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Has wind–wave modeling reached its limit?

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Abstract

This article uses a comparison of four different numerical wave prediction models for hindcast wave conditions in Lake Michigan during a 10-day episode in October 1988 to illustrate that typical wave prediction models based on the concept of a wave energy spectrum may have reached a limit in the accuracy with which they can simulate realistic wave generation and growth conditions. In the hindcast study we compared the model results to observed wave height and period measurements from two deep water NOAA/NDBC weather buoys and from a nearshore Waverider buoy. Hourly wind fields interpolated from a large number of coastal and overlake observations were used to drive the models. The same numerical grid was used for all the models. The results show that while the individual model predictions deviate from the measurements by various amounts, they all tend to reflect the general trend and patterns of the wave measurements. The differences between the model results are often similar in magnitude to differences between model results and observations. Although the four models tested represent a wide range of sophistication in their treatment of wave growth dynamics, they are all based on the assumption that the sea state can be represented by a wave energy spectrum. Because there are more similarities among the model results than significant differences, we believe that this assumption may be the limiting factor for substantial improvements in wave modeling. © 2001 Published by Elsevier Science Ltd.

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1. Introduction

Numerical modeling of wind waves developed concomitantly with the development of the computer era, spanning most of the second half of the 20th century. The

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publication of the book “Dynamics and Modelling of Ocean Waves” (Komen et al., 1994), culminated an international effort of wind wave model development which lasted over a decade. From the results presented in this book it appears that the development of ocean wind wave models has reached a seemingly “fully developed” stage. Whether or not this is true, the study of wind waves has become less active in recent years.

This article presents an assessment of the present status of the wind wave modeling by applying several frequently used wind wave models to a case of active wave generation and growth in Lake Michigan (Schwab et al., 1991) and comparing the results with actual measurements. One of the models used is the state-of-the-art WAM model that generally requires supercomputer operation as described in Komen et al. (1994). Another, by contrast, is a simple parametric model that can be implemented in any basic computer system (Schwab et al., 1984; Liu et al., 1984). Also included are two other models (Resio, 1981; Hughes and Jensen, 1986) that are basically forerunners to the WAM model. All of the models are based on the concept of a wind–wave energy spectrum, which grows and decays in response to changes in the wind field. Although in our earlier work (Schwab et al., 1991) the main emphasis was on model intercomparison, the main impetus of the present article is not model intercomparison, or model validation, but rather to address the question whether wind wave models based on the concept of a wave energy spectrum have reached their limit in terms of simulating the observed natural characteristics of wind waves. We start by presenting the details of the several models, applying them to a ten-day episode of measured wind and wave fields in Lake Michigan, and proceed to discuss the merits and shortcomings of the current state of wind wave modeling. We also speculate that the assumption of a wind–wave energy spectrum may be the limiting factor in the further development of numerical wave prediction models.

2. Numerical wind–wave models

2.1. The WAM model

The framework for modern numerical modeling of wind waves was laid out by Klaus Hasselmann (1963) in a written discussion during the 1961 Conference on Ocean–Wave Spectra at Easton, Maryland. In that discussion, Hasselmann proposed an equation for the energy balance of the wave spectrum, representing the basis of a possible exact theory of wave spectrum dynamics:

$$\frac{\partial F}{\partial t}(\boldsymbol{k};\boldsymbol{x},t)+\boldsymbol{v}\cdot\nabla_x F(\boldsymbol{k};x,t)=S, \tag{1}$$

where $F(\boldsymbol{k};\boldsymbol{x},t)$ is the energy spectrum in terms of wave number vector, $\boldsymbol{k}$, the position vector $\boldsymbol{x}$ in the ocean and time t. The group velocity vector, $\boldsymbol{v}$, is defined as

$$\boldsymbol{v}=\frac{1}{2}\sqrt{\frac{g}{k}}\left(\frac{\boldsymbol{k}}{k}\right) \tag{2}$$

The second term on the left-hand side is the divergence of the convective energy flux, $\boldsymbol{v} \cdot F$, and S is the total rate of change of the spectrum due to the generation, dissipation, and nonlinear processes in the sea. As the function S was essentially unknown at the time, Hasselmann inferred that S could be developed partly from theoretical results and partly from observations, so that wave forecasts could be made from wind conditions derived from weather maps. The effects of fetch, duration, and varying wind fields "would be solved automatically by the computer integration of the differential equation." In revisiting this discussion, it is difficult not to marvel at Hasselmann's vision of the approach to numerical wind wave modeling at a time when computer technology was still in its infancy. Indeed, two "generations" of wind wave modeling corresponding to Eq. (1) have been developed.

The WAM model, (Komen et al., 1994) was developed as the global third generation model to solve the action balance equation in spherical coordinates for the action density ocean wave spectrum $F(\omega,\theta,\phi,\lambda,t)$ with respect to wave frequency ω and direction θ as a function of latitude ϕ, longitude λ and time t, which is governed by:

$$\frac{\partial F}{\partial t}+\frac{1}{\cos\phi}\frac{\partial}{\partial\phi}(\dot{\phi}\cos\phi F)+\frac{\partial}{\partial\lambda}(\dot{\lambda}F)+\frac{\partial}{\partial\omega}(\dot{\omega}F)+\frac{\partial}{\partial\theta}(\dot{\theta}F)=S \quad (3)$$

where the dotted variables, $\dot{\phi},\dot{\lambda},\dot{\omega}$ and $\dot{\theta}$, represent the rate of change of the positions, the dispersion relation and propagating direction of waves traveling globally. The source function, S, on the right hand side is represented as superposition of source terms due to wind input, nonlinear wave–wave interaction, dissipation due to wave breaking, and bottom friction as:

$$S=S_{\mathrm{in}}+S_{\mathrm{nl}}+S_{\mathrm{ds}}+S_{\mathrm{bot}} \quad (4)$$

The amalgamation of these source terms signifies the current state of understanding of the physical processes of wind waves, namely the inputs from the processes of wind field, non-linear interaction, dissipation, and bottom friction balance each other to form self similar spectral shapes corresponding to the measured wind wave spectra. Except for the non-linear source term, which uses the discrete interaction approximation that simulates an exact nonlinear transfer process formulated by the four-wave resonant interaction Boltzmann equation and characterizes the third generation model, all the other source terms are individually parameterized to be proportional to the action density spectrum, F. The numerical integration of the source function is performed with an explicit scheme to handle the large difference between the dynamic adjustment time of the highest frequency and the integration time step. Details of the processes and their implementations are given in Komen et al. (1994).

2.2. The GLERL/Donelan model

Recognizing the observation that sea states affect the drag of wind on the water surface and surmising that the physics of wind waves are inextricably linked to the wind stress on a water body, Donelan (1977) developed a simple wave prediction model based on the concept of local momentum balance rather than energy balance. Schwab et al. (1984) provided the required numerical framework to make the model operational for general wind wave prediction applications. The momentum balance equation for the momentum vector, $\boldsymbol{M}$, is given as:

$$\frac{\partial \boldsymbol{M}}{\partial t}+\boldsymbol{v}\cdot\nabla\boldsymbol{M}=\tau_{\mathrm{w}} \tag{5}$$

where ∇ is the horizontal gradient operator, $\boldsymbol{v}$ is again the group velocity vector corresponding to $\boldsymbol{M}$, and τ_{w} is that part of the momentum input from the wind that produces net wave momentum growth. Assuming equipartition of potential and kinetic energy in the wave field, the momentum vector is expressed by

$$\boldsymbol{M}=\rho_{\mathrm{w}}g\int\int\frac{F(\omega,\theta)}{c(\omega)}\begin{pmatrix}\cos\theta\\ \sin\theta\end{pmatrix}d\theta d\omega, \tag{6}$$

where ρ_{w} is the water density, $c(\omega)$ the phase speed, and $F(\omega,\theta)$ the two-dimensional directional spectrum of energy density as a function of angular frequency ω and direction θ. In practice the model follows the observations of JONSWAP (Hasselmann et al., 1973) and the directional wave energy spectrum is assumed to have a cosine-squared angular dependence about a single dominant mean wave direction which is independent of frequency.

Momentum input from the wind consists of two parts: the part parallel to the wind vector, τ_{u}, and the part parallel to the wave momentum vector, τ_{m}, i.e.,

$$\tau_{\mathrm{w}}=\tau_{\mathrm{u}}+\tau_{\mathrm{m}}. \tag{7}$$

Assuming the form drag of the wind on the waves is proportional to the square of the wind speed relative to the form of the waves represented by the phase velocity, the scalar values of the two components as suggested by Donelan (1977) are:

$$\tau_{\mathrm{u}}=\frac{\lambda}{2}\rho_{\mathrm{a}}D_{\mathrm{u}}|U-0.83c_{\mathrm{p}}\cos\theta_0|(U-0.83c_{\mathrm{p}}\cos\theta_0), \tag{8}$$

and

$$\tau_{\mathrm{m}}=\frac{\lambda}{2}\rho_{\mathrm{a}}D_{\mathrm{m}}|U\cos\theta_0-0.83c_{\mathrm{p}}|(U\cos\theta_0-0.83c_{\mathrm{p}}), \tag{9}$$

where c_{p} is the wave phase velocity corresponding to peak frequency, ρ_{a} is the air density, U is the wind speed at the 10 m level, θ_0 is the angle between the wind and the waves, λ=0.028 is the empirical fraction of the wind stress that is retained by the waves, and the drag coefficients D_{u} and D_{m} at the 10 m height are given by

$$D_u = \left[\frac{\kappa}{\ln \frac{10}{z_0 \cos\theta_0}} \right]^2, \tag{10}$$

and

$$D_m = \left[\frac{\kappa}{\ln \frac{10}{z_0}} \right]^2, \tag{11}$$

where κ, the Von Karman's constant, is taken to be 0.4 and z_0 is the roughness length. To solve the momentum balance equation, Donelan (1977) used a relation of $z_0=\sigma/5$ that yields the best fit for the observed stress with σ being the root mean square surface elevation given by the empirical JONSWAP relation:

$$\sigma^2 = 6.23 \times 10^{-6} \left[\frac{f_p U}{g} \right]^{-10/3} \frac{U^4}{g^2}. \tag{12}$$

This is thus a semi-empirical, parametric model with nonlinear interactions totally neglected that resembles a conventional first generation model. Eq. (5) can be readily solved with a simple numerical integration scheme (Schwab et al., 1984). Forward time differences are used to calculate the momentum components at the center of the elementary grid squares, and a combination of upwind and centered differences are used to evaluate the momentum advection terms at the edge of the grid squares. Model output at each grid point consists of significant wave height (defined by $H_s=4\sigma$), peak-energy wave frequency, and average wave direction.

2.3. The DWAVE and SHALWV models

Representative of conventional second generation spectral wave models, the SHALWV and DWAVE models (Resio, 1981; Hughes and Jensen, 1986) developed at the Corps of Engineers have the same organizational structure for solving the radiative transfer equation, Eq. (1), as the WAM model. While the source function for the DWAVE model incorporates only three of the four terms given in Eq. (4): S_{in}, S_{nl}, and S_{ds}, excluding the bottom friction term S_{bot}, the SHALWV model contains all four terms of Eq. (4). What characterizes DWAVE and SHALWV as second, rather than third, generation models is their ad hoc approach for parameterizing the nonlinear interactions which is strongly dependent on the a priori spectral form.

Currently the application of the SHALWV model has been discontinued. A revised version of the DWAVE model is still the most widely used wave model for the Corps of Engineers.

3. Testing of the numerical wind–wave models

3.1. The wind field specification

Wind waves are generated by the wind blowing over the sea surface. Therefore one of the most important elements in a successful wave prediction is an accurate representation of the wind field. A 10 percent error in the estimate of surface wind speed can lead to 10–20 percent errors in significant wave height and 20–50 percent errors in wave energy. (Cavaleri, 1994) For our study, we used the wind field over Lake Michigan during a 10-day period in October 1988 when detailed wind and wave measurements were available. The meteorological data were assembled from 16 coastal stations, two mid-lake NDBC buoys, and occasional ship reports. Fig. 1 presents meteorological observations from the two mid-lake NDBC buoys, 45002 and 45007, in Lake Michigan for the period. Most fixed stations report at hourly intervals, some at two-hour intervals and ship reports are only posted at synoptic, three-hour intervals. In all, over 3000 reports were assembled for the 240-hour experimental period. All wind speed reports were adjusted to a uniform 10 m height by the profile method described in Schwab (1978). In addition, wind speed reports from coastal stations were modified to be more representative of overwaters wind speed. A regression equation correlating representative overwater wind speed to wind speed at the coast and air–water temperature difference was developed for each coastal station. The regression coefficients were selected so that the histogram of calculated overwater wind speed from the coastal station was similar to the histogram of wind speed at the nearest overwater NDBC buoy. A spatial and temporal weighting technique similar to that described by Schwab (1989) was used to interpolate wind speed and direction to a uniform 15 km grid covering the whole lake.

3.2. The wave measurements

Wave measurements during October, 1988 were made from two offshore NDBC buoys in the middle of the northern and southern basins of Lake Michigan, and a nearshore GLERL satellite reporting Waverider buoy near Ludington, Michigan. The locations are shown on the map in Fig. 2. The NDBC buoys in the Great Lakes during 1988 were boat shaped NOMAD buoys, 6 m in length, with an electronic payload to measure wind speed, wind direction, barometric pressure, air temperature, sea surface temperature, and surface wave spectral data. Most of the meteorological sensors are located 5 m above the water surface. Wind speed and direction, as well as air and surface water temperatures, are measured at 1 s intervals, averaged over 8.5 minutes and reported hourly. The waves are measured with an accelerometer using an on-board Wave Data Analyzer system (Steele and Johnson, 1977) that trans-

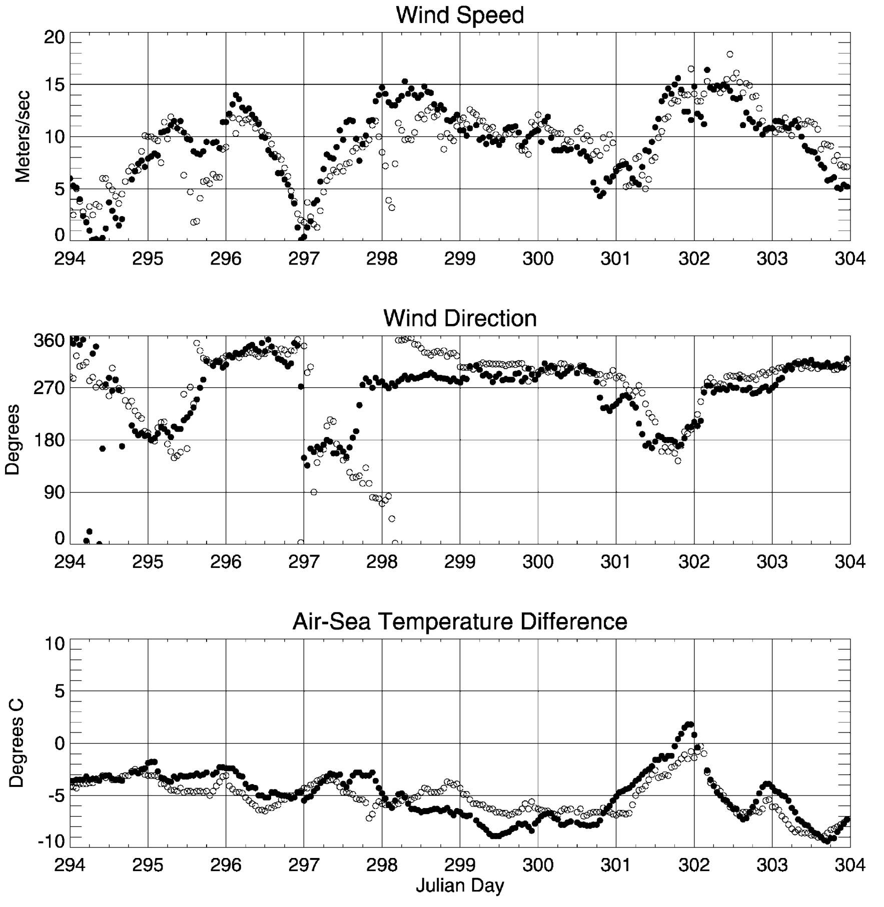

Fig. 1. Measurements of wind speed, wind direction, and air–sea temperature difference from the two NDBC buoys 45002 (open circles) and 45007 (filled circles) in Lake Michigan during the 10-day period in October 1988.

mits acceleration spectral data via the UHF GOES satellite to a shore receiving station. Wave frequency spectra with 48 degrees of freedom are calculated from 20 min of measurements each hour. The nearshore GLERL Waverider buoy measures hourly significant wave height, obtained as four times the variance from 20 min of data, along with mean zero-crossing wave period obtained from the same data to be used for the model comparisons.

3.3. The results

In an effort to provide a systematic and equitable comparison of the performance of the models and to minimize possible disparities of wind input, we chose to work with the same over-lake wind field developed from objective analysis along with the

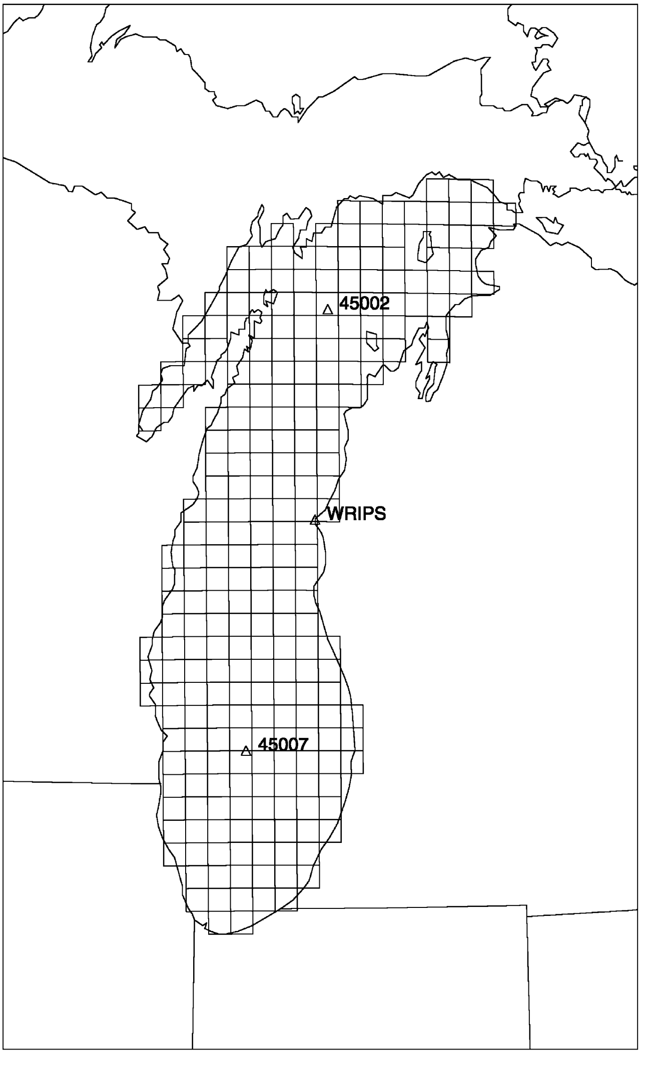

Fig. 2. Lake Michigan map with the locations of NDBC buoys 45002 and 45007 and GLERL WRIPS buoy.

same 15 km grid structure applied to all the models. The WAM, DWAVE, and SHALWV models require a discretization of the wave spectrum representation with corresponding usual directional resolution and frequency distribution (24 directional bands and 25 frequency bands between 0.06 and 0.4 Hz for WAM and 16 directional bands and 10 frequency bands between 0.03 and 0.21 Hz for DAVE and SHALWV). All four models generate a complete two-dimensional wave field at each grid point and time step. For this study we shall focus on the specific gage locations in Fig. 2 where NDBC buoys and GLERL Waverider are deployed to compare the model results with respective measurements. Figs. 3–5 present results from the different models for NDBC buoys 45002, 45007, and the GLERL Waverider buoy, respectively. The individual dots indicate the measured significant wave height. Model results are represented by the solid curves. A perfect model result would be a curve connecting those dots. As these models are understandably far from being perfect, an immediate observation of the figures reveals that each different model has a different degree of deviation from the measurements, but they all tend to reflect the general trend and patterns of the wave measurements.

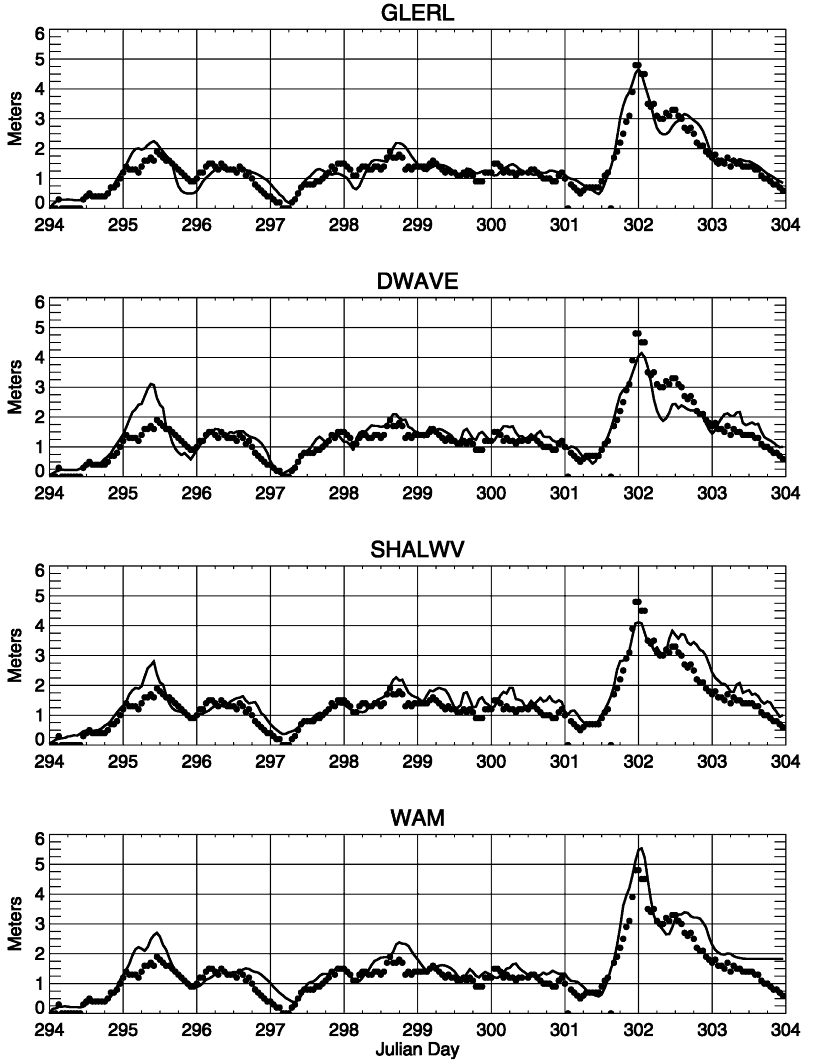

Fig. 3. Comparison of measured significant wave height at buoy 45002 shown in filled circles with corresponding hindcast results of the four models shown by the continuous line.

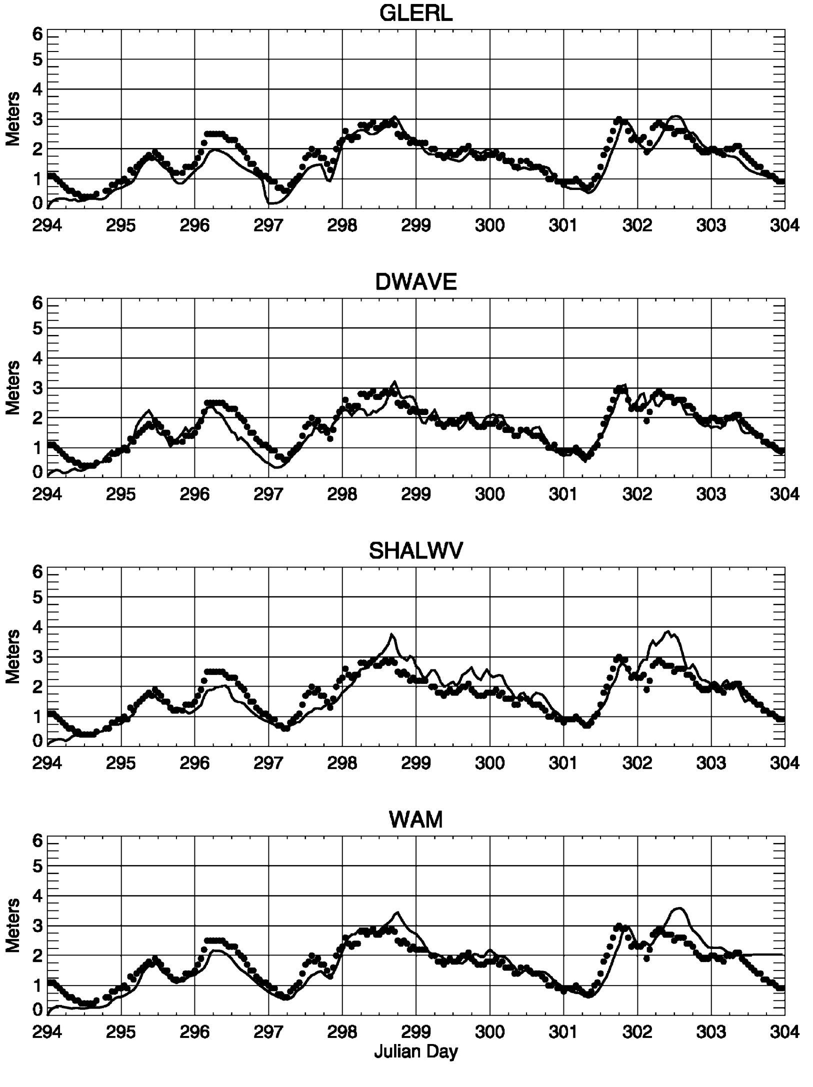

Fig. 4. Comparison of measured significant wave height at buoy 45007 shown in filled circles with corresponding hindcast results of the four models shown by the continuous line.

One customary approach to assess the extent of deviations between model performance and measurements is to calculate their RMS differences. Table 1 presents the RMS differences between the results of the measurements and the models and also between the different models for both signi_cant wave height, hs, and peak spectral energy wave period, T_p. Clearly, with average RMS differences on the order of 0.45±0.13 m and 1.33±0.6 s, the model results are practically equivalent and generally predict h_s better than T_p. As the numbers display feeble differences among the models, it might be tempting to rate a model “better” with lower RMS results.

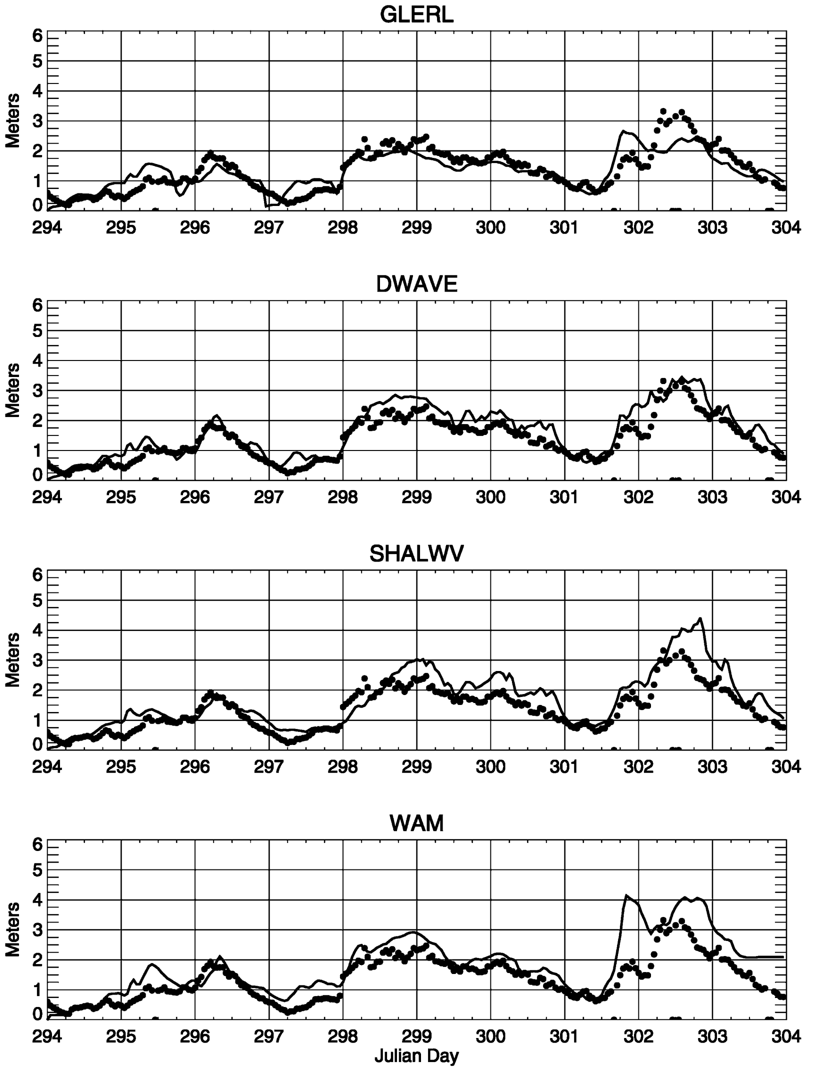

Fig. 5. Comparison of measured significant wave height at WRIPS buoy shown in filled circles with corresponding hindcast results of the four models shown by the continuous line.

For example, the GLERL model has relatively lower numbers as shown in Table 1. However, the relatively slight variations among the corresponding RMS differences are really not sufficient to be able to specify one particular model as superior or inferior. Application to a different episode of measurement could easily change the relative numeral variations in RMS values among the models.

Another customary approach on comparison of model performance can be made by examining the correlation of non-dimensional parameters. It is well established that the empirical relation of Eq. (12) provides a linear correlation between the non-

Table 1
RMS differences between model and measurement

Data	Gage/Model	WAM	SHALWV	DWAVE	GLERL
h_s	NDBC 45002	0.44	0.41	0.43	0.33
	NDBC 45007	0.36	0.42	0.30	0.32
	GLERL Waverider	0.67	0.52	0.40	0.41
	WAM	0.00	0.44	0.44	0.69
	SHALV	0.44	0.00	0.28	0.64
	DWAVE	0.44	0.28	0.00	0.49
	GLERL	0.69	0.64	0.49	0.00
T_p	NDBC 45002	0.92	1.91	1.07	0.85
	NDBC 45007	1.17	1.96	1.06	1.07
	WAM	0.00	2.21	0.78	0.63
	SHALV	2.21	0.00	2.02	1.95
	DWAVE	0.78	2.02	0.00	0.74
	GLERL	0.63	1.95	0.74	0.00

dimensional energy, $Eg^2=U^4$, and non-dimensional frequency, f_pU/g, in the log–log domain. Figs. 6 and 7 present the results of plotting the measured and modeled non-dimensional parameters for the NDBC buoys 45002 and 45007 respectively. The straight line, representing Eq. (12), fits the measured data quite well. The model results also follow the trend of the straight line, but here, again, with varied degrees of deviations, the results among the models are practically indistinguishable.

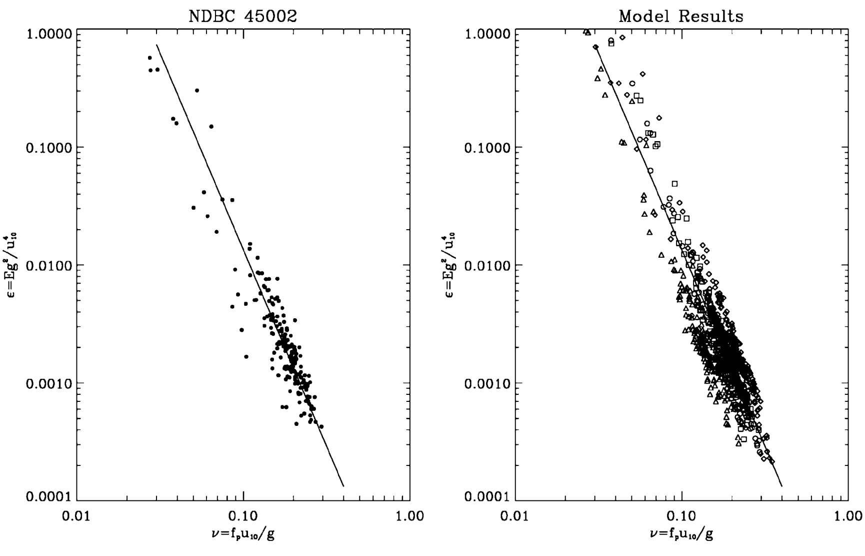

Fig. 6. Comparison of measured correlation of nondimensional energy and nondimensional frequency at buoy 45002 with corresponding model results [Symbols: diamond for WAM, triangle for SHALWV, square for DWAVE, and open circle for GLERL].

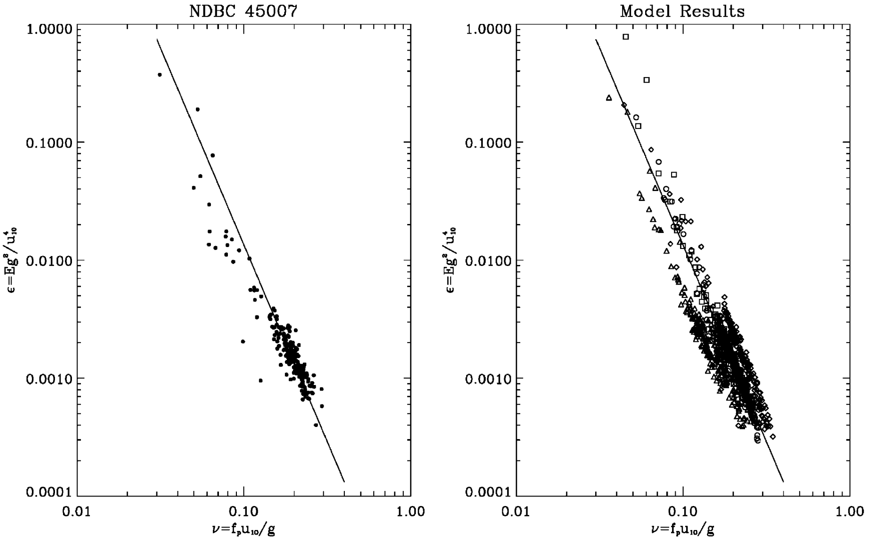

Fig. 7. Comparison of measured correlation of nondimensional energy and nondimensional frequency at buoy 45007 with corresponding model results [Symbols same as Fig. 6].

Now still another frequently used approach of assessing model performance with measurements can be applied to examine their corresponding correlation coefficients. Table 2, similar to Table 1, presents the correlation coefficients between the results of the measurements and the models and also between the different models, again, for both significant wave height, h_s, and peak spectral energy wave period, T_p. It is rather interesting to examine the mean correlation coefficients between each model

Table 2
Correlation coefficient between model and measurement

Data	Gage/Model	WAM	SHALWV	DWAVE	GLERL
h_s	NDBC 45002	0.93	0.92	0.86	0.92
	NDBC 45007	0.91	0.87	0.91	0.93
	GLERL Waverider	0.86	0.90	0.93	0.82
	WAM	1.00	0.90	0.92	0.94
	SHALV	0.90	1.00	0.96	0.85
	DWAVE	0.92	0.96	1.00	0.91
	GLERL	0.94	0.85	0.91	1.00
T_p	NDBC 45002	0.86	0.70	0.66	0.81
	NDBC 45007	0.73	0.57	0.52	0.63
	WAM	1.00	0.85	0.80	0.89
	SHALV	0.85	1.00	0.82	0.73
	DWAVE	0.80	0.82	1.00	0.78
	GLERL	0.89	0.73	0.78	1.00

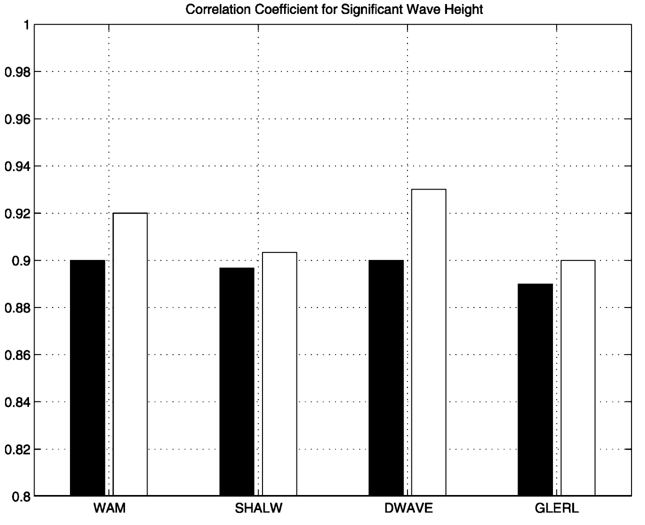

Fig. 8. Mean correlation coefficients for significant wave height between model and measurement (the darker bars) and between model and model (the lighter bars).

and measurements and between each model and other models separately, as illustrated in Figs. 8 and 9, it is readily apparent that the correlation coefficients between the models are higher than those between model and measurements. This rather surprising outcome exemplifies that in terms of overall correlation, the model results are closer to each other than they are to actual measurements.

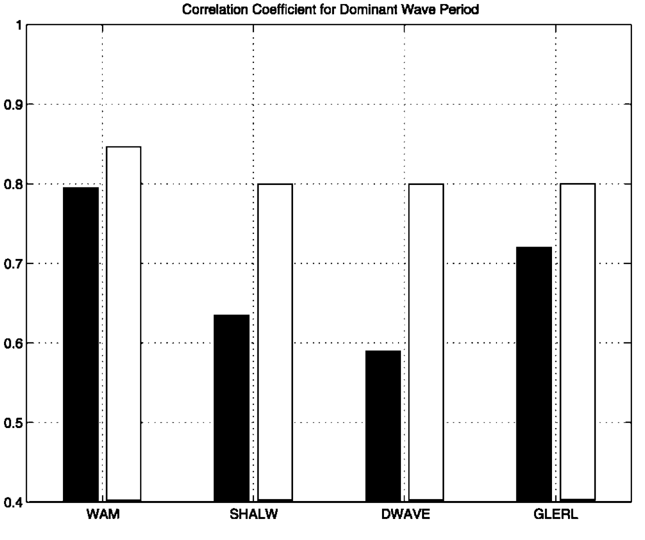

Fig. 9. Mean correlation coefficients for dominant wave period between model and measurement (the darker bars) and between model and model (the lighter bars).

4. Discussion and implications

The results presented in the previous section led us to further consider the following question: why do four rather disparate wind–wave models produce results that are more similar to each other than they are to the measured data, particularly with the WAM model which is known to embody the most complex physics and the GLERL model which includes only a single empirical wind stress term?

It is unlikely that there is an easy and completely objective answer to this question at the present time. We think that the following comments regarding the WAM model Komen et al. (1994) made in their "Summary and outlook" chapter may be germane:

> Despite the progress, we still are not able to make wave predictions that always fall within the error bands of the observations. One may wonder whether it will be possible further to ameliorate modelling of the sea state by introducing "better" physics, better numerics or higher resolution. In view of the progress that has been made by going from second to third generation models, one should not be too optimistic about the effect of further refinement…

Komen et al. proceeded to suggest three possible sources of error: inadequate input wind, inadequate wave model physics, and inadequate numerics and resolution. In this study, at least for the purpose of model comparisons, we tried to minimize the effect of inadequate wind input as well as inadequate resolution by using the same objectively analyzed wind field derived from available wind measurements around the lake and using the same grid size for all models. We indirectly addressed the question of adequacy or inadequacy of model physics by testing various models with widely varied degrees of physical complexity. Since the results are all similar and seem to be insensitive to the proportions of physics content of the models, it appears that either the role of physics as currently defined is essentially insignificant or some fundamental aspect in the wave modeling procedure is preventing further improvement in model results or both. Nevertheless, the results led us to envision that may be it is time to explore alternative or contrary approaches with physics themes separate from those currently formulated frameworks. Regarding the possible error on inadequate numerics and resolution, we endorse the contention of Komen et al. that higher order schemes never lead to better prediction and expect that the usual resolutions utilized in the respective models would suffice.

A common theme that is relevant to all the current models is that they are all based on the prevailing concept of wind–wave energy spectrum characterization. The basic wind wave prediction process is simply a resolution of predicting wind–wave energy spectrum. All the efforts over recent decades have been focused on using the energy action balance equation to predict the wind–wave energy spectrum. If we consider possible aspects of the wave modeling procedure that might be preventing prospective improvement in the model results, the basic concept of a wave energy spectrum which has never been previously questioned, certainly warrants closer examination.

One of the fundamental premises of the concept of a wave energy spectrum is that it is the realization of a stationary process, so much of the earlier theoretical and empirical wind–wave modeling efforts were based on characterizing wind waves as a stationary process. Wave modeling based on the wave energy spectrum prospered during the era of explosive advancement in computer technologies. With generally reasonable results being produced from such models, the stationarity of wind waves seemed to have been practically taken for granted in more recent years. However, as any casual lake or oceanic observer can readily attest, the intermittent nature of real wind waves are certainly not representative of a stationary process.

A well-established observable fact, that wind waves regularly move, advance, and propagate in groups, is clearly incompatible with the basic wave spectrum concept. This is probably the most troublesome feature of the current state-of-the-art wind wave modeling. In practical applications, using the conventional recording time length (~1200s) as the basic time scale, the models generally provide useful results, which is probably more of a statistical coincidence rather than an indication of fundamental wave dynamics. There is no effort, however, to approach the modeling process from the time scale and perspectives of wave groupings at the present, which is likely to be the promising direction for new modeling endeavors to follow.

Wave breaking, which is closely related to wave groupiness, has been incorporated in the WAM model through some complicated approximations relating wave breaking to the wave energy spectrum. In view of the results shown in this study, it is doubtful that the inclusion wave breaking in the model provided any tangible improvement over the simpler models.

The self-similar form of the wave energy spectrum and the slope of the equilibrium range on the high frequency side of the spectrum have been the subjects of various empirical and theoretical studies during the earlier stages of wave model development. A number of formulations for the generalized spectrum form have been proposed and the assumed slope of the high-frequency equilibrium range has evolved from an intuitive representation of f^{-6} to the dimensionally fitting f^{-5}, and subsequently to the semi-theoretical f^{-4}. Although the three spectral models used in this study all assume f^{-5} equilibrium range, it is unlikely that any improvement in the comparison with observations would result from a different assumption.

Therefore, upon laborious and conscientious deliberations, we would like to suggest that the present concept of the wind wave spectrum, which has been a central concept in wind wave studies for over five decades, has reached the limit of its usefulness as the basis for modeling wind wave processes. The application of wave spectrum analysis is an approach that was basically a recourse for convenience and expediency rather than for intrinsic and deterministic dynamical reasons, as discussed in Liu (1999). A wave spectrum is only a time-averaged portrayal of the complete time-frequency energy content of the wave field over the segment of time for which the spectrum is calculated. The length of the time segment has turned out to be the default time scale of the models. But within this time segment, there are active wave groups which redistribute spectral energy on a continuous basis. The processes that occur within the time segment exemplify a critical part of the wind wave dynamics which is totally overlooked by the current generation of models.

Donelan et al. (1996) indicated that spectral representations for waves require the assumptions of stationarity and ergodicity of the wave field, which preclude unsteady conditions or isolated events, so that “the common analytical approach is to omit these events, yet these very conditions are often the ones that are least understood and of greatest practical concern.” Donelan et al. also proposed that wave studies should take into account the “observed groupiness of wind-generated waves.” Although Komen et al. (1994) considered wave packets in connection with wave–wave interactions in developing the WAM model; an assumption of Gaussian stationarity and the emphasis on the wave action spectrum seemed to diminish the importance of wave packet processes. For these reasons we believe that the traditional approach to wave modeling based on the wave energy spectrum may have reached its limit in terms of reproducing observed wave characteristics and that a whole new approach to wind wave modeling focused specifically on the wave group processes and nonstationary energy transfer processes might be an appropriate route for further development.

5. Concluding remarks

There are two conclusions frequently encountered in connection with wind wave model verifications. One is rather subjective and implies that inaccuracy in wave model prediction is due to inaccuracy in wind field prediction. Imperfect specification of the wind field will always be a limiting factor in the accuracy of wave model results, but it is often hard to isolate this effect. The other conclusion is more realistic and acknowledges that it is difficult to separate wind and wave model errors. In this study, by comparing four models with substantially different formulations under the same realistic wind field, we tried to show that there may be another more fundamental limitation of the model. In the previous discussion of these model intercomparison results, (Schwab et al., 1991) we concluded that “when results from all four models differ from observed wave data during a storm episode, yet agree with one another, the differences are most likely due to inaccurices in the interpolated wind field, but when results from the models differ from observed data, and from each other, the differences are more likely due to inadequacies in the models.” The key issue we are trying to address in this paper is to underscore the fact that for the same input wind field, regardless of the accuracy of the wind field, results from different models often vary among each other as much as they vary from observed conditions. This is an intrinsic concern that most previous studies seem to have overlooked. Similar errors from similar models should not be surprising, but our results show similar errors from models with significantly different physical formulations. Additional model verification and model comparisons may lead to further refinement or improvement for particular case studies, but we believe that there may be an underlying limitation to further improvement of models based on the concept of a wave energy spectrum. Fresh and new approaches to wave modeling may be required for further substantial improvement.

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