SOME STUDIES ON WAVE PREDICTION IN INDIAN SEAS

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CERTIFICATE

This is to certify that this thesis is an authentic record of research work carried out by Mr.C.V.K.Prasada Rao under my supervision and guidance for Ph.D. degree of the Cochin University of Science and Technology and no part of it has previously formed the basis for the award of any other degree in any university.

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PREFACE

Knowledge is like ocean! It is said so, perhaps to imply the vastness of knowledge vis-a-vis the oceans. As in the case of knowledge our quest for understanding oceans continues since we derive lot of benefits from it and yet we know very little about it. Nearly 71% of the earth is covered with water which acts like a large reservoir containing food, medicines, minerals, oil, energy, *etc.* Besides the wealth it contains, oceans from the time immemorial have been used for trade and navigation.

There has been an increasing awareness in recent times about the importance of the study of ocean waves. During the entire processes of generation, propagation and dissipation, waves play a very crucial role and influence almost every human activity at sea. Knowledge of waves is deemed necessary for many ocean engineering applications because of the tremendous forces exerted by waves on marine structures. Problems related to beach erosion, sediment transport and circulation in coastal waters are influenced by waves. Of late, the importance of waves is recognised for generation of electrical power. The recent progress in the prediction of waves and radio probing of ocean surface from satellites has opened a new epoch. The current efforts in this area are aimed at understanding the implications of rough sea surface for monitoring oceans and marine atmosphere by using satellites.

Ocean waves are the continuous undulations produced at the air-sea interface by the action of wind which vary both in time and space. The surface gravity waves whose wave periods range from 1 to 30 s are considered very important as they contain significant quantity of energy and these are the most commonly seen waves at sea. Generation, propagation and dissipation are the three major stages involved in the life cycle of waves. After generation, waves do not remain static and they propagate over vast stretches of the ocean and ultimately break near the land-sea boundary.

Prediction of gravity waves is normally done with the help of known meteorological data on wind or atmospheric pressure field over the sea. In the absence of sufficient wind data it is possible to derive geostrophic or gradient winds from the pressure pattern shown on weather charts. For wave prediction apart from data on wind speed and direction, often it becomes necessary to know the fetch and duration of wind. It is worth remembering that the 'Beaufort Scale' with its associated wave height values was the only operational means available for sea-state description in the beginning of this century.

The current century saw many milestones in the area of operational wave prediction and analysis. Notable among the advancements made are the significant wave models and spectral wave models. The advent of digital electronic computers further accelerated the pace of work on numerical wave models. The present thesis attempts to evaluate some of the widely used models and to develop a suitable prediction method for Indian seas. The results of the investigations are documented in the following manner:

Chapter 1 provides a general introduction to the proposed study. A brief background on ocean waves and review of literature on wave prediction are covered. In *Chapter* 2 information on data needs, data sources and standard wave data processing and analysis methods are described. Wave hindcasting analysis based on SMB method for a nearshore location is discussed under *Chapter* 3. A new approach for wave prediction is presented in *Chapter* 4. The concept of 'time-delay' has been introduced for the first time. Wave prediction utilising a numerical wave model (TOHOKU model) is discussed in *Chapter* 5. A critical discussion and evaluation of the three different wave prediction methods, conclusions and recommendations are given in *Chapters* 6 and 7.

A list of research papers published and reports issued by the author based on the work reported in this thesis is given in APPENDIX-I. Other publications of the author on ocean waves are given in APPENDIX-II.

CONTENTS

CHAPTER 1 : INTRODUCTION

1.1 WAVES IN THE OCEAN

Waves are the travelling perturbations which occur either at the interface of two different media or within the medium itself. Three factors become almost inevitable for waves to be generated in any medium: an initial steady state, a disturbing force which actually creates waves and a restoring force for sustenance of these waves. Normally we come across several types of waves in the ocean. The ubiquitous capillary and surface gravity waves, internal waves, inertial and planetary waves are some examples which are peculiar to oceans.

There are different ways of classification of waves and quite often they are grouped as free or forced waves and transverse or longitudinal waves. In the ocean, waves are classified by the wave period or by its reciprocal, wave frequency. Kinsman (1965) provided such a classification of waves (Fig.1.1) in which one end of the spectrum contains capillary waves with periods less than one-tenth of a second whereas long period waves of 12 h or even 24 h might well be present on the other end. For capillary waves and ultra-gravity waves the main restoring force is surface tension and the effect of acceleration due to gravity is practically negligible. Long period waves like Tsunamis, storm surges, *etc.* are governed by Coriolis force. In between these two extremes there are the gravity waves, whose periods vary

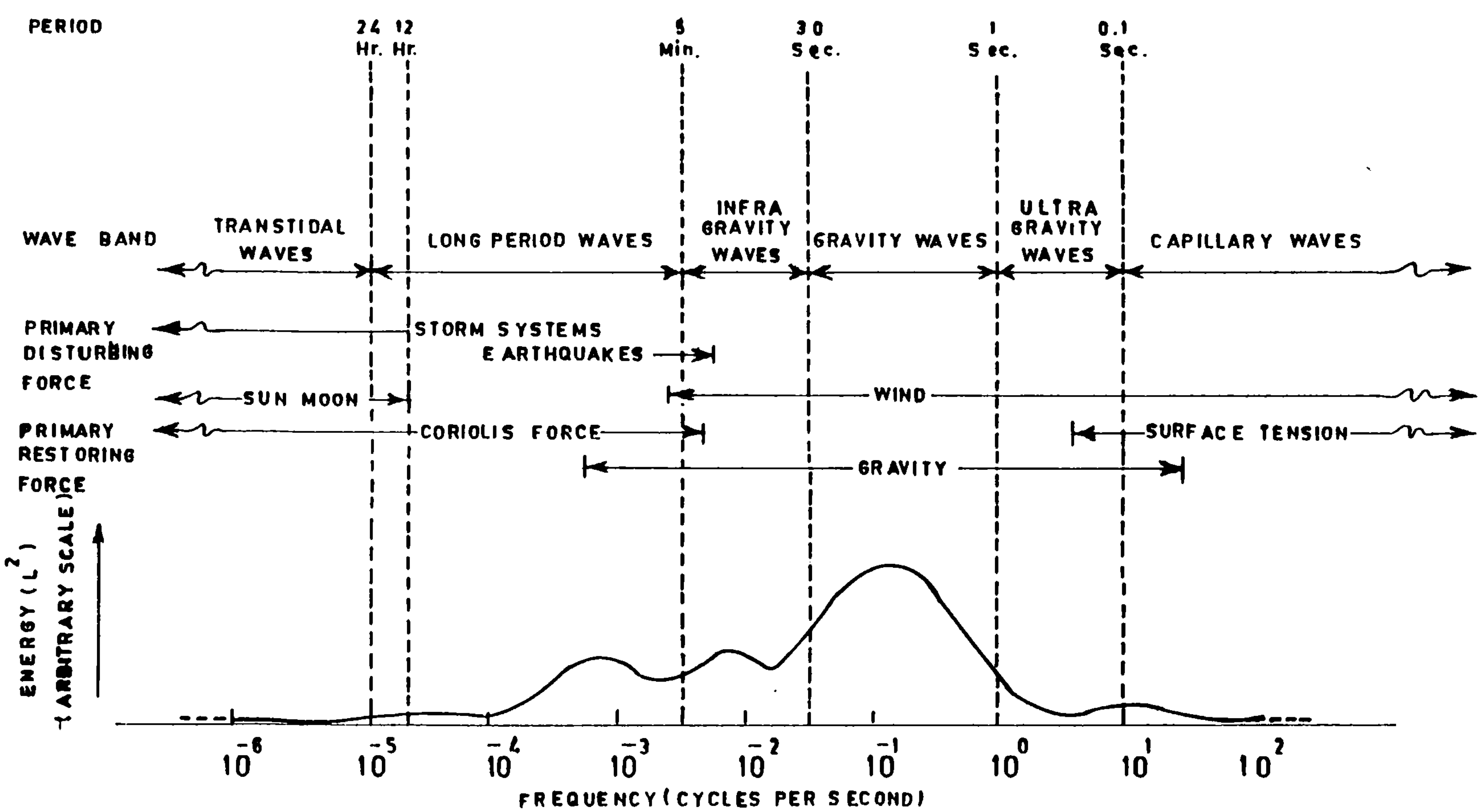

Fig.1.1 Classification of ocean waves according to wave period (Kinsman, 1965).

from 1 to 30 s. It may be seen from the wave spectrum (Fig.1.1) that most of the energy is contained in the gravity wave band . Le Blond and Mysak (1978) offered a similar schematic representation for ocean scale variability based on wave period (Fig.1.2). This latter classification includes planetary waves of the order of 100 days on the low frequency end of the spectrum. The present investigations are, however, confined to the studies on surface gravity waves. Though the gravity wave band encompasses wave periods from 1 to 30 s, the period range of 3 to 18 s is considered more important for many applications. Hence the present study looks only into the latter part of the gravity wave spectrum.

1.2 GRAVITY WAVES

Sea surface gravity waves are generated by the continuous action of wind at the air-sea interface. The waves thus produced at the sea surface vary both in time and space depending on the strength of the wind forcing. As the name implies, the acceleration due to gravity is the restoring force for these waves. Further they can be considered as transverse waves as the direction of wave propagation is perpendicular to the wave motion. Generation, propagation and dissipation are the three major stages involved in the life cycle of the waves. After generation, waves do not remain static and they propagate over vast stretches of the ocean and ultimately break near the land-sea boundary. Gravity waves are dispersive in nature and the long period waves travel faster

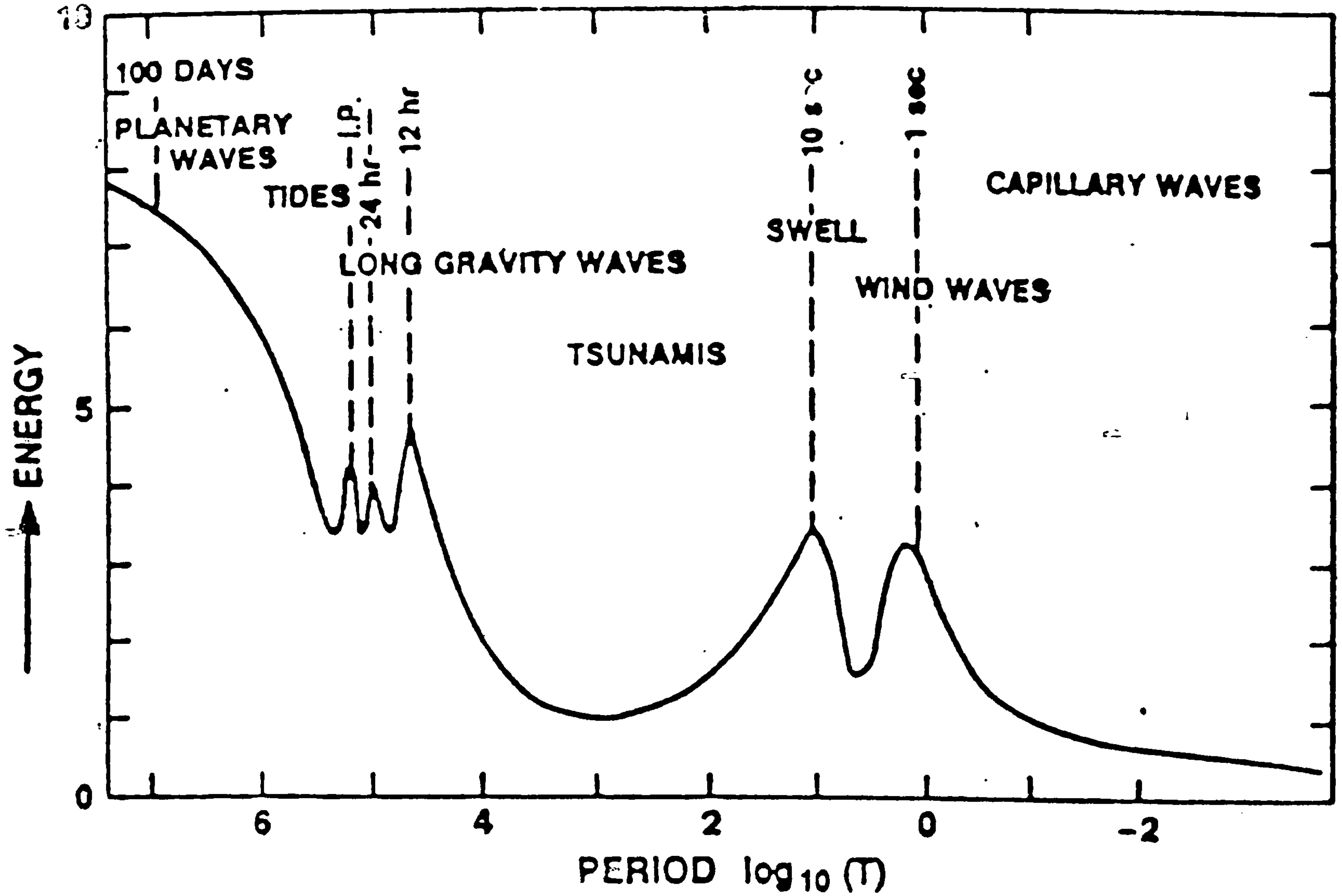

Fig.1.2 Schematic energy spectrum of ocean variability (Le Blond and Mysak, 1978).

than the short period ones. Moreover, the low amplitude and short period waves die down quickly whereas the long period ones are less attenuated and propagate to very long distances in the ocean. Waves prevailing in the generating area are termed as 'seas', which are under the influence of local winds. Once they move out of the generating area the waves are known as 'swells' and they are no longer influenced by local winds. Hence in a crude sense, seas may be attributed as 'forced waves' and swells as 'free waves'.

Gravity wave phenomena are quite complex and mathematical descriptions are difficult due to their non-linear characteristics and random behaviour. Studies on this subject started long ago (Russell, 1844; Stokes, 1847) but several aspects still remain unknown. For example the physics and wave mechanics of wind wave generation still remain a mystery even after 150 years. No doubt several wave theories are postulated but these are still inadequate to explain the observations. For this reason, the presently available knowledge on waves mostly comes under semi-empirical or semi-theoretical category. In other words, the various formulae available now are obtained by utilising observational data evidences which are backed by certain theoretical concepts.

1.3 WAVE PREDICTION

The present work is confined to the wave prediction aspects. The word 'prediction' is used in a broad sense and usually it conveys the meaning of either hindcasting or forecasting. In the current context it signifies wave hindcasting which is normally done based on historical or past meteorological data available for a particular location.

Wave prediction has been gaining considerable importance since early 1940s because of its application to defence as well as to the civil sector. Apart from its military uses like Anti-Submarine Warfare (ASW), Naval operations, *etc.* the knowledge about coastal and offshore wave climate has contributed significantly in the development of Ocean Engineering. Today for construction of any major structure at sea either in coastal or offshore region, the information on wave climate is regarded as a basic input to arrive at the design specifications. The long term wave statistics of a given location at sea can be obtained - either by making instrumented wave observations over a reasonable period of at least one or two years or by adapting wave hindcasting methods which in turn utilise the available meteorological data for that particular area. The former is not always possible or uneconomical and therefore the wave prediction techniques have to be evolved/developed to meet the above requirements.

1.3.1 AN OVERVIEW

The configuration of sea surface can best be represented as the superposition of many sinusoidal waves of different heights and periods with random phase differences which combine to form a constantly changing interference pattern. As mentioned earlier, the configuration of waves varies irregularly both in time and space. Hence it poses considerable difficulties for describing them in precise mathematical terms. Therefore, probabilistic or statistical representations are often used to describe ocean surface waves. An important feature which needs to be remembered about the gravity waves is that they are usually assumed as locally homogeneous, stationary (for a limited duration of at least 15 to 20 min) and 'Gaussian'. These assumptions make it possible to quantify waves either in terms of statistical moments or as the ratios of various statistics which can be deduced from a wave record (Longuet-Higgins, 1952).

1.3.1.1 SIGNIFICANT WAVE APPROACH

The concept of 'significant wave' to describe a given sea state was first introduced by Sverdrup and Munk (1947). They defined it as the average of the highest one-third of waves measured over a duration of 15 to 20 min. The significant wave height is represented by H_s. The significant wave period , T_s is the average of the periods of the highest one-third of waves. Apart from these significant wave characteristics other wave statistics are also discernible like the average wave height, $\overline{H}$, the root-mean-square wave height, H_{rms}, the average of the highest 10% of the waves, $H_{1/10}$ and the maximum wave height, H_{max}. Among all these wave parameters H_s is the most widely used one.

Guided by the significant wave assumptions and, perhaps, by realising the difficulties in dealing with the spectrum of waves (wave spectrum concept did not exist at that time !) Sverdrup and Munk (1947) put forth semi-empirical formulae for wave prediction. They explained the energy transfer mechanisms from wind to waves by using normal and tangential wind stress components. The constants were derived from field data which were used in their wind-wave prediction relationships.Wave characteristics after decay were also given by Sverdrup and Munk. Later Bretschneider (1952a, 1952b) by using additional data had modified Sverdrup and Munk wave prediction relationships. The revised formulae are now known as Sverdrup-Munk-Bretschneider or in short SMB wave prediction formulae. Bretschneider (1958, 1970) had further revised the SMB relationships by incorporating more data. SMB prediction method shall be discussed in detail in one of the following sections as this method is used in the present investigations.

Contemporarily, Darbyshire (1952) and Darbyshire and Draper (1963) produced a set of wave forecasting graphs similar to that of SMB curves. Data used for Darbyshire wave forecasting technique had mainly come from the weather ships that were deployed in North Atlantic ocean and in coastal waters of England. He gave separate nomograms for oceanic and coastal waters but these did not include wave decay analysis. This wave forecasting method is available only in the graphical form and equations are not reported in literature.

The wave prediction methods described above, both SMB and Darbyshire, are prescribed for stationary wind conditions. In other words it is assumed in these methods that over a given area the winds are steady both in magnitude and direction for a certain duration. But in nature, winds do vary even for very short durations. Fluctuations in winds are more when the winds are too strong (cyclone situation) or too weak. Considering this fact Wilson (1955) developed a graphical method which takes into account the varying wind fields both in time and space. The space-time wind field diagrams introduced by Wilson for this purpose have become very popular for prediction of waves during storms and cyclones. Wilson in a series of papers (1961, 1963, 1965, 1966) had described the details of further developments of his model. Wilson's wave prediction model considers wave decay aspects and are used for approaching and receding storm conditions.

1.3.1.2 WAVE SPECTRUM APPROACH

The introduction of wave spectrum approach for description of sea state has marked the beginning of a new era in ocean wave studies. Neumann (1953) wave spectrum was the first analytically expressed wave spectrum and this had been widely used between 1953 and 1964. Pierson *et al.*, (1955) had developed a wave forecasting scheme based on the wave spectrum concept and in short form it is known as PNJ method. It describes mechanics of wave generation in terms of the complete spectrum of frequencies. This method is based on the conclusion of Neumann (1953) - that for a given wind velocity, a fully developed sea exhibits a unique spectrum. PNJ wave forecasting curves are actually the integrated forms of frequency versus wave energy spectra. They are called co-cumulative spectra or in short form CCS curves. The significant wave height and range of wave periods can be read from these CCS curves for different wind velocities. PNJ method also provides details for computation of wave heights and periods after decay.

Understandably, Neumann wave spectrum has evinced growing interest among many workers on waves which culminated into developments of wave spectrum formulations. Thus several formulae have been given in the past by relating energy and frequency of wave spectrum *i.e.*, $E(f)$ versus f^n (Phillips, 1958a, 1958b, 1958c; Bretschneider, 1959; Pierson and Moskowitz, 1964; Hasselmann *et al.*, 1973, 1976; Kruseman, 1976; Huang *et al.*, 1981). These formulae are not discussed here in detail as they do not have direct bearing on the present investigations. However, these basic equations are important for developments of wave prediction techniques as such. Through dimensional analysis Phillips derived an empirical formula which predicts that at high frequencies the energy density decreases with increasing frequency as inverse fifth power of the frequency *i.e.*, f^{-5}. The inverse fifth power law has been used in almost all the subsequent wave spectrum formulations mentioned above and holds good for the equilibrium range, *i.e.*, for frequencies higher than the peak frequency, f_p of the wave spectrum. However, recently Phillips (1985) has re-examined the power-law variations based on the knowledge of non-linear wave interaction. He proposes now that the energy is proportional to $U_* g f^{-4}$(inverse fourth power law) where U_* is the friction wind velocity.

The concept of wave spectrum and the recent advent of high speed digital computers have brought significant advances in wave modelling. Over the past three decades several developments have taken place in the field of spectral wave modelling or numerical wave modelling. The physical background of these numerical wave models will be discussed in detail later in this Chapter.

1.3.2 SMB METHOD

The Sverdrup-Munk-Bretschneider (SMB) method assumes that wind blows for a certain duration in almost the same direction over the generating area in order to create waves. The horizontal distance over which the wind blows with constant speed and direction is known as the wave generating area or 'fetch'. Fetch and duration are considered to be the limiting factors of wave development for given wind conditions. It is necessary to have minimum duration of wind, t_{min} and the minimum fetch distance, F_{min} in order to reach steady state or 'fully developed' condition for waves. Thus waves developed by a given wind velocity, U are determined by fetch and duration of wind. During the process of wave development *i.e.*, till they reach steady state, increase of wave height as well as wave period occurs as they propagate in the generating area.

The inputs for SMB wave prediction method are: (i) mean surface wind speed, U and direction, θ (ii) fetch, F (iii) wind duration, t and (iv) decay distance, D *i.e.*, the distance in the direction of wind in which the waves travel from the end of fetch to the point of interest (forecast point). The decay of waves occur when wind speed decreases or its direction changes to such an extent that wave development ceases or when waves propagate out of generating area. When any of these events take place the wave field begins to decay. Hence it is necessary to compute the wave height and period at the end of decay distance from the time waves leave the generating area till they reach the forecast point. Details of wave attenuation processes in shallow waters may be seen in Ippen (1966).

Nomograms are available in the Shore Protection Manual (1984) which provide significant wave height, H_s and period, T_s as a function of wind speed, U, fetch length, F and duration, t. The nomograms of wave prediction were developed based on the semi-empirical relationships which may be summarised as follows:

$$gH_s / U^2 = A_1 \tanh\left[B_1 \; (gF/ U^2)^{m_1}\right] \tag{1.1}$$

$$C/ U = gT_s / 2\pi U = A_2 \tanh\left[B_2 \; (gF/ U^2)^{m_2}\right] \tag{1.2}$$

In the above equations, H_s and T_s are the significant wave height and period, F is the fetch length, U is the mean surface wind speed at 10 m height above water level, C is the phase velocity of the significant wave and A_1, A_2, B_1, B_2, m_1 and m_2 are all empirical constants obtained from the analysis of field data. These constants had been revised by Bretschneider (1958, 1970,) as and when additional field data were acquired. The use of nomograms as well as of wave prediction formulae are illustrated in the Shore Protection Manual.

Once the waves leave the generating area, they travel as swells over long distances. While waves propagate as swells, they lose energy through lateral diffraction, spreading due to wave dispersion, air-resistance and wave-current interaction. SMB method provides suitable information for the computation of wave decay aspects. The nomograms give wave height and period as a function of the decay distance. If the forecast point is located in coastal area, the effects of shoaling,wave refraction and bottom friction also have to be considered.

1.3.3 NUMERICAL WAVE MODELS

The SMB method as well as other wave prediction methods discussed so far are based on early works (post World War II era) which were aimed at developing simple empirical relationships between wind and wave parameters. These methods have been widely accepted over the years for several practical applications due to their easy adaptability and less computational effort. No doubt, these conventional wave prediction methods provide first estimates of wave response to uniform and steady winds but fail to offer satisfactory results for varying non-homogeneous complex wind field. Neumann's wave spectrum concept and invention of high speed computers have ushered a new era of wave modelling in 1960s. Barnett (1968) illustrated the prediction of ocean waves with a numerical model. The developments on numerical wave modelling that took place over the past three decades are discussed here briefly.

The basic governing equation used in numerical wave prediction models is the energy balance equation or the radiative transfer equation. It may be written as :

$$\frac{\partial E}{\partial t}(f,\theta,\overline{X},t) + \overline{C}_g.\nabla E = S = S_{in} + S_{nl} + S_{ds} \qquad (1.3)$$

where E is the 2-dimensional wave spectrum dependent on frequency, f, direction of wave propagation, θ, position vector, $\overline{X}$, time, t and group velocity, $\overline{C}_g$. S is defined as the source function which represents the physical processes that transfer energy to and from the wave spectrum and is assumed to be the sum of three terms S_{in}, S_{nl} and S_{ds}. The term S_{in} represents input to the waves from the atmosphere and it is formulated based on wave generation theories of Phillips (1957) and Miles (1957). The weak non-linear energy transfer that takes place through resonant wave-wave interactions within the wave spectrum is represented by S_{nl}. The effect of resonant wave-wave interactions is studied by Hasselmann (1961, 1962, 1963a, 1963b). He developed energy transfer equations in terms of coupling coefficients characterising the interactions between the wave field and its physical environment. The third term constituting the source function, S_{ds} represents wave energy dissipation both in deep and shallow waters. In deep waters the dissipation is generally believed to be caused by turbulence and white capping. For quantifying S_{ds} wave breaking and bottom friction are considered important.

The existing models are primarily based on various efforts made to solve the energy balance equation (1.3). These wave models can be broadly categorized into three classes, namely, decoupled propagation models (DP), coupled hybrid models (CH) and coupled discrete models (CD) (SWAMP Group, 1985). These are also often referred in the literature as first, second and third generation wave models. First generation models consider discrete decoupled frequency bins based on linear wave theory and the energy in each bin propagates with appropriate group velocity. When this class of models were first attempted very little was known about the three components of the source function, *i.e.*, S_{in}, S_{nl} and S_{ds}. However, wave generation theories (Phillips, 1957; Miles, 1957, 1959, 1967), the concept of a universal equilibrium range for wave spectrum (Phillips, 1958a) and non-linear interactions between various frequency bins (Hasselmann, 1962) provided a solid base for the development of first generation models. In this class of models wave spectrum was given by a one-dimensional frequency spectrum of the form f^{-5} with an empirical equilibrium directional distribution function. Hence, for growing wind seas the spectrum was in effect limited to wave components in the neighbourhood of the spectral peak frequency. SWAMP group (1985) study reveals two shortcomings of first generation models: (i) they overestimate the wind input and (ii) underestimate the magnitude of non-linear energy transfer mechanisms.

The second generation wave models attempted to overcome some of these shortcomings by considering more effective energy coupling through non-linear processes from high frequency to low frequency side of the wave spectrum. In this class of models also certain restrictions became inevitable like the spectral shape of the wind-sea spectrum had to be prescribed for frequencies higher than the peak frequency. For example, the spectral shape specification was made either in the formulation of the energy balance equation or as a side condition in the energy computations. Thus second generation models were also unable to simulate well the complex seas occurring in cyclone or storm conditions. Some difficulties were also encountered while treating the transition between sea and swell regimes. SWAMP study points out that the problems of second generation models are largely numerical rather than physical.

The third generation wave model has been recently put forth by the Wave Modelling Group (WAMDI Group, 1988). The central theme of this model is the integration of spectral energy balance equation (1.3) without 'apriori' assumptions on the spectral shape. Therefore attempts were made in the third generation model to incorporate the exact form of the non-linear transfer term (S_{nl}), energy dissipation, *etc.* These criteria were added explicitly and a bottom dissipation source function and refraction were also incorporated. The third generation wave model presents 2-dimensional ocean wave spectrum without ad hoc assumptions on spectral shape. The model was run for both global and regional applications and it employs a spherical latitude-longitude grid. It was calibrated against fetch-limited wave growth data and only two tuning parameters were used for describing white capping dissipation source function. Hindcast studies are done using third generation model (WAMDI Group, 1988) for six North Atlantic and North sea storms, three Gulf of Mexico hurricanes and a global run of SEASAT scatterometer data.

1.3.4 WORK DONE IN INDIA

As such, studies on wave prediction in India are very few probably due to lack of appropriate wind and wave data. Wave prediction methods applied to Indian seas shall be reviewed here briefly. Srivastava (1964a, 1964b) presented a comparison of Wilson's method with other wave hindcast methods utilising some observations. Dattatri and Renukaradhya (1971) and Dattatri (1973) have studied the wave prediction aspects off Mangalore on the west coast of India. The recorded wave data collected in coastal waters for monsoon months of June and July were used by them. A comparison has been made between SMB and PNJ wave forecasting methods with the observed wave data and they reported that the SMB method gives better agreement than PNJ. In another study Dattatri and Vijayakumar (1974) have applied Wilson's graphical method for prediction of waves off Visakhapatnam, on the east coast of India, under cyclonic storm conditions. They reported that predicted waves were in good agreement with the observed waves. Daskaviraj and Sarkar (1976) have made attempts to correlate wave height and wind speed for the Digha area on the east coast. Similar studies were also reported for Bombay high area on the west coast (Mukherjee and Sivaramakrishnan, 1981). Gokhale (1979) discussed about sources of errors in wind field determination and its implications on wave prediction in tropical storms. Reddy *et al.*, (1980) have studied on the applicability of SMB and PNJ methods for hindcasting waves off Visakhapatnam during cyclone conditions. They found that SMB method provides better comparison of hindcast results with observed data. Wave conditions over the Arabian sea and Bay of Bengal during monsoon as well as in cyclonic conditions were reported in the literature (Mukherjee and Sivaramakrishnan, 1977, 1982, 1983; Thiruvengadathan, 1984). These studies were mostly based on visual wave data reported by ships. Thiruvengadathan (1984) in his study has recommended a relationship for wind speed and wave height based on data pertaining to monsoon season from the Arabian Sea and the Bay of Bengal :

$$H = 0.17 + 0.0087\, U + 0.014167\, U^2 \qquad (1.4)$$

where H is the characteristic wave height in meters and U is wind speed (m/s).

Some hindcast case studies were reported earlier for southwest coast of India (Joseph, 1984, 1988) using a second generation SWAMP group wave model which was originated from TOHOKU University of Japan. This model is referred in the literature as TOHOKU wave model. Wave data obtained with a 'Datawell' waverider buoy in the coastal waters and wind data derived from the synoptic daily weather reports were utilised for the above study. Mandal and Nayak (1986) made a review on wave prediction models. Several aspects related to ocean wave research in India and its current status have been reported recently by Baba (1985).

1.4 OBJECTIVES OF THE THESIS

The following points emerge from the review of literature presented above on wave prediction in general and with reference to Indian seas in particular. The conventional wave prediction techniques like SMB, PNJ, Darbyshire, *etc.*, are simple and involve less computational efforts. These are primarily based on certain assumptions with regard to wind field and fetch conditions. In spite of the limitations which arise due to the assumptions mentioned above, the conventional wave prediction methods have been widely accepted as they provide first estimates of wave field over a given area. Availability of nomograms also made them more popular in their applications. The spectral and numerical wave models belong to another category which require high speed computers and large data network systems for their effective utilisation. These models offer complete 2-dimensional wave information. They can be utilised for regional or global wave prediction purposes. Numerical wave models are best suited for providing routine as well as real time forecasts. The users, at times, find it difficult to choose a wave model which will be most suitable for the application at hand. Therefore, clear guidelines regarding the extent of usage of each model, its reliability, mode of operation, *etc.*, are very essential. By taking the above aspects into consideration, the following objectives are set forth for the present thesis work :

(i) To study and evaluate a typical conventional wave prediction model with the recorded wave observations collected at a coastal site. The influence of variable fetch size and the importance of wave transformation processes from deep to shallow waters will also be covered in this study.

(ii) To study the correlations between wind and waves at a given point in the sea which is farther from the coast. Time-series data on winds and waves will be utilised for this purpose. Based on these correlation studies, attempts will also be made to develop new formulae for wave prediction.

(iii) To evaluate and study the response of a numerical wave model with some appropriate data sets collected in deep as well as shallow waters of the Arabian Sea and the Bay of Bengal. The observed and predicted wave data for different situations will be compared.

(iv) A critical discussion on merits and/or demerits of different approaches of wave prediction will be presented based on the present investigations. Recommendations for effective implementation of different models for different practical situations will be given.

CHAPTER 2 : DATA AND METHODS

2.1 DATA NEEDS FOR WAVE PREDICTION

In this chapter the type of data required for wave prediction, sources of data, data processing and analysis techniques utilised for this study are discussed. The basic inputs for wave prediction (hindcasting) are wind and wave data. When specific programs/experiments are undertaken at sea, the necessary input parameters can be obtained by making measurements. Data generated during such programs are more reliable and useful for wave prediction. Data sets thus obtained for certain locations which are utilised for this study are given in Table 2.1. Apart from it, wind information available in the Indian Daily Weather Reports (IDWR) issued by India Meteorological Department (IMD) and visual estimates of wave parameters reported during MONSOON-77 Expedition are also used in this study.

2.2 WIND DATA

Wind data reported in IDWR are utilised for wave prediction using SMB method in Chapter 3. IDWR provide isobars over the land and oceanic regions from which geostrophic winds can be derived. During cyclonic storms ships/vessels generally avoid them and hence data on such situations are sparse. Under such conditions isobar data provide very useful information for estimation of winds. However, during fair weather it is preferable to take the actual wind data reports. In the

Table.2.1 Particulars of wind and wave data used.

S.No.	Location of observations	Period of observations	Sources of wave data	Sources of wind data
1	Off Mangalore, West coast of India, depth 9m.	June to August of 1968 and 69.	Sub-surface wave gauge.	IDWR
2	Off Goa, West coast of India, depth 80m.	17-24 March 86.	Waverider buoy.	ship-board anemograph
3	Off Cochin, West coast of India, depth 12.5m.	11-26 August 86.	Waverider buoy.	anemograph installed at beach
4	Arabian Sea $12^\circ 30' N$, $64^\circ 00' E$.	12-21 June 77.	Visual data collected during MONSOON-77.	ship-board anemograph
5	Arabian Sea $12^\circ 30' N$, $69^\circ 00' E$.	7-20 June 77.	-do-	-do-
6	Bay of Bengal $17^\circ 12' N$, $90^\circ 54' E$.	12-19 August 77.	-do-	-do-

present case the wind speed and direction given in IDWR are used. Wind data collected on board ships/vessels which took part in specific experiments/programs are utilised for wave prediction works discussed in Chapters 4 and 5. For ship board wind measurements the standard cup anemometers are used. In these cases the time series measurements are obtained at specified locations at sea.

2.3 WAVE DATA

Wave data collected by a sub-surface pressure gauge installed at a coastal site off Mangalore (Sundararamam *et al.*, 1974) are utilised in Chapter 3. Data acquired by a Datawell waverider buoy at two places off the west coast of India (off Goa and Cochin) are used in Chapters 4 and 5. Apart from these data, the visual wave height and period estimates made during the MONSOON-77 Expedition for deep water areas in the Arabian Sea and Bay of Bengal are utilised for wave prediction work described under Chapter 5. A brief description of the principle of sub-surface pressure gauge device is given here and particulars of installation, functional aspects *etc.*, may be seen in earlier studies (Dattatri, 1973; Sundararamam *et al.*, 1974). The details of Datawell surface measuring accelerometer wave buoy used in the data collection programs are given.

2.3.1 SUB-SURFACE WAVE GAUGE

Sub-surface pressure transducers used for wave measurements may be mounted at the bottom or attached to some underwater structure. Normally these are used for shallow water wave measurements and the depth of immersion of sensors depends upon the expected wave period range in a given location. As the surface wave heights get attenuated with depth, the measurements require compensation for hydrodynamic attenuation of pressure to obtain corrected wave heights.

2.3.2 DATAWELL WAVERIDER BUOY

Datawell waverider buoy system consists of three parts, namely, (i) a spherical surface floating buoy (ii) a receiver and (iii) a mooring system. The buoy with 0.7 m diameter which is used for data collection weighs about 106 kg in air. The hull of the buoy is made of copper-nickel alloy and it houses an accelerometer sensor. The vertical acceleration measured by the buoy is integrated twice to obtain wave height information. Data are then transmitted to receiver through telemetry. The frequency of transmission is 27.505 MHz.

The receiver equipment comprises of analog and digital recording units. The receiver is equipped with a programming unit possessing a clock which enables measurement at specific intervals of time. The interval between successive records can be varied from 1 to 24 h. The duration of a wave record can be set to 5/10/20/40 min using a timer switch. The speed of the analog chart paper can be adjusted to 600/1800/3600 mm/h. The receiver is provided with a phase unlocking system which gives an indication when buoy signal is too weak or noise is too strong or any other malfunctioning of receiver is noted. Under noise-free conditions a maximum range of 50 km is possible for wave data transmission over the sea. The digital data recording unit is directly interfaced to analog recording system. Data words of 23 bit magnitude and 1 cm/bit resolution are recorded on standard digital cassette. Data sampling rate is 0.5/1.0 s and storage capacity of each tape is about 19 h of continuous data or 38 h for 1 s interval.

A schematic diagram showing the configuration of waverider buoy system is given in Fig.2.1. Generally the recommended mooring length is twice the water depth. The mooring consists of a rubber cord, nylon covered steel wire rope and polypropylene rope. The rubber cord attached to buoy-end allows free floating with low stiffness. A mild steel chain weighing about 300 kg is normally used as anchor.

Waverider buoy system is capable of providing continuous time-series of wave data for long durations. The batteries housed inside the buoy would be sufficient for 9 months continuous operation. Since it operates at the surface no attenuation correction to wave height data is needed.

2.4 WAVE DATA PROCESSING

Since sea surface waves are random in nature it is necessary to adapt statistical and spectral techniques to

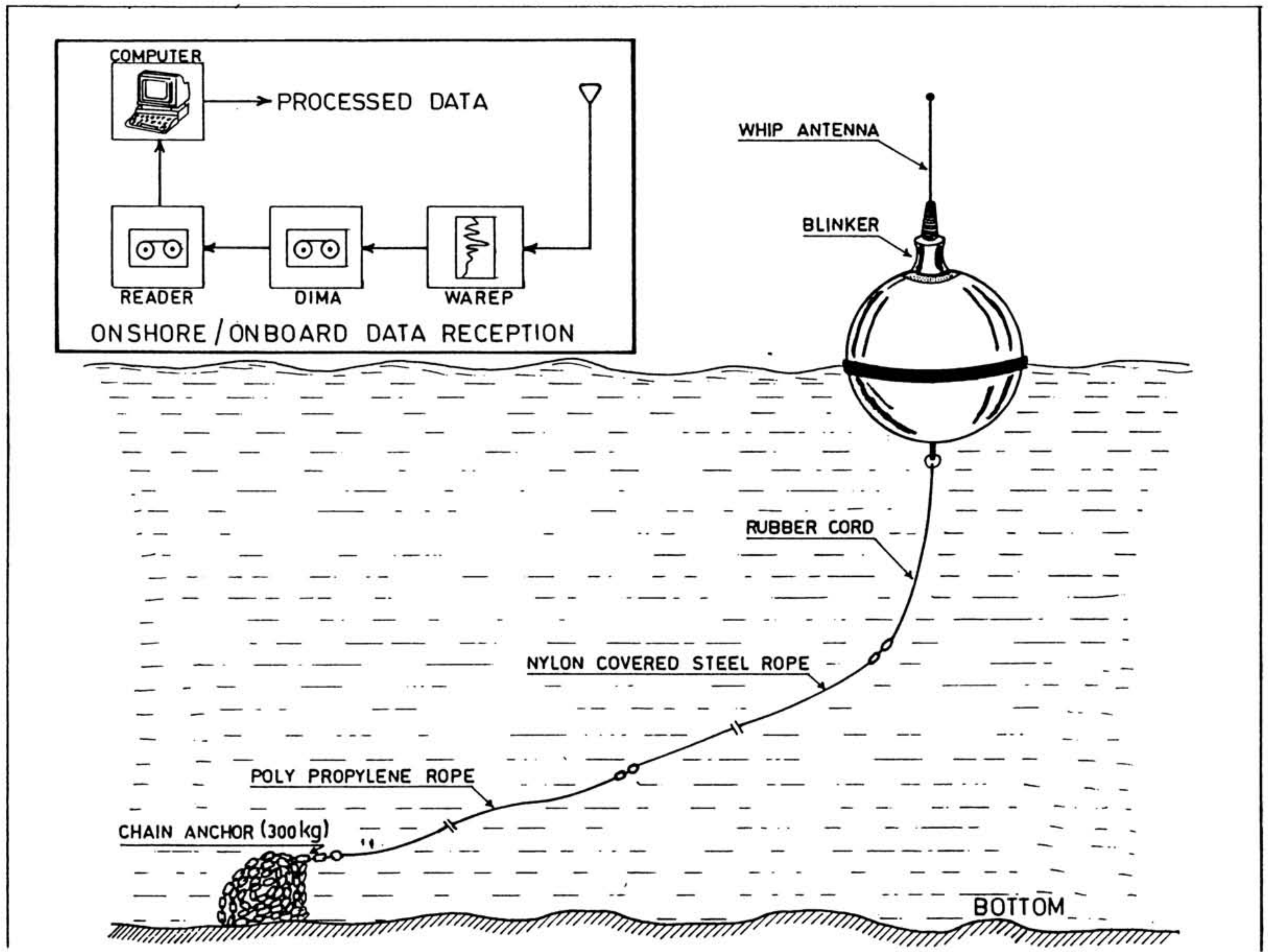

Fig.2.1 System configuration of Datawell waverider buoy.

describe them. There are two approaches for analysis of wave records: (i) significant wave approach and (ii) spectral approach. The former method provides significant wave characteristics such as mean height, $\overline{H}$, significant height, H_s, mean of 1/10 th highest waves, $H_{1/10}$ and the corresponding wave periods. Whereas, in spectral approach the variance of sea surface elevations is computed and frequency - energy spectrum is constructed. Further, by using spectral moments, various other significant wave parameters can also be obtained (Goda, 1974). Both these techniques are very useful for obtaining information from wave records. These two techniques will be discussed here in detail as they are utilised in the present study.

2.4.1 WAVE - BY - WAVE ANALYSIS

Putz (1952) introduced a method for analysis of wave records which is referred in the literature as wave -by - wave analysis. This technique gives the significant wave characteristics. One need to count all the waves in a given record and find crest-to-trough heights for obtaining the necessary parameters.

2.4.2 TUCKER'S ZERO-CROSSING ANALYSIS

Tucker (1963) and Draper (1966) recommended a simple method for analysis of sea wave records which is based on zero-crossing analysis (see Fig.2.2). Firstly a mean water line is drawn or visualised for a given analog wave record.

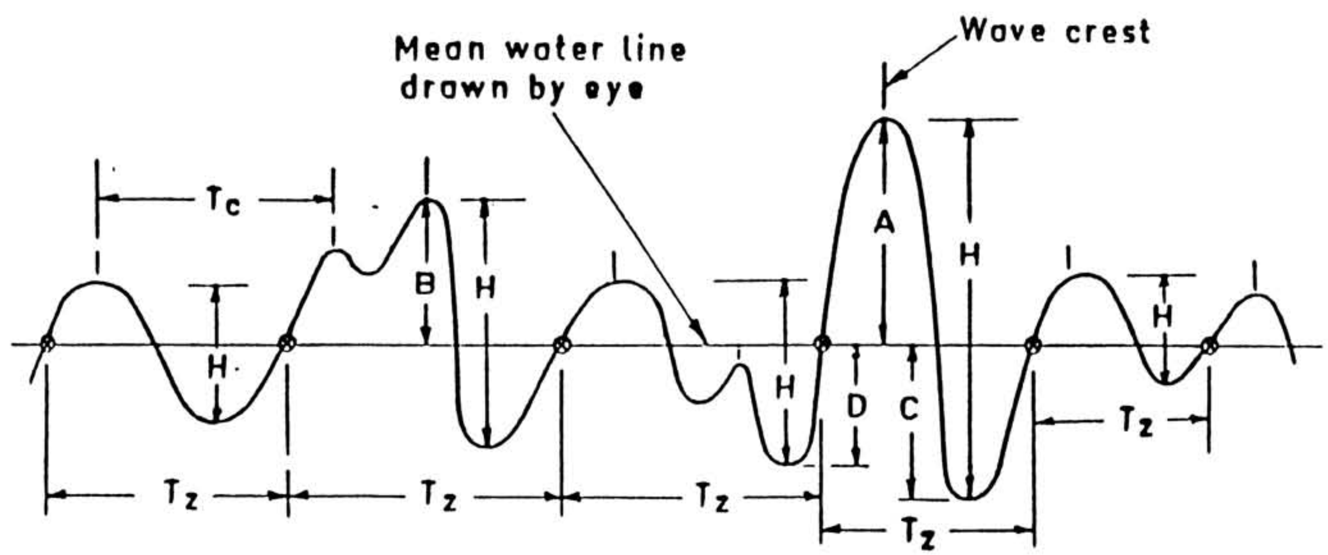

Fig.2.2 Tucker's zero-crossing wave analysis:
A schematic view.

Total number of crests, N_c are noted from this record. A crest is defined as a point where the water level is momentarily constant and thereafter falls to either side. Sometimes the crests may be found below the mean water line. Number of zero-up crossings, N_z are read whenever the wave train crosses the mean line in the upward direction. The height of the highest crest, A, the second highest crest, B, the lowest trough, C and the second lowest trough, D are measured with reference to mean water line. Both values of C and D are to be taken as positive. From these quantities the heights H_1= A+C and H_2= B+D are estimated. The root mean square heights/displacement values of H_{rms} are deduced from H_1 and H_2 using the following equations based on the theory of Cartwright and Longuet-Higgins (1956).

$$H_{rms(1)} = \frac{1}{2} H_1 \left(2\theta\right)^{-1/2} \left[1+0.289\left(\theta\right)^{-1} - 0.247\left(\theta\right)^{-2}\right]^{-1} \qquad (2.1)$$

$$H_{rms(2)} = \frac{1}{2} H_2 \left(2\theta\right)^{-1/2} \left[1-0.211\left(\theta\right)^{-1} - 0.103\left(\theta\right)^{-2}\right]^{-1} \qquad (2.2)$$

where $\theta = \ln \left(N_z\right)$

The significant wave height, H_s can be derived using the following formulae:

$$H_{s(1)} = 4.0\ H_{rms(1)} \qquad (2.3)$$

$$H_{s(2)} = 4.0\ H_{rms(2)} \qquad (2.4)$$

From $H_{s(1)}$ and $H_{s(2)}$ the largest value may be taken as H_s. The wave periods are to be determined using N_z and N_c values. For example, there are two representative wave periods, namely, the mean zero-up crossing period, T_z and the mean crest period, T_c.

$$T_z = \frac{\text{Length of wave record in seconds}}{N_z}$$

$$T_c = \frac{\text{Length of wave record in seconds}}{N_c}$$

The spectral width parameter, ε_T may be written as:

$$\varepsilon_T = \left[1-(N_z/N_c)^2\right]^{1/2} \qquad (2.5)$$

2.4.3 SPECTRAL ANALYSIS

In spectral approach it is assumed that the oscillating sea surface is the linear superposition of several sinusoidal waves with varying amplitude and phase distributions. Spectrum analysis of ocean wave data was first explained by Pierson and Marks (1952). The wave energy density spectrum (power spectrum) gives the frequency composition with respect to spectral density function. The concept of power spectrum can be explained from the basic expression of mean square value:

$$\psi^2 = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} \eta^2(T)\, dT \qquad (2.6)$$

In the above equation ψ^2 is proportional to the mean square energy per unit time and which is by definition known as power. In the present context for wave studies η represents the sea surface elevation and T is the time in seconds. If we define the one-sided spectral density function as $G(f)$, we can write:

$$\psi^2(f_1,f_2)= \int_{f_1}^{f_2} G(f)\, df \qquad \text{for } 0 \le f_1 \le f_2 \qquad (2.7)$$

where $G(f)$ gives power between the frequencies f_1 and f_2.

There are two methods by which one can compute the energy spectrum: (i) covariance or autocorrelation method and (ii)Fast Fourier Transform (FFT) method. Both give essentially the same results. Details of these two methods may be seen in Bendat and Piersol (1971) and Jenkins and Watts (1968). For wave spectrum studies it is the auto-correlation method which is more commonly used (Dattatri, 1978; Narasimhan and Deo, 1981). One important reason attributed for adapting this method is that it provides valuable intermediate stage information namely the autocorrelation function values. Though the autocorrelation and spectral density functions are considered as Fourier Transform pairs, it is believed that for ocean waves the former gives additional information for interpretation of wave data (Vosnessensky and Firsoff, 1957; Dattatri, 1981). Considering these facts the autocorrelation technique has been employed for the present investigation. The

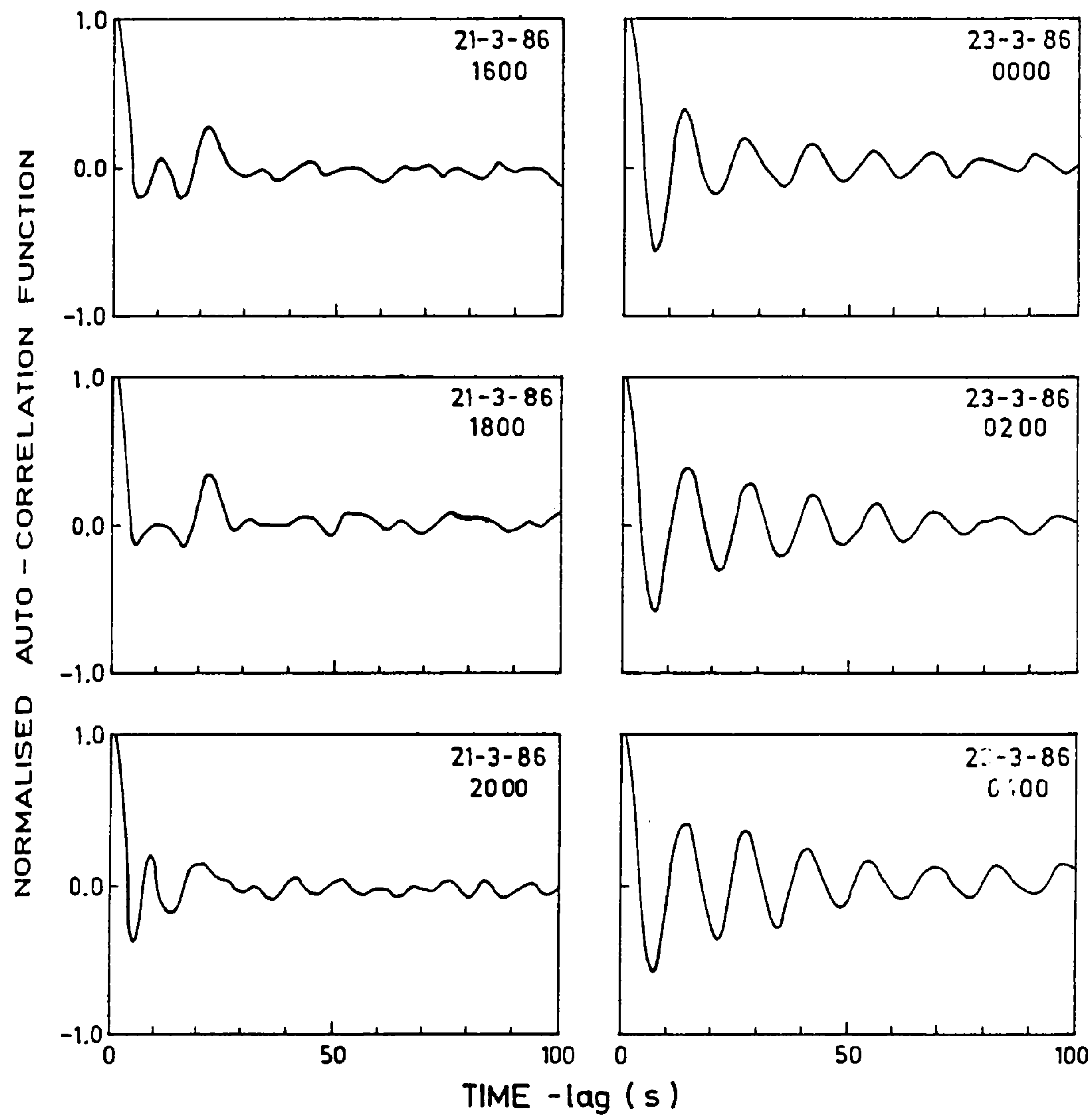

Fig.2.3 Typical examples of variation of autocorrelation function.

variations of autocorrelation function for some typical wave conditions observed in this study are shown in Fig.2.3. It is noticed that the decay of autocorrelation function with time is smooth as well as periodic for wave spectra containing a single dominant peak. The variation of autocorrelation function is irregular for wave spectra with multiple peaks.

For a continuous spectrum the one-sided spectral density function, $G(f)$ may be written as:

$$G(f) = 2\int R(\tau)\ \exp(-i\omega\tau)\ d\tau \qquad (2.8)$$

where ω is frequnecy in radians and τ is time-lag in seconds. In the above equation $R(\tau)$ represents autocorrelation function which is given by:

$$R(\tau) = \mathrm{Lt.}1/T \int_0^T \eta(t)\ \eta(t+\tau)\ dt \qquad (2.9)$$

$\eta(t)$ and $\eta(t+\tau)$ are sea surface elevations noted from the mean water level at instances of time t and $(t+\tau)$ respectively.

2.5 MODEL COMPARISONS

Comparisons of model-predicted and observed wave parameters are usually shown in X-Y time-series plots and the same method is adapted in this study. Apart from it in certain cases (see Chapter 3) the % deviation of significant wave height, H_s and period, T_s for predicted and observed data are shown in histograms with the corresponding % frequency of such occurrences. Similarly for quantifying the errors percentage Mean Deviations (%MD), percentage Root Mean Square Deviations (%RMSD) and the Root Mean Square (RMS) error are also given (see Chapters 4 and 5). It may be noted that the %MD Value suggests a positive or negative bias of the prediction whereas %RMSD value quantifies the error in prediction.

CHAPTER 3 : WAVE PREDICTION WITH SMB METHOD

3.1 INTRODUCTION

Several earlier workers (see sections 1.3.1, 1.3.2 and 1.3.4) have recommended SMB method over the other significant wave prediction methods. By following this method a wave hindcasting analysis is made in the present investigation to study the wave transformation that takes place from deep to shallow waters, which was not done earlier. Detailed investigations are carried out to study the effect of fetch variations for wave prediction at a particular site using SMB method. Wave hindcast analysis is carried out for Mangalore, south-west coast of India.

3.2 DATA AND METHODS

3.2.1 WAVE DATA

Continuous wave measurements were made off Mangalore (south-west coast of India) from June 1968 to September 1969 using a sub-surface wave gauge (Dattatri, 1973; Sundararamam *et al.*, 1974). The location of wave measurements is shown in Fig.3.1(a). The sensor of the wave recorder was installed at a distance of 4 km from the coast. The average water depth at this point was around 9 m. Wave data were transmitted to the shore station through cable laid on the sea floor. The analog wave records on chart paper of 15 to 20 min. duration at 1 h interval were obtained between June and September 1968 and the sampling interval was increased to 3 h for the rest of the

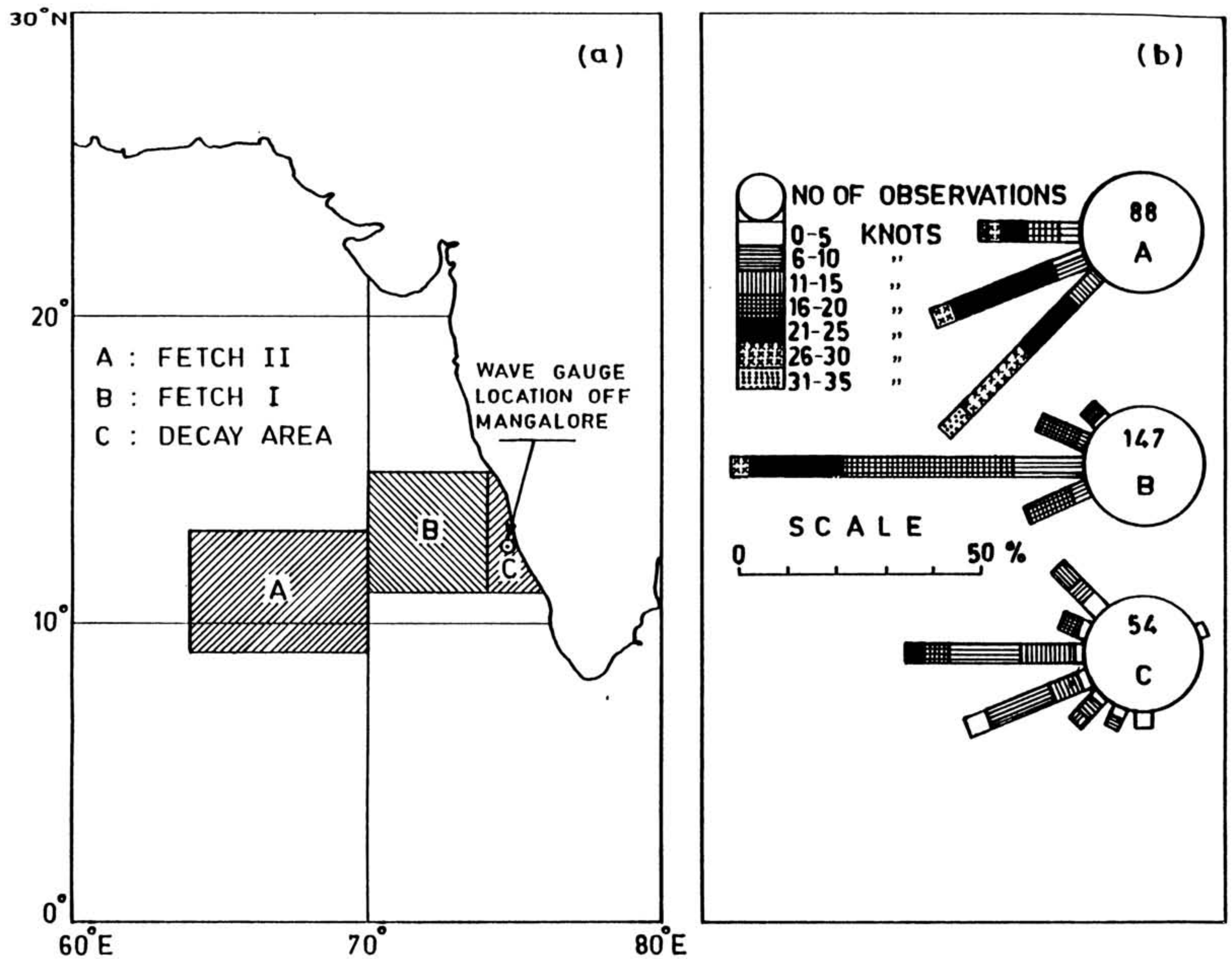

Fig.3.1 (a) Wave gauge location and fetch demarcation
(b) Wind roses for areas A, B and C.

observations. These wave records were processed earlier by Sundararamam *et al.*, (1974) following wave-by-wave analysis to obtain significant wave height, H_s and period, T_s. H_s and T_s data for June to August for both 1968 and 1969 are utilised in this investigation. The observations pertaining to south-west monsoon season have been preferred as higher waves are observed during this period.

3.2.2 WIND DATA

It is preferable to have recorded wind data for wave hindcasting purposes as they are more accurate. Since it is difficult to gather measured winds over large sea areas for longer durations, one need to look for other sources for acquiring necessary inputs. The wind data reported in IDWR, which are issued twice daily for 0830 and 1730 IST are used for the present study. Over the given study area the daily mean wind speeds are calculated from the reported wind observations. Generally 2 to 6 wind observations were available to compute daily mean values of wind speed. On some days no data were reported.

3.2.3 FETCH ESTIMATION

Next important step for wave hindcasting is the estimation of fetch. In this study, standard techniques available in literature are employed for delineation of fetch (Kaplan, 1953; Kaplan and Saville, 1954; Wilson, 1955; Shore Protection manual, 1984).

A first look of the synoptic daily weather reports *i.e.*, IDWR for south-west monsoon of 1968 and 1969 revealed that for the south-west coast of India in general and particularly for Mangalore region, the predominant wind direction is west in the near-shore whereas it is south-west in deep sea areas (Fig.3.1(b)). It is noticed that the wind direction varies from 270° to 290° between 70° and 74° E while it ranges from 230° to 260° between 64° and 70° E. Apart from wind direction the daily mean wind speeds for these two regions are found conspicuously different. Hence, two generating areas are considered for wave hindcasting off Mangalore. The area bounded by 11° to 15° N and 70° to 74° E is marked as Fetch I (area 'B') and the area between 9° to 13° N and 64° to 70° E as Fetch II (area 'A'). The area beyond 74° E and up to the coast is treated as wave decay zone (area 'C'). Areas 'A', 'B' and 'C' are hatched in Fig.3.1(a).

The daily mean wind speed values for each of the above three areas are computed based on wind velocities reported in IDWR following the procedure suggested by Wilson (1955). Then the deep water significant wave height, H_s and period, T_s are derived using Bretschneider (1970) curves. The waves generated in Fetch II travel towards the coast passing through a secondary wave generating area *i.e.*, Fetch I. Hence, H_s and T_s of Fetch II at the end of Fetch I are to be evaluated by using the concept of 'effective fetch' (Sverdrup and Munk, 1947).

However, on such occasions, when wind velocities are found to be same in Fetch II and in the subsequent generating area (Fetch I), then both can be merged into a single fetch. The waves thus predicted at the end of Fetch I have to travel over the area 'C' before they enter into shallow water. During this phase, decay of waves occur mainly due to low winds prevailing in the area'C'. Following Sverdrup and Munk (1947) the H_s and T_s at the end of decay area (area 'C') have been computed.

3.2.4 WAVE TRANSFORMATIONS IN COASTAL WATERS

The wave parameters predicted at the end of area 'C' represent deep water wave characteristics. According to linear wave theory, depending on the ratio of water depth, h to wave length, L, waves are classified into three types:

$h/L > 1/2$	deep water waves
$1/20 \leq h/L \leq 1/2$	intermediate water waves
$h/L < 1/20$	shallow water waves

As waves propagate from deep to shallow waters the wave heights are altered considerably whereas wave periods remain almost unchanged. Shoaling, K_s, refraction, K_r and bottom friction, K_f are the three important coefficients which need to be considered for wave transformations in coastal waters. The shallow water significant wave height, H_s is derived from deep water significant wave height, H_o, using the relationship:

$$H_s = H_o\ K_s\ K_r\ K_f \tag{3.1}$$

3.2.4.1 SHOALING

As waves approach towards coast the group velocity, C_g increases slightly and then decreases with decreasing water depth. Initially when the C_g increases, wave crests move further apart resulting in decrease of wave heights corresponding to a decrease in wave energy. The reduction or attenuation of wave height caused in the initial phase is due to change of orbital shape of water wave particles from circular to elliptical. However, as waves pass through intermediate to shallow region the decrease in water depths become more prominent so that C_g decreases and wave crests move closer resulting in increase of wave heights. This increase of wave heights occur in shallow region ($h/L < 1/20$) until waves finally break at the shore. The shoaling coefficient values for the present study are derived from nomograms (Shore Protection Manual, 1984).

3.2.4.2 REFRACTION

As waves enter intermediate and shallow waters they begin to "feel" the bottom. The portion of the wave in deep water ($h/L > 1/2$) moves more rapidly than the portion of wave which lies in shallow water. This causes wave crests to orient themselves parallel to the bottom topographic contours. Therefore waves undergo refraction due to decrease in phase velocity, C as they move towards shallow water. It is to be noted that group velocity is equal to phase velocity for shallow water waves.

The method proposed by Arthur *et al.*, (1952) is used for wave refraction computations. A typical wave refraction diagram illustrating two cases: waves approaching Mangalore coast from south-west and west is given in Fig.3.2. Refraction coefficient, K_r is obtained from the relationship:

$$K_r = \left[b_0 / b_1 \right] \qquad (3.2)$$

where b_0 and b_1 are perpendicular distances between successive wave orthogonals for deep and shallow waters respectively. K_r is a function of wave period, water depth and wave direction in deep water. Because of refraction either convergence or divergence of wave orthogonals occur in near-shore region which result in the increase or decrease of wave heights respectively. The refraction coefficients for typical wave periods and wave directions are given in Table.3.1.

Table 3.1 Wave refraction coefficients, K_r off Mangalore.

wave period (s)	south-west	west
7	0.760	1.020
9	0.910	1.040
11	0.890	1.054

3.2.4.3 BOTTOM FRICTION

In shallow water the wave particle motion is elliptical with the major axis of the ellipse in the wave direction.

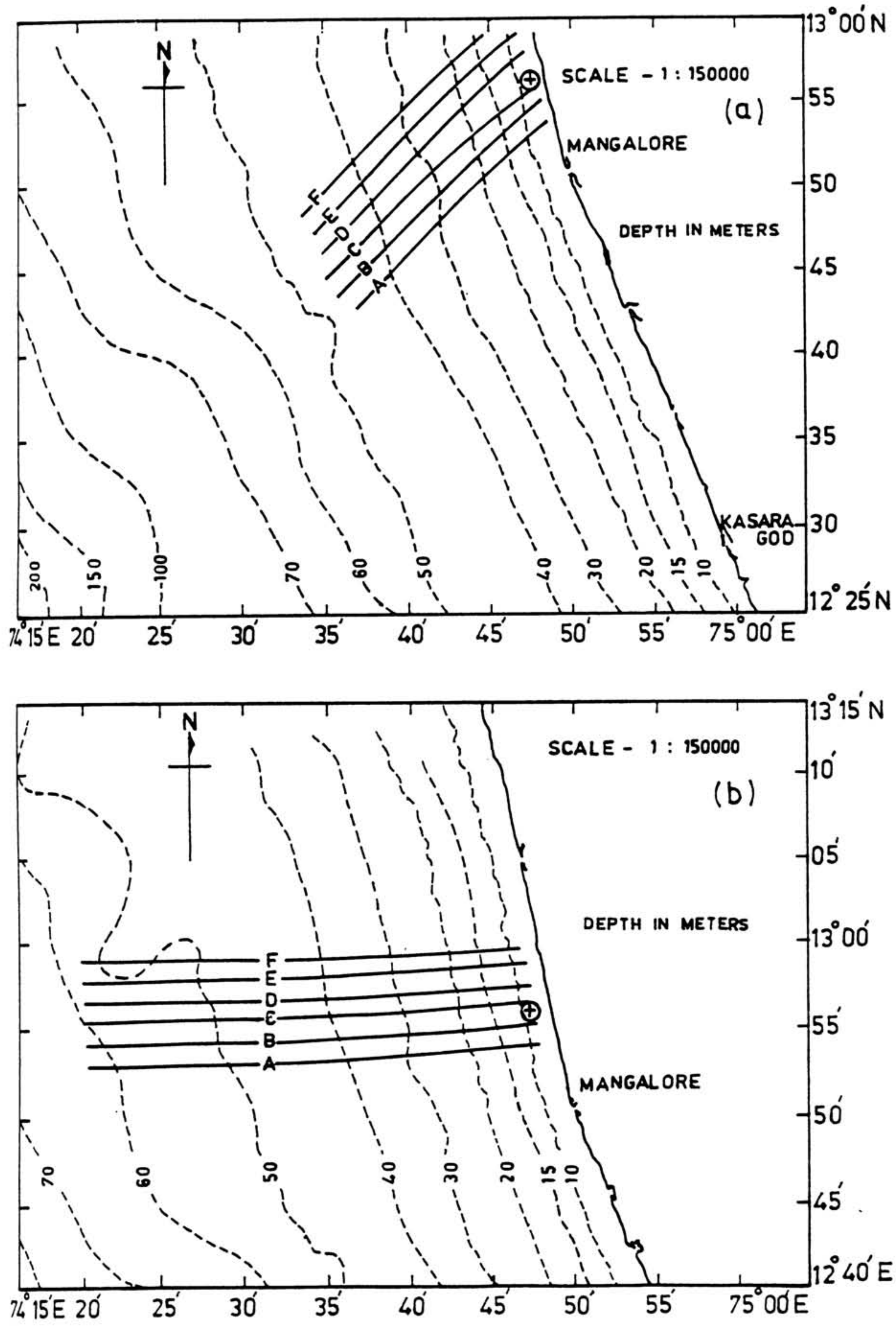

Fig.3.2 Wave refraction diagrams for: (a) south-west with T_s 7 s and (b) west with T_s 11 s.

Particle motion decays with depth and the orbital velocities of wave particles are finite at the bottom. The sea bed acts like a rough surface and offers resistance to wave motion. Therefore certain amount of energy is lost by waves in overcoming resistance and shear forces caused by sea bed. The loss of energy encountered to waves due to this process is termed as bottom frictional loss and it is denoted by K_f. Bretschneider (1954), Bretschneider and Reid (1954) studied the wave energy losses in shallow water. The formula for estimation of K_f is shown below:

$$K_f = \frac{4\,\pi^2 \rho\, f\, H^3}{3\, T^3 (\sinh kh)^3} \tag{3.3}$$

where
- ρ density of sea water
- f dimensionless friction factor
- H wave height
- T wave period
- h water depth
- k wave number ($2\pi/L$)

Laboratory as well as field experiments (Bretschneider, 1954; Bretschneider and Reid, 1954) have shown that a value of 0.01 may be used for friction factor, f in the above equation. However, the subsequent studies (Iwagaki and Kakimura, 1967; Dattatri and Vijayakumar, 1974) pointed out that f = 0.01 is too low for sloping sea bottoms. Values of f ranging between

0.01 to 0.05 were suggested in the latter studies. Kurian *et al.*, (1985) and Kurian and Baba (1987) studied the effect of refraction and bottom friction on the near-shore wave heights. These studies are mostly related to the Kerala coast. So far no appropriate value for bottom friction factor is reported for Mangalore coast. In the light of this both the highest and the lowest values recommended earlier (*i.e.*, 0.05 and 0.01) have been tried to see which of the transformed (predicted) waves agree well with observations. Based on this study, a proper value for *f* is recommended for future.

3.3 DISCUSSION OF RESULTS

From the wind roses drawn for the areas 'A', 'B' and 'C' (Fig.3.1(b)) it can be inferred that the predominant direction of wind in Fetch II is south-west and west-south-west whereas it is west and west-north-west for Fetch I. In the decay area winds are unsteady and variable compared to the Fetch I & II. The wind rose diagrams are prepared by clubbing all data for June, July and August of both the years. But the distribution of daily mean winds did reveal certain variations between June, July and August. An average wind speed of 25 kts (25 knots, 1 knot= 1 nautical mile per hour) is prominently seen in Fetch II during June and July but in August winds reduced to average speeds around 15 kts. Though wind speeds decreased in August no significant change in wind direction is observed from June to August and the predominant wind direction remained south-west/west-south-west for the entire period in

Fetch II. On the contrary in Fetch I the wind direction is west during June and July but it is shifted to west-north-west in August. The daily variations of wind speed in Fetch I also show fluctuations (12 to 26 kts). In the decay area both wind speed and direction are unsteady and wind speeds are mostly less than 10 kts.

The effect of wave refraction is more prominent for waves approaching from south-west than from west (Fig.3.2). The divergence of wave rays at the observation site for south-westerly waves implies stretching of wave fronts and consequent reduction in wave energy or wave height. Waves approaching the coast from west indicate slight convergence at the observation point but its effect seems to be minimal in increasing the wave height. The refraction coefficient, K_r less than 1.0 implies convergence and more than 1.0 -divergence of wave orthogonals (Table 3.1). It may be noted that due to the wave refraction there is about 10 to 20 % decrease in wave height for waves coming from south-west and a marginal increase in wave height of 2 to 5 % for waves arriving from west.

After applying corrections for wave refraction, shoaling and bottom friction the predicted shallow water significant wave heights are compared with the data. These comparisons are shown separately for waves originating from Fetch I and II (Fig.3.3 & 3.4). For waves emanating from Fetch II the

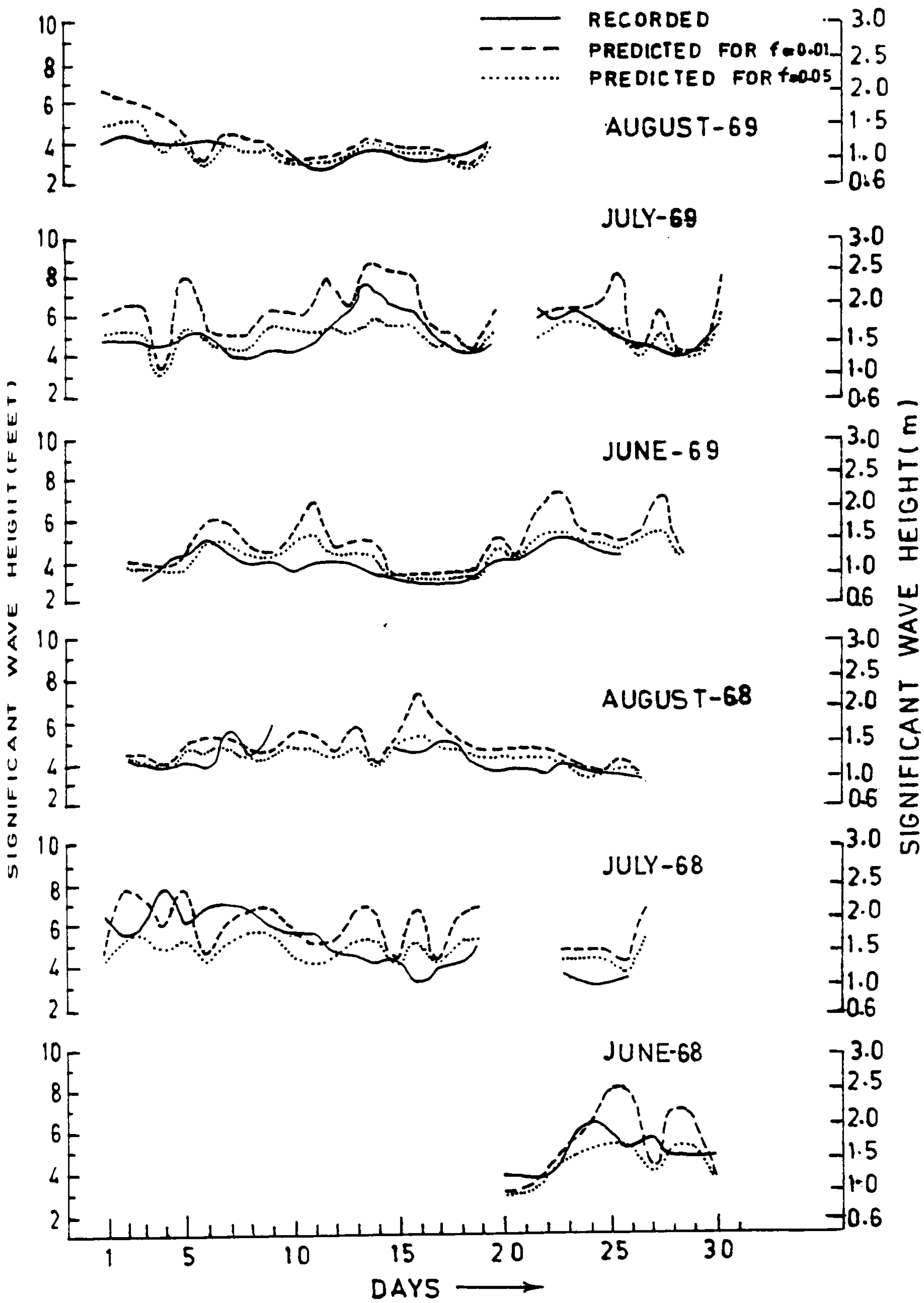

Fig.3.3 Comparison of observed and predicted H_s for Fetch I.

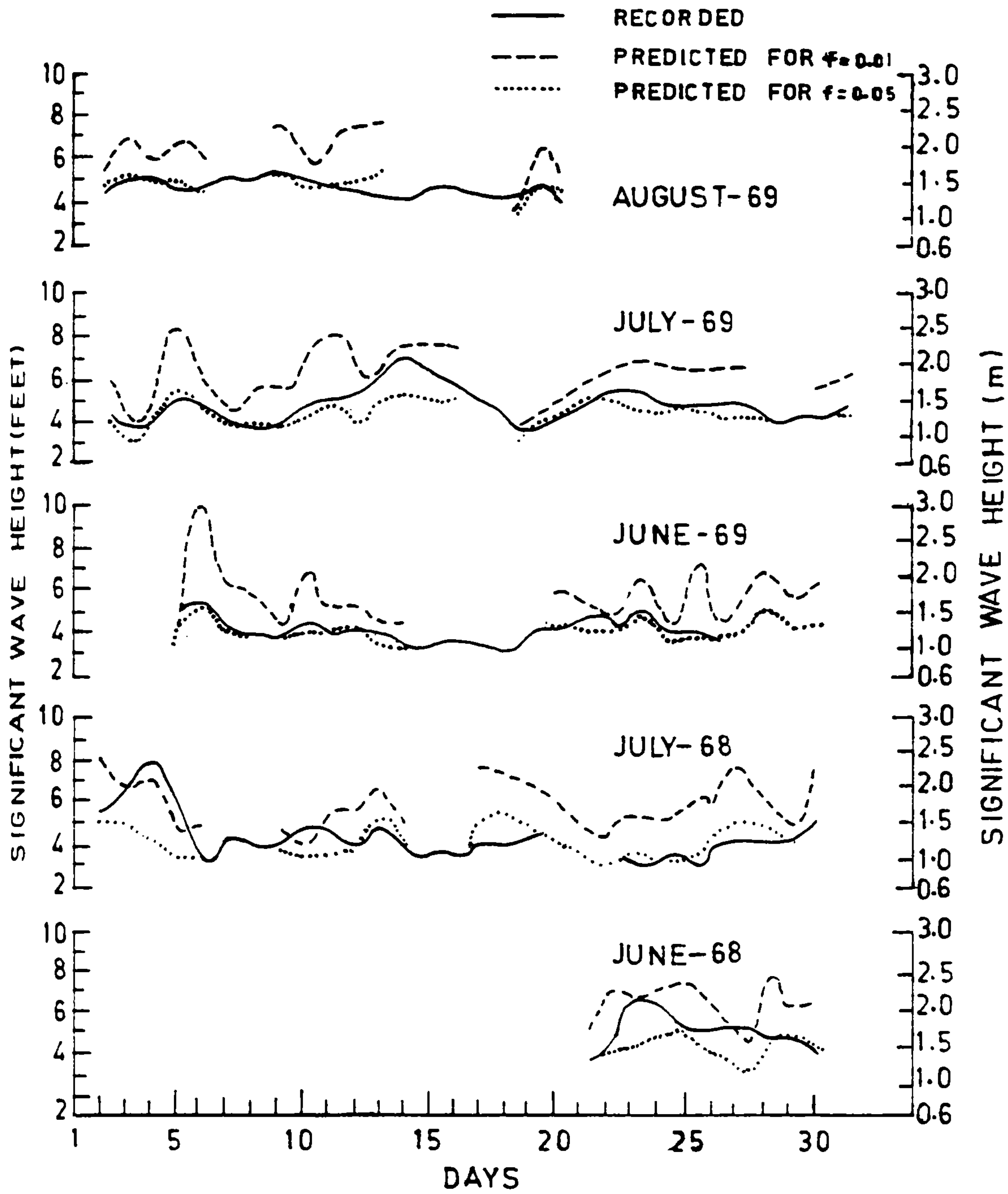

Fig.3.4 Comparison of observed and predicted H_s for Fetch II.

comparison between predicted and observed data are not shown (Fig.3.4) during August 1968 due to lack of wind data reported in weather charts. In all, about 120 predictions from Fetch I and 80 from Fetch II are compared with recorded wave data. From Fig.3.3 and 3.4 it may be seen that the predicted H_s data obtained by using a bottom friction factor of f= 0.05 agree more closely with observations compared to predictions derived using f = 0.01.

Fig.3.5 shows comparison of predicted and observed T_s data of waves originated from Fetch II. Unlike wave heights, the wave periods do not change when waves propagate from deep to shallow waters. Hence no shallow water corrections are needed for T_s. The values obtained at the end of decay area can be compared directly with the observations in shallow water. Except on a few occasions, the observed T_s are higher than the predicted ones. Incidentally the IDWR of July 1968 and 1969 show strong winds of 30 kts and above in the area west of 64° E. Wind data from IDWR are available only for some days *viz.* 21 to 25 July '68 and on 10,12,18,25,26,27,30 and 31 July '69. The wind data reported in the area west of 64° E are also used on these days in addition to data from the areas 'A', 'B' and 'C' for prediction of wave parameters. Considerable improvement in predictions is seen (Fig.3.4 and 3.5) particularly on these days. The above inferences suggest that during July, waves generated beyond 64° E reach the Mangalore coast and the corresponding T_s values vary between

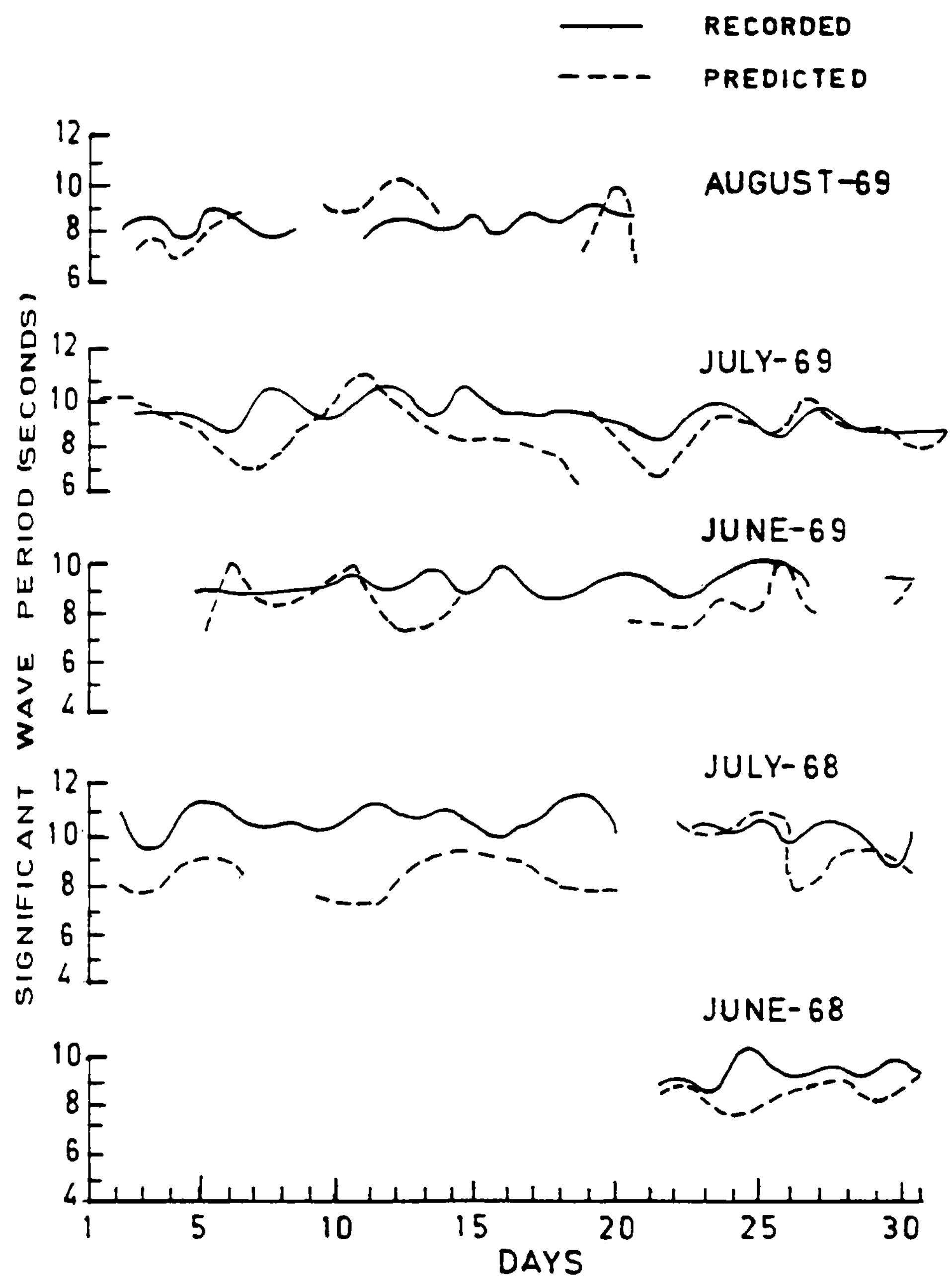

Fig.3.5 Comparison of observed and predicted T_s for Fetch II.

10 and 12 s . The predictions made in this study fairly agree with observations and the deviations can be minimised if more wind data are available.

Percentage deviations of predictions of H_s and T_s are shown in Fig.3.6. It is clearly evident from this figure that the predictions based on Fetch II are much better than Fetch I. Predictions of H_s from Fetch II show 66 % data within 10 % deviation whereas only 42 % of data falls within 10 % deviation for Fetch I. In case of T_s all predictions are more than 10% deviation for Fetch I whereas 47 % of data are within 10 % limit for Fetch II. These inferences clearly point out that the wave predictions from Fetch II are better than those from Fetch I.

Following points emerge from the above discussion:-

(i) Though wave periods do not change, the wave heights are altered considerably from deep to shallow water due to processes like wave refraction, shoaling and bottom friction. Hence these processes are to be taken into account for shallow water wave height predictions.

(ii) Fetch II plays a key role for wave prediction off Mangalore.

Considering these aspects an attempt is made to provide suitable relationships for obtaining shallow water H_s from the deep water significant wave height H_o and T_s. Multiple linear regression methods are used for this purpose and the following

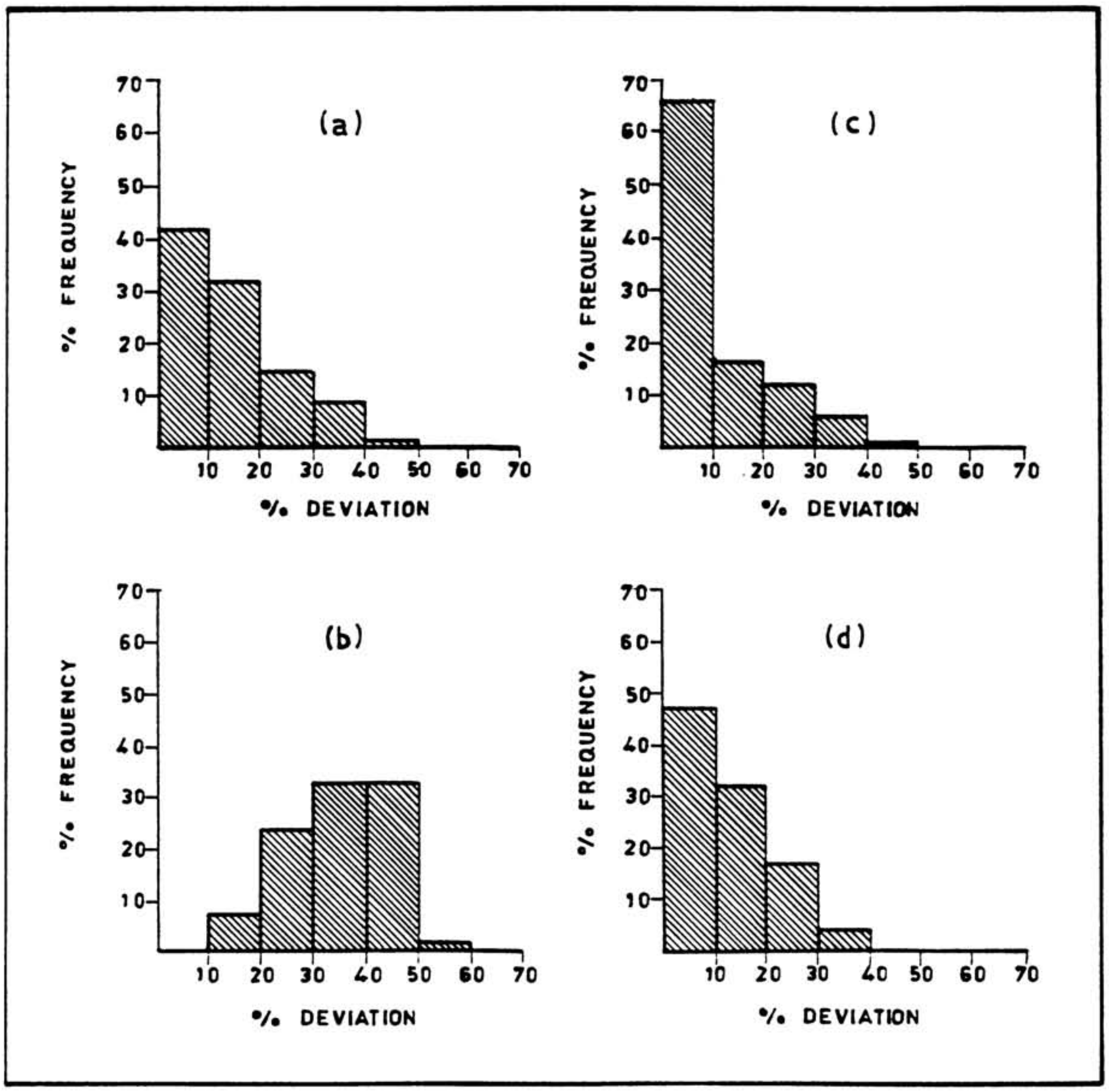

Fig.3.6 Percentage deviations of predicted and observed wave parameters: (a) H_s for Fetch I (b) T_s for Fetch I (c) H_s for Fetch II and (d) T_s for Fetch II.

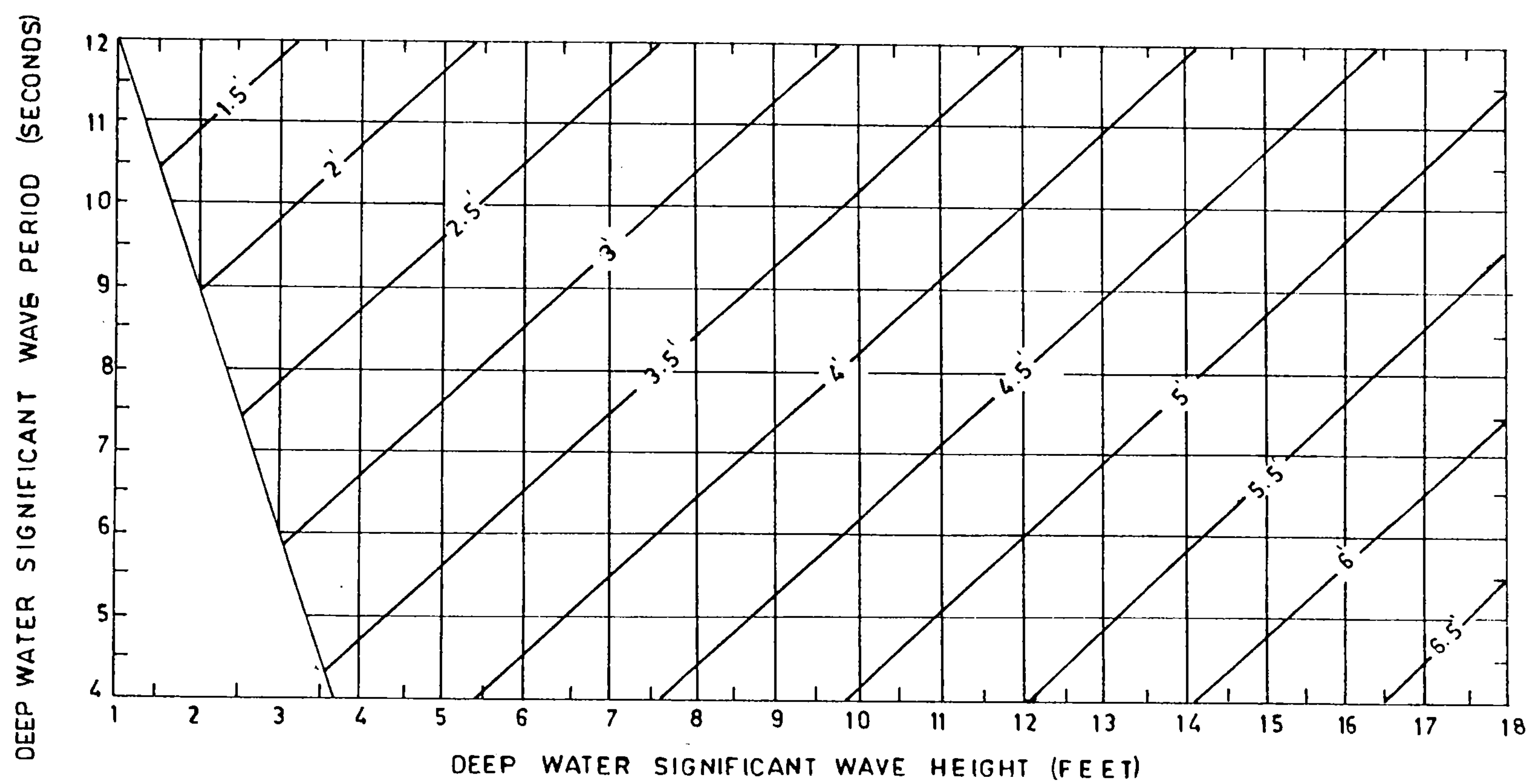

Fig.3.7 Nomogram for prediction of shallow water H_s for waves coming from south-west.

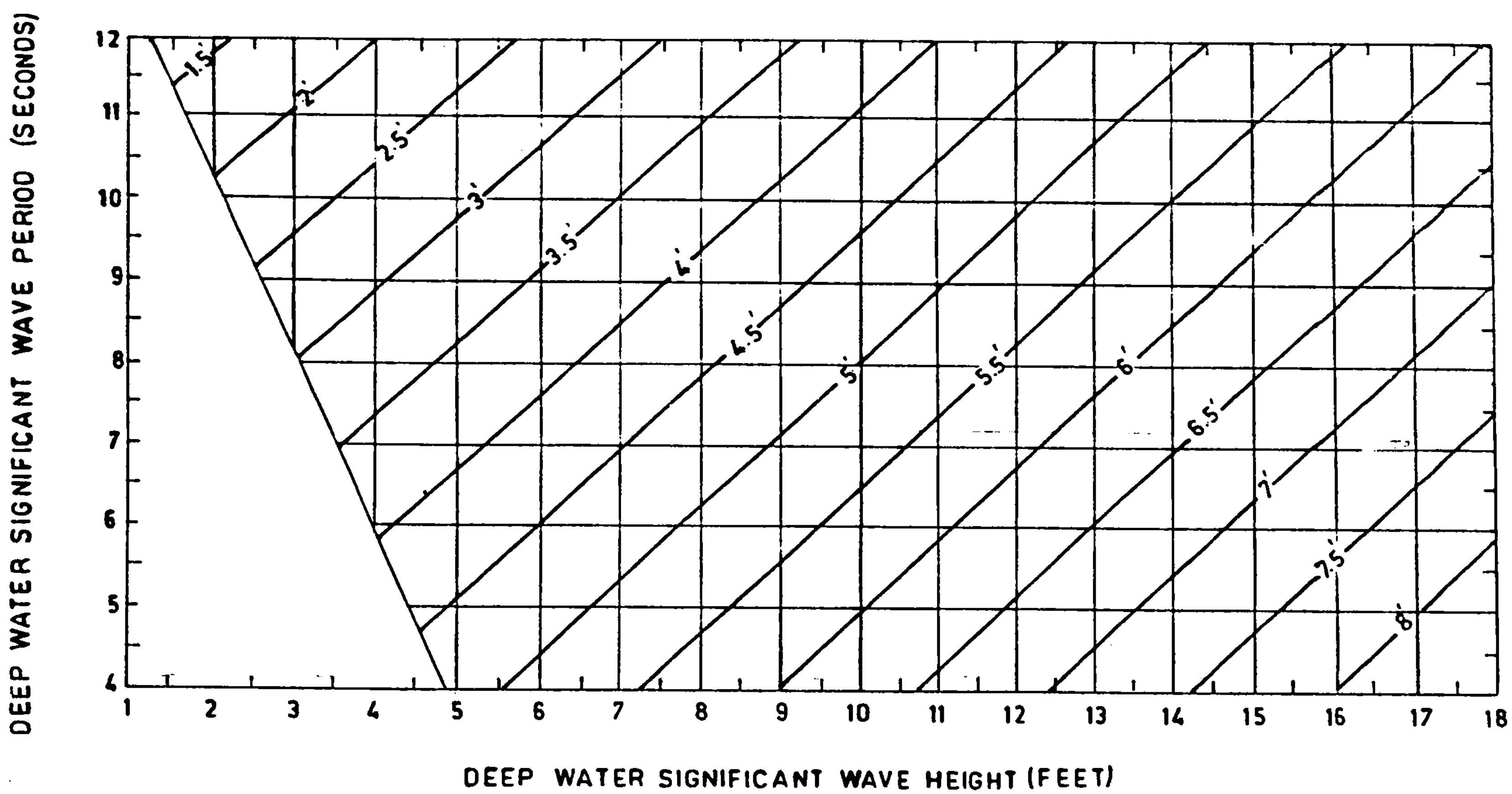

Fig.3.8 Nomogram for prediction of shallow water H_s for waves coming from west.

formulae are recommended for waves approaching the Mangalore coast from south-west and west:

$$H_s = 0.228\ H_o - 0.25\ T_s + 3.764 \qquad \text{(south-west)} \qquad (3.4)$$

$$H_s = 0.287\ H_o - 0.332\ T_s + 4.72 \qquad \text{(west)} \qquad (3.5)$$

The correlation coefficients for the equations 3.4 and 3.5 are 0.85 and 0.75 respectively. The nomograms prepared using the above relationships (Fig.3.7 & 3.8) are useful to obtain shallow water significant wave height from deep water wave observations (either for predicted or observed wave data) directly without making attenuation corrections for K_r, K_s and K_f. As such the above nomograms are valid for Mangalore coast. If these are to be used for other areas, care must be taken to see that bottom topography and wave refraction patterns do not change significantly for the area concerned.

3.4 CONCLUSIONS

Wave hindcasting off Mangalore has been carried out using SMB method for south-west monsoon of 1968 and 1969. H_s and T_s predictions agree fairly well with the observations in shallow water. In this area waves generated between 64° E and 70° E play a predominant role for wave prediction in shallow water. During peak monsoon (July) waves generated west of 64° E also reach the Mangalore coast with significant wave periods of 10 to 12 s. Considerable reduction in H_s takes place when waves propagate from deep to shallow water due to wave refraction, shoaling and bottom friction. A bottom friction factor of f = 0.05 is found suitable for Mangalore coast. Multiple linear regression relations and nomograms for obtaining shallow water significant wave height, H_s from deep water significant wave height, H_o and period, T_s are presented based on the present study.

CHAPTER 4 : A NEW APPROACH FOR WAVE PREDICTION

4.1 INTRODUCTION

SMB method discussed in the previous chapter as well as other conventional wave prediction methods are primarily based on non-dimensional ratios like gF/U^2, gt/U, *etc.* Apart from wind speed, determination of fetch and duration is also important for wave prediction. In steady state conditions, when uniform winds blow over large distances, SMB and other conventional methods yield fairly accurate predictions. While using these methods one would encounter difficulties with fluctuating winds on synoptic time scales. Winds are more variable during low wind speed regime which normally associate with moderate sea states. In such situations, estimation of the fetch and duration becomes difficult. Moreover, when winds are fluctuating, it is the wind duration which is more critical than the fetch for open sea conditions. Hence the assumptions made in SMB and other contemporary wave prediction methods do not always hold good. Therefore a new approach for wave prediction is attempted in this study.

It is well known that waves are caused by wind forcing on the sea surface. When two physical processes are involved, one the 'cause' and the other 'effect', it is reasonable to assume some 'time-delay' between the two processes. 'Time-delay' concept has been well conceived and accepted in other fields especially in electronics and communication studies.

Several techniques and algorithms are available to study this aspect and one simple approach is the cross-correlation function, R_{xy} , details of which will be discussed later in this Chapter. Application of 'time-delay' concept to ocean waves is rather justified since growth of waves does not take place instantaneously and some time-lag occurs between wind action and wave evolution process. Therefore in place of wind duration one can think of 'time-delay' for wind-wave prediction. Attempts are therefore made in this investigation to study this aspect and to develop suitable wave prediction formulae based on this new approach.

4.2 SOURCES OF DATA

A Datawell waverider buoy was moored off Goa, west coast of India (Fig.4.1) during March 1986. The depth at the mooring location was around 80 m. Details of waverider buoy system is already described in Chapter 2. All receiver equipment were positioned onboard ship (R.V.Gaveshani) and the ship was anchored in the vicinity of buoy mooring for the whole period of observations. Both analog and digital wave data were collected continuously at 1 h interval between 17 and 24 March 1986. Time series wind data were also obtained during this period by using ship-board cup anemometers. Analog strip chart wave records of each 20 min duration are processed to obtain significant wave height, H_s and zero-upcrossing period, T_z following Tucker's analysis (see Chapter 2). Apart from this

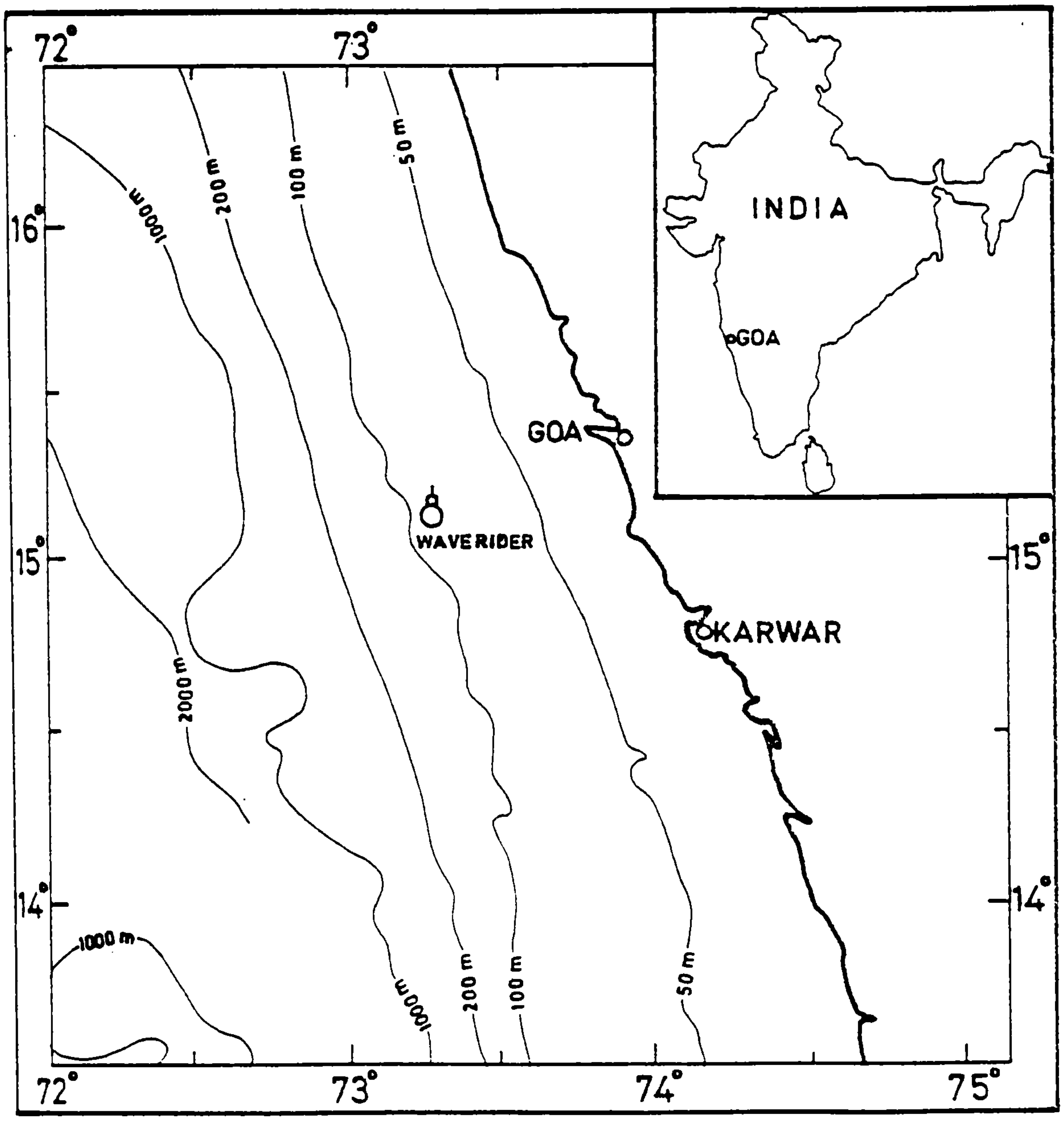

Fig.4.1 Location of wave measurements.

the height of the highest wave , H_{max} and the corresponding period, TH_{max} from each wave record are also noted. The spectral width parameter, ε_T is derived using Eq.2.5. The digital wave data recorded at 0.5 s interval are utilised for spectral analysis following auto-correlation technique (see Chapter 2).

4.3 TIME-DELAY APPROACH

The cross-correlation analysis adapted to study 'time-delay' between wind and wave processes is given here. Time histories of any two sets of time-series data can be tested to know their general dependence through cross-correlation function, R_{xy}. If $X(t)$ and $Y(t)$ are the given pair of data then R_{xy} can be expressed as

$$R_{xy}(\tau) = 1/T \int_0^T X(t)\ Y(t+\tau)\ dt. \qquad (4.1)$$

In the above equation T is the total duration of record, τ is the time-lag and dt is sampling time interval. For different values of τ = 0,1,2.....n, the corresponding R_{xy} values can thus be obtained by taking the average product of $X(t)$ and $Y(t+\tau)$. The function R_{xy} is always real-valued possessing either positive or negative value. For auto-correlation, R_{xx}, we take only one data series and compute R_{xx} function values for different time-lags. Therefore R_{xx} is always maximum when τ =0. In the case of cross-correlation function, R_{xy}, it does not necessarily have maximum value at $\tau = 0$. Both for auto-correlation as well as for cross-correlation the normalised function values, $\bar{R}_{xx}$ and $\bar{R}_{xy}$ are obtained by dividing with the maximum values of R_{xx} and R_{xy} respectively.

4.4 WIND AND WAVE PARAMETERS

The observed wind along with the atmospheric pressure for the period 17-24 March 1986 is shown in Fig. 4.2. Though wind speed varied from 0 to 11.5 m/s, the wind direction remained almost steady (north-north-west) for the entire one week observations. Climatological data (Hastenrath and Lamb, 1979) available for Goa, show mean wind direction north-north-west during March which matches with the present observations. However, the climatological mean wind speed values are very low *viz.* 3 m/s compared to the present data. The increasing and decreasing trends of winds are very important for wave growth and decay. The observed wind speed shows diurnal oscillation with the lowest value occurring at noon and the highest value around midnight. In the initial period, *i.e.*, 17-18 noon, the wind speed was very low *viz.* 2 m/s. The variation in atmospheric pressure followed a semi-diurnal pattern. The weather during the observation period was clear and no depressions or cyclones occurred.

Fig.4.3 presents hourly variation of analysed wave parameters. Wave data used here mainly comprises of sea state 2 and 3, *viz.* slight to moderate, with H_s varying between 0.6

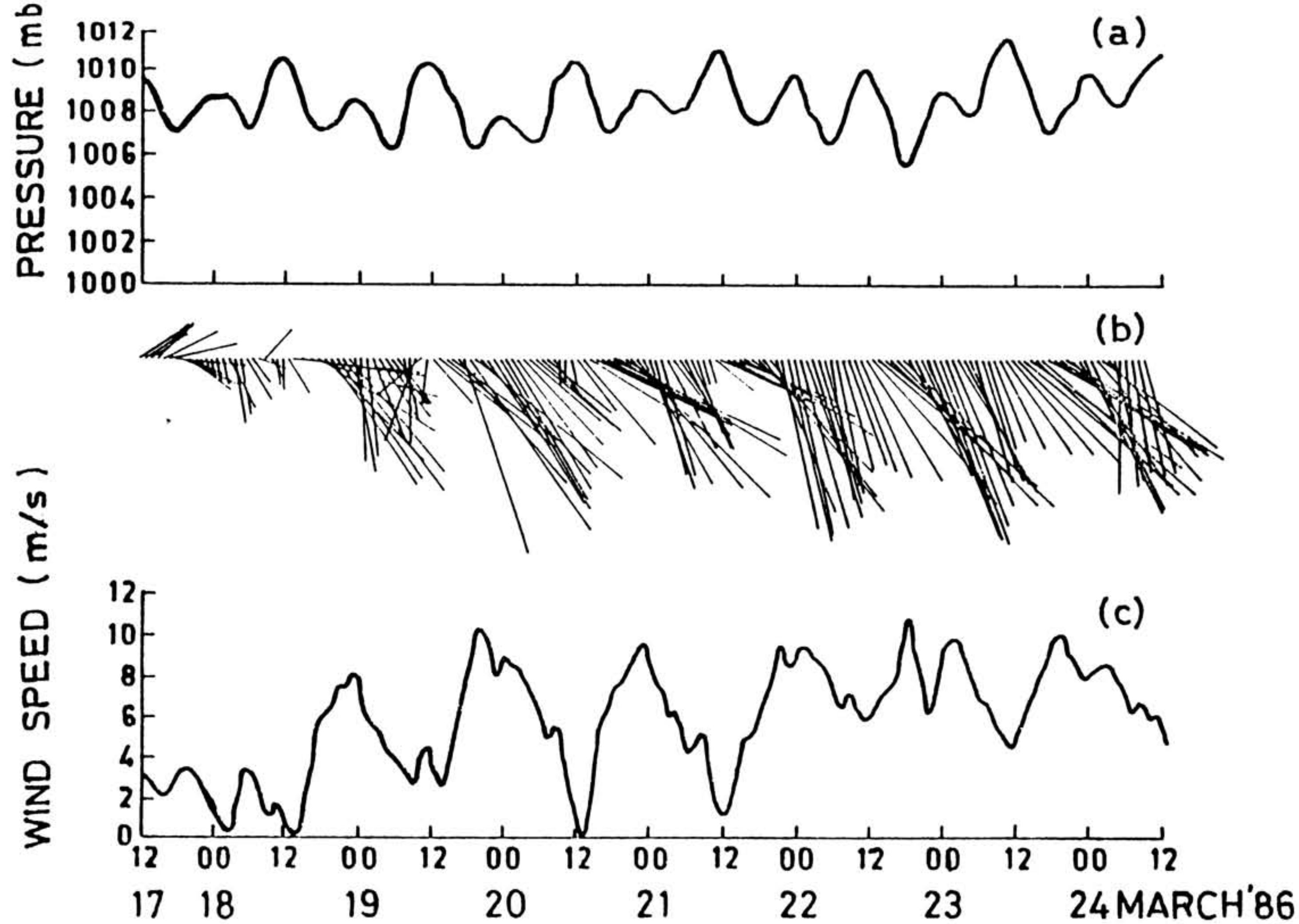

Fig.4.2 Observed variability of (a) atmospheric pressure (b) wind velocity (stick plot) and (c) wind speed.

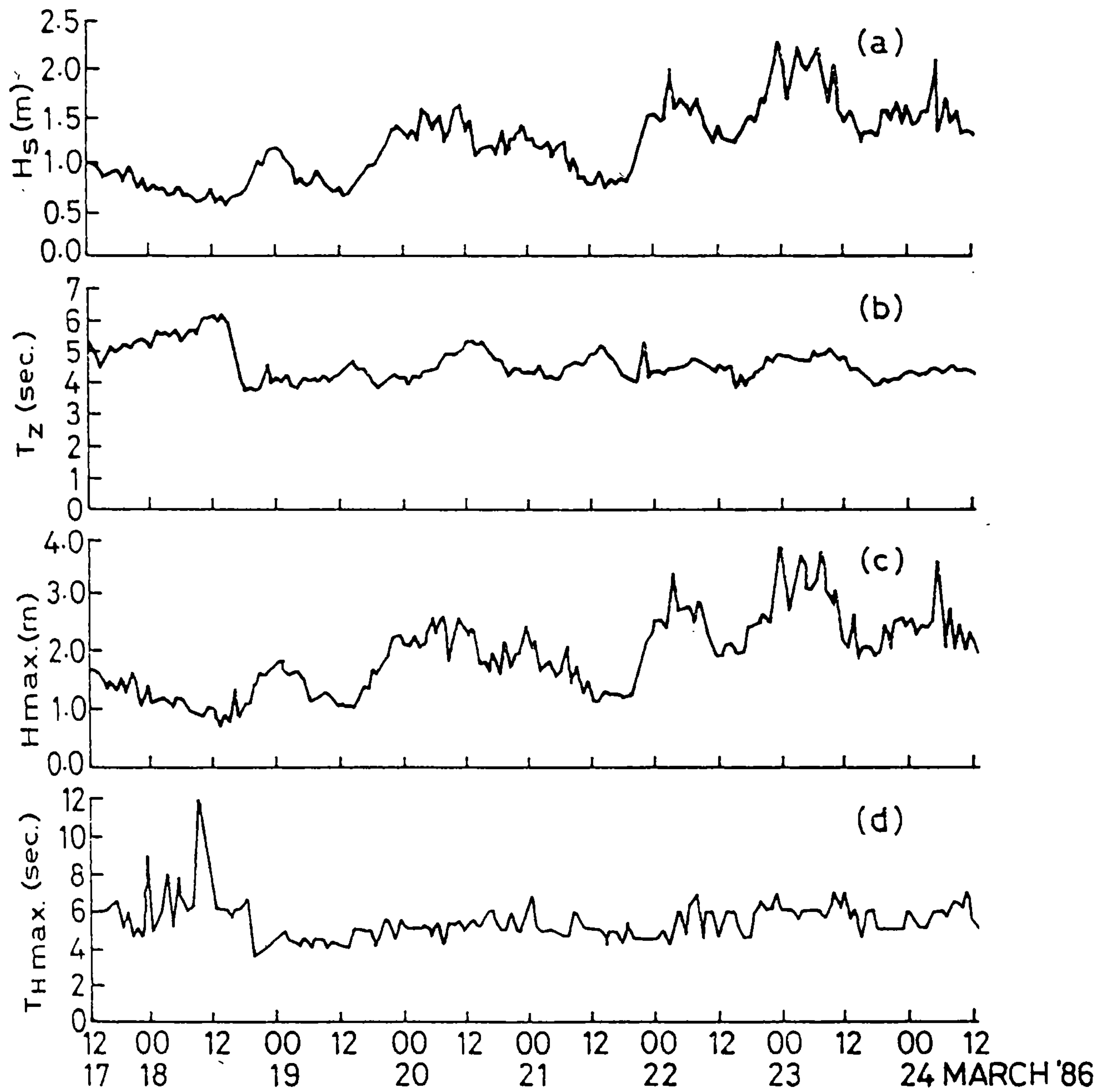

Fig.4.3 Analysed wave parameters: (a) significant wave height, H_s (b) zero-upcrossing period, T_z (c) maximum wave height, H_{max} and (d) period corresponding to maximum wave height, TH_{max}.

and 2.3 and T_z from 3.7 to 6.2 s. Comparison of H_s versus H_{max} and T_z versus TH_{max} shows similar trends. A good correlation exists between H_s and H_{max} and the correlation coefficient is 0.98. It is worth mentioning here that H_s is a statistical mean of the highest one-third waves whereas H_{max} is an occurrence of a single event within the 20 min duration of observation. High degree of correlation between H_s and H_{max} implies the Gaussian-stationarity of random wind generated waves (Longuet-Higgins, 1952). From 17 to 18 noon, wave heights declined (both H_s and H_{max}) and wave periods (T_z and TH_{max}) increased. Also it is observed that wind speed is very low, *i.e.*, 2 m/s, during this period. Winds of this order can only be expected to raise 'seas' of about 0.2 m height with wave periods less than 2 s. These are maximum possible values under fully grown sea conditions. But H_s varied from 0.5 to 1.0 m and T_z from 5.0 to 6.2 s during the initial one-day (17-18 noon), indicating presence of swells during this period.

4.5 COMPOSITION OF SEA STATE

Since the aim of this investigation is to correlate wind and waves and evolve certain relationships for wind-wave prediction, it is necessary to study 'sea' and 'swell' compositions. Swells are to be eliminated for wind and wave correlation . Spectral width parameter, ε_T gives us some insight of the sea state. ε_T value tending towards zero implies narrow-band wave spectrum and if it is close to one it indicates wide-band wave spectrum. In this study computed ε_T values mostly varied between 0.8 and 0.9. Wave energy versus frequency spectra also provide us clues about the nature of sea state. Some typical wave spectra are shown in Fig.4.4. The spectra in general showed single as well as multiple peaks. Incidentally, wave spectra containing higher energy are associated with peaks on the high frequency side indicating local wave activity. Peak frequencies of such spectra varied between 0.15 to 0.25 Hz depending on the stage of wave development (growth/decay). During the growth phase the peak frequency shifts towards low frequency implying energy transfer from high to low frequency side of wave spectrum. On the decay phase along with decrease in wave energy the peak-frequency shifts towards right *i.e.*, in the opposite direction on the frequency axis. Except for the initial one day observation, during the rest of the period the energy peaks of wave spectra are associated with high frequencies (0.15-0.25 Hz) implying domination of seas. The low energy swell waves are mostly centered around the frequency 0.10 Hz. Hence the wave spectra also reveal the predominance of 'seas'.

The wave spectra provide one-dimensional representation of wave energy and frequency. In order to know the evolution of wave field with time, wave energy contour plot is shown in Fig.4.5 over a two-day cycle (21-23 March 86). The variations of sea and swell peak frequencies and the corresponding maximum energy densities are also shown in Fig.4.6 and 4.7.

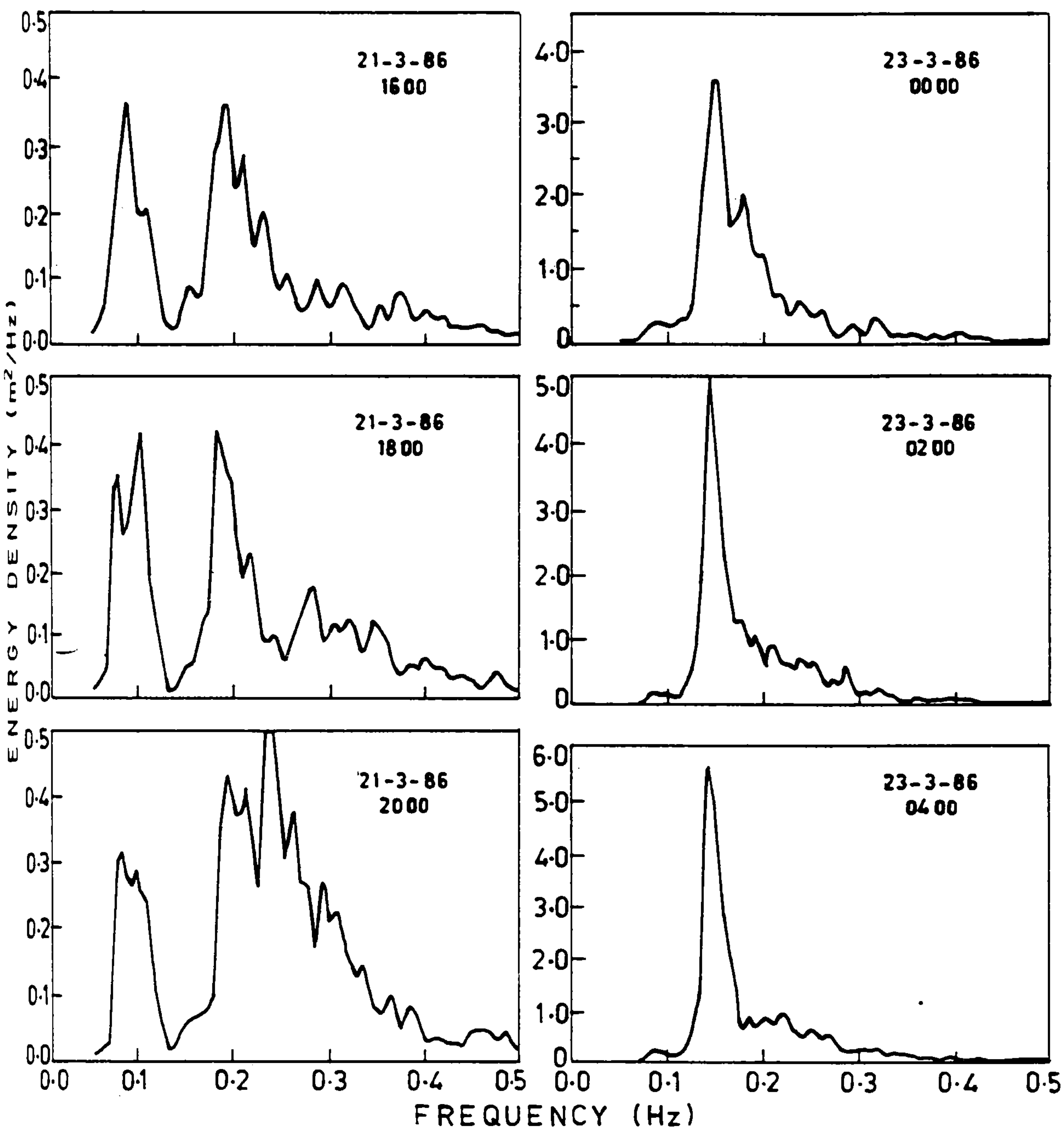

Fig.4.4 Typical examples of observed wave spectra.

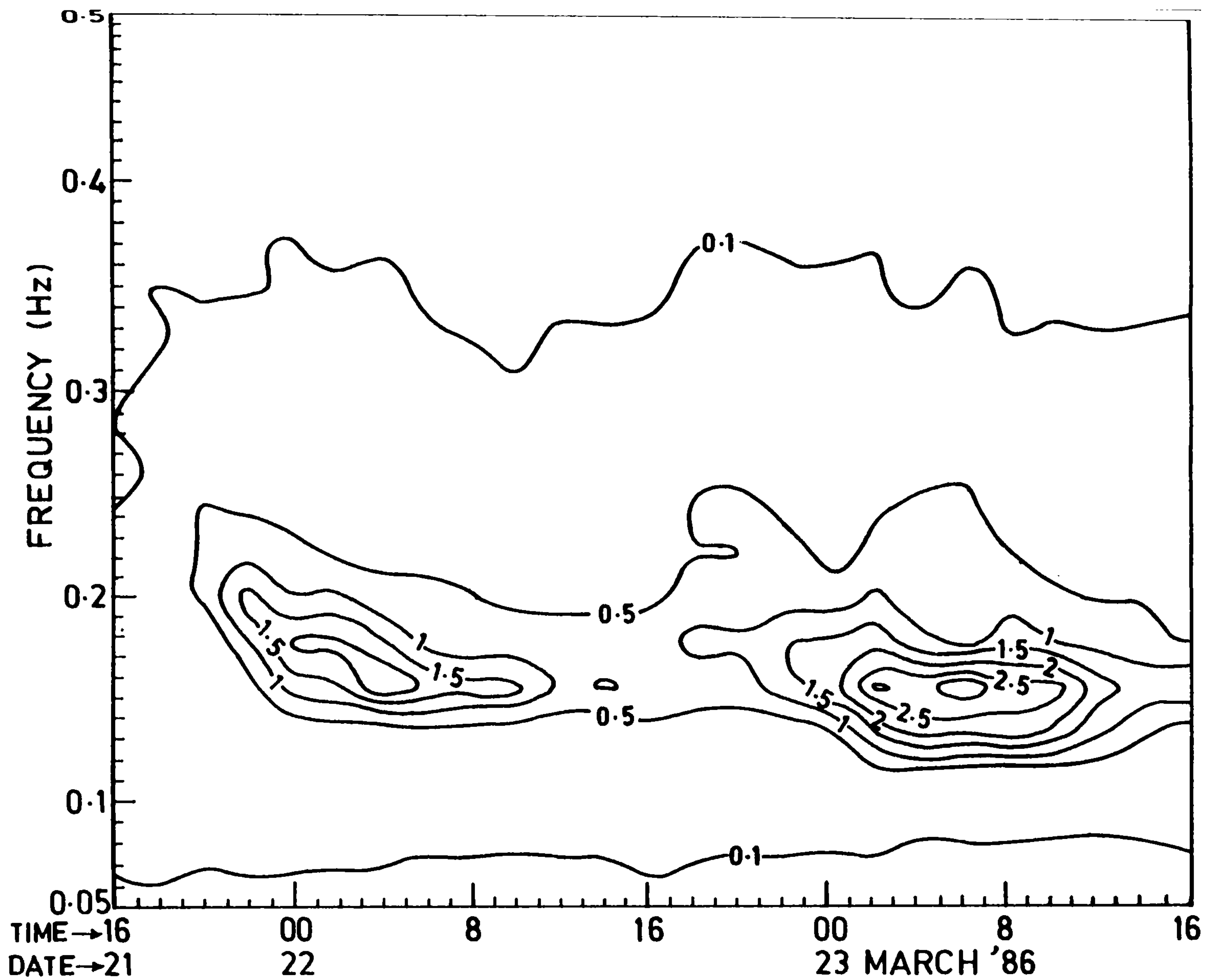

Fig.4.5 Contours of wave energy density (shown at 0.5 m^2/Hz).

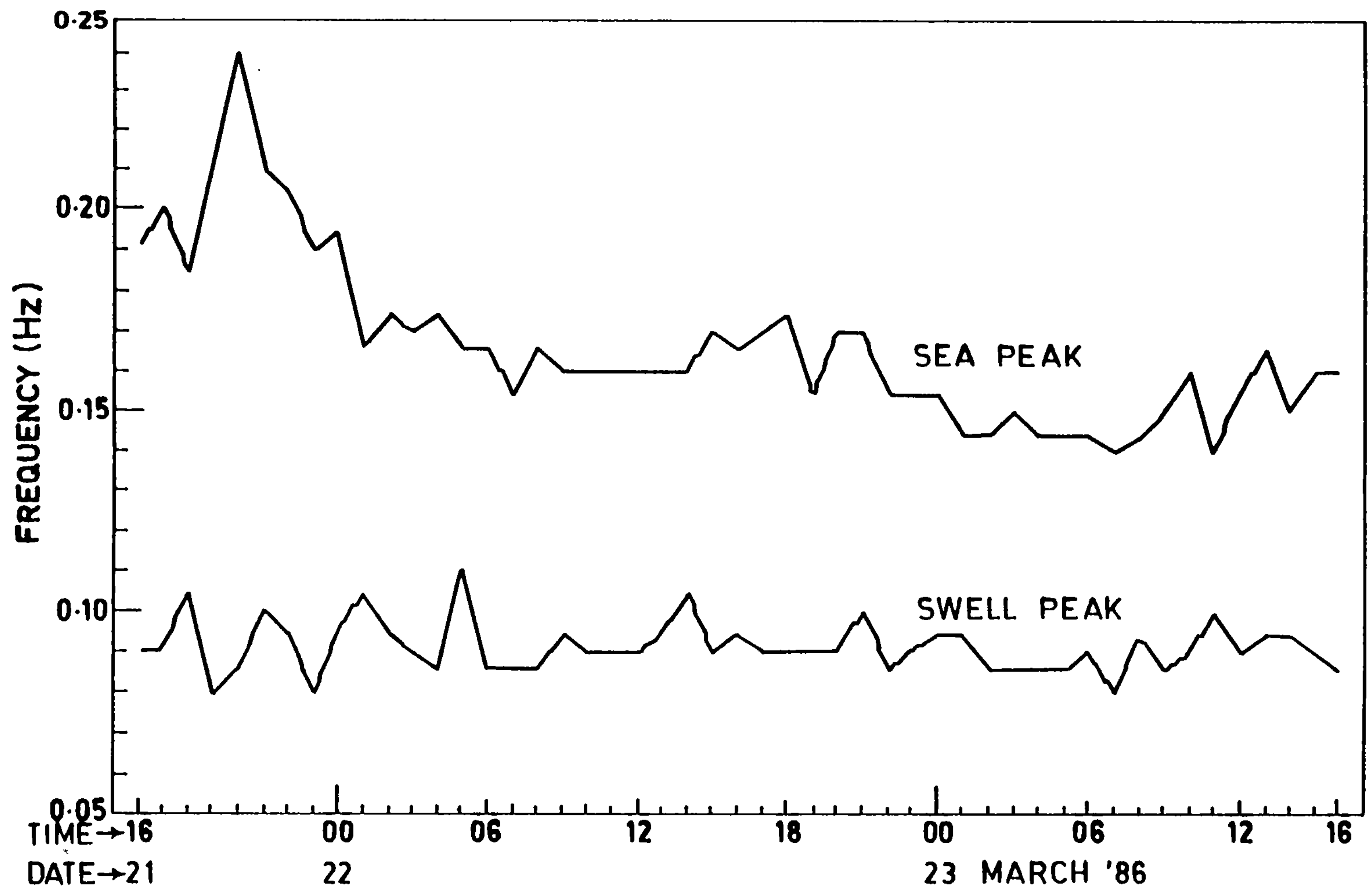

Fig.4.6 Variation of sea and swell peak frequency.

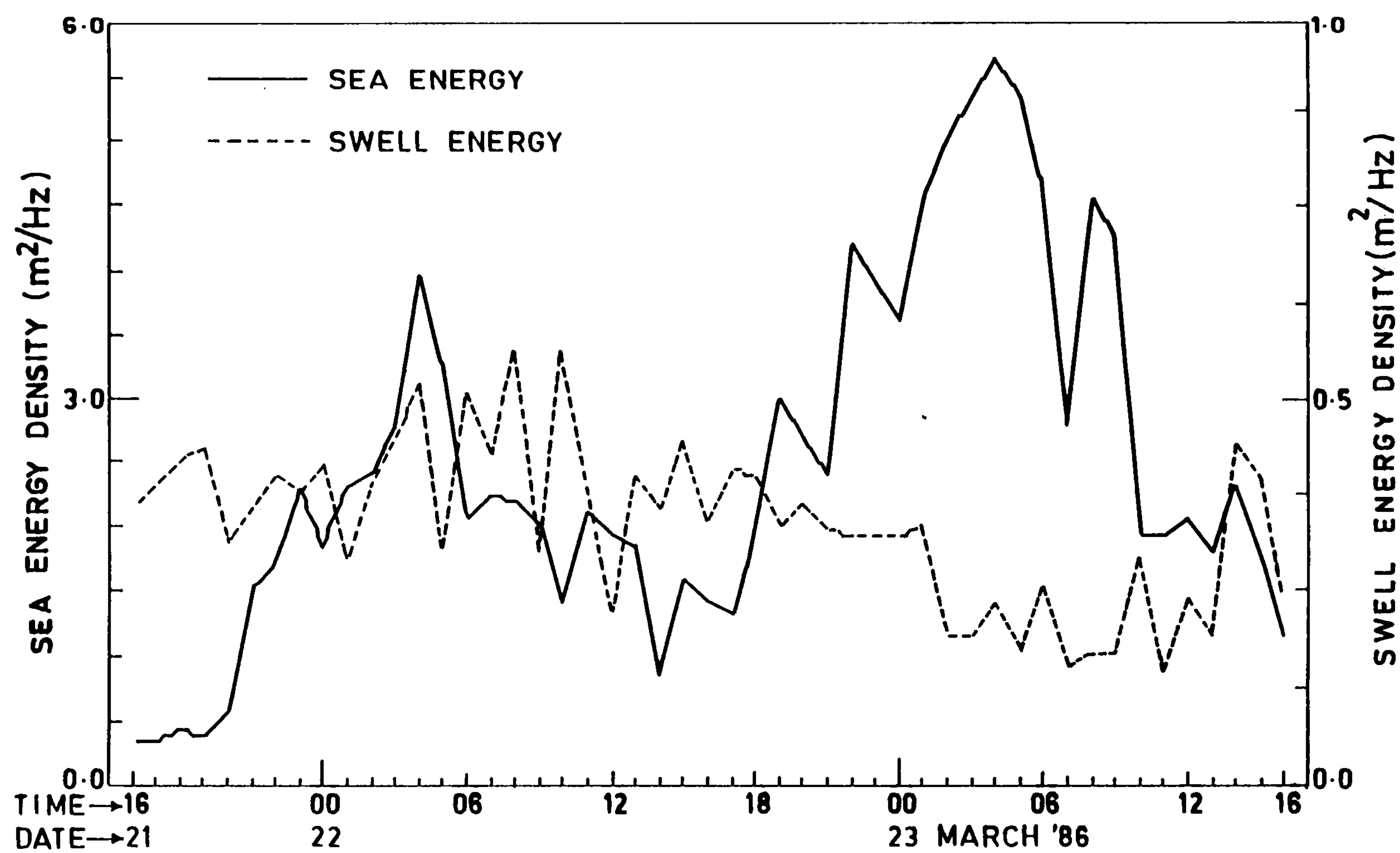

Fig.4.7 Variation of sea and swell energy density.

The values of peak frequency and the associated energy density for sea and swell are obtained from individual wave spectra. These diagrams illustrate clearly the growth and decay of seas whose frequencies are above 0.15 Hz. The two cell structures (Fig.4.5) associated with high energy concentration represent the wave growth activity. There is a considerable reduction of wave energy at 1600 IST on 22 March 86. This implies decay of locally generated waves by that time. The wave activity continues on the next day *i.e.*, 23 March similar to the one observed above. The same pattern repeated for the entire one-week period and hence contour plots of other days are not shown.

In spectral wave model formulations the equilibrium range of the spectrum is considered very important. Among the several formulations existing, the one proposed by Phillips *i.e.*, f^{-5} type, is most commonly used (see section 1.3.3). Hence an attempt is made here to see how best the present data agree with the Phillips type wave spectrum. The test is carried out for some typical individual wave spectra (Fig.4.8) as well as for an envelope of wave spectra (Fig.4.9). A reasonable agreement is seen in both the cases.

The methods described above offer qualitative assessment of sea state, showing predominance of 'seas' in the recorded data. To study further and to eliminate 'swells' from the data, the non-dimensional wave parameters namely wave

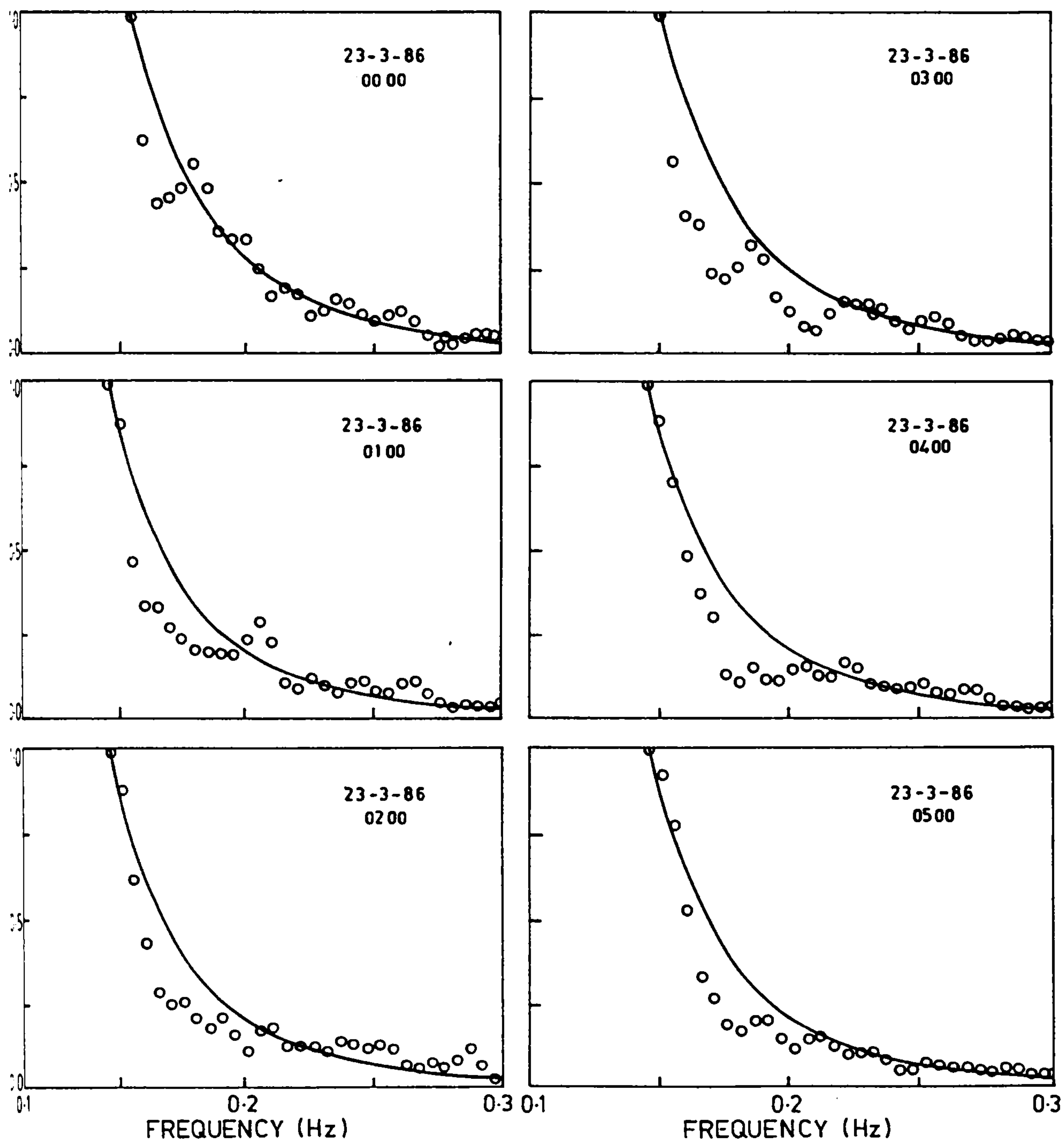

Fig.4.8 Energy versus frequency correlation in the equilibrium range for some individual wave spectra (thick curve shows Phillips theory).

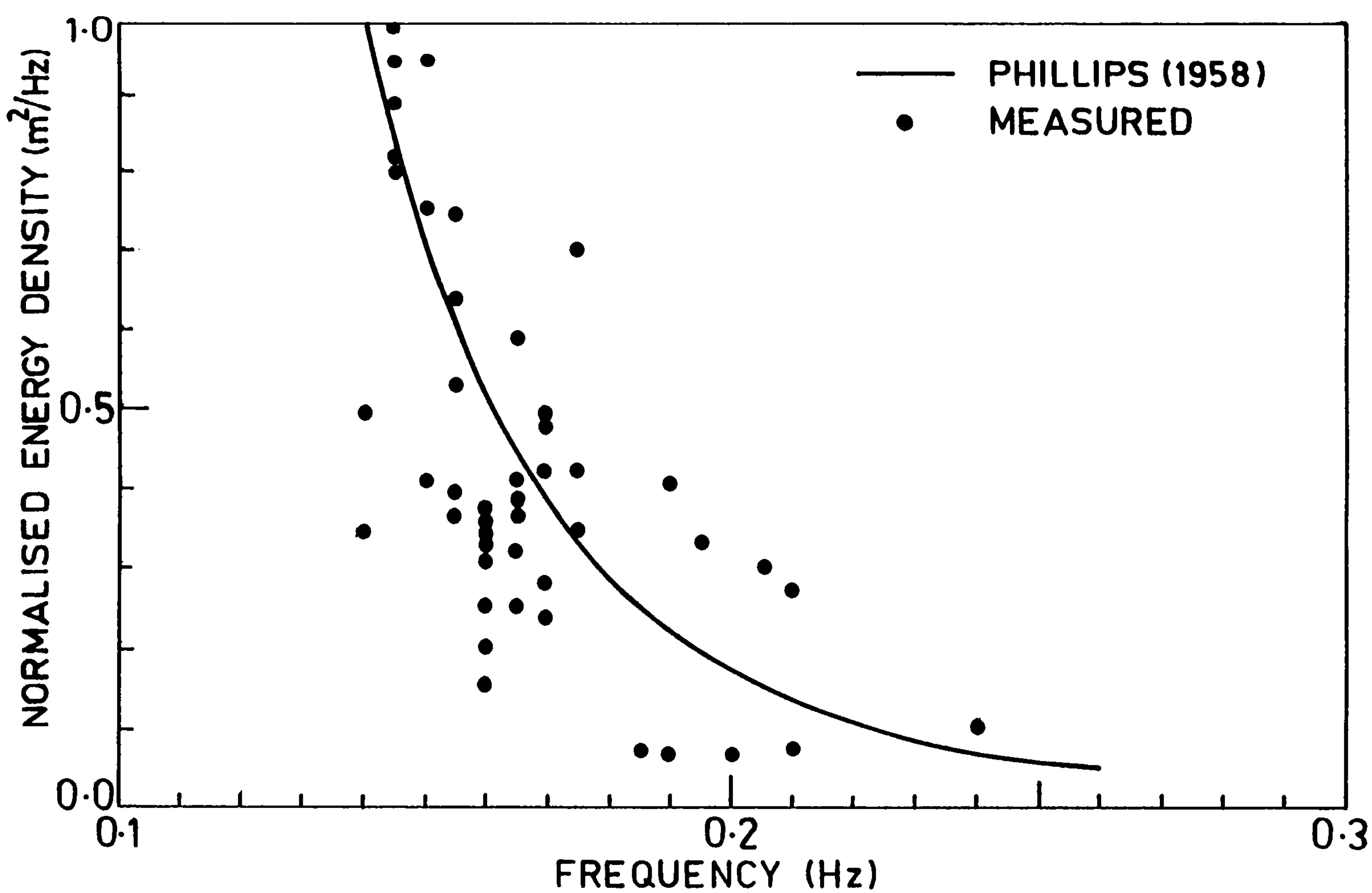

Fig.4.9 Energy versus frequency correlation in the equilibrium range for an envelope of wave spectra.

steepness (the ratio of H_s to wave length, L) and wave age (the ratio of wave celerity, C, to wind speed, U) are also examined. C and L parameters are derived using the following relationships:

$$C = \left[g/2\pi\right] T_z \tag{4.2}$$

$$L = \left[g/2\pi\right] T_z^2 \tag{4.3}$$

Since the depth, d at the observation site is sufficiently large *i.e.*, $d>L/2$, the waves observed come under the 'deep water' category. The linear wave theory is fairly valid for deep water waves. The relation between wave age, C/U and wave steepness, H_s/L is shown in Fig.4.10 along with the analytical curve given by Sverdrup and Munk (1947). It is evident that 'young waves' are steeper than 'old waves'. Thompson *et al.* (1984) gave a classification for waves, namely, sea, young swell, mature swell and old swell depending on the wave steepness. According to this classification waves can be grouped as 'seas' for wave steepness greater than 0.025. From 0.01 to 0.025 steepness range the waves are treated as 'young swells'. Majority of data used in this study fall under the first category (seas) with few exceptions of young swells. Similarly using wave age criterion one can distinguish seas and swells. When the wave age becomes 1.0, it implies that waves are travelling with the same speed of wind. Also it is possible that waves can be faster than winds but in that case

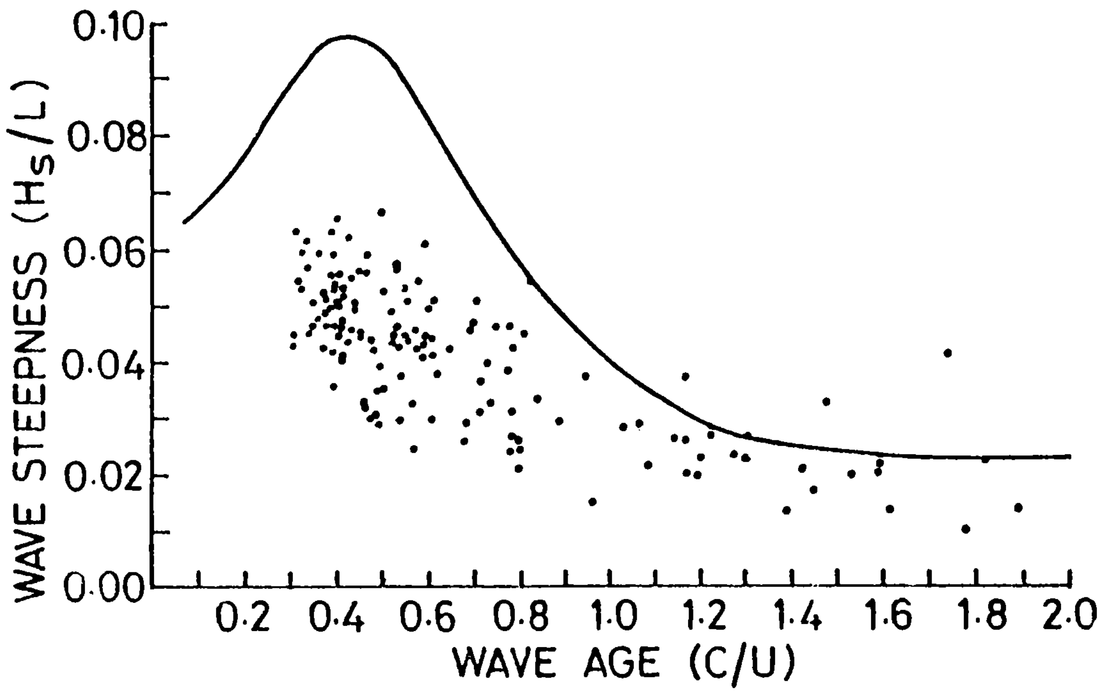

Fig.4.10 Correlation between wave age and wave steepness (thick curve is obtained from theory).

they cease to be under the influence of prevailing wind and hence to be treated as swells. Thus using the wave steepness and wave age criteria the 'swell' waves are eliminated for the present study. Incidentally swell waves which are eliminated, occurred on 17 and 18 March.

4.6 DISCUSSION OF RESULTS

The technique adopted for computing cross-correlation between wind and waves has been explained in section 4.3. Using this technique normalised cross-correlation function, $\bar{R}_{xy}$ values for wind speed, U and significant wave height, H_s are computed for different time lags, τ. Values for τ are assigned from 0 to 48 at 1 h interval. Results are shown in Fig.4.11. The primary peak of $\bar{R}_{xy}$ is seen at 6 h time-lag. A secondary peak is also present around 28 h time-lag but it is less significant than the first one. The secondary peak resulted due to strong diurnal variability of wind and waves.

The primary peak of $\bar{R}_{xy}$ noticed at 6 h time-lag is an indication that wave processes (growth and decay) lag behind winds by about six hours. The maximum correlation is not seen at τ = 0. Another important feature is that $\bar{R}_{xy}$ function does not show significant variation in the neighbourhood of 6 h time-lag. The differences are only marginal for departure times up to 2 h *viz.* 6±2 . Therefore the time-delay function exhibits certain amount of tolerance on either side of its peak at 6 h. However, for departure time more than 2 h,

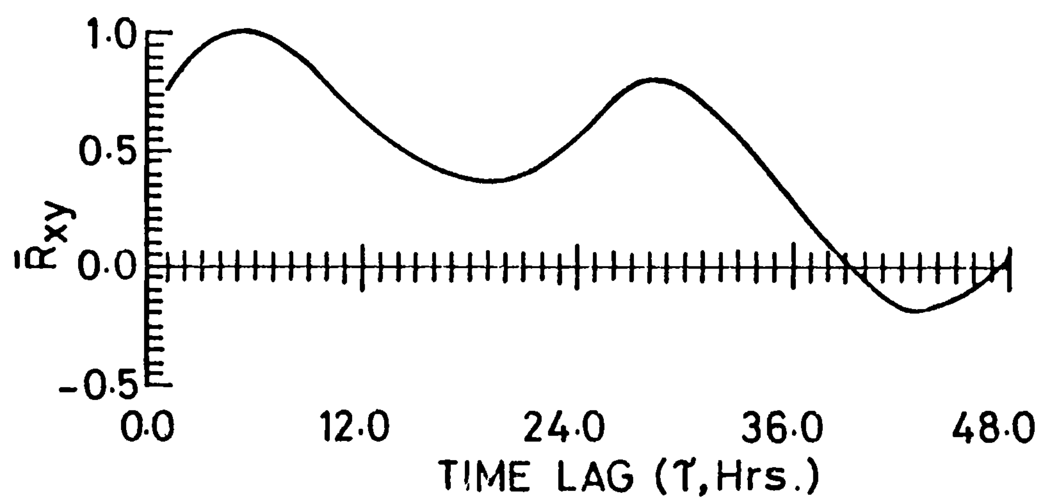

Fig.4.11 Normalised cross-correlation function, $\bar{R}_{xy}$ for wind speed and H_s.

considerable variations in $\overline{R}_{xy}$ are noticed in the present investigation.

4.6.1 WAVE HEIGHT

Based on dimensional analysis and physical considerations a simple relationship between the significant wave height, H_s and wind speed, U may be written as

$$H_s = K\ U^2/g \qquad (4.4)$$

where g is acceleration due to gravity and K is a non-dimensional constant. For fully developed sea state the constant K takes a maximum value of 0.283 (Kraus, 1972). In this study the observed H_s and wind speed recorded 6 h prior to wave observation, U_6 are substituted to obtain the range of K values (Fig.4.12). It is evident that K exponentially increases for lower wind speeds (< 7 m/s) and it decreases below 0.283 for higher wind speeds. However, K<0.283 can be explained due to non attainment of fully developed condition. But the increase of K for lower wind speeds (5 to 7 m/s) implies underestimation of H_s.

Hence, to derive a suitable relationship between H_s and observed wind, an assumption is made that the wave field at any given instant of time is a function of wind speed at the time of wave observation, U_0 and also a function of wind speed observed 6 h prior to wave observation, U_6. Hence H_s may be written as a product of two functions:

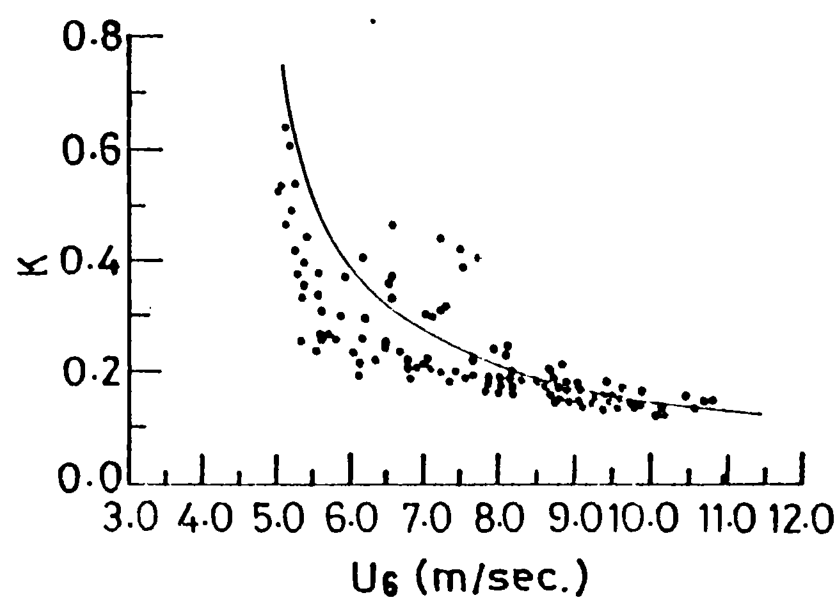

Fig.4.12 Variation of K with wind speed, U_6.

$$H_s = f(U_0) * f(U_6) \tag{4.5}$$

It is found that the variations of U_0 and U_6 can be best approximated as:

$$f(U_0) = U_0/(U_0^{1/2} + C) \tag{4.6}$$

$$f(U_6) = A + B\ U_6^2 \tag{4.7}$$

where A, B and C are constants. Substituting Eq.4.6 and 4.7 in Eq.4.5, we get

$$H_s = U_0(A + B\ U_6^2)/(U_0^{1/2} + C) \tag{4.8}$$

The constants A and B are obtained as 0.56 and 0.0047 through least squares method. The value of C is obtained as 1.5 by trial and error. The functional relationship between $f(U_6)$ and U_6 is shown in Fig.4.13 which exhibits a parabolic trend.

Comparison of the observed and predicted H_s is shown in Fig.4.14. Very good agreement is seen between the predicted and observed data. A root mean square error of only ± 0.12 m is noticed for the predicted H_s. The growth as well as decay phases of sea state are well represented by the prediction.

4.6.2 WAVE PERIOD

Unlike the significant wave height, the variation in zero-upcrossing wave period, T_z is small after removing 'swell' waves. Essentially, the variation in T_z consisted of mean and random fluctuating components. Preliminary studies of

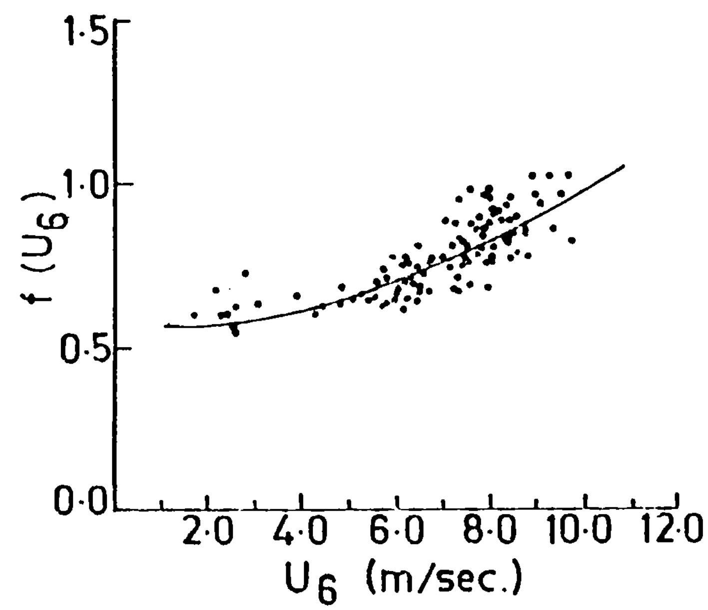

Fig.4.13 Functional relationship of U_6 and $f(U_6)$.

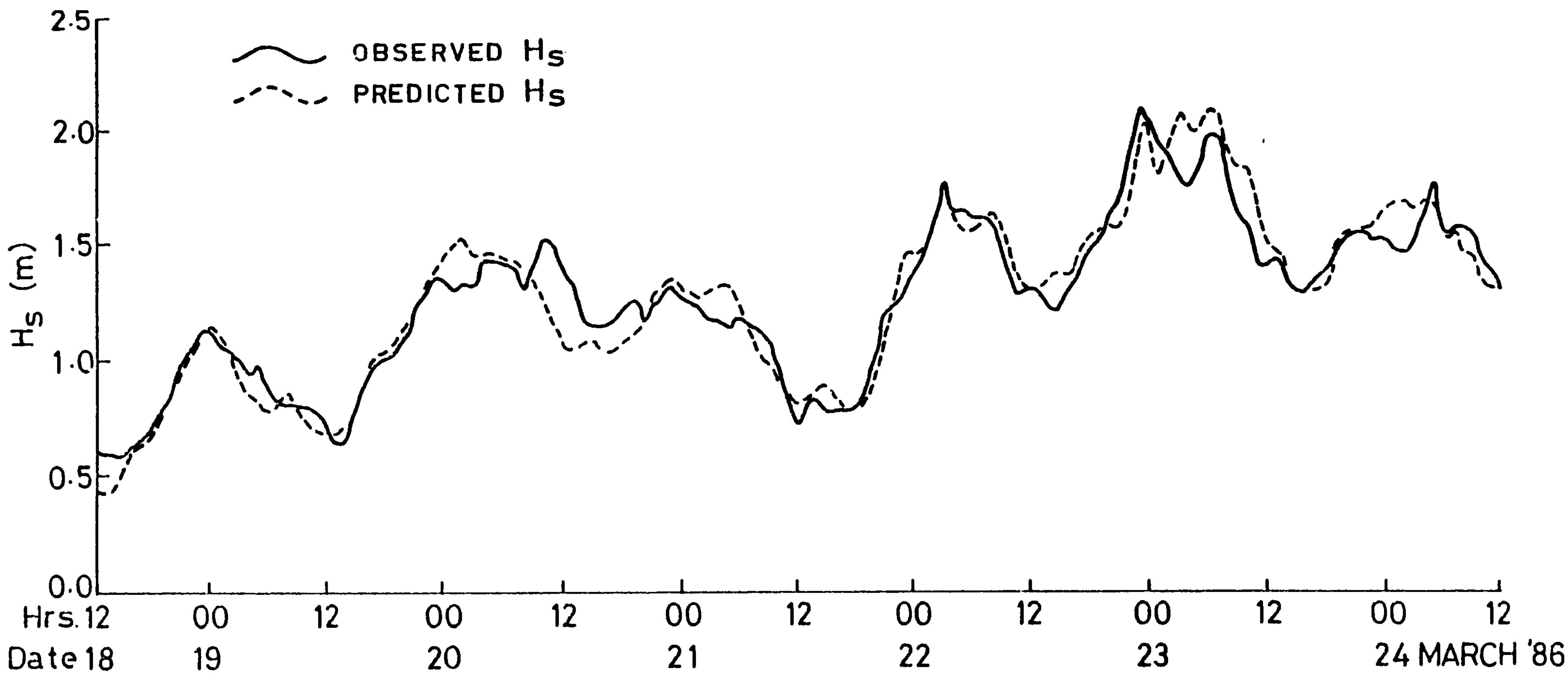

Fig.4.14 Comparison of observed and predicted H_s.

data revealed a positive correlation of T_z with the product U_0 and U_6 when high frequency variations are eliminated. The random fluctuating component of T_z apparently shows a good correlation with the quotient of U_0 and U_6. Thus the relationship for T_z may be written as

$$T_z = f(U_0 U_6) + f(U_6^*/U_0) \tag{4.9}$$

where $U_6^* = U_6 + U_0^{1/4}$

It may be noted that the composition of U_6^* is obtained after evaluating all the relevant parameters in Eq.4.9. Further it is found that $f(U_0 U_6)$ may be approximated as

$$f(U_0 U_6) = a + b(U_0 U_6)^x \tag{4.10}$$

In the above equation, the constants a and b are evaluated following non-linear least squares method. The optimal value of x is obtained as 0.625. Fig.4.15 shows the functional relationship of $f(U_0 U_6)$ with $U_0 U_6$. This gives the mean component of variation in T_z which is directly proportional to to wind speed.

The random component of T_z *viz.* $f(U_6^*/U_0)$ shows a logarithmic relation (Fig.4.16) and accounts for apparent decrease in period during wave growth and an increase in wave period in the decay phase. One reason for such random variation of wave period could be due to its slow response to wind speed variation. The fluctuating synoptic wind speeds

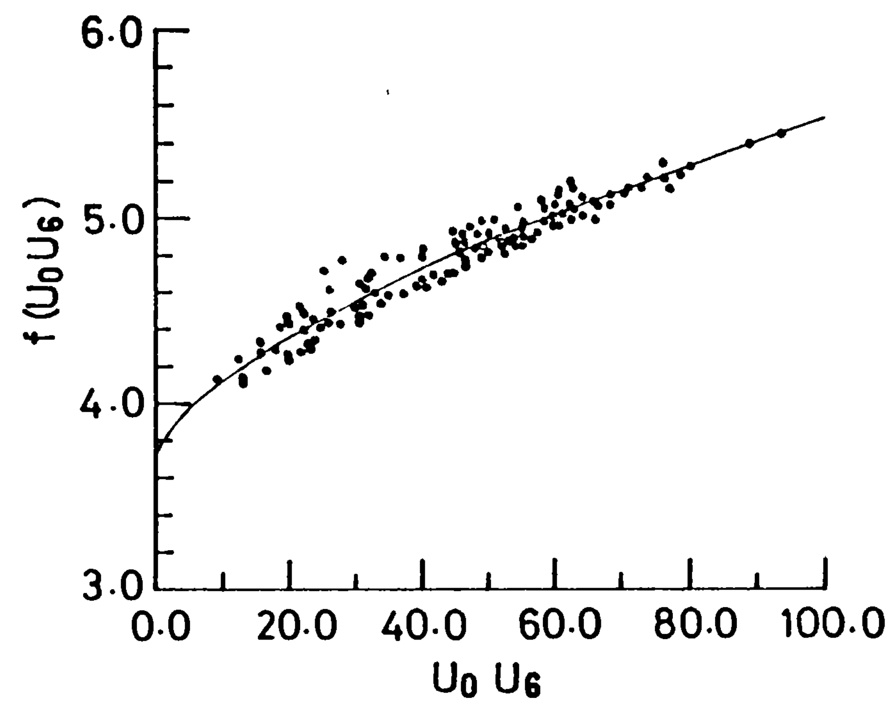

Fig.4.15 Functional relationship of $U_0 U_6$ and $f(U_0 U_6)$

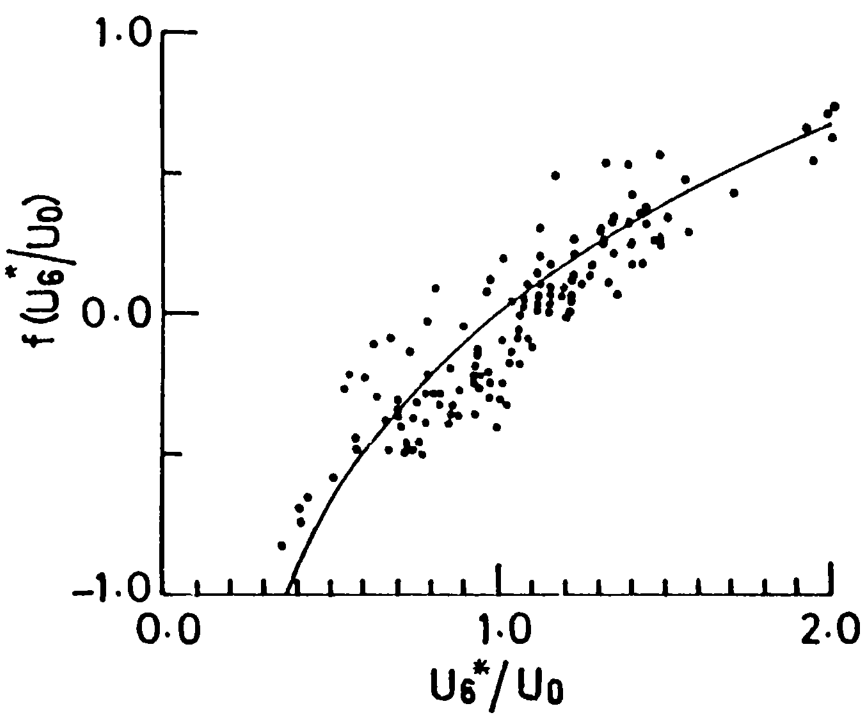

Fig.4.16 Functional relationship of random varying component of Γ_z.

recorded at 1 h interval might not have caused corresponding order of changes in the wave period T_z. It is seen from Fig.4.16 that the random component becomes zero when $U_6^* = U_0$ and it takes positive and negative values for decreasing and increasing wind speeds respectively. Hence, the random component can be written as:

$$f(U_6^*/U_0) = \text{Log } (U_6^*/U_0)^{\lambda} \qquad (4.11)$$

$$\text{where } \lambda = 2.25 + 0.0006 \text{ Log } (U_6^*/U_0) \qquad (4.12)$$

The second term on the right hand side of Eq.4.12 is small and negligible compared to first term. Variation of λ with $\text{Log}(U_6^*/U_0)$ is shown in Fig.4.17 from which it is obvious that the value of λ may be taken as 2.25. The composition of U_6^* is estimated at this stage by varying a, b and λ independently such that the deviations are minimum for predicted data. The term $U_0^{1/4}$ is important when wind speed increases. By substituting Eq.4.10 and 4.11 in 4.9, we get

$$T_z = a + b(U_0 U_6)^{5/8} + \text{Log}\left[(U_6 + U_0^{1/4})/\ U_0\right]^{9/4} \qquad (4.13)$$

where a = 3.7 and b = 0.102.

A good agreement is seen (Fig.4.18) between observed and predicted T_z data.

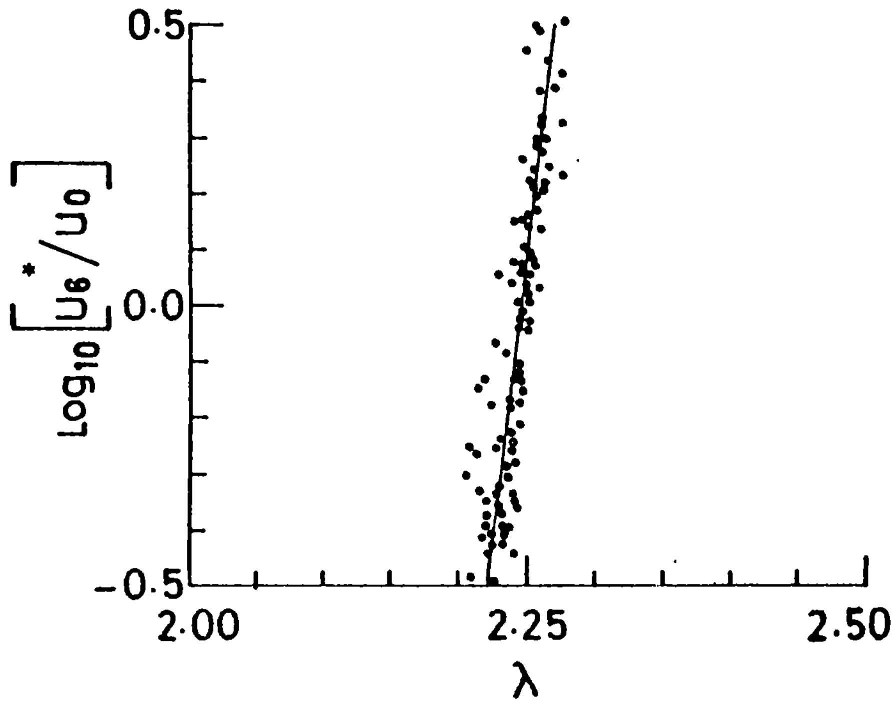

Fig.4.17 Functional relationship of λ used for T_z formulation.

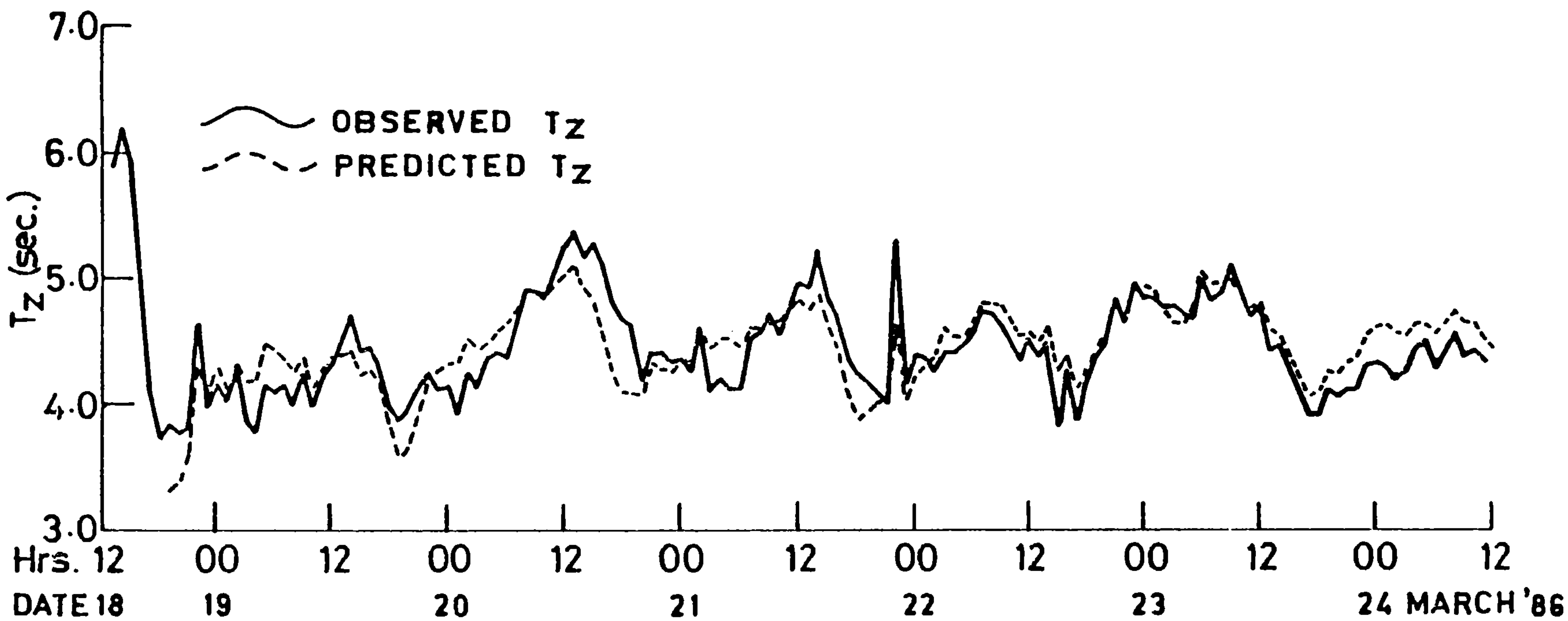

Fig.4.18 Comparison of observed and predicted T_z.

4.7 CONCLUSIONS

Wave prediction formulae for significant wave height, H_s and zero-upcrossing period, T_z are obtained based on the analysis of 1 h time-series data on wind and waves collected off Goa, west coast of India, during March 1986. The wave data used here mostly reflects slight and moderate sea state conditions. The observations indicated successive growth and decay phases of wind-waves. While formulating wind and wave relationships, swells were eliminated. The 'duration' of wind normally used in conventional wave prediction methods (SMB, PNJ, *etc.*) is replaced in this study with a new criterion called 'time-delay'. For slight to moderate sea states estimation of wind duration becomes rather difficult due to fluctuating winds. The time-delay approach is more convincing in such circumstances. A time-lag of about 6 h between wind speed and wave height is observed. Prediction formulae for H_s and T_z are derived which are based on wind speed observations at the time of prediction and 6 h prior to it. A good agreement is seen between predicted and observed waves by using new set of relations for H_s and T_z. Like other wave prediction formulae available in literature, the present wave forecasting relationships are also based on empirical considerations and the derived parameters/constants are dependent on the observations used.

CHAPTER 5 : WAVE PREDICTION USING A NUMERICAL MODEL

5.1 INTRODUCTION

Wave prediction methods discussed in the previous two chapters have one thing in common. In both methods the input wind information is considered at certain time intervals or the wind is assumed steady over a given duration of time. Or one can say that the predictions are carried out by using discrete inputs at pre-defined time intervals. But in a real situation the wave generation process is a continuous phenomenon wherein the wave evolution takes place both in time as well as space. The wave evolution mechanism is related to continuous wind forcing which varies both in magnitude and direction. Therefore it is more appropriate to consider continuous input of wind to derive wave field. Numerical wave models aim at this objective by making temporal and spatial integration of input used for the model. While carrying out integrations at close time-steps, these models attempt to reduce errors in predictions. With the advent of digital computers and development of new concepts like wave spectrum, a new era had begun for ocean wave modelling in 1960s. Certain details on numerical wave models are presented in Chapter 1. In the current Chapter more particulars of a specific model used and the results obtained are discussed.

5.2 THE WAVE MODEL

The wave model used in this study belongs to the second-generation group of models (SWAMP Group, 1985) and it originated from TOHOKU University of Japan. Hence, it is often referred as TOHOKU wave model. It is a coupled hybrid model wherein for seas a parametric approach is used and swells are treated spectrally. The basis for this model is the single-parameter growth equation of wind-waves which was proposed by Toba (1978). Later Kawai *et al.* (1979) utilised the concept of similarity for wind-waves or seas and developed a scheme for wave prediction.

5.2.1 PHYSICAL AND MATHEMATICAL CONCEPTS

Toba (1972, 1973a, 1973b, 1978) has discussed various concepts which ultimately led to the development of TOHOKU Model. In this section some relevant features of this model are described briefly. The wind stress, τ, or the momentum of wind when it is imparted at the sea surface results into the momentum of waves and drift current. The major part of wind stress is utilised for generating currents whereas the remaining portion of it only goes into the formation of waves. If we represent γ, as the portion of momentum which is used for generation of waves, then it may be written as

$$\gamma = \tau_w/\tau \qquad \text{where } \tau = \tau_w + \tau_c \tag{5.1}$$

γ decreases exponentially with the increase of wave age, C/U and for young waves it is about 7.5% of the total wind stress,

τ. The relationship between friction wind velocity, U_* and τ is given by

$$U_* = (\tau/\rho_a)^{1/2} \tag{5.2}$$

where ρ_a is the density of air . U_* can be obtained from wind speed at 10m height, U_{10}.

$$U_* = (C_D)^{1/2}\, U_{10} \tag{5.3}$$

where C_D is the friction drag coefficient and details regarding selection of a suitable value for it is given by Kawai *et al*., (1979). For the development of the present wave model about ten parameters are used:

Three independent variables :- friction wind velocity, U_*
fetch length, F and
wind duration, t.

Three dependent variables :- wave height, H
wave period, T and
the fraction of wind momentum for generation of waves, γ.

Four physical constants :- acceleration due to gravity, g
surface tension of sea water, S
density of air, ρ_a and
kinematic viscosity of air, ν_a.

By following non-dimensionalisation methods the above ten parameters may be reduced to seven non-dimensional variables as given below:

$$U_*/g\nu = U_*^*$$ (5.4)

$$gF/U_*^2 = gF/C_D U^2 = F^*$$ (5.5)

$$gt/U_* = gt/(C_D)^{1/2} U = t^*$$ (5.6)

$$gT/U_* = T^*$$ (5.7)

$$gH/U_*^2 = H^*$$ (5.8)

$$\tau_w/\tau = \gamma$$ (5.9)

and $S^3/g\rho_a^3\nu_a^3 = S^*$ (5.10)

Thus the relationships among the three independent variables U_*^*, F^* and t^* and the three dependent variables H^*, T^* and γ are to be established. Three basic concepts were utilised while deriving wave growth equations of the model.

Concept 1 : According to this concept the physical processes of the transfer of momentum and mechanical energy from air to sea are determined locally. It postulates that growth of wind waves is predicted by an integration with respect to fetch and duration. Consequently F^* and t^* become variables for integration and U_*^* is the only external variable.

Concept 2 : The rate of work done by the wind stress to wind waves or the time rate of increase of the average wave energy per unit horizontal area depends only on γ and U_*^* .For a simple case it is proportional to γU_*^*. On the basis of this concept a three-second power law was derived for wind waves:

$$H^* = B\ (T^*)^{3/2} \tag{5.11}$$

For equilibrium conditions, using empirical formulae of Wilson (1965) the value of the constant in the above equation may be obtained as B=0.059. Further studies with field observations and from laboratory wind-wave tunnel data (Stewart, 1961; Toba, 1961; Toba *et al.*, 1971; Mitsuyasu *et al.*, 1971) also established three-second power law for wind waves and these studies proposed the value to be assigned to the constant as B= 0.062.

Concept 3 : The rate of dissipation of wind wave energy or the rate of transfer of wave momentum to currents is proportional to the dimensionless quantity $\gamma U_*{}^* T^{*2}$.

5.2.2 GOVERNING EQUATION

Utilising the above three concepts a growth equation for wind waves in terms of non-dimensional energy, E^* was derived by Toba, (1978):

$$\frac{\partial (E^{*2/3})}{\partial t^*} + \frac{E^{*1/3}}{a} \cdot \frac{\partial (E^{*2/3})}{\partial F^*} = G_0 R \left[1 - \mathrm{erf}(bE^{*1/3}) \right] \tag{5.12}$$

where E^* is non-dimensional wave energy and it is given by

$$E^* = g^2 E / U_*{}^4 \tag{5.13}$$

G_0R, a and b are the non-dimensional empirical constants whose values are given as:

$G_0R= 2.4 \times 10^{-4}$, a= 0.74 and b= 0.12.

The error function (erf) used in Eq.5.12 is a simple stochastic function which may be written as:

$$\mathrm{erf}(x) = 2/(\pi)^{1/2} \int_0^x \exp(-t^2)dt \tag{5.14}$$

From Eq.5.12 wind-wave energy can be predicted in its total derivative form (Kawai *et al.*, 1979). Also it is possible to derive the simple parametric formulae for fetch and duration-limited wave growth equations after dropping the error function. A spectral form in terms of peak frequency was also given earlier (Kawai *et al.*, 1977; Mitsuyasu *et al.*, 1980; Joseph *et al.*, 1981). Details of it are not discussed here as these aspects are not utilised in this study. The decay of swell energy is computed using the formula given by Inoue (1967):

$$B(f,U_*) = \left[0.00139 \exp\left[-7000\left[(U_*/C)-0.031\right]^2\right] + 0.725(U_*/C)^2\exp\left[-0.0004(C/U_*)^2\right]\right]f \tag{5.15}$$

where B is a function of wave frequency, f and friction wind velocity, U_*. C is the wave celerity.

5.2.3 MODEL FLOW CHART

This section describes the sequence of various steps of the wave prediction model. A flow chart containing details is shown in Fig.5.1. The initial input for the model comprises of wind speed and direction. Apart from it wave energy, wave period and wave direction are also to be fed to start the model. In case the information about initial sea state is not available the model automatically assumes zero energy as initial input. The model is then expected to stabilise only after a few integrations. Wind data for the past 12 h may be provided in such situations. As wind varies temporally and spatially, it is necessary to adopt a suitable scheme. In this model it is assumed that the locally generated waves follow the prevailing wind direction. The partitioning of total wave energy is made over three ranges of $\Delta\theta$, *i.e.*the difference between wind and wave directions. If $|\Delta\theta|<30^\circ$ the wave energy propagates in the new wind direction. For $30^\circ<|\Delta\theta|<60^\circ$, the energy of wind wave part is given by $E_0= E_i \cos^2(\theta)$, which propagates in the new wind direction and the remaining energy, $E_s= E_0-E_i$, moves as swell energy (swell partition-1). For $60^\circ<|\Delta\theta|<90^\circ$ the entire energy is treated as swell energy, $E_s= E_i$ (swell partition-2).

After partitioning the wave energy into three bins, the wind wave part is tested to know whether it is fully developed or not. The condition given for this test is $E^*= 3700$ or $T^*= 248$ or $C/U= 1.37$. If $E_0<E_m$ *i.e.*, non-fully developed sea, and wind speed increases, the wave growth is computed using Eq.5.12. For decreasing wind speeds, when $E_0>E_m$, the excess energy *i.e.*, $E_s=E_0-E_m$, is considered as swell energy (swell

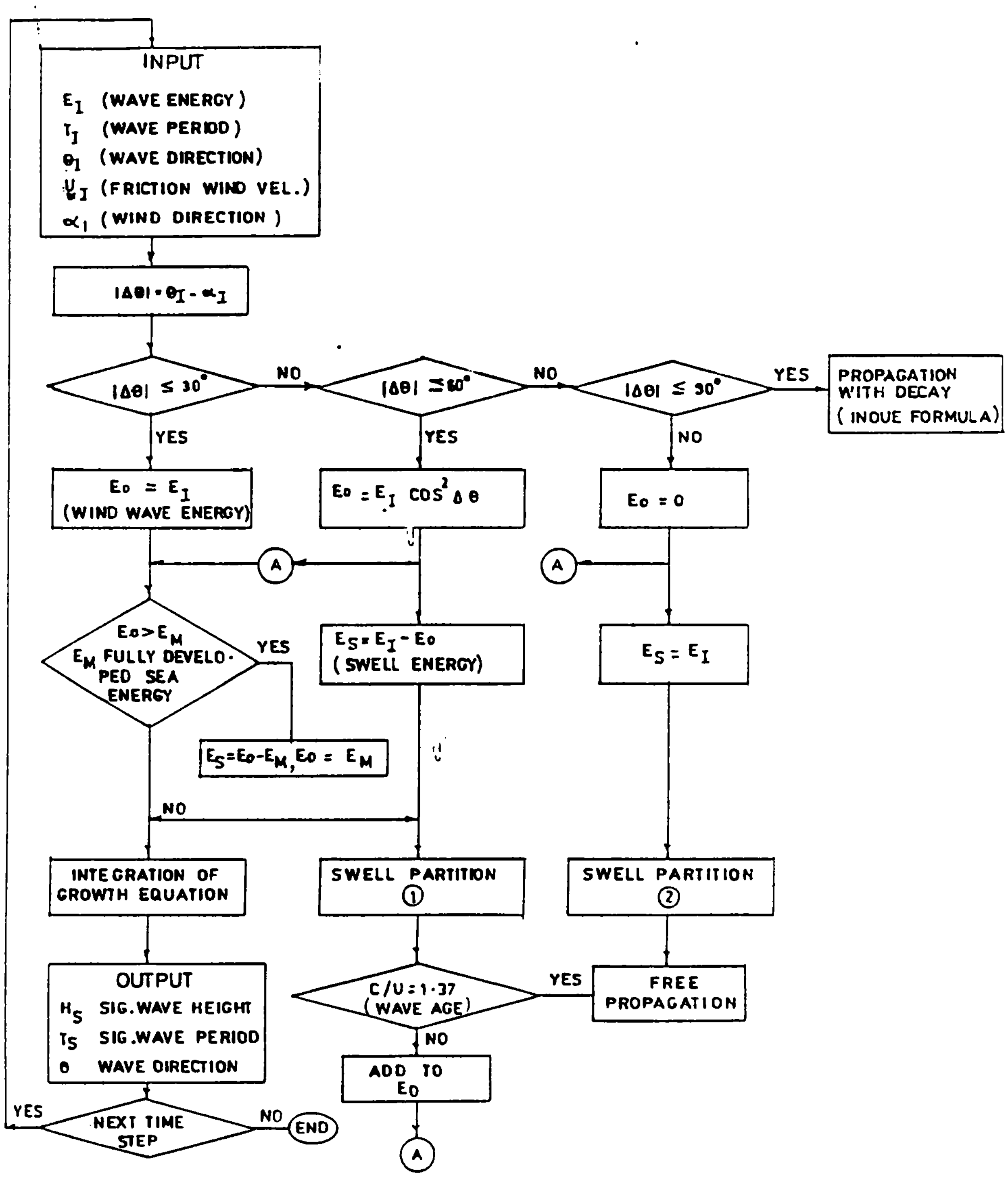

Fig.5.1 Flow chart of the model used.

partition-1) and fully developed sea energy is retained ($E_0=E_m$). For adverse winds, *i.e.*, $|\Delta\theta|>90^\circ$ the wind wave energy is considered as nil ($E_0=0$) and swell energy ($E_s=E_i$) is assumed to propagate freely. For free propagation of swells, the decay of swell energy is computed using the Eq.5.15. In the present study the observations made at a single point are utilised and therefore the advection of wave energy in the form of swells is not included. Hence the total wave energy available is assumed to be the sum of sea and local swell. The combined energy of seas and swells is obtained as given below:

$$E(f)_{comb} = E'(f) + E\sin^2\theta_{swell} \qquad (5.16)$$

where $E'(f) = \mathrm{Max}\left[E(f)_{sea},\ E(f)\cos^2\theta_{swell}\right]$

5.3 MODEL EVALUATION AND DISCUSSION

The numerical model described above is run with a few time-series data sets collected in the Arabian Sea as well as Bay of Bengal. Five hindcast case studies are presented. The first two cases pertain to wave data collected with a waverider buoy whereas the remaining three case studies are carried out based on visual observations made onboard Russian vessels during MONSOON-77 International Expedition. The wave data collected by waverider buoy cover the shelf and near-shore regions and the visual observations include the deep sea areas where no recorded data are available. Locations of wave hindcast studies are shown in Fig.5.2. A brief summary

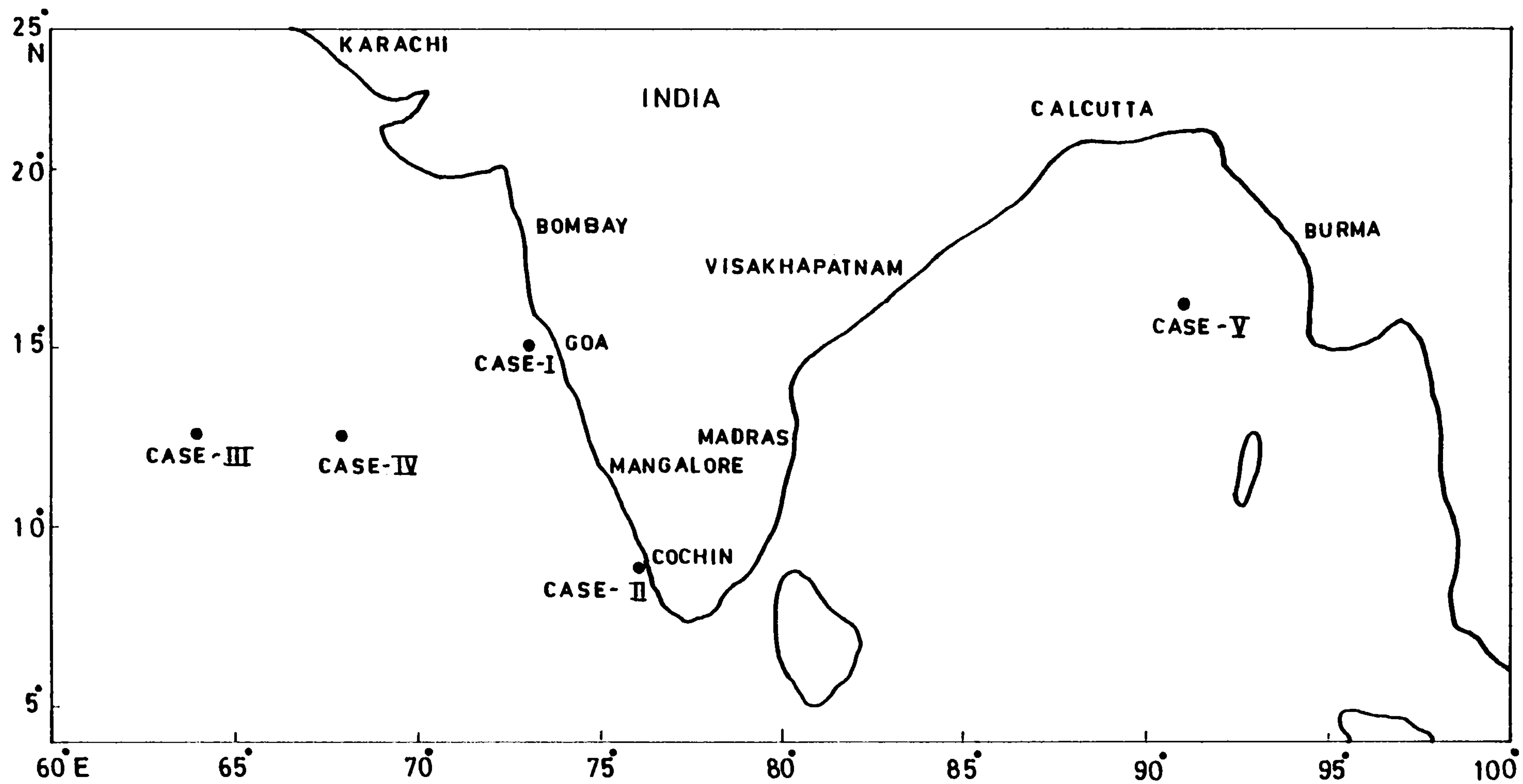

Fig.5.2 Locations of wave hindcast studies.

containing sources of data, model comparisons, *etc.*, are given in Table 5.1.

5.3.1 MODEL RUN : CASE I

Wind and wave data used for this case were collected off Goa, and particulars are given in Chapter 4. Fig.5.3 shows comparison of predicted significant wave height, H_s and mean zero-upcrossing period, T_z. The variation of wind speed is also shown in this figure. The wind direction was north-north-west and it remained almost steady. A strong signal of diurnal variability of wind is seen and wind speeds varied between 0 and 11 m/s. The depth at the observation location (80 m) is large enough for wind-waves to grow freely without being influenced by the sea bottom. Barring few observations, most of the data reflect wind-sea conditions. A remarkable agreement between predicted and observed wave parameters, H_s and T_z, is noticed. The error estimates are given in terms of the percentage mean deviation (%MD) and percentage root mean square deviation (%RMSD) for H_s as well as T_z (Table 5.1). In general the %RMSD value gives a quantitative error whereas the % MD offers the positive or negative bias in the prediction.

5.3.2 MODEL RUN : CASE II

In this section the model results obtained for a typical shallow water case are presented. The wave data are recorded using the waverider buoy off Cochin during south-west monsoon

Table.5.1 Comparison of predicted and observed wave data

Model Run	Location	Number of Data	Significant wave height (m)		Wave period (s)	
			% MD	% RMSD	% MD	% RMSD
Case I	Off Goa	144	4.2	13.7	-10.2	15.5
Case II	Off Cochin	192	-13.7	36.5	-34.3	36.4
Case III	Arabian Sea	216	-6.9	18.3	-5.1	10.7
Case IV	Arabian Sea	330	-13.5	21.7	-10.7	16.5
Case V	Bay of Bengal	168	-12.3	19.1	-11.2	17.1

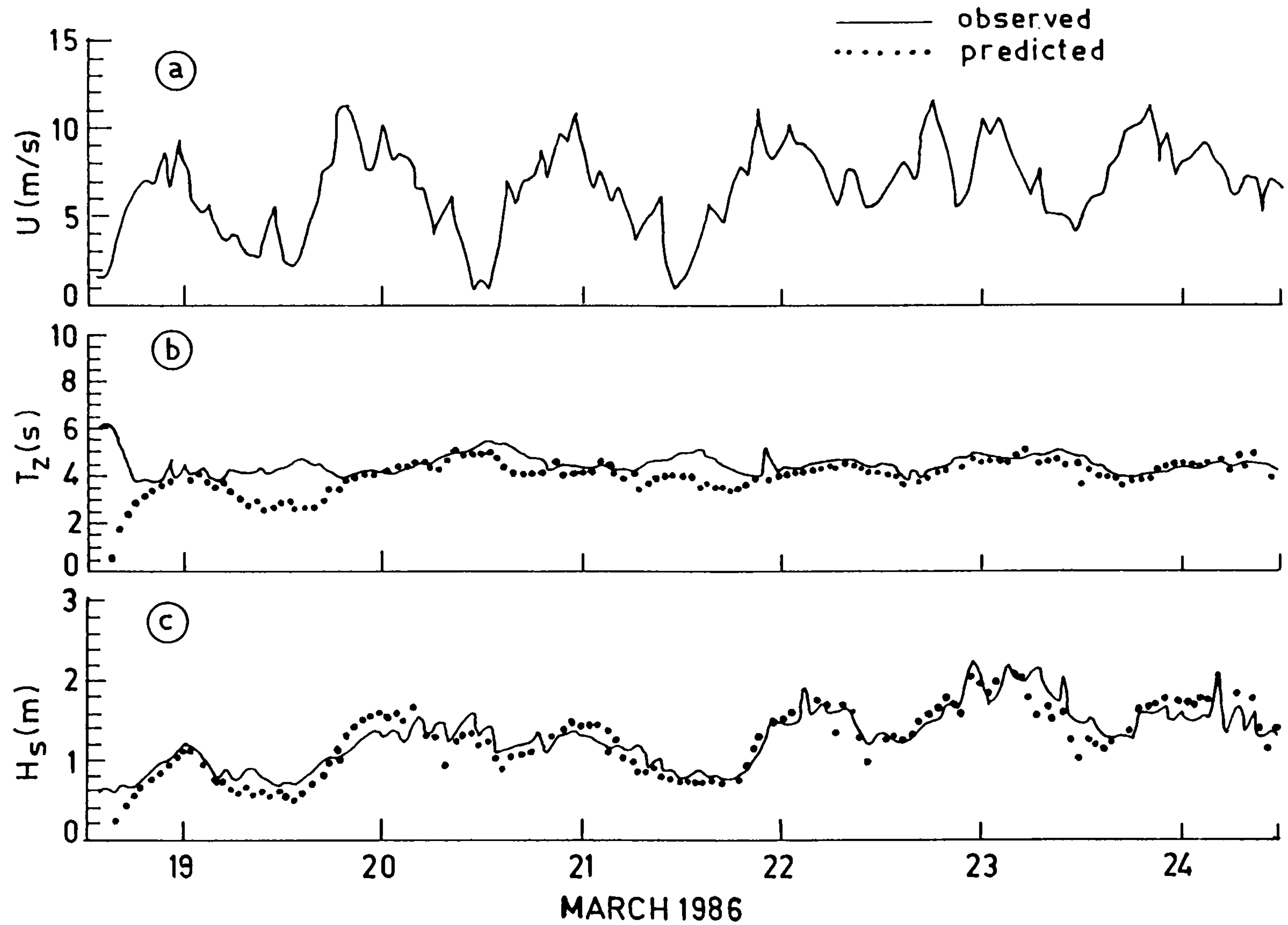

Fig.5.3 Model Run (case I): Off Goa (depth 80 m).

(May-Oct) of 1986 at a depth of about 12.5m, which is approximately 9 km from the coast. The wave records, which are obtained during 11 to 26 August 1986 and the corresponding wind data recorded at the coast are utilised for this model test run. The effect of land and sea breeze is persistently seen and almost 180° shift in the wind direction is noticed from morning to afternoon. Comparison of predicted and observed wave parameters is shown in Fig.5.4. The errors in predictions show that the %RMSD values are 36.5 and 36.4 for H_s and T_z respectively. Thus the model results are accurate up to 60% in this case. Larger deviations observed in this case may be attributed partly to the shallow water effects and also due to the advection of swell energy from deep seas. During the monsoon season, winds over the open ocean are generally more stronger than the winds near the coast. Large waves are likely to be generated in deep waters which contain more energy and propagate as swells towards the coast. Another reason for the deviations in predictions can be the location for wind measurement which is somewhat away (9 km) from the buoy location. The variations in wind field, if any, at these two points of observations may cause errors in prediction.

Some case studies were reported earlier (Joseph, 1988) for the south-west coast of India using waverider data collected during 1982-84 . Measurements were made (Baba and Joseph, 1988) during monsoon season at 15m water depth off Cochin and at 25m depth off Trivandrum (Vizhinjam) . Wave

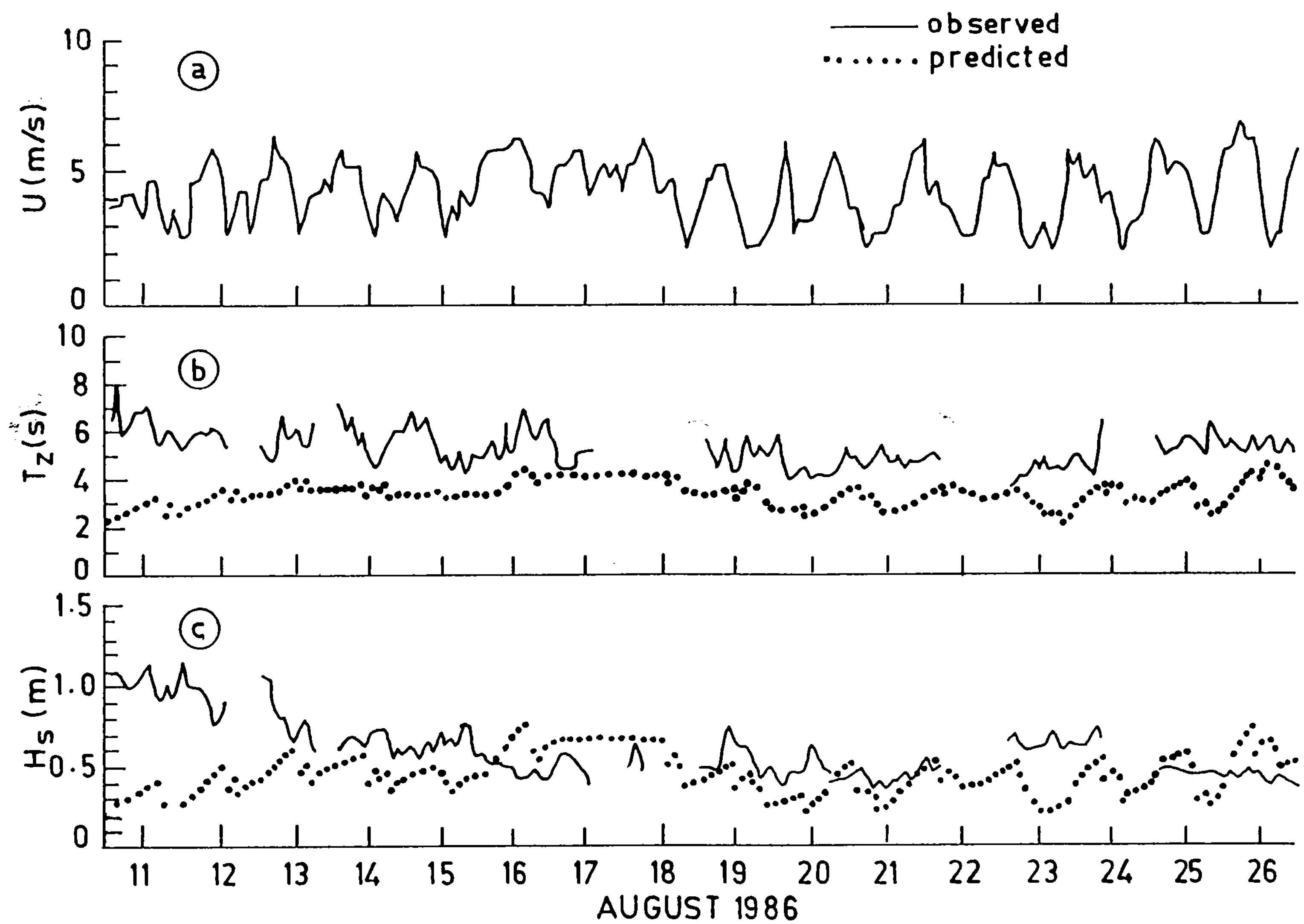

Fig.5.4 Model Run (case II): Off Cochin (depth 12.5 m)

hindcasting was done using geostrophic winds derived from weather charts. As some amount of wave energy in the form of swells is likely to flow into the prediction region, wave hindcasts were carried out for two cases: (i) by assuming zero wave energy for the initial sea state (case A) and (ii) by assigning average wave energy as initial input (case B) for running the model. The results obtained in these studies are shown in Fig.5.5. Though the predicted H_s and H_{max} in these cases give the increasing and decreasing trends satisfactorily, large amounts of deviations are seen especially for case B. Hence it appears the errors in prediction would be high for shallow water areas.

5.3.3 MODEL RUN : CASE III

The present as well as the following two case studies utilise the visual wave data reported by the Russian ships, namely SHIRSHOV and PRIBOY, during the International MONSOON-77 Expedition in the Indian Ocean. Wind data are obtained by anemographs fitted to these ships. Unlike the previous two cases, the data available from MONSOON-77 experiments reflect open ocean conditions. The winds are stronger in this period due to monsoon activity. For this case, the significant wave height, H_s, period, T_s and the wind data recorded onboard R.V.PRIBOY during 12-21 June 1977 in the Arabian Sea are utilised for model evaluation. Predicted and observed data are shown in Fig.5.6. During the period of observation the wind speeds ranged from 12 to 19 m/s and wind

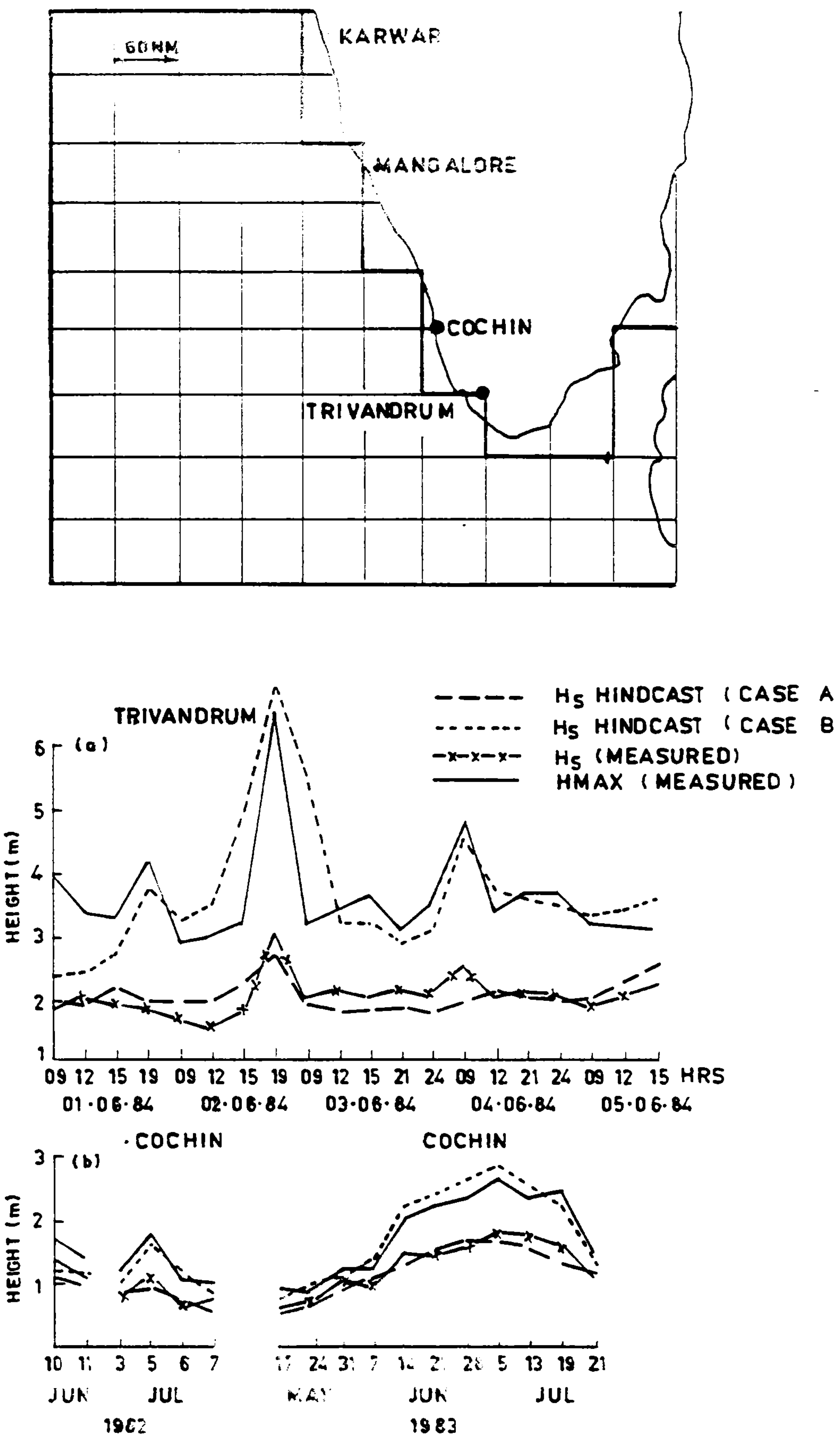

Fig.5.5 Comparison of model predictions in earlier studies (Joseph, 1988) with shallow water wave data.

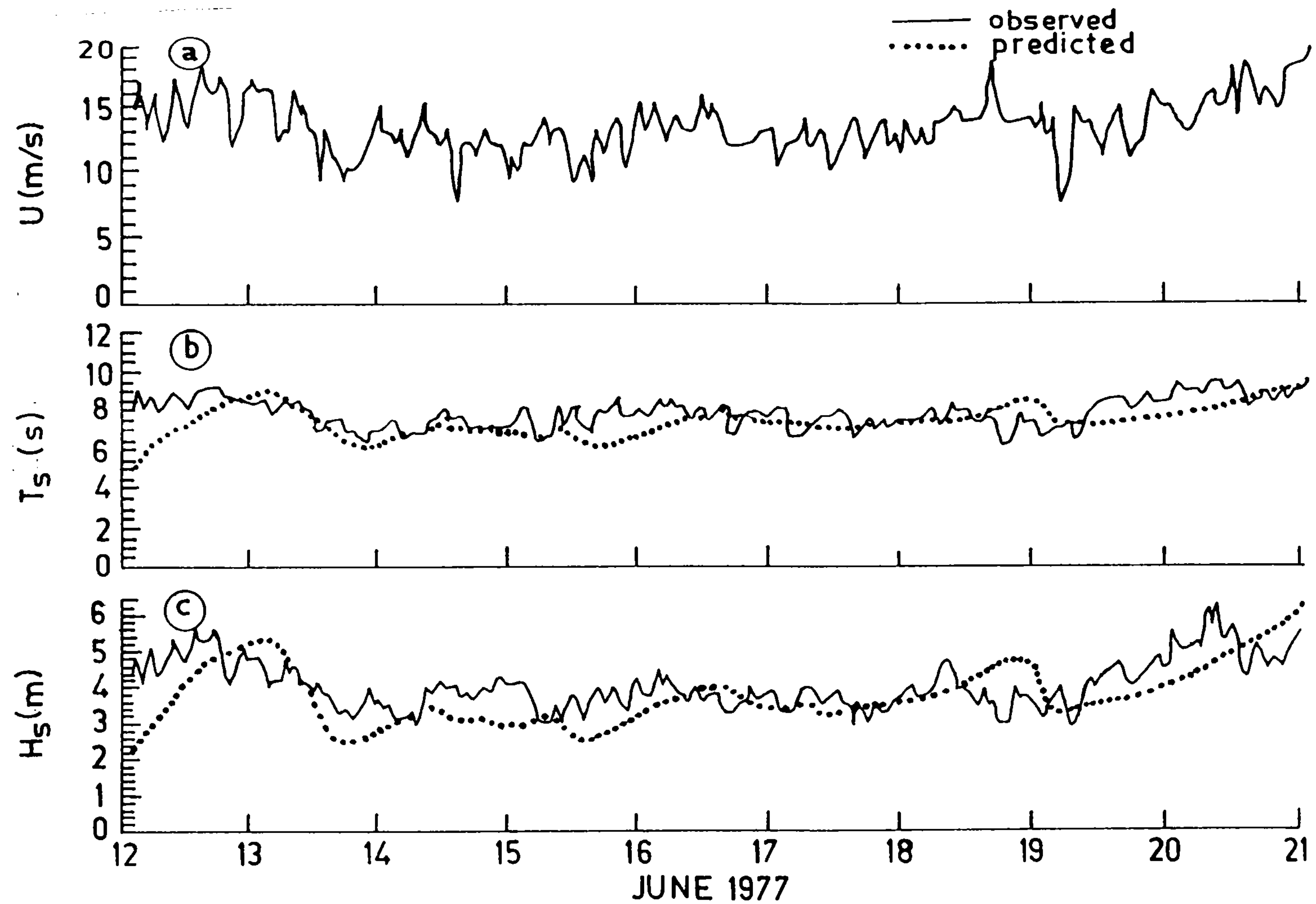

Fig.5.6 Model Run (case III): Arabian sea (deep water).

direction varied between 240° and 270°. Though wave data are noted visually, a fair amount of agreement may be seen between predicted and observed wave fields. The analysis shows % RMSD of H_s and T_s as 18.3 and 10.7 respectively. Considering the fact that the wave data are visual estimates, the agreement seen is quite remarkable.

5.3.4 MODEL RUN : CASE IV

Time series wind and wave data collected onboard R.V.SHIRSHOV in the Arabian Sea (12°30′N, 68°00′E) from 7 to 21 June 1977 are utilised for this case study. The results are presented in Fig.5.7. It may be noted that the wind speeds are lower during 13-16 June '77 compared to the rest of the observation period. Incidentally the model results also show some deviations from the observed data especially during the above period. The observed H_s and T_s are higher compared to predicted data. Therefore it is likely that the deviations are caused due to advection of swell waves from surrounding areas. The errors in prediction show % RMSD of 21.7 and 16.5 for H_s and T_s respectively.

5.3.5 MODEL RUN : CASE V

Data collected in the Bay of Bengal (17°12′N, 90°54′E) from 12 to 19 August 1977 onboard R.V.SHIRSHOV are utilised for this study. In general the winds measured during this period are found to be weak, ranged from 5 to 11 m/s, when compared to the previous two cases. Consequently the predicted

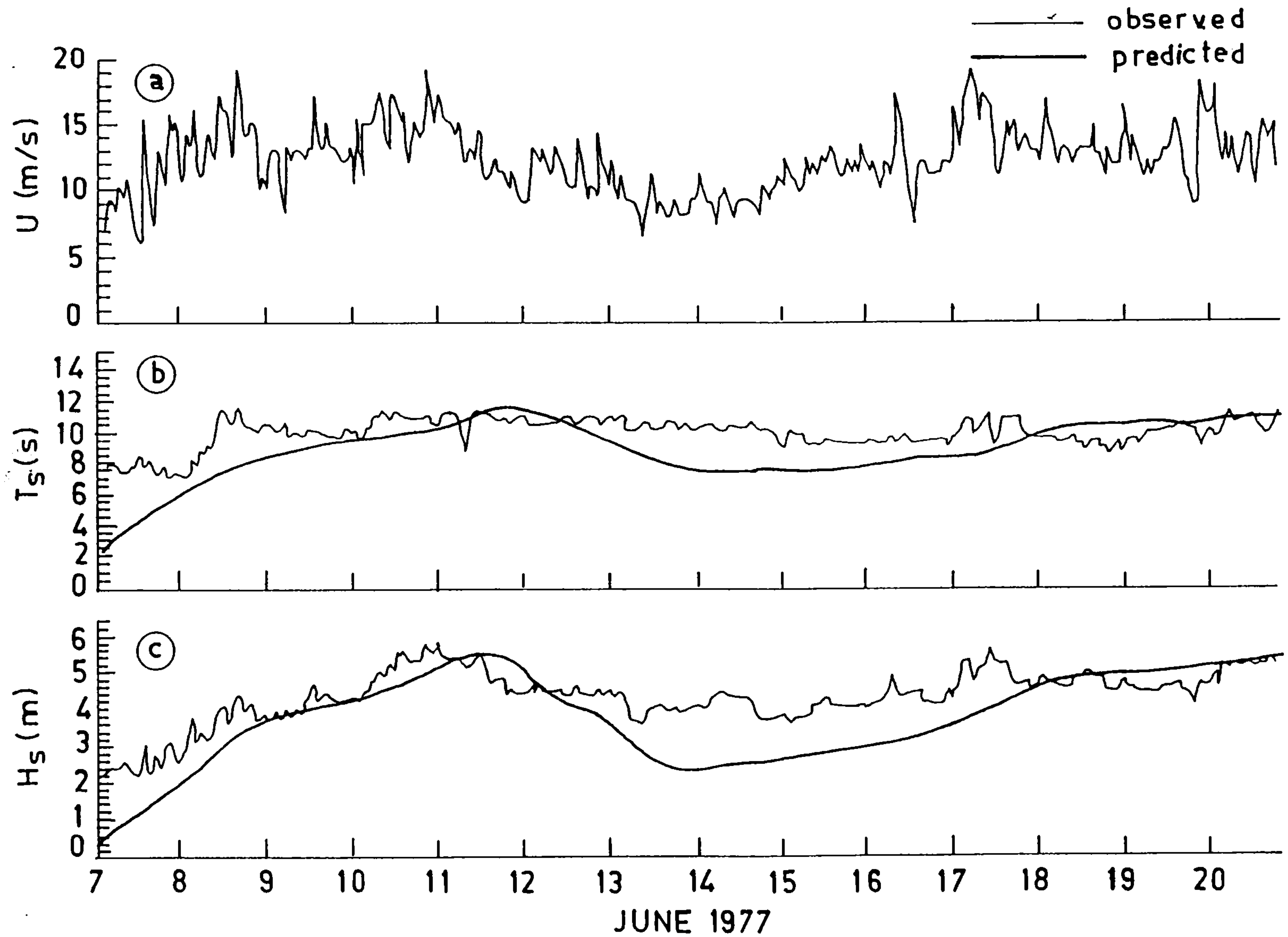

Fig.5.7 Model Run (case IV): Arabian sea (deep water).

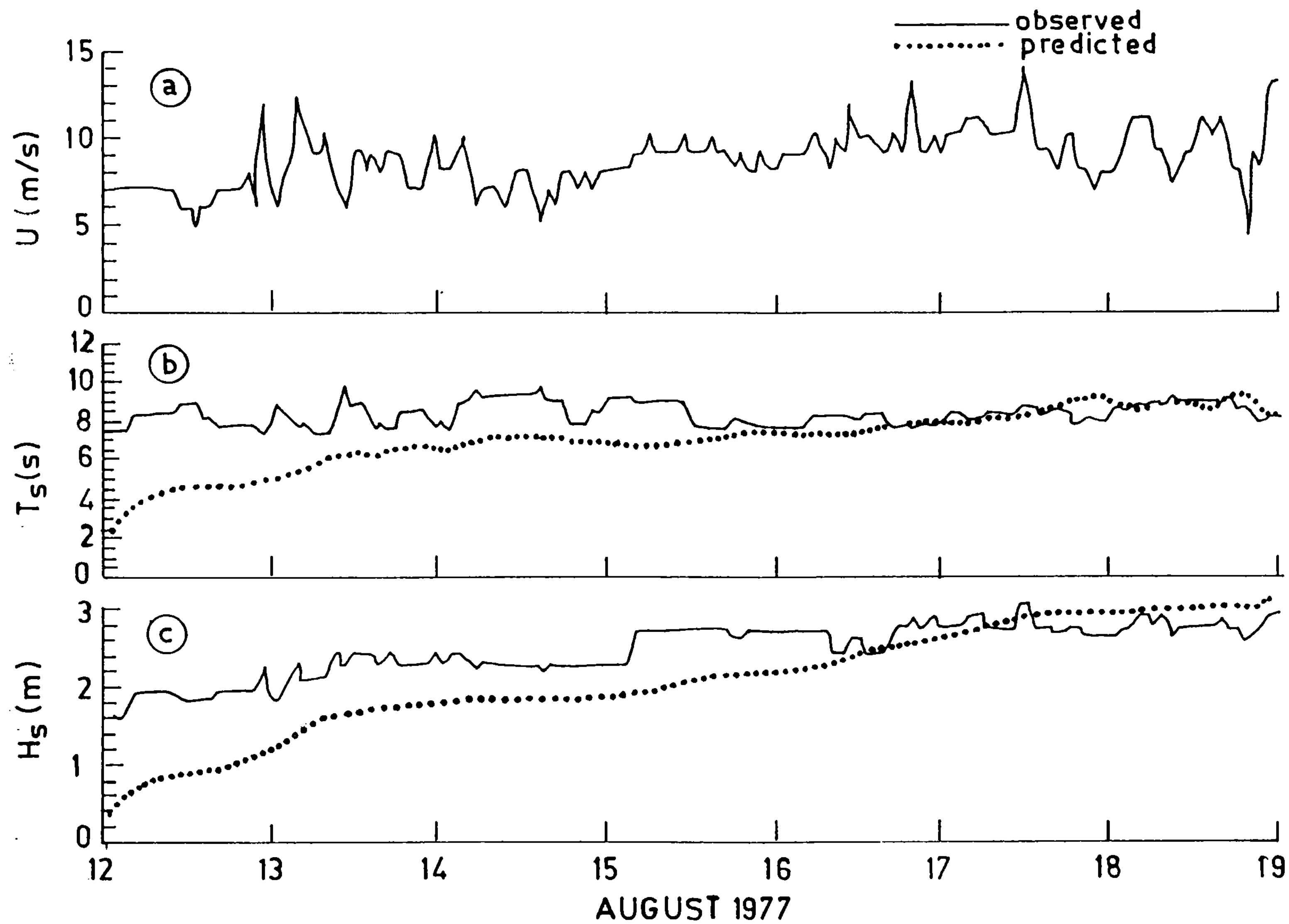

Fig.5.8 Model Run (case V): Bay of Bengal (deep water).

wave parameters, H_s and T_s , are conspicuously low during the first half of the observation period, whereas the predicted data agree reasonably well with the observations in the latter half (Fig.5.8). The agreement seems to be better when wind speeds are high *viz.* 10m/s.The present analysis reveals % RMSD of 19.1 and 17.1 for H_s and T_s respectively.

5.4 CONCLUSIONS

Results obtained through a second generation SWAMP group wave model (TOHOKU scheme) are presented in this Chapter. Model evaluations are carried out for shallow and deep waters of the Arabian Sea and Bay of Bengal. Comparison of predicted and observed wave data shows a good agreement when waves are predominantly of 'wind-sea' type. During south-west monsoon the model results show deviations on some occasions especially when wind speeds are low. Similarly in the shallow water also some deviations are noticed between observed and predicted data. By and large these deviations may be attributed to advection of swell energy which is quite common in the monsoon season. However, for locally generated waves the model predictions are fairly good.

CHAPTER 6 : DISCUSSION ON WAVE PREDICTION METHODS

A critical evaluation of the three wave prediction methods examined in this thesis is presented in this Chapter.

The significant wave parameters, H_s and T_s, are obtained using SMB method for open ocean areas and shallow water corrections are applied before the results are compared with the data recorded near Mangalore. This method assumes that wind blows with constant speed and direction over a given fetch distance for a particular duration. The predicted parameters, therefore, depend on the fetch length in addition to wind speed and duration. It must be mentioned that waves do not grow infinitely though wind blows continuously over the sea surface. For a given wind speed the growth of wave height and period are limited either by the available fetch length or duration of wind. Once the minimum fetch and minimum duration criteria are met, waves attain steady state or equilibrium condition. It is also known as the fully developed sea state after which wave growth ceases to occur. Further addition of energy by winds to the sea surface neither increases wave height nor period but this excess energy will be dissipated through wave breaking processes. Nomograms are given in SMB method to compute H_s and T_s parameters for different fetch lengths, wind duration and wind speed. Selection of a proper fetch size becomes an important task in this method.

Synoptic weather charts provide useful information to implement this method. IDWR are quite handy for this purpose. In the south-west monsoon season winds are mostly south-westerly for areas west of 70°E, whereas westerly winds are commonly seen towards east of 70°E. Based on this observation two fetches (Fetch I and II as described in Chapter 3) are considered for wave prediction off Mangalore. When wind blows over the fetch it generates waves of varying heights and periods. The most significant waves propagate for long distances whereas short period waves die down quickly. Fast decay of short period waves generally occurs because of air resistance. The significant waves pass through a secondary generating area (since two fetches are considered) before they enter into the decay zone.

Standard curves are given for SMB method to estimate wave decay after the waves leave generating area and travel over the decay zone. Wave travel time, t_D computations are necessary from fetch to the forecast point for comparison of predictions with the recorded data. t_D is determined by dividing decay distance, D with decay wave period, T_D. Variations of wind velocities are more in the decay zone and wind speeds less than 10 kts are mostly observed in this area. Off the west coast of India during the monsoon season the onshore winds are quite strong. Therefore waves generated in deep water propagate shoreward as swells. As swells propagate towards shore they feel bottom far from the coast and start losing energy at an early stage compared to short period waves. Attenuation of swell energy occurs through wave refraction, shoaling and bottom friction. To estimate losses of swell energy one has to determine the bottom profile along the fetch direction up to the forecast point and then this traverse is to be divided into suitable segments. By linear interpolation the average depth, h in each segment can be obtained. Computations begin at a depth equal to half of the wave length and for each segment wave attenuation corrections are to be applied till the forecast point is reached. Hence in SMB method wave transformation corrections are made at various stages as wave trains pass through intermediate and shallow waters. This is a unique feature of this method.

As regards limitations of SMB method the following points may be relevant. This method simplifies the prediction by making an assumption that winds blow with constant speed and direction for a given fetch and duration. Therefore variations of winds at short time intervals can cause errors in predictions. For practical applications it is generally assumed sufficient to consider wind speed as reasonably constant if variations do not exceed 2.5 m/s from the mean. Variations in wind direction can be tolerated up to $\pm$ 15°. IDWR are prepared only at standard synoptic time intervals. For short durations one has to make interpolation between successive weather charts to obtain wind characteristics. When waves propagate freely they might interact with other wave trains arriving from a different direction or fetch. Interactions of two or more wave trains can alter wave energy. In SMB method, the length of fetch is only considered and the fetch width is ignored. Moreover, it is assumed that in open sea conditions width of fetch is not as important as in the case of lakes and reservoirs. But in a more practical sense even the width of fetch might well influence the wave predictions at sea. Another limitation of this method is that it is based on monochromatic (significant wave) wave approach but the actual sea state comprises of several waves of different periods and heights.

As discussed above, SMB method gives estimates of significant wave parameters derived from mean wind conditions. It may be mentioned that delineation of fetch and duration is difficult when fluctuations in winds occur. Variations in magnitude and direction of winds are quite common during low wind speed conditions. Further it was observed in the past (Pierson, *et al.*, 1955) that the wave height and period predictions obtained by the conventional methods like SMB and PNJ for low wind speeds (<10 m/s) fail to agree well with the observations. Mostly the predictions are found to be under-estimates due to fluctuating nature of winds. By and large this may be attributed to poor understanding of wave generation mechanisms and initial wave growth processes. It is in this context the new method suitable for low and moderate sea states is suggested here (Chapter 4).

Parameterisation of seas is achieved through correlation studies of winds and waves utilising the concept of time-delay. Relationships have been derived for H_s and T_s and a good agreement is seen between predictions and observations. The new method proposed here has also got certain limitations. Wave prediction formulae arrived at in this method purely reflect locally generated waves. But in any given location the observed sea state is a combined effect of seas as well as swells arriving from other generating areas. Since seas are more predominant, good results could be obtained in the present case. For other situations when swells are more prevalent the present method may not yield better results. As the wind speed decreases the correlation between local winds and waves reduces, thereby leading to increased significance of swells.

Therefore it is essential to incorporate methods by which swells are also taken into account for routine and practical wave predictions. In spite of its limitations, SMB method is considered effective for tracking of swell energies over long distances. Hence a combination of the proposed new method and the SMB method, for prediction of seas and swells respectively, might be well suited for practical applications. When continuous wind observations are available at the forecast point, prediction of seas can be done with the new formulae given in this study. At the same time swell parameters may also be estimated using SMB method by availing wind inputs for surrounding fetches from IDWR. It is thus possible to get both sea and swell characteristics by adopting the combined approach.

Another point which needs mention here is about the time delay criterion used in this study. One of the observations made in this study based on the analysis of present data is that a 6 h lag exists between winds and waves. The range of wind speeds observed in this case is from 0 to 11 m/s. It is not known whether any variations are to be anticipated in the lag for higher wind speeds. Therefore further studies are required in this regard.

Both SMB as well as the new method suggested for wave prediction consider that wind speed remains constant for certain duration. Wind data required for prediction are normally derived from synoptic weather charts. As these charts are available only for certain time intervals, assumptions on wind duration become inevitable. However, to achieve more accuracy in the predictions it is necessary to have wind information at close intervals of time. Numerical wave models are designed to have wind inputs at very close intervals. Such models cater for integrations over both time and space. Time steps for numerical integrations can be chosen depending upon the requirement, availability of data and also keeping in view the total computation time.

Due to non-availability of wind data for the entire area, only the local winds are considered in the current investigations. With the availability of more data the entire area (Arabian Sea/Bay of Bengal) can be divided into small grids for running the above model. Integrations over the space can provide information on swells. But to run a grid model with space-time integrations one must have input data for all the grids covered in an area. Data from synoptic weather charts are not adequate for this purpose. Sea level winds obtained through remote sensing can meet this requirement to some extent.

CHAPTER 7 : CONCLUSIONS AND RECOMMENDATIONS

7.1 SUMMARY OF CONCLUSIONS

Wave prediction models are basically semi-theoretical type and the constants/coefficients used in these models were derived with the help of measurements made at sea. Currently available models had utilised data collected mostly in Atlantic and Pacific Oceans. Data pertaining to Indian Ocean had not gone into the existing models during their formulation. As we know the Indian Ocean is unique for its seasonally reversing monsoons which are not present in the other two major oceans. Therefore wind field, fetch, *etc.*, which are responsible for wave development process are different for Indian Ocean when compared to other oceans.

Hence, to adapt the current wave models it is necessary to evaluate them with the data collected in Indian seas. Barring a few studies, no comprehensive approach is made so far in this regard. Hence in the present study evaluation of a significant wave model as well as a numerical wave model are carried out utilising wind and wave data obtained in the Arabian Sea and Bay of Bengal. Efforts are also made to derive new formulae for wave prediction which are suitable for low and moderate sea states.

Review of literature on wave prediction reveals that the existing methods can broadly be classified into two categories: (i) significant wave methods and (ii) spectral and/or numerical wave models. The significant wave methods or the fetch-graph techniques provide simple empirical relationships for significant wave parameters, wind speed, fetch and duration of wind. These methods give first estimates of wave response to uniform and steady winds. Because of their easy adaptability and less computational effort the significant wave methods have been accepted for many practical applications in the past. The limitations of these methods are that they are based on the monochromatic wave approach and utilises average wind conditions over a certain duration and given fetch. In spite of these limitations the significant wave methods are still preferred for various applications as they provide very useful information.

Numerical wave models are more versatile and capable of offering accurate predictions when the required inputs are fed to them. This class of models are based on the concept that the sea state comprises of several waves with varying heights and periods and they propagate in different directions. Spectral wave models describe the sea state in terms of energy spectrum in relation to frequency as well as direction. Hence they provide two-dimensional distribution of waves. It is possible to derive significant wave parameters from the energy spectrum by using some standard relations.

An evaluation of SMB wave prediction method is carried out for Mangalore coast. The influence of south-west monsoon is normally seen over the Arabian Sea during May-September. During this period the strong monsoonal winds blow over long fetch distances which in turn generate higher waves compared to the rest of the year (October to April). The study period covers June to August of 1968 and 1969. H_s and T_s predictions obtained for deep waters in Fetch I and II are corrected for wave energy attenuation in shallow water. Comparison with the recorded data near the coast has revealed that waves coming from Fetch II, *i.e.*, between 64°E and 70°E agree better than those coming from Fetch I *i.e.*, 70°E to 74°E. In July, waves generated west of 64°E are also observed at the coast with significant wave periods of 10 to 12 s. For computation of wave energy attenuation due to bottom friction, a factor of f= 0.01 was proposed in earlier studies (Bretschneider, 1954; Bretschneider and Reid, 1954). But this value is found very low and a bottom friction factor of f= 0.05 is found more suitable for wave prediction at Mangalore. During the south-west monsoon, wave trains generally approach the Mangalore coast either from west or south-west. As waves travel towards the coast, due to shallow water influence the reduction in wave height occurs but the wave period remains almost unaltered. Therefore based on the present study multiple linear regression formulae and nomograms are given for estimation of shallow water significant wave height, H_s, from deep water significant wave height, H_0 and significant period, T_s. Separate relationships are given for waves coming from west and south-west directions.

Results of analysis of 1 h time series data collected off Goa, during March 1986, revealed diurnal variations of winds and waves. Active phases of growth and decay of waves are observed. The energy peaks of wave spectra during the growth phase are noticed in the frequency range 0.15 to 0.25 Hz and during the decay phase they are centered around 0.10 Hz. As waves grow, the spectral peak frequency, f_p shifts towards low-frequency side. Thus during growth phase it is found that f_p moves from 0.25 to 0.15 Hz and the corresponding wave spectra contained more energy than swell wave spectra. The swell wave spectra are observed at the time of wave decay with f_p around 0.10 Hz. The predominance of 'sea' wave spectra is confirmed by examining the ratio of wave steepness and wave age and distribution of spectral width parameter. The energy versus frequency correlations of the equilibrium range both for individual as well as for an envelope of wave spectra have shown a fair agreement with f^{-5} formula (Phillips, 1958a).

The cross-correlation studies of winds and waves indicated a 6 h time-lag. Hence, the wind speed, U_6 observed 6 h prior to the forecast time is used for deriving new formulae for wave prediction. Predicted wave parameters H_s and T_z agreed well with the observed data. The new formulae suggested for wave prediction are valid for locally generated waves and do not cater for swells coming from elsewhere.

The TOHOKU numerical wave model is evaluated with the data of Indian seas. The model simulations are done using the winds observed at the forecast point. For computation, the total wave energy is partitioned into three different bins by considering the differences of wind and wave directions. The wind-sea part and residue of swell energy are computed and stored separately. However, for model comparisons the summed up energy values of seas and local swells are considered. Since the single point wind observations pertaining to the forecast site are only available, the influence of non-local swells could not be incorporated in this study.

The numerical model results are presented for five cases (see Chapter 5). The model is run with the data in shallow and deep seas for Arabian Sea and Bay of Bengal. The first two case studies are based on waverider data whereas the remaining three case studies utilised shipboard visual wave observations made during MONSOON-77 Expedition. Data set for Case I (off Goa) is the same as the one used in Chapter 4. In this case a very good agreement is seen for predicted results. Similarly for Case III (Arabian Sea, R.V.PRIBOY, 12-21 June 1977) also fairly good comparison is seen for predicted and observed data. For Case II (off Cochin), Case IV (Arabian Sea, R.V.SHIRSHOV, 7-21 June 1977) and Case-V (Bay of Bengal, R.V.SHIRSHOV, 12-19 Aug 1977) the model predicted values have shown some deviations. Since the model integrations are done using the available wind data at the forecast point, the results showed good agreement when seas are more predominant. However, in all the cases presented above it is possible that swells arriving from other generating areas are also contributing to the wave field observed at that particular location. When local winds become weak the swells contribute more to the existing wave field. Therefore the deviations noticed may be due to swells. In shallow water (Case II) the bottom interaction also causes some deviations in predictions. Error analysis revealed % RMSD (root mean square deviations) from 13.7 to 36.5 and 10.7 to 36.4 for H_s and T_s respectively. The errors in predictions are generally below 20% RMSD, except for the shallow water case.

7.2 RECOMMENDATIONS

For wave prediction in coastal waters it is necessary to consider the effects of shoaling, refraction and bottom friction. The computations involved for these shallow water effects are normally time consuming and laborious. Therefore based on the present study, nomograms are given for prediction of shallow water significant wave height from the deep water wave characteristics. These nomograms are recommended for use at Mangalore coast for waves approaching from south-west as well as west.

The current investigations show that the prediction of seas can be done with a reasonable degree of accuracy by adopting the new method proposed in this thesis. However, more efforts are needed to incorporate advection of wave energy which enables prediction of swells. For practical applications the new method is recommended for prediction of seas whereas swells may be obtained using SMB method.

Numerical wave models require adequate wind inputs over the vast sea areas. Wind data over large areas cannot be acquired by resorting to conventional ship-board measurements or from synoptic weather charts. There is a need to adapt remote sensing methods for providing wind inputs at synoptic time intervals at close grid spacings over the ocean. Hence, satellite derived information on winds is very crucial for wave models.

At present the model initialization is done with zero wave energy and it is generally referred to as 'cold-start'. For large area grid models, normally the 'spin-up' time of 1 to 2 days is used to bring up the wave energy to realistic levels. Thus for running the operational wave models the initial sea state conditions have to be specified.

The currently available observations mostly reflect one-dimensional wave spectrum *i.e.*, wave energy versus frequency. More directional wave data are needed to understand two-dimensional evolution, propagation and decay of waves.

Studies on wave energy interactions between sea and swell need more emphasis in future wave modelling.

The complex circulation features which normally prevail in coastal waters cause significant changes in shallow water wave characteristics. Hence, in shallow water wave modelling the role of wave-current interactions have to be incorporated.

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APPENDIX - I

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