

WAVE PREDICTION TECHNIQUES - A REVIEW

S. MANDAL
Scientist,
Ocean Engineering Division
National Institute of Oceanography
Dona Paula, Goa - 403 004

B. U. NAYAK
Head, Ocean Engineering Division
National Institute of Oceanography
Dona Paula, Goa - 403 004

ABSTRACT

In the early 1940's the wave predictions were made based on the simple empirical formulations, whereas in the last few decades, greater emphasis is given to numerical models based on the spectral energy balance equation due to availability of adequate computer facilities. The numerical wave models are validated based on the extensive experiments and observations. Very recent development shows the importance of non-linear wave-wave interactions in wave generation. This paper presents a critical review of various wave prediction techniques with an approach to be followed for India.

INTRODUCTION

Meteorologists generally use the term wave forecasting and wave hindcasting to convey the same meaning, namely wave predictions. From the scientific point of view, however, we speak of the wave hindcasting when historical wind data are used for the purpose of wave prediction, whereas the term wave forecasting is used to mean the prediction of present and future waves based on real time wind data.

The importance for the prediction of the ocean surface waves was felt as early as in 1940's for planning of amphibious operations during the second world war. A wave prediction method was first developed by Sverdrup and Munk (1947) which is based on the significant wave height approach. This method has been revised many times and is still being used, largely because of its simplicity and efficiency. The application of the spectral concept was introduced by Pierson & Marks (1952). The spectral concept was incorporated into a practical wave forecasting method by Pierson et al. (1955). The widely accepted energy balance equation was first introduced by Hasselmann (1960). The source functions of the energy balance equations represent the process of wave generation, wave breaking and dissipation. The theoretical concept of non-linear wave-wave interactions was first studied by Hasselmann (1962, 1963). The models developed by Barnett (1968) and Ewing (1971) include approximate representation of these non-linear interactions. Based on the analysis of measurements on

wave growth with fetch in the JONSWAP (Joint North Sea Wave Project) experiment, Hasselmann et al. (1973) have shown the importance of the non-linear wave-wave interaction in the energy balance equation. But the consideration of this term fully in the model has not been possible as this would require very large computing facility. To overcome this, Hasselmann et al. (1976) proposed a simplified parametric wave model in which a dimensionless peak frequency is used to characterise the stage of the wave growth.

Many wave models have ever since been developed but, only a very few critical reviews on the subject are available. Cardone & Ross (1979) reviews the structure of the state-of-the-art spectral and parametric methods and validation of the models. World Meteorological Organization (WMO, 1976) gives the fairly representative description on various wave models. The review by Holthuijsen (1983) gives a description on wave generation and a brief qualitative and quantitative evaluation of the performance of various models. An extensive state-of-the-art on the numerical wave prediction models is presented in Ocean Wave Modelling, published by the SWAMP Group (1985). A critical upto-date review has been presented in this paper with a few recommendations regarding the approach on wave modelling which can be followed in India.

GENERATION OF OCEAN WAVES

The most generally accepted condition to consider the wave generation is the ideal fetch limited situation where a constant wind (U) blows perpendicular to the coast over deep water. As the wind blows, the significant wave height (H_s) and significant wave period (T_s) increase with increasing distance (Fetch, F) from the coastline. Initially a constant wind blows over the calm sea causing the waves to grow. The rate of wave growth decreases as the waves grow higher upto a stage beyond which waves no longer grow. This situation is called "fully developed sea".

From the Shore Protection Manual (CERC, 1973) the approximate empirical relationships between wind parameters and wave parameters are expressed as

$$\bar{H} = 0.283 f_1(\bar{d}) \cdot \tanh \left(\frac{0.0125 \bar{F}^{0.42}}{f_1(\bar{d})} \right) \quad \dots \quad 1a$$

$$\bar{T} = 7.54 f_2(\bar{d}) \cdot \tanh \left(\frac{0.077 \bar{F}^{0.25}}{f_2(\bar{d})} \right) \quad \dots \quad 1b$$

where, $\bar{H} = gH_s/U^2$, g = gravitational acceleration.

$$\bar{T} = gT_s/U, \quad \bar{F} = gF/U^2$$

$$\bar{d} = gd/U^2, \quad d = \text{water depth.}$$

In deep water,

$$f_1(\bar{d}) = f_2(\bar{d}) = 1. \quad \dots \quad 2$$

In shallow water,

$$f_1(\bar{d}) = \tanh(0.530 \bar{d}^{0.750}) \quad \dots \quad 3a$$

$$f_2(\bar{d}) = \tanh(0.833 \bar{d}^{0.375}) \quad \dots \quad 3b$$

A more scientific description of sea surface is represented by means of wave spectrum. The sea surface is composed of a large number of sinusoidal waves of different frequencies (f), amplitudes ($H/2$) and phases. A complete wave spectrum contains components of different wave frequency and of different wave direction. During the extensive and detailed study of the wave growth (Hasselmann et al. 1973), it was found that the shape of the spectrum was constant during the wave growth period. In fully developed sea, spectrum peak was found to flatten to some extent. To formulate this shape in an analytical expression, Hasselmann et al. (1973) adopted an expression as

$$E(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp[-1.25(f/f_m)^{-4}] \cdot \gamma \exp\left[-\frac{(f-f_m)^2}{20^2 f_m^2}\right] \quad \dots \quad 4$$

where $E(f)$ is the frequency spectrum. The scale parameters (α, f_m) and shape parameters ($\gamma, \sigma_a, \sigma_b$) are obtained through observed best-fit values by JONSWAP Experiment (1973) as

$$\left. \begin{aligned} \alpha &= 0.076 \tilde{F}^{-0.22} \\ \tilde{f}_m &= 3.5 \tilde{F}^{-0.33} \end{aligned} \right\} \text{for } \tilde{F} < 10^4 \quad \left. \begin{aligned} \tilde{f}_m &= U f_m / g, \text{ dimensionless peak frequency} \\ \sigma_a &= 0.07 \text{ for } f < f_m \\ \sigma_b &= 0.09 \text{ for } f \gg f_m \\ \gamma &= 3.3, \text{ the enhancement factor at } f_m \end{aligned} \right\} \dots \quad 5$$

For fully developed sea, the JONSWAP spectrum reduces to Pierson-Moskowitz (1964) spectrum with values:

$$\left. \begin{aligned} \alpha &= 0.0081 \\ \tilde{f}_m &= 0.13 \end{aligned} \right\} \text{for } \tilde{F} > 10^5 \quad \dots \quad 6$$

$$\gamma = 1.0$$

The above frequency spectrum gives sufficient wave information for many engineering problems. Sometimes it is essential to have additional directional information as expressed by the two-dimensional spectrum $E(f, \theta)$. The two-dimensional energy spectrum is constructed from equation - 4 by assuming a fixed cosine square spreading factor defined relative to the local wind direction

$$E(f, \theta) = E(f) \cdot \frac{2}{\pi} \cos^2(\theta - \theta_w) \quad \text{for } (\theta - \theta_w) \leq \frac{\pi}{2}$$

$$= 0.0 \quad \text{for } (\theta - \theta_w) > \frac{\pi}{2} \quad \dots \quad 7$$

Observation of $E(f, \theta)$ are undertaken in North Sea and other places, but it is yet to be observed in Indian Coastal waters.

WAVE PREDICTION MODELS

The wave models developed to forecast and hindcast waves may be classified under three categories. The first generation models are simple and each spectral component evolves independently of all other components. In the second generation model, the concept of nonlinear wave-wave interaction is introduced with simplified terms. The third generation models take into consideration the exact solution of nonlinear wave-wave interaction terms. Both the second and third generation models consider the wave spectrum as explicit as possible under varying wind field conditions.

First generation wave models:

The first generation models are, in general, simple and mostly validated in the ideal situation of constant wind field. There are different types of models under the class of first generation models.

Seymour (1977) proposes a directional decoupling model, where a stationary homogeneous windfield is considered over a deep water basin with an arbitrary geometry of the coastline. Here the wave components which are coming from a direction θ_0 off the wind direction are assumed to be generated independently from other wave components. For the wave components from the direction θ_0 , the only relevant independent variables are the wind speed and the distance $L(\theta_0)$. The directional decoupling means that another geometry of the water basin with same values of the independent variables will give identical results. The most convenient choice of such a different geometry for hindcast/forecast is the ideal situation with fetch $L \cos\theta_0$. The simplest method to predict the two-dimensional spectrum in an ideal situation is to assume a standard spectrum, that is, the JONSWAP spectrum with $\cos^{2S}(\theta_0/2)$ - directional distribution. The parameter relationships are considered as given in equation (5). The full two-dimensional spectrum is obtained by repeating the above procedure for all the directions. Similar approach is used in the model developed by Cavaleri & Rizzoli (1977).

A different approach from above is considered in the model proposed by Pierson, Neumann and James (1955). The model is also called as PNJ-Model, for estimating wave conditions created by the distance storm. Here a storm is assumed to be in rectangular box in which the wind field is constant. This box propagates over the ocean to simulate the storm wave statistics. If the box is stationary, the 2-D spectrum at the downward end of the box can be estimated using the expression shown in equation (7). Effective fetch is used when the box is not stationary. The waves generated in the storm area are described as the superposition of a large number of wave trains, each propagating with different wind speed (U_i) and direction (θ_i). This indicates that the generated wave energy spreads over the ocean as distance to the generating storm increases.

A modified version of the PNJ-model was used by Darbyshire (1961). In this model he assumed that the sea state was fully developed after 12 hours and 200nm of constant wind. Considering the Atlantic Ocean into boxes of each 200 x 200 nm and a time step of 12 hours, he always found a locally generated fully developed sea. This sea state was superimposed on swells which were formed for other boxes sometime back.

The model for ideal condition was proposed by Wilson (1955) and later on extensive studies were made by Bretschneider (1963) and Trajer

(1966). This has also been published in the form of a handbook by WMO (1976). In this model, the local sea state is expressed as one wave train of small horizontal dimensions as compared with wind and wave field variation. The propagation of wind field is calculated by considering the group velocity of the significant wave period and the predominant wave direction. The significant wave period may be determined from the relationship \bar{T} and \bar{F} given by Wilson (1955). Change of \bar{T} per unit \bar{F} can be determined as a function of \bar{T} . Here \bar{F} is not defined for varying wind field. The integration of the rate of change of \bar{T} under varying wind field gives the path of developing wave train. Using a similar technique, the development of \bar{H} can be determined.

The model developed by Ross & Cardone (1978) is applicable to the tropical hurricanes where non-dimensional radial distance ($R = cR/U^2$) from the point of the forecast to the eye of the hurricane is one among the characteristic wind parameters. They have found the expression similar to JONSWAP parameters based on the number of wave observations in slowly moving hurricanes (less than 15 knots).

Second generation wave models:

The second generation models are used under varying wind fields. Here the sea surface is defined as the sum of a large number of individual wave components, each wave propagating with constant frequency according to the linear wave theory. To calculate the energy spectrum of one such above component at one time and one location, the following procedures may be adopted. The path of wave components (from the origin/coastline to the forecast point) are calculated by the conventional methods. After leaving the origin, the wave component interacts with the wind, the bottom, wave breaking and also interacts with other wave components. Thus, at regular interval of time, the energy gained or released in the process can be evaluated till it reaches the forecast point. This procedure can be repeated for a large number of wave components of different frequencies and directions at a given time so that total energy is obtained at the point of forecast. The final two-dimensional spectrum can be defined for a large number of grid points in time and space.

The above process of evolution of the surface wave field in space and time is the integration of the energy balance equation for each wave component

$$\frac{\partial E}{\partial t} + C_g \cdot \nabla E = S \equiv S_{in} + S_{nl} + S_{ds} \quad \dots \quad 8$$

where $E(f, \theta, x, t)$ is the 2-D wave spectrum, dependent on frequency f and propagation direction θ , $C_g(f, \theta)$ is the group velocity. The total source function S is represented by S_{in} - input by wind, S_{nl} - nonlinear wave-wave interaction and S_{ds} - the dissipation. Initially very little information is available to clearly express the growth of the energy density in growing wind sea. Phillips (1957) shows a linear growth of energy due to wind input. Later on this growth is expressed as sum of a linear growth and an exponential growth. The following processes may take place contributing to the exponential growth.

(a) A feed back mechanism by Miles (1957) - Wave induced pressure differences across a non-breaking wave-crest transfer energy from wind to wave component at a rate proportional to the energy density of wave component.

(b) Sheltering mechanism by Jeffreys (1926), Banner & Melville (1976) - Wind energy is transferred to waves by the wave induced pressure differences across breaking waves.

(c) Non-linear wave-wave interactions by Hasselmann (1960, 1963) and Hasselmann et al. (1984) - When groups of wave components interact with other wave component, during the exponential growth, there is a net gain of energy (E) by the wave-wave interaction. Thus,

$$\frac{dE}{dt} = A + B.E$$

... 9

Where A is Phillip's constant, B is determined from observations, dependent on frequency, wind speed and direction. B represents all the above three mechanisms and any other mechanism related to the exponential growth.

The dissipation power function is generally treated in the wind sea region. This term is used in models developed by Cavaleri & M. Rizzoli (1981), Hasselmann et al. (1973), Komen & Hasselmann (1984). The non-linear term S_{nl} was not used effectively due to lack of knowledge until late 1960's. However, more simplified version of S_{nl} is used by Barnett (1968) and Ewing (1971). The numerical experiments by Hasselmann et al. (1973) have shown the importance of non-linear wave-wave interactions. Due to lack of large computing facility, the analytical expression of S_{nl} is simplified into a parametric representation and used for second generation wave forecasting models.

Recently a large group of experts on wave models (SWAMP, 1982, 1985) from USA, Japan and Europe has made an attempt to interpret all the available operating models for intercomparison study. They have shown that (a) the first generation models generally don't show the overshoot phenomenon of growing wind sea as observed by Barnett & Wilkerson (1967) and others and (b) non-linear wave-wave interaction term is implemented in 2nd generation models (Hasselmann et al. (1976), Toba et al. (1982), Gunther et al. (1979), Mitsuyasu et al. (1980)) resulting in improvement and better results.

Very recently a numerical wave prediction model DOLPHIN is being developed (Mandal, 1985). It is a hybrid point model applicable to only deep sea conditions, as the combination of the parametric wind-sea and spectrally treated swells. A comparative study with SWAMP, 1982 report shows satisfactory results for a few important test conditions. For a given bottom and wind-field geometry, the model predicts various wave parameters namely significant wave height, one-dimensional and two-dimensional energy spectra, mean wave direction etc. at a particular desired location. This model is being developed based on the work carried out by Hasselmann et al. (1973), Mitsuyasu et al. (1980), Holthuijsen (1983) and others. In this model, the JONSWAP spectrum is considered and various parameters are determined from the following relationships.

$$\begin{aligned} d &= 3.63 \times 10^{-2} \tilde{f}_m^{0.87} \tanh^c(a\tilde{f}_m^b) &) \\ a &= 1.068 \times 10^{13}; b = 17.4; c = -0.05 &) \quad \dots \quad 10 \\ \tilde{f}_m &= 2.03 \times 10^{-2} \tilde{E}^{-0.33} &) \end{aligned}$$

$$\gamma = 30.00 \left[\frac{\bar{E}(2\pi)^4 \bar{E}_m^{0.4}}{\alpha - 0.135} \right]^{1.245}$$

σ_a, σ_b are the same as that of the JONSWAP spectra.

Some interesting results are shown to verify how different models including DOLPHIN behave under some conditions as reported by Mandal (1985). Fig. 1 shows the fetch limited one-dimensional spectral growth curves. Overshoot phenomena could be observed from this figure.

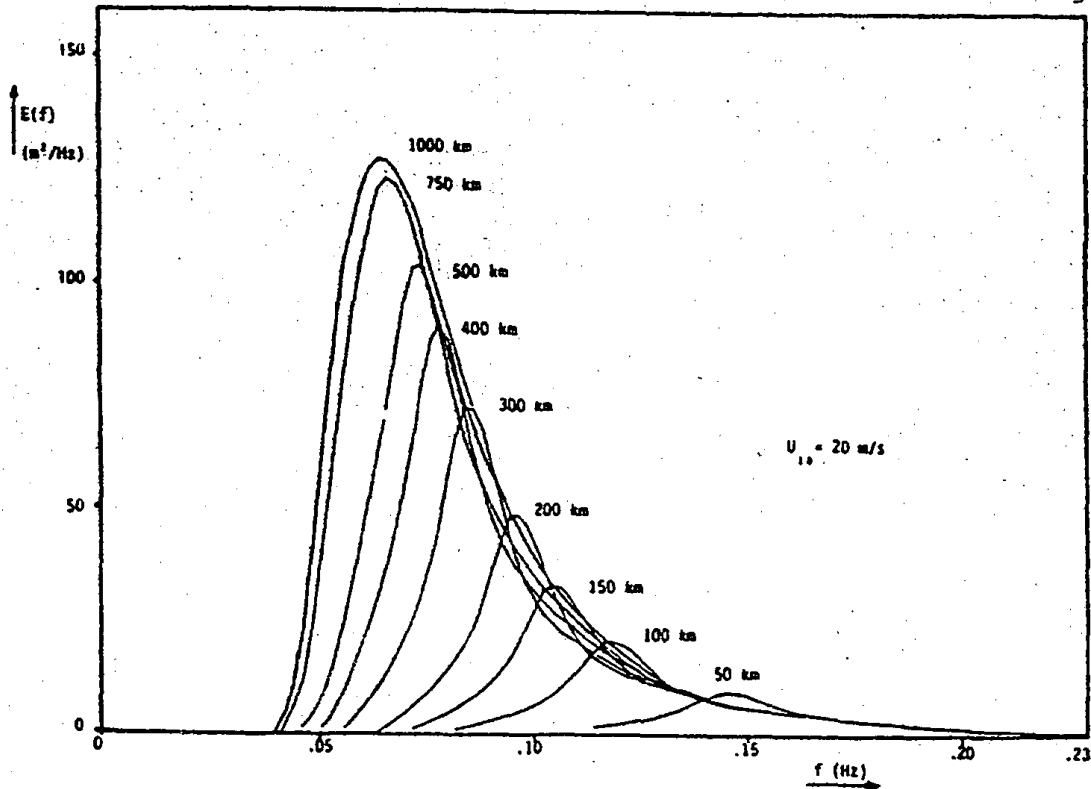


Fig.1 Fetch limited 1 - D Spectral growth curves

Fig. 2 and 3 show the fetch and duration limited growth curves for the total energy, where it is clearly seen that due to lack of clear physical concept, there are wide variation of results, eventhough all models show similar trend in the growth curves.

Third generation wave model:

The present wave prediction (2nd Generation) models are based on the integration of the radiation transfer equation which describes the propagation of different wave components of the spectrum with different frequencies and propagation directions at their appropriate group velocities, and the change in the energies of components produced by wind forcing, dissipation and higher order nonlinear interaction. Due to lack of accurate representation of the nonlinear transfer process, the present 2nd generation models have to make a priori-restrictions on the spectral shape. The third generation model which is being developed by coordinating all European wave modelling groups is based on a complete

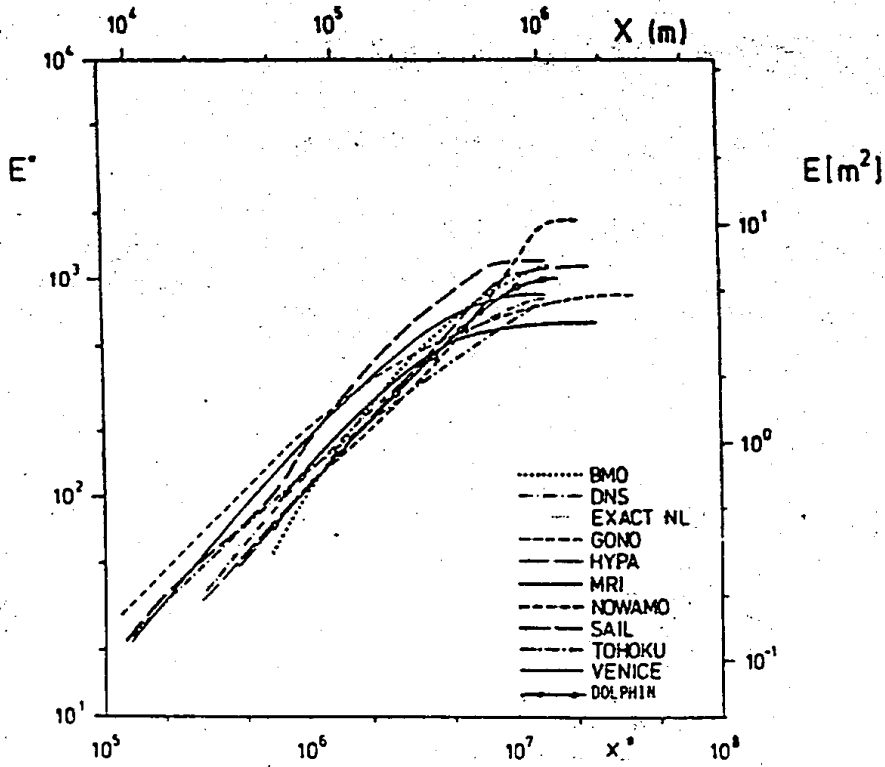


Fig. 2 Non-dimensional fetch limited growth curves for the total energy E^2

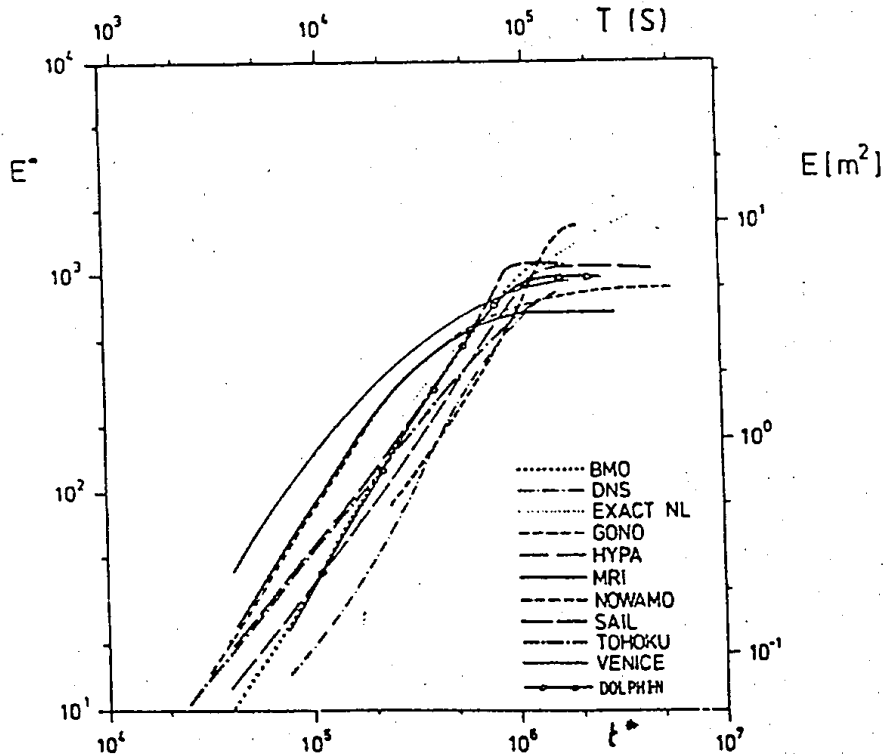


Fig. 3 Non-dimensional duration limited growth curves for the total energy E^2

representation of all source terms without any priori-restrictions on the spectral shape (Komen, 1984). The SWAMP (1985) has clearly shown that such an approach is required for a correct description of the wave phenomena in the situation of wind-sea to swell transition and in case of turning wind fields when directional relaxation has taken place.

Some tests were made on a CRAY and a CIBER-205 Computer using this Global (3rd generation) model in which both the parameters and the exact form of nonlinear interaction are incorporated for comparison. The model reproduces the complete two-dimensional spectral distribution without any prior constraints on the spectral shape.

PROPOSED PROGRAMME AT NIO

Keeping in mind the limitation of the computing facility available at NIO, it is proposed to develop the second generation wave prediction model - DOLPHIN (Mandal, 1985) on a priority basis. It is a deep water point model (predicts wave parameters at a required location). This model will be modified by introducing the shallow water conditions to make it applicable to nearshore and estuarine region. The point model will then be modified into a grid model. Data on various cyclones which occurred on the East and West coasts of India during the last 20 years (Weather charts to be collected from Indian Meteorological Department, Pune) will be analysed to obtain various wave parameters using the model. Thus a very useful wave data base will be created at NIO. Based on these data various design parameters can be obtained at the place of interest. Such hindcast data in conjunction with instrumentally collected data would be essential for the design of cost-effective and functionally efficient ocean structures.

CONCLUSION

There are many operating numerical wave models which are being used for real time wave forecasting. SWAMP (1982, 1985) shows inter-comparison study of different operational models where weak points of different models are highlighted and emphasis is given to use the non-linear wave-wave interaction term as explicit as possible for yielding exact computation.

The first hand information on wave statistics could be obtained by First generation models which are relatively simple and less computing cost, whereas 3rd generation model is much complex than 2nd generation model and it also needs bigger computing facility. The global model does the computation of the non-linear terms with exact computation without any simplification and it gives most accurate results as compared to other models.

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