}{a_H + a_{e1} + a_{e2} + a_{s1} + a_{s2}} \quad . \tag{10}$$

To assure that the wave height is well represented, the weight factor a_H is initially set to 10, whereas all other weight factors are set to 1.

The optimization is performed with a combination of genetic algorithms and steepest descent methods (see Tolman, 2005). For increasingly complex quadruplets, the number of components N of the MDIA was increased until no further improvement of the cost function ζ was found, or as dictated by economical limitations of the optimization procedure (most complex quadruplet only). Three different quadruplets with increasing complexity are defined as

1) A one parameter quadruplet defined by λ only. By taking $\mu \equiv 0$ and $\Delta\theta = 0$, this represent the original quadruplet definition of the DIA.
2) A two parameter quadruplet defined by λ and μ. $\Delta\theta$ is computed by assuming the $\boldsymbol{k}_1 + \boldsymbol{k}_2 = 2\boldsymbol{k}_d$. This quadruplet definition was introduced by Tolman (2003a, 2004).
3) The full three parameter quadruplet definition defined by λ, μ and $\Delta\theta$.

Increasing the complexity of the quadruplet and the number of components N in the MDIA indeed systematically improves the model behavior as measured by the

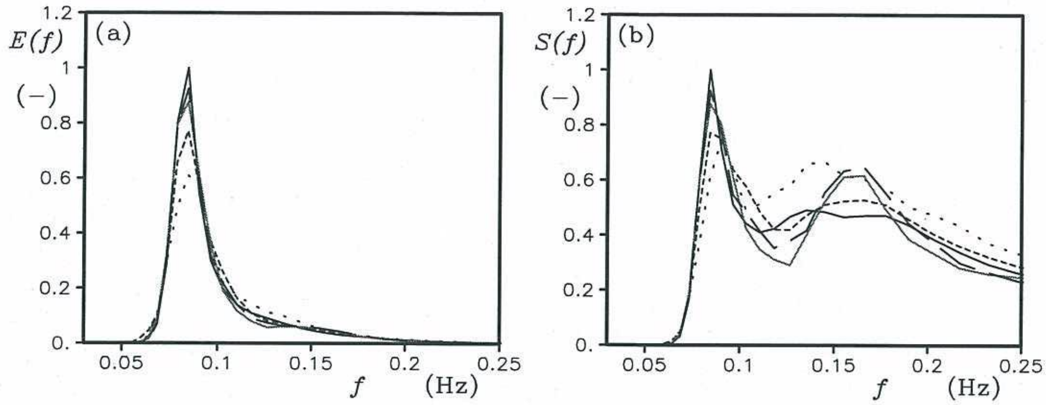

Fig. 2: One dimensional spectrum $F(f)$ (panel a) and steepness spectrum $S(f) = k^2E(f)$ for the time limited test after 24 h. Legend as in Fig. 1. The two-parameter quadruplet with $N = 3$ is replaced by a red line for clarity. Spectra normalized with maximum value for WRT results (from Tolman, 2005).

cost function ζ. This is illustrated in Table 1 with some selected MDIA settings. Note that the number of components N for each entry in this table except for the first represent the N above which ζ does not improve notably. This implies that a more complex quadruplet definition benefits most from additional components in the MDIA.

Examples of model results obtained with the MDIAs as defined in Table 1 are presented in Figs. 1 and 2. Figure 1 present wave height H_s from the time and fetch limited tests. Even for the simplest optimized MDIA, the results are excellent, with a small but notable improvement for increasingly complex MDIAs. Figure 2 presents example energy and steepness spectra. Spectral errors are much larger than wave height errors. The spectral peak energy is systematically underestimated. The underestimation is systematically reduced by introducing more complex MDIAs. The most complex MDIAs, however, tend to introduce larger errors in the steepness spectra for frequencies above the spectral peak frequency.

CONCLUSIONS

Since the last public release of WAVEWATCH III, much effort has been put into the further development of this model. More flexible I/O options, and a continuously moving grid version have been published elsewhere, as mentioned above. In addition, development is ongoing in several directions.

A multi scale version of the model is being developed to allow for two way nesting. For hurricanes, telescoping nests will be relocatable following the hurricane track. The basic model modifications necessary for this functionality have been completed. Actual nesting techniques are expected to be available in the summer of 2006.

Additional development work is geared toward improving the description of the nonlinear interaction source term. It has been shown that the conventional Discrete Interaction Approximation (DIA) can be improved upon significantly. Whereas wave heights can be modeled at high levels of accuracy, spectral shape errors remain significant at the present level of development of the multiple DIA. Progress reports for ongoing development of a Neural Network Interaction Approximation (NNIA) are presented elsewhere.

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