CHAPTER I. INTRODUCTION

I.1 GENERAL TERMINOLOGIES

There are five basic types of waves namely sound, capillary, gravity, inertial, and planetary waves which have been identified in the oceans with five basic restoring forces all acting simultaneously to produce more complicated mixed type of waves and oscillations (Khandekar, 1989). The present study deals with the wind-induced surface gravity waves of periods 1 to 30s which are most common and have maximum impact on human activity. Therefore, knowledge of the surface waves is essential for efficient management and appropriate utilization of our coastal as well as deep sea environment. Since long, scientists and engineers have recognized the fact that these waves are dominating and influential factors to be considered in various applications. They influence considerably the air-sea interaction processes of the coupled ocean-atmosphere system. Hence the requirement of establishing a climatic wave database cannot be overemphasized. Wave information acquired over several years from any given region forms a basis for updating the currently used wave prediction models and for the development of models for future. Moreover, an evaluation of the long-term representativity of any of the ocean environmental variabilities including the surface waves becomes essential from climatic considerations.

Ursell (1956) in his well known paper entitled "Wave generation by wind" stated that, wind blowing over the water surface generates waves in the water by physical processes which can not be regarded as completely known at present. Despite several theoretical and observational advances which took place subsequently over the last 40 years, Ursell's statement is still applicable. One of the most fascinating features of the surface of the sea is the innumerable waves of different sizes and shapes present at any given time. The sea surface remains calm very rarely. With a light breeze, an intricate pattern of capillary waves are formed. As the wind continues to blow, the capillary waves grow in size and become surface gravity waves in which gravity is the most dominating restoring force. These gravity waves continue to grow as long as the incoming energy from all sources is greater than the energy dissipated by all possible means such as wave breaking and turbulent water motions etc.
Growth of waves depends on the wind speed normally referred to 10m above the sea surface, wind duration and fetch. Fetch is the length of water surface over which wind blows. Waves are also influenced by the presence of surface currents and get modified when they propagate to shallow waters. However, the present study deals with only the deep water waves. Sea surface waves are special type of oscillatory water waves which propagate along the air-water interface. In the deep water, their speed depends on wavelength or period as they are dispersive. Hence the longer waves move ahead of the shorter ones and can be observed first at a distant point from the generating area. Wind waves are classified into sea and swell. Waves are known as seas (or windseas) as long as they are under the influence of prevailing wind in the local generating area. When these waves move out of the generating area and are no longer subject to significant wind input, they are known as swells.

A common statistical representation of the sea-state or the wave field containing innumerable waves of different heights and periods is by means of significant wave height (Hs) and significant wave period (Ts) that satisfy most practical applications. Sverdrup and Munk (1947) define Hs as the average height of the one-third highest waves which is equal to the average height of the waves estimated by an experienced observer. The value of Ts obtained by visual observations is likely to be the average of 10 to 15 successive prominent waves. If we examine a typical wave record, Ts is apt to be the average period of all waves whose troughs are below and crests are above the mean water level (CERC, 1984). The most commonly used method of estimating height (Hs) and period (Tz) from a wave record is known as zero-up-crossing method as suggested by Tucker (1963) and Draper (1967). Tz is known as zero-up-crossing period which can be replaced by Ts (CERC, 1984). The corresponding wave parameters for Hs and Ts are Hmo and Tp obtained through spectral analysis by computing Fast Fourier Transform (Bendat and Piersol, 1971) of the digital wave record where Hmo is defined as four times the square root of the area under the wave variance spectrum and Tp is the inverse of the frequency at its peak. In deep water, it is commonly found that Hmo ≈ Hs (Longuet-Higgins, 1952; Goda, 1974) and Tp ≈ 1.05 Ts (Goda, 1974 and 1985). For many engineering applications, Tp can be directly used in the place of Ts (Bishop et al., 1989).

As wave information is needed for various applications, it is generally predicted following two different methods namely significant wave method and wave spectrum method. In the case of significant wave method,
the statistical parameters of the sea-state such as $H_s$ and $T_s$ are estimated using constant wind speed, wind duration, and fetch. In reality, the wind system is often associated with variable wind speed, duration, and fetch. The significant wave concept does not take into account the spectral character of the sea-state. The wave spectrum method predicts the spectrum of the waves from which various wave parameters can be derived. During the last forty years, several spectral forms have been proposed which provide a sound basis for describing the sea-state using a prescribed analytical form (Khandekar, 1989). This has led to the development of modern spectral wave models to predict the sea-state. The wave prediction is called as hindcasting when it is based on the past winds and forecasting when predicted winds are used. Sometimes, the prediction is made on real-time basis based on the observed and/or analyzed winds which is referred to as nowcasting.

I.2 DEFINITION OF WAVE CLIMATE

Wave climate is a fairly new concept introduced with an analogy to the atmospheric weather climate (Goda, 1990). It can be expressed in terms of several long-term wave statistics which are formulated depending on the type of application. In simple terms, wave climate refers to the general condition of the sea-state of a specific location or over a coastal or offshore region. The principal elements that are associated with wave climate are the significant wave parameters such as $H_s$, $T_s$ and direction. As in the atmospheric climate, the wave climate is also described in terms of months, seasons, and years.

Wave statistics as such can be classified into short-term and long-term. Short-term wave statistics deals with the statistical properties of individual waves which belong to a short time-duration, say 20 minutes (one typical wave record). It may sometimes be considered as a representative statistics for a duration of 1 to 3 hours around the time of the wave recording. Long-term wave statistics is associated with the wave climate as defined previously or with the lifetime of a coastal or offshore structure and is subdivided accordingly. It means that, long-term wave statistics are generally formulated for a specified time interval considering the type of requirement.
1.3 DATA SOURCE FOR WAVE CLIMATE

Various data sources for establishment of wave climate are visually observed data, instrumentally measured wave data, wave hindcast data and operational wave forecast data. The quality, duration, and limitations of these data sources are discussed below.

1.3.1 Quality and duration of wave data

The fundamental requirements for the generation of a suitable wave climate or the extreme wave statistics of any given region are quality and duration of the wave data acquired from one or more sources as indicated above. Visually observed wave data involve a significant degree of estimation variability. Measured wave data using the latest available equipment is most reliable compared to all other sources. Accelerometer (heave) buoys and their directional counterparts (heave-pitch-roll buoys) have become the wave measurement standards of today. The buoy measurements are generally restricted to specific sites of interest where they are deployed. However, the modern remote sensing methods of observing waves have a greater potential in future as it can provide a spatial coverage in time. The accuracy of remote sensing data has to be established with real-time measurements obtained using standard equipment. As the availability of remote sensing data is limited and their accuracies are not yet fully established, either measured or visually observed wave data are currently in use for most applications. Visually observed data can be replaced by hindcast or operational forecast data after validation using the sea truth measurements.

From the wave climate point of view, accuracy and duration of the wave data without significant gaps are considered to be of equal importance. In some cases, wave measurements over a minimum period of one year is being used for coastal engineering applications. But it is too short a duration to yield reliable information on wave climate or extreme wave statistics. Goda (1984) has demonstrated that the annual mean of $H_s$ in a single year may deviate up to 15% from the average value obtained over long durations. The deviation may be still more for regions where seasonal wind reversal and year-to-year variations are predominant.

In the present case, wave conditions in the Arabian Sea and Bay of Bengal (hereinafter referred to as the Indian Seas) solely depend on the
strength of the monsoon. During a weak monsoon year, the annual mean of $H_s$ can vary significantly from the mean for several years. Therefore, the duration of wave data should be sufficiently long for a reliable estimate on wave climate. A time period of minimum five to twenty years may be considered for this purpose (Bishop and Donelan, 1989).

I.3.2 Visually observed wave data

Visual wave observations are routinely made from weather ships, land based stations like lighthouses, and ocean going vessels who voluntarily comply with the request of meteorological agencies. Therefore, these observations are available over long durations covering a large area of the ocean where ships routinely cruise. The most famous compilation of ship reported visual wave observations is Ocean wave statistics by Hogben and Lumb (1967) which was revised later by Hogben et al. (1986). The U.S. Navy has also published a worldwide marine climatic atlas (1981). A number of publications either on wave climate or long-term wave statistics are available on regional basis for different parts of the world oceans. For the Indian Seas, excepting some port and harbor authorities who routinely estimate the prevailing wave condition visually, the Indian Daily Weather Reports (IDWR) published by India Meteorological Department (IMD) are the main source of visual wave data. The Naval Physical and Oceanographic Laboratory, Cochin has published Wave statistics of the Arabian Sea based on IDWR charts (NPOL, 1978). Similarly, the National Institute of Oceanography, Goa has also published Wave (Swell) atlas for Arabian Sea and Bay of Bengal and Wave tables/atlas for the Indian coast based on ship observations (1982, 1989a, 1989b).

Visually observed wave data may not be of good quality as its accuracy is wholly dependent on the experience and skill of the observer. Even the observations made by experienced observers of ocean weather ships are said to have bias. Attempts have been made to establish correlation between visual and measured wave heights (Sores, 1986). In most cases, visual wave heights are reported to the nearest 0.5m and wave periods to the nearest 1s. Compared to wave heights, the wave periods reported by experienced observers are less accurate. Hence, the correlation on visual and measured wave periods is not well established (Goda, 1990). The possible reason may be that the windsea and swell periods are reported separately for visual data as opposed to a single average or significant wave period provided by instrument measurements. The wave periods published in IDWR charts range
from 5 to 14s while the actual periods measured by instruments can vary from 2 to about 30s. There is another major drawback for visual wave data that the ships have a tendency to avoid rough weather. In spite of all these limitations, visual wave information still remains the major source of data that covers the most of the ocean areas and for longer durations.

I.3.3 Measured wave data

A few governmental research institutions (Table 1) in India have been conducting short-term as well as long-term wave measurement programmes using pressure and/or accelerometer sensors. Most of them use wave-rider and wave directional buoys. There are a few Indian research vessels and some of them are fitted with ship-borne wave recorders. These vessels collect wave data during their scientific cruises. During some field experiments using these vessels, time-series wave measurements of short durations have been conducted by deploying wave buoys in the shelf waters. Information on the observed wave characteristics or short-term wave climate of some specific regions has appeared in various research papers (Swamy et al., 1976; Das et al., 1979; Fernandez et al., 1981; Gouveia et al., 1981; Dattatri, 1983; Vethamony et al., 1984; Baba and Harish, 1985; Baba and Joseph, 1988; Nayak et al., 1989; Swain and Ananth, 1992; Swain et al., 1993). However, considering all the available measurements, the amount of measured wave data in the Indian Seas is very limited. A comprehensive catalog of the measured wave data (deep and shallow) collected up to 1985 from the Indian Seas was published by Baba (1985). Similar comprehensive reports are not available beyond 1985. Recently, based on GEOSAT radar altimeter data of about three years (November 1986 to January 1990) Young and Holland (1996) have published the Atlas of the Oceans: Wind and wave climate. It presents the monthly charts of average wind speed, wind direction, and wave height over 4x4 degree resolution covering the entire globe.

The quality of measured wave data using standard instruments depend on the type of the sensor. The duration of measurement varies from site to site. One of the drawbacks of measured wave data using pressure sensors, ship-borne wave recorders and wave-rider buoys is the lack of directional information. In some cases, the visually observed wave direction is used to supplement these measurements. By and large, out of the available wave measurements found in the literature, the directional measurements using heave-pitch-roll buoys are very limited in the Indian Seas.
Table 1. Indian Institutions involved in wave data collection

<table>
<thead>
<tr>
<th>Name of the agency</th>
<th>Place</th>
</tr>
</thead>
<tbody>
<tr>
<td>CESS</td>
<td>Trivandrum</td>
</tr>
<tr>
<td>CMFRI</td>
<td>Cochin</td>
</tr>
<tr>
<td>CWPRS</td>
<td>Pune</td>
</tr>
<tr>
<td>IIT</td>
<td>Madras</td>
</tr>
<tr>
<td>NIO</td>
<td>Goa</td>
</tr>
<tr>
<td>NPOL</td>
<td>Cochin</td>
</tr>
</tbody>
</table>

1.3.4 Hindcast wave data

Wave hindcasts are generally carried out for generating major storm wave data over longer durations. The duration is chosen over a period of known storm activity and hindcast is performed for that period. Another type of wave hindcast is the daily generation of wave data over several years for wave climate analysis in the areas where measured wave information is either limited or not available. Wind data covering the region of interest for the whole duration is constructed using synoptic weather charts and used as input to the wave model for hindcasting. Hindcast wave data should be preferably calibrated with instrument measurements before any statistical analysis is made. However, the accuracy of the hindcast depends on the accuracy of the derived wind field information and the adequacy of suitable wave growth models. There cannot be any remedy for the former problem if the weather maps are constructed with sparse barotropic data. The latter problem is being resolved gradually in the recent years. However, presently no such hindcast studies have been carried out for the Indian Seas for longer periods using state-of-the-art wave models. The main advantage of hindcast method is that wind data is more abundant and generally reliable than visual observations of sea surface waves. A few wave forecast and hindcast case studies are reported by Srivastava (1964), Dattatri and Renukaradhya (1971), Reddy et al. (1980), Prasada Rao and Durga Prasad (1982), Joseph (1988) and Swain et al. (1989). All of them used empirical models except Joseph (1982) who used a second generation wave model. These studies were more of an academic nature. Similarly, Gadre et al. (1981) and Nayak (1983) attempted for estimating the extreme wave conditions required for coastal and offshore
designs. Although there are a few other studies not cited here, the results obtained from all these studies are not adequate for the establishment of wave climate for the Indian Seas.

1.3.5 Operational wave forecast data

Several countries like France, Germany, Japan, and Norway have been providing routine regional wave forecasts which are being used for various operational applications. Similar routine operational wave forecasts are not available for the Indian Seas. The U.S. Navy Fleet Numerical Oceanography Centre at Monterey gives routine global wave forecasts. The European Centre for Medium-Range Weather Forecasts (ECMWF), U.K. also provides both global as well as regional wave forecasts for the North Atlantic and the Gulf of Mexico. Such forecasts over the entire globe is mainly used for ship routing to avoid storm areas.

There are several shortcomings in operational wave forecasts. The first is the reliability or the accuracy of the forecasts. The second is the scarcity of data points or low resolution of the models used which results in lack of information in coastal waters and near storm centres. The third is the delay in compilation of the forecast data into workable wave climate database. However, operational wave forecast data has a greater potential of becoming an important data source over several parts of the world oceans in the near future.

I.4. SIGNIFICANCE OF WAVE CLIMATE SIMULATION

In the absence of both long-term hindcast and routine operational forecast data for the Indian Seas, visually observed wave data is being used for several applications. However, as already mentioned, visual wave data cannot be considered as reliable. The main drawback for conducting a long-term wave hindcast for the Indian Seas is the limited wind as well as barotropic data used for the preparation of IDWR charts (0830 and 1730 hrs). As the atmospheric pressure is more accurately measured compared to winds, wind fields are usually estimated based on the pressure values. However, if the available measurements are limited, the estimation of winds for the whole of the Indian Seas (proposed grid size 1x1 degree) based on these synoptic charts will involve greater uncertainty. For a long-term wave hindcast, winds should be estimated at regular intervals of, say, 3 or 6 hours. If the wind input to the wave model has a bias, the hindcast based
on these estimates will have further bias. To overcome the above problem, an altogether different approach has to be adopted.

I.4.1 Concept of "mean climatic year of winds"

Considering the scarcity of barotropic data over the Indian Seas, the observed winds can be directly used to estimate a "mean climatic year of winds" based on the data gathered over several years. Mean climatic year of winds consists of estimated mean wind fields for the region of interest over a selected time interval (say 1 to 6 hours) for all the 365 days. Hence, the wind data is averaged for the synoptic hours corresponding to the time of observation as indicated earlier in the case of IDWR charts or at least for each day of the year covering 365 days. Hence, the historical data over all the years for which the hindcast has to be made is ultimately reduced to one year. Further, if the data strength is found to be still insufficient, a mean climatic year of winds may be established following statistical and probabilistic approaches which will be discussed in Chapter-III. It would be appropriate to do so because it helps in removing the uncertainties involved in the widely scattered (both space and time) individual wind estimates. Hence, if a mean climatic year of winds is used as the input to generate a mean climatic year of waves in a way similar to the long-term wave hindcast, it can be treated as a simplified approach provided that the results agree with the mean wave fields computed from the observed wave variability. There is a basic difference between the long-term hindcast and the method explained above. In the former case, wave fields are generated for a period of, say, 5 to 20 years and then averaged over the months, seasons, and years whereas in the latter case, wave fields will be generated only for a period of one year using directly the mean climatic year of winds. Although the wave model has to run for one full year of wind input (termed as the mean climatic year of winds) representing the most general pattern of wind variations, the method cannot be considered as hindcasting as it does not try to predict the actual wave conditions of the past. It only tries to simulate the wave field for an assumed mean wind field variation. Therefore it would be a right choice to name it as a process of simulation.

1.4.2 The simulation process

From theoretical and applied literature on the simulation process, it is apparent that the various disciplines apply the same basic set of
fundamental rules to understand and predict the real world systems that are very complex in nature. The present simulation process will be formulated based on our experience of wind and wave variability over the region. Here it is not aimed at simulating very complex wind and wave conditions which are normally encountered during severe weather conditions such as cyclones. Moreover, the input wind which will be estimated from historical data and used by the model shall not involve such complex wind conditions which are observed during severe weather conditions. Hence the wind specification for the wave model based on available historical data will be carried out so as to simulate only the mean wave conditions representing several years. The main objective here is to simulate and study the wave climate for the Indian Seas in the absence of sufficient input data which would generate wind fields at regular time intervals as required for long-term wave hindcasting.

Wave climate simulation using a suitable wave model is attempted in this study as the available wind measurements are limited and widely scattered in space and time. However, the method which is adopted here will be able to take care of the input wind specification for the wave model to a large extent. Secondly, it is realized that the present day numerical models are quite capable of providing accurate and detailed spatial and temporal representations of the ocean compared to the existing climatologies, real-time oceanographic measurements and a simple combination of the two (Clancy, 1992; Clancy and Sadler, 1992). In fact, the models are also capable of augmenting the extremely sparse in situ oceanographic data in a substantial way by inferring oceanographic information from other sources by employing sophisticated physical and statistical methods (Michael Clancy, 1979). Hence, the present simulation experiment can be more advantageous as it aims at inferring the sea-state variability only from a climatic consideration.

1.5. SCOPE OF THE PRESENT WORK

Day-by-day, there is an increasing emphasis on the sea-state information. Hence, the ocean wave modelling community, coastal engineers, marine forecasters, and meteorologists are very much concerned for the establishment of a reliable and up-to-date wave database for sufficiently longer duration. A long-term wave database of a region can be utilized effectively for many practical applications including planning of various coastal and offshore activities. Wave data is very useful for the modern
shipping industry for safe and optimum ship routing. It can also help in the computation of wave induced ship motions which is required for design of ships. The same is the case with offshore structures. A long-term wave climatology is essential in identifying the areas of maximum wave power potential along the coastal belt.

In addition to civilian applications, wave climate has a variety of applications in Naval defence. Some of the important areas are navigation, landing and take off operations at sea, mine laying/sweeping, towing of hydrophones, missile launching, torpedo firing, search/rescue operations, and amphibious warfare. As on today, underwater acoustic detection is the principal means of locating subsurface vehicles and targets. Sound propagation in the sea is often affected by the surface disturbances. The surface waves scatter the sound and produce Doppler shifts. The presence of near-surface bubbles in a rough sea results in absorption and scattering of sound. Rough seas are also a major source of locally generated ambient noise in the sea.

In the absence of reliable and up-to-date wave climate information for the Indian Seas, simulation appears to be the only alternative. The present simulation experiment is planned for the seas around India (Fig.1) which extend from 50° to 100°E and 0° to 25°N. India has a long coast line of about 7000 Km bordering the Arabian Sea (West coast) and Bay of Bengal (East Coast). The assumed boundary separating the Arabian Sea and Bay of Bengal is the 80° longitude. The area covered in this study has only one open sea boundary to the south (0° latitude). The other three sides are almost enclosed by land. Wave conditions which prevail in this region show both temporal and spatial variability along with the wind. Although the data available for this region is limited, we have some qualitative picture of the problem addressed here. In this study, attempts are made for a clear understanding and quantification of the same from a climatic point of view. Long-term winds representing a mean climatic year and the monthly mean surface current fields will be utilized as the inputs. The wave model outputs are to be generated over 1x1 degree resolution and the same shall be the basis for establishment of wave climate of this region.
Fig. 1 Location map for Indian Seas.
CHAPTER II. SELECTION OF WAVE MODEL

II.1 INTRODUCTION

In the early days of navigation, mariners and sailors were using different wind-scales for describing the sea-state. Based on these descriptive wind-scales, a numbering system known as Beaufort scale was suggested by British Rear-Admiral Sir Francis Beaufort in 1805. The Beaufort scale with its associated wave-height values was the only operational procedure available for describing sea-state in the early 1900s. However, the description of sea-state in terms of a numbering system was not considered as satisfactory since the requirement of wave information was increasingly felt both for defence and well as civilian applications. There were serious efforts towards the development of simple operational wave prediction procedures. Hence, following the simple empirical relationships which were developed during the early phases of wave modelling and prediction, there have been several theoretical developments leading to the use of present day third generation wave model for routine forecasts. The following two sections will discuss the development, classification, and the limitations of the models which are extensively used.

II.2 EARLY WAVE PREDICTION TECHNIQUES

Simple empirical wave prediction models were developed during the Second World War in response to a crucial need for operational wave forecasting for the Allied Forces’s amphibious invasion at Normandy and France (Bishop et al., 1989). Sverdrup and Munk (1947) developed the first semi-empirical method to predict the significant wave height and period. It was mainly used for forecasting the sea-state conditions over the North Sea. After Svedrup and Munk, several other models were developed. The models which are widely used are SMB (Bretschneider, 1970) and JONSWAP (Hasselmann et al., 1973). Some other available models are Darbyshire and Draper (1963), Kruseman (1978), Toba (1978), Mitsuyasu et al. (1980), and Donelan (1980). However, these models can only be applied to such conditions where the advection of swells into the forecast area remains insignificant. The main assumption in these models is that the wind field over the generating area at any given time can be represented by a mean value. These models yield estimates of wave height and period as empirical functions of wind speed, fetch, duration of wind, and water depth.
Since the pioneering paper of Gelci et al. (1957), a number of numerical wave models have been developed. They are grouped into first, second, and third generation wave models. The first generation models were developed during sixties and early seventies. These models avoided the problem of explicitly modelling the complete energy balance. The details regarding how the wave spectrum attained its equilibrium form were not specified as it was assumed that the wave components suddenly stop growing when they reach a universal saturation level (Phillips, 1958). However, it is generally recognized today that universal high frequency equilibrium spectrum originally proposed by Phillips does not exist (The WAMDI group, 1988). By and large, first generation models exhibit basic quantitative shortcomings by overestimating the wind input and underestimating the strength of nonlinear transfer by almost an order of magnitude. Later, with the aid of extensive wave growth experiments (Mitsuyasu, 1968, 1969; Hasselmann et al., 1986) and direct measurements of wind input to the waves, fundamental changes in the basic concept of spectral energy balance took place leading to the development of second generation wave models during late seventies. However, these models too had restrictions resulting from the simplified nonlinear transfer parameterization effectively required for the spectral shape of the windsea spectrum to be prescribed for frequencies higher than the peak frequency. The specification of the spectral shape was introduced either at the outset in the formulation of transport equation for parametric and hybrid models or as a side condition in the computation of spectrum for discrete models. Although the adjustment to a quasi-universal spectral shape could be justified theoretically, the second generation models were unable to simulate the complex wave field generated by the rapidly changing wind fields. The problems of these models remained largely numerical than physical. Some techniques to overcome such difficulties are discussed in SWAMP (1985). Subsequently, it was proposed that, third generation model should be developed in which the wave spectrum can be computed alone by integration of the basic transport equation without any prior assumption on the spectral shape. Hence, during late eighties, a major thrust towards the development and implementation of the third generation wave model was achieved by The WAMDI group (1988). The model involves improved physics and includes the exact specification of non-linear transfer of wave energy due to resonant wave-wave interactions.
The numerical wave models available so far are classified into three broad categories depending on the way they are formulated. These are decoupled propagation wave models, parametric and hybrid wave models, and coupled discrete wave models. The decoupled propagation wave models involve representation of directional wave spectrum by a discrete number of finite band widths, the spectral components travelling in a specified number of directions along the ray paths. Parametric description of wave field in case of parametric wave models is suitable only for the windsea region of the spectrum in which the non-linear energy transfer is dominant. Normally, parametric wave models are combined as hybrid models with standard discrete spectral representations for the swell components and referred as parametric and hybrid or coupled hybrid wave models. These models encounter difficulties in the windsea-swell transition regime of wave spectrum in which non-linear energy redistribution is neither negligible nor dominant. Such a transition regime arises whenever wind speed decreases or wind changes its direction. To avoid this difficulty, some models tried to forego the basic informational economy offered by the parametric approach and retained the traditional representation for the entire spectrum, including both windsea and swell region. These models are referred to as coupled discrete models. However, the uniform representation of windsea-swell transition regime could not be properly exploited by most of the coupled discrete models (except the third generation wave model) as long as the parametric representation of the nonlinear energy transfer remains limited to relatively few degrees of freedom. The wave models which belong to the above mentioned model classes are listed in Table 2 (Khandekar, 1989; SWAMP, 1985). Most of those listed are participants of SWAMP wave model intercomparison study.

II.4 WAVE MODEL INTERCOMPARISON STUDY

A group of researchers on wave models had proposed for a wave model intercomparison study to understand the interrelations existing among the various wave models developed in the past. The results of the study are discussed extensively in SWAMP (1985). Some salient features of the SWAMP study, highlighting the model used in the present simulation experiment, are discussed below.

During the SWAMP intercomparison study, ten spectral wave models were tested using several idealized wind fields representative of typical atmospheric flow patterns like uniform wind blowing orthogonally off a
<table>
<thead>
<tr>
<th>Model</th>
<th>Institution</th>
<th>Model Class</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) DSA</td>
<td>Central d'Oceanographie et d'Etude, France.</td>
<td>DP (1g)</td>
<td>Routine wave forecast for Atlantic.</td>
</tr>
<tr>
<td>b) GSOWM</td>
<td>U. S. Navy.</td>
<td>DP (1g)</td>
<td>Global operational wave forecast.</td>
</tr>
<tr>
<td>c) ODGP</td>
<td>Oceanweather Inc., USA.</td>
<td>DP (1g)</td>
<td>Operational forecast, Western North Atlantic.</td>
</tr>
<tr>
<td>d) MRI</td>
<td>Meteorological Research Institute, Japan.</td>
<td>DP (2g)</td>
<td>Operational wave forecast, North Pacific regional wave statistics.</td>
</tr>
<tr>
<td>e) VENICE</td>
<td>Istituto per lo Studio della Dinamica delle, Venice, Italy.</td>
<td>DP (2g)</td>
<td>Regional wave statistics.</td>
</tr>
<tr>
<td>f) NOWAMO</td>
<td>Norwegian Meteorological Institute, Norway.</td>
<td>CH (2g)</td>
<td>Operational wave forecast for north-east Atlantic.</td>
</tr>
<tr>
<td>g) GONO</td>
<td>Royal Netherlands Meteorological Institute, The Netherlands.</td>
<td>CH (2g)</td>
<td>Operational wave forecast for North Sea.</td>
</tr>
<tr>
<td>h) TOHOKU</td>
<td>Geophysical Institute, Tohoku University, Japan.</td>
<td>CH (2g)</td>
<td>Regional wave statistics, Japan Sea.</td>
</tr>
<tr>
<td>i) HYPA</td>
<td>Institut fur Meereskunde, Federal Republic of Germany.</td>
<td>CH (2g)</td>
<td>Regional wave statistics, Operational forecast for North Atlantic and North Sea.</td>
</tr>
<tr>
<td>j) BMO</td>
<td>British Meteorological Office, UK.</td>
<td>CD (2g)</td>
<td>Operational forecast, Atlantic, North Pacific, North Sea, Mediterranean; Regional wave statistics.</td>
</tr>
<tr>
<td>k) SAIL</td>
<td>Atlantic Oceanographic &amp; Meteorological Lab., NOAA, USA.</td>
<td>CD (2g)</td>
<td>Regional wave statistics.</td>
</tr>
<tr>
<td>l) DNS</td>
<td>Scripps Institution of Oceanography, USA.</td>
<td>CD (2g)</td>
<td>Regional wave statistics.</td>
</tr>
<tr>
<td>m) WAM</td>
<td>European Centre for Medium-Range Weather Forecasts (ECMWF), UK, (&amp; several other users).</td>
<td>CD (3g)</td>
<td>Global wave forecast, Regional wave forecast for North Atlantic and Gulf of Mexico.</td>
</tr>
</tbody>
</table>

Note: DP -> Decoupled Propagation model.  
CH -> Coupled Hybrid model.  
CD -> Coupled Discrete model.  
1g -> First generation wave model.  
2g -> Second generation wave model.  
3g -> Third generation wave model.
straight coast line, wind field with sudden change in wind direction, stationary and moving hurricanes etc. Ideally, for a prescribed wind field and boundary conditions, a numerical wave prediction model should compute the two dimensional wave spectrum starting from a postulated functional form of the three basic source functions of the spectral energy balance (see equation 2.3). However, the first generation of decoupled propagation models compute the initial growth rate from prescribed source functions and presume a given limiting form for the equilibrium spectrum. The second generation of coupled hybrid models assume a given quasi-equilibrium shape for the entire windsea spectrum while the coupled discrete models integrate the full transport equation using simple parameterization of non-linear transfer leading to spectral instabilities at frequencies beyond the peak frequency. Therefore, the second generation coupled discrete models too have to assume a prescribed spectral shape over much of the windsea spectrum. Unlike these models, the third generation of coupled discrete model (EXACT-NL, present name WAM) employs a discretised continuous-operator parameterization of non-linear transfer containing an equal number of degrees of freedom as used in the discrete representation of the wave spectrum. All the 10 models were executed for seven different type of wind fields and the results were compared. The comparisons revealed that the first and the second generation wave models performed reasonably well in most of the test cases but they did not provide a proper description of the sea-state during rapidly varying wind conditions. For the same hurricane wind fields, it was demonstrated that the maximum wave height computed by these models varied from 8 to 25m. The short-comings of first and second generation wave models are available in SWAMP (1985) and Komen et al. (1994). The difficulties faced by first and second generation models in dealing with the problem of rapidly changing wind fields were not encountered by the third generation wave model. However, the SWAMP study fails to provide any insight into the performance of the wave models under operational environments.

II.5 THE PRESENT MODEL

Selection of a model is an important task while dealing with the problem of wave climate simulation. Several empirical models are used to hindcast wave climate using hourly values of wind input. These models are termed as wave climate models. They use a pragmatic backstepping procedure to handle varying wind speeds from a constant direction but the treatment of variation in wind direction is too complex (Bishop and Donelan, 1989).
The averaging procedure for input wind speed is continued as long as the wind direction remains within a practicable range and the duration of average does not exceed a prescribed limit. These problems are not encountered if one uses a numerical wave model by neglecting the computational economy offered by the empirical models. The empirical models normally compute the significant wave parameters of the regions for which the winds are assumed to be more or less uniform while numerical models are capable of providing two dimensional wave spectra at each grid point of the model. Moreover, the present task being a simulation experiment, it involves a special procedure for specifying the wind input which is not similar to hindcast methods. Therefore, the use of an empirical model cannot yield the expected results. However, several other aspects should also be considered before selection of a numerical model. The important ones are the following:

1) type of input data for the model
2) model capability and performance
3) computational requirements
4) validation of the model output

From these considerations, the third generation wave model 3g-WAM (The WAMDI Group, 1988) appears to be the most appropriate in the present study because, it is capable of simulating wave fields for a variety of wind conditions. However, the model is computation-intensive. The total computation requirement may be minimized by following certain specified procedures. The following sections contain detailed discussions on the above model including its capabilities and performance.

II.5.1 Background of the model

Integration of the basic transport equation without any additional constraints on the spectral shape requires an explicit prescription of the three components of the source function (wind input, non-linear interaction, and dissipation). This was first realized in 3g-WAM. The model represents the physics of wave evolution in accordance with our knowledge today for the full set of degrees of freedom of the two dimensional wave spectrum and solves the wave transport equation explicitly without any prior assumption on the shape of the wave spectrum. The global version of the model is implemented in an operational setup at ECMWF. The analyzed and forecast wind fields from a high resolution atmospheric model are being
used as the inputs for wave hindcast studies and 10-day wave forecasts respectively. The 3g-WAM is currently used by the Naval Meteorology and Oceanography Command of the U.S. Navy for issuing routine operational forecasts (Michael Clancy and Johnson, 1997; Wittmann and Farrar, 1997).

II.5.2 Fundamental equations

The model used in this study is the revised version of the model called WAMODEL, Cycle-4 (Gunther et al., 1992). In contrast to first and second generation wave models, 3g-WAM computes the 2d-wave variance spectrum through integration of the basic transport equation

\[
\frac{\partial F}{\partial t} + \frac{\partial}{\partial \phi} (\phi F) + \frac{\partial}{\partial \lambda} (\lambda F) + \frac{\partial}{\partial \theta} (\theta F) = S \quad (2.1)
\]

where:

F - represents the spectral density with respect to \((f, \theta, \phi, \lambda)\)
f - denotes frequencies
\(\theta\) - directions
\(\phi\) - latitudes and
\(\lambda\) - longitudes.

\(\phi, \lambda\) and \(\theta\) are the rates of changes of position and propagation direction of wave packets travelling along the great circle path.

\[
\phi = \frac{d\phi}{dt} = -1 = v R \cos \theta \\
\lambda = \frac{d\lambda}{dt} = v \sin \theta (R \cos \phi) \\
\theta = \frac{d\theta}{dt} = v \sin \theta \tan \phi R 
\]

where \(v = g/4\pi f\) denotes the group velocity, \(g\) is acceleration due to gravity, and \(R\) is the radius of the earth.

The time and space evolution of ocean surface wave field or the source function \(S\) in equation 2.1 may be represented by
\[
\frac{\partial F}{\partial t} + v \cdot \nabla F = S = S_{in} + S_{nl} + S_{ds}
\]  

(2.3)

where \( v = v (f, \theta) \) is the deep water group velocity and the net source function \( S \) is represented as the sum of the input \( S_{in} \) by the wind, the non-linear transfer \( S_{nl} \) by resonant wave-wave interactions, and dissipation \( S_{ds} \).

As momentum is transferred from the air flow to the waves, the stress in the surface layer depends both on the wind speed and the wave induced stress \( \tau_w \). The growth rate of waves then depends on the friction velocity \( U_* \) and the roughness length \( Z_0 \).

The wind input term is given by

\[
S_{in} = \gamma \cdot F
\]

(2.4)

where \( F \) is the two-dimensional spectrum and \( \gamma \) is the growth rate of waves. For a logarithmic wind profile \( \gamma \) depends on the following two parameters

\[
X = U_* \cos (\theta - \varphi) / C \quad \text{and} \quad \Omega = \frac{g Z_0}{U_*^2}
\]

(2.5)

where \( U_* \) is the friction wind speed, \( \Theta \) is the direction of wave propagation, \( \varphi \) is the wind direction, and \( C \) is the phase speed of waves. Thus, through \( \Omega \), the growth rate of waves depends on the sea surface roughness which on its turn depends on sea-state.

The growth rate normalized by angular frequency \( \omega \) is represented by

\[
\frac{\gamma}{\omega} = \beta
\]

(2.6)

where

\[
\beta = \frac{\beta_m}{k^2} \mu \ln^4 (\mu), \quad \mu < 1
\]

\( k \) is the von Karman constant, \( \beta_m = 1.2 \), and \( \mu \) is the dimensionless critical height, \( \mu = k Z_c \) where \( k \) is wave number, \( Z_c \) the critical height defined by \( U_0 (Z = Z_c) = C \).
The stress $\tau$ of the air flow over sea waves depends on the sea-state and from the consideration of momentum balance of air, it is found that

$$\tau = C_d U^2(L)$$

(2.7)

where $C_d$ is the drag coefficient given by

$$C_d = \left\{ k / (\ln (L/Z_0)) \right\}^2$$

(2.8)

and

$$Z_0 = \frac{\alpha \tau}{g} \left[ (1 - (\tau_w/\tau))^2 \right]^{-1}$$

(2.9)

The constant $\alpha$ is chosen in such a way that for old wind seas the usual Charnock relation for the drag over sea waves is used.

$L$ is the mean height above the waves and $\tau_w$, the wave-induced stress, are given by

$$\tau_w = \rho_w \int \omega \gamma (F \cdot \cos(\theta - \varphi)) d\Omega d\phi$$

(2.10)

In practice, the wave stress $\tau_w$ is in the direction of the wind.

The nonlinear source function $S_{nl}$ is represented by the discrete interaction operator parameterization which retains the basic form of the exact nonlinear transfer expression given by

$$S_{nl}^{exact}(k_4) = \int \omega_4 \sigma \left\{ k_1 + k_2 + k_3 + k_4 \right\}
\times \delta \left( \omega_1 + \omega_2 - \omega_3 - \omega_4 \right) \left[ n_1 n_2(n_3 + n_4) - n_3 n_4(n_1 + n_2) \right] dk_1 dk_2 dk_3$$

(2.11)

where $n_j = F(k_j)/\omega_j$ denotes the action spectrum and the coefficients $\sigma(k_1, k_2, k_3, k_4)$ describes the coupling strength of a resonantly interacting wave number quadruplets $k_1, k_2, k_3$ and $k_4$. However, the five
dimensional continuum of all resonant quadruplets (three integration and two for \( k_4 \)) is reduced to two-dimensional continuum by considering only a mirror symmetrical pair of discrete interaction configurations. Two continuous dimensions are still needed to define the magnitude and direction of the reference wave number vector, scaling the interaction configuration.

In order to obtain proper energy balance at high frequencies the dissipation by white capping is extended by adding a \( k^2 \) term. Thus

\[
S_{\text{dis}} = (-\gamma_d) F \tag{2.12}
\]

where

\[
\gamma_d = \frac{1}{2} c_{\text{dis}} \langle \omega \rangle \left( \frac{2}{\langle k \rangle} \right)^2 \left( \frac{k}{\langle k \rangle} \right)^2
\]

The value of \( c_{\text{dis}} = 4.5 \), \( E \) is the total wave variance, \( k \) is the wave number, and \( \langle \omega \rangle \) and \( \langle k \rangle \) are mean angular frequency and mean wave number respectively are given by

\[
\langle \omega \rangle = \left( E^{-1} \int \int F(f,\theta) \cdot \omega^{-1} df d\theta \right)^{-1} \tag{2.13}
\]

\[
\langle k \rangle = \left( E^{-1} \int \int F(f,\theta) \cdot k^{-1/2} df d\theta \right)^{-1} \tag{2.14}
\]

where

\[
E = \int \int F(f,\theta) df d\theta \tag{2.15}
\]

The dependence of the proportionality factor on the square of the frequency is consistent with the white capping dissipation function.

II.5.3 Numerical scheme

The source function integration is carried out using an implicit scheme which enables the use of an integration time step greater than the dynamic adjustment time of the highest frequencies of wave spectrum, still treated prognostically in the model. The high frequency adjustment time scales are considerably shorter than the evolution time scales of the energy-containing frequency bands near the peak of the spectrum. Hence, in
high frequency region, it is sufficient to determine the quasi-equilibrium level to which the spectrum adjusts in response to more slowly changing low-frequency waves. The implicit second order, centered difference equations excluding the advection terms are given by

\[ F_{n+1} = F_n + \frac{\Delta t}{2} \left( S_{n+1} + S_n \right) \]  \hspace{1cm} (2.16)

where \( \Delta t \) is the time step and the index \( n \) refers to the time level. If \( S_{n+1} \) depends linearly on \( F_{n+1} \), equation 2.16 could be solved directly for the spectrum \( F_{n+1} \) at the new time step. However, \( S_{n+1} \) is the only term which is linear. It may be written as

\[ S_{n+1} = \beta_{n+1} + F_{n+1} \Delta F + \beta_{n+1} F_n \]  \hspace{1cm} (2.17)

where

\[ \beta_{n+1} = \beta \left( \frac{n+1}{u*} \right) \]  \hspace{1cm} (2.18)

and

\[ \Delta F = F_{n+1} - F_n \]  \hspace{1cm} (2.19)

For the remaining source function

\[ S_{n+1} = S_{n+1}^\text{res} + S_{n+1}^\text{ds} \]  \hspace{1cm} (2.20)

By introducing the Tailor expansion

\[ S_{n+1} = S_n + \frac{\partial S_{n+1}}{\partial F} \Delta F + \ldots \]  \hspace{1cm} (2.21)

The functional derivative in equation 2.21 is numerically a discrete matrix which is divided into a diagonal matrix \( \Lambda_n \) and a nondiagonal residual \( N_n \). That is

\[ \frac{\partial S_{n+1}^\text{res}}{\partial F} = \Lambda_n + N_n \]  \hspace{1cm} (2.22)
Substituting equations 2.17, 2.20 and 2.22 in 2.16:

\[
\begin{bmatrix}
1 - \frac{\Delta t}{2} \left[ \sum_n \right] \\
\end{bmatrix}
\begin{bmatrix}
\Lambda_n + N_n + \beta_{n+1} \\
\end{bmatrix}
\Delta F

= \Delta t \begin{bmatrix}
\frac{\beta_n + \beta_{n+1}}{2} \\
\end{bmatrix} F_n + S_n^{\text{rest}} 
\ldots \ldots \quad (2.23)

If nondiagonal terms are not too large, the matrix on the left hand side can be inverted by expanding with respect to the nondiagonal contributions, leading to

\[
\Delta F(f,\theta) = A(f,\theta) + \sum_{f',\theta'} B(f,\theta; f',\theta') A(f',\theta') + \ldots \ldots \quad (2.23)
\]

where

\[
A(f,\theta) = \left\{ \begin{bmatrix}
\Delta t \frac{(\beta_n + \beta_{n+1})}{2} F_n + S_n^{\text{rest}} \\
\end{bmatrix}
\right\}^{-1}

X \begin{bmatrix}
1 - \frac{\Delta t}{2} \left[ \sum_n \right] \\
\end{bmatrix}
\begin{bmatrix}
\Lambda_n + \beta_{n+1} \\
\end{bmatrix}
\quad (f,\theta) \quad (2.24)
\]

and the first diagonal matrix in the expansion takes the form

\[
B(f,\theta; f',\theta') = \frac{N_n(f,\theta; f',\theta') \frac{\Delta t}{2}}{1 - \frac{\Delta t}{2} \left[ \sum_n \right]}
\quad (2.25)
\]

The matrix \( M_n \) can be readily determined in the course of computing the two source functions \( S_{n1} \) and \( S_{ns} \). The inclusions of the diagonal contributions require slightly more computation time than the explicit scheme.

Two alternate propagation schemes were originally included in the model (The WAMDI Group, 1988).
a) a first order upwind scheme

\[ F_j^{n+1} = F_j^n - \sum_k \frac{\Delta t}{\Delta x_k \cos \theta_j} \left( (u \cos \theta F)_j^n - (u \cos \theta F)_{k-}^n \right) \]

\[ \ldots (2.26) \]

and b) a second order leapfrog scheme

\[ F_j^{n+1} = F_j^{n-1} - \sum_k \frac{\Delta t}{2 \Delta x_k \cos \theta_j} \left( (u \cos \theta F)_{k+}^n - (u \cos \theta F)_{k-}^n \right) \]

\[ + \text{diffusion} \ldots (2.27) \]

In the above two equations, the index \( n \) refers to the time level and the indices \( k-, k+ \) to the neighboring grid points in the upstream and downstream propagation directions respectively (relative to the reference grid point \( j \)). The index \( k \) runs over the three propagation directions \( \lambda, \phi \) and \( \theta \); and \( u_k, \Delta x_k \) denotes the velocity components and grid spacing respectively in the relevant directions. In general, the difference between the model results using both the propagation methods was found to be small. The present version of the model uses the former method.

11.5.4 Model grid structure

The grid system considers only the sea grids as model grids in contrast to the earlier versions of this model which include both sea and land grids. The grids are arranged into blocks of say 512 grids each. The grids in a block run from west to east and south to north always. As the computation of the nonlinear source function is not vectorizable, the grid points are placed into the innermost loop running from south to north in the form of one dimensional blocks. To account for the wave propagation across the north or south boundaries of the block, the blocks overlap by two latitudes. So, computations are done from second southern-most latitude to one before the northern most-latitude. The schematic diagram shown below gives an idea about the arrangement of model blocks.
II.5.5 Model system

The model system consists of 1) pre-processing programs, 2) processing programs and 3) post-processing programs. The flow charts for all the programs (total eight program modules) are shown in Appendix-A and the purpose of individual main programs, subroutines and functions are given briefly in Appendix-B. All the program modules have the standard extension "FOR" and their include files are shown in Appendix-C. The programs PREPROC and PRESET are the pre-processing modules. PREPROC generates all the time independent information for the wave model. The initial wave field is generated by PRESET for wave model cold start. Outputs from PREPROC and PRESET are used by the stand alone version of the wave model or the shell program CHIEF. Both CHIEF and BOUINT are the processing programs. CHIEF carries out the model integration for chosen propagation, source term, wind input and output time steps. Program BOUINT interpolates the boundary output spectra from a coarse grid model run in time for the fine grid boundary input. This program is required only when nested grids are used. The post processing programs are PGRID, PSWGRID, PSPEC and PSWSPEC. PGRID and PSWGRID print the gridded output and gridded swell output files while PSPEC and PSWSPEC print the spectral output and swell spectral output files (at selected grids) respectively. It may be noted that the routines which are placed inside dashed boxes in Appendix-A are supporting routines which do not take part in model computation.

II.5.6 Model options and user inputs

The 3g-WAM wave model has various options which can be set by the user before execution. Brief details of the model options are given below:
1. Model runs for any given regional or global grid system (grid resolution is arbitrary in space and time);

2. Wave propagation can be either in spherical or cartesian coordinate grid system;

3. User can opt for either deep water run or for shallow water including current refraction;

4. Model runs for coarse and/or fine grids (infinite levels of nesting can be done). Nested grids consist of a coarse grid model and time interpolation of the boundary spectrum is done for fine grid model;

5. The wind input can be interpolated in space and/or time;

6. All model time steps and output options can be set as per the specifications of the model;

7. The source integration can be interrupted and restarted at arbitrary times.

The user can control a range of model options through the user input files. Each main program as described under model system has a user input file which has the name with extension "DAT" (Example: CHIEF.DAT). A list of all the user input files are given in Appendix-D. These files contain information regarding each input to be specified before execution of the different program modules of 3g-WAM. However, there are certain restrictions for some of the user inputs and the important ones are given below:

1. Nested grids consist of a coarse grid model and a fine grid model. Fine grid model should have rectangular grids inside the coarse grid and all corner points of the fine grid system should be coarse grid points;

2. All model time steps should be specified as integers in seconds or hours. They have to be multiples of one minute;

3. The wind input time step should be the time difference between two wind fields in the sequential input file;
iv. The source function time step should not be greater than 1200s for deep water run and 600s for shallow water;

v. All model output time steps (spectra as well as gridded outputs) should be multiples of the propagation time step;

vi. The time increment to save result and restart files should be a multiple of the wind input time step.

The model requires the following data at all the grid points at each time step:

i. Topographic data in meters ( -ve for sea & +ve for land grids);
ii. Surface current speed in meters/second and direction in degree;
iii. Wind speed in meters/second and direction in degrees at 10m from sea surface.

II.5.7 Model outputs

The gridded outputs of various parameters are available at selected time steps of the model. However, the two dimensional spectral outputs will be only for selected grids and time steps. A list of all the model outputs are given below.

I. Significant wave height
II. Mean wave direction
III. Mean wave frequency
IV. Friction wind speed
V. Friction wind direction
VI. Peak wave frequency
VII. Sea-state dependent drag coefficient
VIII. Normalized wave stress
IX. Swell wave height
X. Mean swell direction
XI. Mean sea direction
XII. Mean swell frequency
XIII. 2-dimensional wave spectra
XIV. 2-dimensional swell spectra
The 3g-WAM model is being used operationally for global as well as regional forecasts, validation/interpretation of satellite measurements and finally as a research tool by various users (Janssen et al., 1996). The capabilities of this model have been studied in detail by the WAMDI group (1988) and Komen et al. (1994). However, a systematic verification study of the model has not been achieved except by Zambresky (1989) using conventional buoy data and Romeiser (1993) using Geosat altimeter data. Romeiser (1993) carried out global validation of 3g-WAM using Geosat wave height data for a period of one year. Both these authors concluded that the model wave heights using ECMWF winds showed good agreement with the observed data in general. However, Zambresky (1989) also noticed that, 3g-WAM often has a tendency to under-predict extreme sea-states and Romeiser (1993) found a significant regional as well as seasonal disagreement between model output and satellite data. Wave heights were underestimated by about 20% during southern hemisphere winter in large parts of southern hemisphere and the tropical regions, while the agreement was fairly good for the rest of the year.

The verification studies mentioned above used modelled wave heights for 1988 obtained from Cycle-2 of the 3g-WAM wave model. Since 1988, a few important changes have been introduced in the wind as well as wave forecasting systems at ECMWF. In September 1991, the resolution of ECMWF's atmospheric model was doubled in the horizontal and nearly doubled in the vertical. First of all, the increased resolution of the atmospheric model is expected to improve the predictions of sea-state along the storm tracks especially in the southern oceans. Secondly, the new version of 3g-WAM (Cycle-4) was launched in November 1991 which has improved physics regarding wind input and dissipation of wave energy compared to the previous versions. Thirdly, the assimilation of ERS-1 altimeter wave height data started in August 1993. Finally, the horizontal resolution of the wave model was increased from 3 degrees to 1.5 degrees which has a beneficial impact on the prediction of extreme sea-states as more details of generating wind fields are considered. Hence the model is expected to have better prediction capability than before. Janssen et al. (1996) have reviewed the present status of the 3g-WAM, Cycle-4 at ECMWF. Recently, ECMWF has also upgraded the data assimilation technique to three-dimensional variational approach and the authors have verified the
wave forecasts against the verifying analysis and found that the model performs reasonably well up to a period of five and a half day while the forecast skill in the southern hemisphere is comparatively less. They are hopeful that further progress in wave forecasting is expected to come in near future since the variational assimilation is only a beginning now.