CHAPTER 2: Physical Processes of Wave Evolution and Numerical Modeling: A review

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2.1 Introduction

The systematic study of wave generation, propagation and dissipation was started during World War II for effective marine operations. Sverdrup and Munk initiated to develop an operational wave forecasting technique using parametrical description of the sea state, although limited in many respects. An important advancement was the introduction of the concept of a wave spectrum (Pierson et al., 1955). This approach was practically implemented in dynamical equation by Gelci et al. (1956,1957) and others who introduced the concept of the spectral transport equation. Development of theories of wave generation by Phillips (1957) and Miles (1957) and nonlinear wave-wave interactions by Hasselmann (1962), made it possible to write down the general expression for the source functions.

Modern ocean wave research and modeling efforts are based on spectral energy balance. Before a wave forecast/hindcast model is developed, it is very essential to understand the factors, which contribute to the generation, growth and decay of waves, non-linear energy transfer, white-capping dissipation etc. A reasonably good model depends on how the physical processes are incorporated in the model. The previous studies, which are appropriate to the wave model and deal with the above factors, are referred in this chapter.

2.2 Wave Evolution

The Kelvin – Helmholtz instability mechanism was the first attempt to describe the evolution of the waves. This theory assumes that for sufficiently large wind speeds the pressure distribution over the surface causes small amplitude waves to grow against restoring force of gravity and surface tension. According to this theory minimum wind speed required to generate waves is worked out to be 6.5 m/s. However several field experiments shows that waves exist at much lower wind speeds than that predicted by Kelvin – Helmholtz mechanism.

Later Jeffreys (1924, 1925) used the sheltering hypothesis to explain the wave evolution. In his hypothesis, it was assumed that the energy transfer was exclusively caused by form drag associated with flow separation occurring on the leeward side of wave crests with re-attachment further down on the leeward slope of the wave. The energy transport equation for this hypothesis is given by
\[
\frac{\partial E}{\partial t} = \frac{1}{2 \rho_0 g} S \rho_0 (U - C_p)^2 (ak)^2 C_p \tag{2.2.1}
\]

where the constant of proportionality \( S \) is termed as sheltering coefficient calculated by determining the rate of energy loss due to molecular viscosity and minimum wind speed \((U_{mn})\) that could maintain waves against this loss. The minimum wind speed postulated by Jeffreys is 1.1 m/s, which yields sheltering coefficient 0.3. It should be noted that the energy transfer predicted by this theory is exponential since the square of the wave amplitude is proportional to the total energy and is dependent on the difference of the wind speed \((U)\) and phase speed of the wave \((C_p)\). Hence on the basis of this theory it can be realized that there is no net energy transfer for the waves having phase speed equal to the wind speed \((U=C_p)\). Jeffreys’ theory also predicts that the energy transfer is wave slope \((ak)\) dependent since it is based on the assumption of the flow separation.

Ursell (1956) reviewed the work of Jeffery (1925) and noticed that the pressure difference over a solid profile composed of a number of waves is smaller by an order of magnitude than that postulated by Jefferys’ theory. Banner and Melville (1976) pointed out that airflow separation occurs above the waves only with the onset of wave breaking. Hence sheltering does not contribute significantly to the air-water energy flux. Thus, studies of Ursell (1956), Banner and Melville (1976) elaborated the shortcoming of the Jefferys’ theory and led to development of new theories for explaining wave evolution. After Ursell (1956) two independent theories evolved considering linear wave growth (Phillips 1957) and non-linear wave growth Miles (1957). Phillips (1957) proposed that waves grow by a resonance mechanism; when the speed and the length of atmospheric fluctuations match those of water waves. The wave growth continues until the wave slope becomes large enough that non-linear interactions, which are neglected in this theory, become important. This fluctuation of the water surface was responsible for the birth and early growth of waves. The theory of wave growth proposed by Phillips was also supported by field experiments carried out by Roll (1951). Even though, this theory fails to explain major wave growth, resonance mechanism appears important in bringing the energy level of waves from zero to a point where other mechanisms are important. Miles (1957) postulated that the air is inviscid and incompressible. In the absence of waves, wind can be described
by mean shear flow, which varies only with height above the surface. The wave
induced air pressure perturbations are sufficiently small that they can be neglected.
The Miles mechanism is particularly effective for waves with phase velocities
appreciably lower than the wind speeds. Miles-Phillips wave growth formula can be
given by

\[ \frac{\partial E(t)}{\partial t} = \alpha + \beta E(t) \]  

(2.2.2)

Where \( \alpha \) and \( \beta \) are the linear and exponential growth factors of Phillips and Miles
respectively. Snyder and Cox (1966) proposed the Miles growth factor \( \beta \) as a linear
best fit to the field data as given bellow.

\[ \beta = \frac{\rho_a}{\rho_w} (U_c - \sigma) \]  

(2.2.3)

where \( U_c \) is the mean wind speed normalized to \( U \) via a logarithmic wind profile at a
critical wavelength above the waver surface, \( \sigma \) is the wave frequency and \( \rho_a/\rho_w \) is the
ratio of the density of air to that of water. The subscript ‘c’ denotes the reference
height at which the wind measurement has been done. Further, for determination of
aerodynamic pressure distribution at the interface between air and simple progressive
water waves, the laboratory experiments conducted by Shemdin and Hsu (1967) and
field experiments by Dobson (1971), Elliot (1972), Snyder (1974) and Snyder et al.
(1981) derived the expression of the growth factor as

\[ \beta = C \left( \frac{U_5 \cos(\phi - \theta)}{C_p} - 1 \right) \frac{\rho_a}{\rho_w} \quad \text{for} \quad \frac{U_5 \cos(\phi - \theta)}{C_p} > 1 \] 

(2.2.4)

\[ \beta = 0 \quad \text{for} \quad \frac{U_5 \cos(\phi - \theta)}{C_p} \leq 1 \]

where \( C \) ranges from 0.2 to 0.3 and wind speed \( (U_5) \) measurements are at 5m above
the water surface, \( \theta \) is the wave direction, \( \phi \) is the wind direction. The growth rate
predicted by Miles theory is of the same order of the observations but highly under predicted.

Janssen (1991) obtained the results of wave growth rate ($\gamma$) after modifying the Miles theory by assuming the logarithmic profile of the winds even for the young wind sea. The relation for the growth rate for gravity waves is thus function of friction velocity ($u^*$) wind direction ($\phi$) and wave direction ($\theta$) and can be given as

$$\gamma = \left( \frac{\rho_s}{\rho_w} \right)^{\frac{1}{2}} \left( \frac{u_*}{C_p} \cos(\phi - \theta) \right)^{\frac{1}{2}}$$  \hspace{1cm} (2.2.5)

where $\xi$ is the Miles' parameter as a function of critical height ($\mu$) and Miles' constant ($\xi_n$) chosen in such a way that the growth rate is in agreement with the numerical results obtained from Miles' growth rate. The Miles' parameter is defined as

$$\xi = \frac{\xi_n}{\kappa^3} \mu \ln^4(\mu), \quad \mu \leq 1$$  \hspace{1cm} (2.2.6)

It is realized from the observations of the dimensionless growth rate as a function of inverse wave age (Fig. 2.2.1) from measurements compiled by Plant (1982) that the growth rate varies by four orders of magnitude, which is in fair agreement with Mile's theory.
Fig. 2.2.1 Schematic diagram of dimensionless growth rate ($\gamma/f$) as a function of inverse wave age ($u^*/C_p$) as compiled by Plant (1982)

The process of wave evolution is mainly affected by the atmospheric stability, gustiness of the winds and presence of swell. The influence of atmospheric stability on the wave evolution has been studied by Kahma (1981). This study shows that waves grow more rapidly in unstable conditions i.e. water is warmer than air. Kahma and Calkoen (1992) confirmed this speedy growth in unstable conditions was feature of several data sets used in their study. They also show that frequency is less sensitive than the energy to unstable conditions. The gustiness of the wind has also effect on the wave growth. Gustiness of the wind is explained as the fluctuations of the winds about the mean value. Cavaleri et al (1981) and Smith et al (1990) shows that wind speed has a gaussian distribution. The theory of Miles (1957) indicates that the wind can pump energy to a slower wave, whilst a faster wave remains unaffected. Hence, high wind speed fluctuations transfer extra energy to the wave, which is not compensated during phases of lower speed. Numerical calculations by Cavaleri and Burgers (1992) show enhanced growth rates with increasing gustiness. Donelan et al (1992) has shown that significant effect of the gustiness occurs at large fetches, where increase in gustiness increases the level of the fully developed sea state. Presence of
swell also has effect of the wind wave evolutions. Experiments show that presence of swell reduces the growth of wind generated waves (Mitsuyasu, 1966, Phillips and Banner 1974, Hatori et al 1981, Bliven et al 1986, Kusaba and Mitsuyasu, 1986, Donelan 1987). The mechanism by which this is occurring is not clear. Young et al (1985) have shown that the non-linear coupling between swell and wind-sea should be weak and hence less interaction. However the field experiments of JONSWAP (Hasselmann et al 1973), Kahma and Clakoen (1992), Kahma (1981) and Dobson et al (1989) could not find difference in the growth rate with or without the presence of swell. Observations have suggested that the momentum transfer is much increased when wave breaking occurs. Another phenomenon called non-linear transfer from shorter to longer waves also plays an important role in wave growth, which is described in section (2.5).

2.3 Fetch And Duration Limited Wave Growth

There exist many factors influencing the growth of ocean waves. Among these, major factors for the wave growth are wind speed, wind direction, geometry of the coastline, water depth and their variation. For ocean wave modeling wave growth has been studied due to fetch limited wave growth and duration limited growth. The Fetch is generally defined as the linear distance over which wind blows in a particular direction. The Duration is defined as the period of time for which wind is blowing in a particular direction. In the case of wind of constant magnitude and direction blowing perpendicular to a long and straight coast line is known as fetch limited wave growth, whereas the wave growth due to winds blowing in a uniform direction over sea for certain period of time is called duration limited growth. Sverdrup and Munk (1947) and Kitaigorodskii (1962, 1970) suggested four major non-dimensional variables $\sigma^2$ (variance of the water surface elevation), $U_a$ (the wind speed at measured at reference height $a$), $\chi$ (fetch) and $t$ (duration). The fetch and duration limited growth relations are hence derived in terms of these four non-dimensional parameters. The non-dimensional parameters are defined as
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\[ \varepsilon = \frac{\sigma^2 g^2}{U_a^4} \quad \text{- the non-dimensional energy} \]  
\[ \nu = \frac{f_p U_a}{g} \quad \text{- the non-dimensional frequency} \]  
\[ \chi = \frac{g \chi}{U_a^2} \quad \text{- the non-dimensional fetch} \]  
\[ \zeta = \frac{gt}{U_a} \quad \text{- the non-dimensional duration} \]  

Several field experiments were carried out to establish a relationship among these non-dimensional variables to get the fetch and duration limited growth curves. Pioneering work in investigating fetch and duration limited growth of ocean waves was done by Sverdrup and Munk (1947) and Bretschneider (1952a, 1958) to give SMB curves to predict fetch limited waves. The results of Sverdrup Munk and Bretschneider (SMB) are summarized in CERC (1977). Afterwards series of field experiments were carried out independently to give correct relation for fetch and duration limited growth. These experiments include Pierson and Moskowitz (1964) studies of fully developed seas, JONSWAP experiment during July 1969, to establish growth relationship for very large fetch (Hasselmann et al, 1973) and wave growth studies specific to great lakes (Donelan et al., 1985, Donelan et al. 1992), Bothnian Sea (Kahma, 1981) and North Atlantic coast of Canada (Dobson et al 1989).

The fetch-limited growth largely depends on the fetch geometry. Donelan et al (1985) showed that when the wind is not perpendicular to the land boundary, there is a strong gradient in the fetch about the wind direction causing reduction in the effective forcing winds. In this conditions wave directions differs from the wind directions and wave preferentially propagate form a direction with a longer fetch than that measured directly along the wind direction. Kahma and Pettersson (1996) investigated the fetch-limited growth in the narrow bays. In their study they found that for the same values for \( \chi \), \( \varepsilon \) was significantly lower when the wind direction was along the long axis of the bay. The study of Kahma and Pettersson (1996) also shows that the non-dimensional frequency was also affected but not to the same extent as \( \varepsilon \).

The observations for duration limited wave growth are very small. Wiegel (1961) compiled the duration limited wave growth data. An Approximation to this data was provided by CERC (1977)
\[ \zeta = K \exp \left\{ \left[ A (\ln \chi)^2 - B \ln \chi + C \right]^{1/2} + D \ln \chi \right\} \]  

(2.3.5)

where \( K=6.5882, A=0.0161, B=0.3692, C=2.2024 \) and \( D=0.8798 \).

Sanders (1976) proposed a relationship for the duration limited growth of the waves of the form

\[ \varepsilon = 3.22 E(-3) \left[ \tanh \left( 1.26 E(-3) \zeta^{0.75} \right) \right]^2 \]  

(2.3.6)

This relationship was scaled in terms of the friction velocity, \( u^* \) rather than \( U_{10} \), in order to obtain the asymptotes close to the Pierson Moskowitz value, \( U_{10} \) was assumed to be approximately \( 21u^* \).

### 2.4 Non Linear Wave-Wave Interactions

Ocean waves can be regarded as the superposition of free and independent spectral components. However, there exist interactions between spectral components, which results in a transfer of energy between the components (Phillips 1960). Nonlinear interactions can occur at all orders. The lowest order of such type of interactions is triad interactions in which two waves interact nonlinearly and transfer energy to a third component. It is also observed that even though the two components waves interacting in this way are satisfying the dispersion relationship, the third component may not necessarily satisfy the dispersion relation. The non-linear wave interactions are called resonant only when third component satisfies the dispersion relation. The triad nonlinear interactions are resonant (i.e. the amplitude to third component increases to the same order of primary interacting waves) only when the waves are nondispersive, observed in very shallow waters and hence found important in finite depth conditions but insignificant in deep water (Hasselmann 1962).

In deep water, quadruplet wave-wave interactions dominate the evolution of the wave spectrum. They transfer wave energy from the spectral peak to lower frequencies (Thus moving the peak frequency to lower values) and to higher frequencies (where the energy is dissipated often resulting in higher harmonics (Beji
and Battjes, 1993). The Boltzmann integral describes the rate of change of energy density of a particular wave number due to resonant interactions between pairs of four wave numbers.

\[
\frac{\partial E_1}{\partial t} = \iiint G(k_1, k_2) \delta\left(k_1 + k_2 - k_3 - k_4\right) \delta\left(\omega_1 + \omega_2 - \omega_3 - \omega_4\right) \left[ E_1 E_2 - E_3 E_4 \right] dk_1 dk_2 dk_3 (2.4.1)
\]

Here \( G \) is the coupling coefficient (Herterich and Hasselmann, 1980, Van vledder 1990), \( k_j \) are the wave number and delta functions are used to ensure that the contributions to the integral only occur from four waves satisfying the resonance conditions (Hasselmann 1962).

\[
\omega_1 + \omega_2 = \omega_3 + \omega_4 \quad (2.4.2)
\]

and

\[
\bar{k}_1 + \bar{k}_2 = \bar{k}_3 + \bar{k}_4 \quad (2.4.3)
\]

in which \( \omega_j \) is the frequency in radians and \( \bar{k}_j \) is the wave number. The resonance conditions define the necessary condition for the waves in terms of wave frequency and direction to interact non-linearly. The non-linear energy transfer represented by Boltzmann integral conserves the total energy and momentum of the wave field, merely redistributing it within the spectrum. The Boltzmann equation for four wave resonant interactions is valid for typical ocean-wave spectra for which interactions are sufficiently weak so that asymptotic \( \delta \)-function is applicable and the changes in the spectra due to secular terms can still be regarded as perturbations. However, it breaks down for interactions between very short waves and long waves, when the wavelengths of the short waves become comparable with the wave heights of the long waves and also in the shallow waters.

Understanding of nonlinear interactions and its role in evolution of wind waves were studies during joint north-sea wave project (JONSWAP) (Hasselmann et al 1973) for various fetch-limited spectra ranging from very young to almost fully
developed sea states. A full computation of the quadruplet wave-wave interactions is extremely time consuming and not convenient in any operational wave model. A number of techniques, based on parametric methods or other types of approximations have been proposed to improve computational speed (Young and van Vledder, 1993).

2.5 Wave Growth Due To Non-Linear Interactions

As the wave continues to grow, the non-linear mechanism becomes important. Limitations due to linear approximation in the theory of Miles and Phillips make it unable to explain the wave growth. Phillips (1960) showed that under certain conditions, the third order perturbations become large and unsteady. This perturbation exists when the resonant conditions (Eq 2.4.2; 2.4.3) are satisfied. Phillips showed that there exist configurations of three waves, which interact to give a continuous transfer of energy to a distinct fourth wave whose amplitude grows linearly with time. Longuet-Higgins (1962), Benney (1962) and others extended Phillips' work to calculate non-linear interaction terms. Hasselmann (1962,1963) derived the relation expressing the effect of resonant interactions on the entire wind wave energy spectrum using fifth order perturbations analysis.

The resonant interactions cannot be considered as a source for wave generation or wave dissipation since they do not change the total wave energy. However, these resonant interactions may play important role in wave growth by distributing the wave energy supplied by the wind from the low frequency to the high frequency of the spectrum. The growth measurements during JONSWAP experiments reveal that rapid growth of low frequency waves was primarily associated with nonlinear energy flux due to resonant wave-wave interactions. Hasselmann and Hasselmann (1985a) and Hasselmann et al (1985) demonstrated that the Boltzmann integrals (eq. 2.4.1) could be evaluated completely using an efficient integration algorithm, which can be handled by present generation super computers.

2.6 Wave Dissipation

Dissipation of ocean wind waves occurs primarily due to waves breaking when the waves approach a shoreline. Near a shoreline with evenly sloping beaches, wave breaking can occur in two ways: wave plunging and wave spilling. The plunging breaker has a well-rounded back and a concave front and can form with a
wave steepness of about 0.005 and an offshore wind. Spilling breakers are concave on both faces and are produced by waves with steepness greater than 0.01. According to Stokes (1880), a wave breaks when water particles in its crest advances faster than its profile or crest angle exceeds 120°. This limiting value of the crest angle corresponds to a wave steepness of 1/7, which is theoretically derived maximum wave steepness. Most observations of wave steepness give a value between 0.1 and 0.008. In the open ocean, wave breaking occurs generally in the form white-topped waves commonly known as whitecaps of white horses. According to Phillips (1963), wave breaking over the open sea can occur by two process: one, in which the low frequency wave interact each other and the other in which short wind-generated waves are overtaken by longer waves; Phillips further proposes a mechanism by which short wind-generated waves extract energy from the long waves though a ‘radiation stress’; leading to the attenuation of waves (Hasselmann, 1971).

Wave dissipation due to breaking represents a localized, strongly nonlinear interaction process. A number of studies have been carried out to investigate wave dissipation and spectral characteristics (Banner and Phillips 1974, Hasselmann 1974 and Phillips 1985). Hasselmann (1974) investigated the effect of white-capping on the spectral energy balance by expressing the white cap interactions in terms of an equivalent ensemble of random pressure pulses. He further derived a damping coefficient for white capping which was shown to be proportional to the wave angular frequency ($\omega$). The dissipation coefficient and the associated dissipation function were found to be consistent with the structure of the energy balance derived from the JONSWAP data. Phillips (1985) expanded Hasselmann’s approach and obtained an estimate for the average rate of spectral energy loss resulting from wave breaking. Phillips further postulated that the process of energy input from the wind, loss by wave breaking and the net transfer by nonlinear interactions are of comparable importance throughout the equilibrium range of wind-generated waves. With this hypothesis, Phillips obtained a frequency spectrum, which can be expressed as proportional to the $\omega^{-4}$. This form is similar to the one obtained empirically by Toba (1973).
2.7 Numerical Modeling of Ocean waves

There exist number of empirical methods to predict the ocean wave spectra and their integral properties. These approaches are limited to a very narrow range of applications. A practical wave prediction technique should be able to reconstruct local wind generated sea and swell by incorporating spatially/temporally varying wind, irregular bathymetry and coastlines. After pioneering work of Gelci et al. (1957), numerical wave prediction models simulating temporal and spatial evolution of the two dimensional spectrum due to physical processes such as wind input, white-cap dissipation, bottom friction and weakly nonlinear interactions is formulated in terms of the basic energy transport equation.

\[
\frac{\partial \bar{E}}{\partial t} + \nabla \cdot \left( \bar{C}_g \bar{E} \right) = S
\]  

(2.7.1)

where \(\bar{E}\) is the spectral wave energy density, \(\bar{C}_g\) is the group velocity and \(S\) is the linear combinations of the various source terms representing different physical processes that transfer energy to and from the wave spectrum. Since then wave modeling based on the energy transport equation 2.7.1 has advanced through different generations. These generations of the models are defined on the basis of the physics of the wave evolution described in the source terms of the energy transport equation 2.7.1. Numerical models contemporary to Gelci et al. (1957) are called first generation models. In this generation of models, the source term was describing only the physics of evolution of the waves due to winds and its dissipation and evolution of each spectral component in the model is independent of each other. Hence the models exhibiting this characteristic have been categorized as Decoupled propagation (DP) models e.g. the models of Barnett (1968) and Ewing (1971). The first generation wave models avoided the problem of explicitly modeling the complete energy balance. In the first generation models, the details of how the spectrum attained its equilibrium form were not specified. The atmospheric input term is represented as the sum of linear (Phillips) and an exponential (Miles) term. The exponential growth rate terms were based on direct measurements of wave growth as those of Snyder and Cox (1966). It was assumed that the growth of wave components stops after reaching a universal saturation level (Phillips, 1958). This generation of the models require
suitable tuning to a specific event, geographic region or meteorological system hence are not suitable for operational wave predictions on a global scale. Moreover, they were incapable of predicting many aspects of spectral evolution such as the existence of the "overshoot effect" (Fig. 2.7.1) observed by Barnett and Wilkerson (1967) at frequencies immediately above the spectral peak frequency. The overshoot phenomenon is the rapid growth of the wave energy in the low frequency components of the spectrum and associated with the growth in nonlinear energy flux across the peak due to non-linear wave-wave interaction during the wave generation process. The JONSWAP experiment shows the experimental evidence of the overshoot effect during the wave growth (Hasselmann et al. 1973). Hence it became necessary to include within the operational wave models. The computation of exact of the nonlinear interactions described by Boltzmann integrals (Eq 2.4.1) require significant computer time. Hence suitably parameterized form of nonlinear interactions for a given shape of spectrum was used (Barnett 1968; Ewing 1971; Young 1988a) to reduce the computational time. The wave models having simple parameterized form of nonlinear energy transfer as a feature are termed as second-generation wave models. The second-generation wave models in which the wind sea spectrum is strongly coupled and the swell components are treated as completely decoupled are classified as coupled hybrid (CH) models (SWAMP 1985, Gunther et al 1979, Janssen et al 1984). Coupled hybrid classes of models are not performing well in wind-sea to swell transition regime. This is because the transition is modeled as a simple energy interchange between the windsea and swell region of the spectrum since the nonlinear energy redistribution is neither negligible nor dominant when the wind speed decreases or there is a spontaneous change in the wind direction. The wave models in which both the wind sea and swell has discrete representation while only the tail end of the spectrum beyond the peak is treated parametrically are classified as Coupled Discrete (CD) class of models. In comparison to the first generation wave models, second generation wave model uses wind input source term based on direct measurement of the normal stress exerted on the water surface (Snyder et al. 1981). In this generation of models, the nonlinear interactions are presumed for a given shape of spectrum, puts limitations on the performance in complex situations where spectral shape is not of known type. In order to overcome the difficulties associated with the presumed shape of the spectrum, third generation wave models were developed. The
source term balance in the third generation models is same as in second-generation models but atmospheric input term is based on the coupled air water drag model (Janssen 1991). The nonlinear interactions are carried out using discrete interaction approximation (DIA), which retains the basic physics of process but considers a very small sub-set of all the possible interactions (Hasselmann and Hasselmann 1985a). In contrast to parameterized form of non-linear interactions, which have few degrees of freedom, the DIA has many degrees of freedom as there are values in the discretely specified directional spectrum. The first attempt to include the exact form of the nonlinear transfer term in numerical model was made by Hasselmann and Hasselmann (1985b) and developed EXACT-NL wave model using energy transport equation. The SWAMP study (SWAMP 1985) shows that the first generation DP models compute the initial growth rate from prescribed source functions, but presumes given limiting from for the equilibrium spectrum. The second-generation CH models assumes a given quasi-equilibrium shape for the entire windsea spectrum, predicting very few characteristic windsea parameters. The second generation CD models uses simple parameterized from of non-linear interaction term leading to instabilities at frequencies beyond the peak frequency, so that these models also have to assume a prescribed spectral shape over much of the windsea spectrum (SWAMP 1985). The third generation of CD models employs discredited continuous-operator parameterizations form to non-linear energy transfer containing same number of degrees of freedom as used in the discrete representation of the spectrum.

The WAve Modeling (WAM) group (WAMDI 1988) developed a third generation wave model based on energy transport equation (2.7.1). In WAM model, the computation of non-linear interactions has been carried out using Discrete Interaction Approximation (DIA) given by Hasselmann et al. (1985). This approximation used because it retains the same cubic operator structure as in the original Boltzmann integral. The DIA has been found quite successful in describing the essential features of a developing wave spectrum (Komen et al. 1994), however for unidirectional waves, this approximation is not valid. In fact, the quadruplet interaction coefficient for these waves is nearly zero. In the present study WAM model has been used to hindcast/forecast on global as well as regional scale (Indian Ocean region) at 1° x 1° grid. The WAM model is described in detail in next chapter.