STUDIES ON WAVE CLIMATE ALONG THE SOUTH WEST COAST OF INDIA

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CERTIFICATE

This is to certify that this thesis is an authentic record of research work carried out by Sri.G.Muraleedharan, M.Sc. under my supervision and guidance in the School of Marine Sciences for the 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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ABBREVIATIONS & NOTATIONS

H	- Wave height
L	- Wave length
T	- Wave period
f	- Wave frequency
m	- Metre
K	- Wave number
ω	- Angular velocity
a	- Wave amplitude
C	- Wave velocity (Phase velocity)
h, d	- Water depth
ρ	- Density of the fluid
P.E	- Potential energy
K.E	- Kinetic energy
E	- Total energy
g	- Acceleration due to gravity
S	- Seconds, Sheltering coefficient
KW/m	- Kilowatt per metre
H_{max}	- Maximum wave height
H_s, $H_{1/3}$	- Significant wave height
$H_{1/10}$	- Averaged one-tenth highest wave height
$\bar{H}$	- Mean wave height
P	- Wave power

Cont'd.

T_z	- Zero-crossing wave period
T_s	- Significant wave period
$\bar{T}$	- Mean wave period
η	- Standard deviation

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INTRODUCTION

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INTRODUCTION

1.1. Preliminaries

Although scientific studies on waves, which form an important phenomenon of the global oceans, were initiated in the early nineteenth century by the German scientist Franz Gerstner, a detailed investigation of all the aspects of waves is a recent activity. Not until the Second World War did it become urgent to have both empirical and theoretical studies towards enhancing our knowledge of sea-surface waves. The state of the art before the war was confined to some theoretical developments based on the laws of classical mechanics and a few generalisations employing makeshift observations. Many attempts at developing and verifying theories in this area were inhibited by the difficulties experienced in gathering observations of adequate precision. Inspite of these limitations, recent works on waves such as the precise description of the surface of the sea provided by the oceanographers and the method of spectrum analysis used by them have brought forward the research in this area and its applications on the design and sea-keeping qualities of ships to new and exciting developments. For a comprehensive understanding of the wave phenomena it is essential to supplement the notion of wave spectrum with a detailed analysis of the factors that induce wave generation and decay. The studies made by Harold and others to forecast wave and surface movements for naval operations during the last World War provided a timely impetus in this direction.

1.1.1. Relevance of wave studies

In the hydrosphere, sea surface is a most familiar entity and its importance to human activities cannot be over emphasized. Accordingly investigations aimed at realising a clear picture of this portion is of utmost interest and direct practical implications. The major dynamic forces that lead physical changes in the regions near the shores are caused by wind waves. The importance of waves in the planning, design and construction of shore protection structures, harbours, water ways and other coastal facilities have been widely recognised. With increased maritime activities like off-shore oil exploration, utilisation of wave energy, construction of maritime structures, movements of all kinds of vessels, activities such as landing and take-offs of war planes from aircraft carriers and laying of mines etc., the study of ocean waves have earned added significance in recent years.

Any coastal engineering work requires a clear perception of the structure of waves in an around the design area as also in the determination of zones of energy concentration. An accurate account of the wave climate is an essential ingredient in the extraction of energy from waves. Since the effect of the waves in the surface is partially experienced down the depths even submarine designs cannot overlook the wave characteristics of the regions, the vessel is supposed to operate.

Wave information is helpful in tracking the path and even outbreak of storms. The small capillary waves produce sea return on radar equipments and create noise interference, which blank out the targets. These are only some examples that reveal the relevance and importance of wave studies from the strategic, economic and commercial points of view with perhaps, more exciting and useful areas yet to emerge.

1.1.2. Wave parameters

In this section we focus attention on some concepts and definitions that enable the analysis of wave characteristics.

The maximum elevation of a wave from the mean sea level is known as a wave crest and the lowest depression from the same level is termed wave trough. The vertical distance from crest to trough constitutes the wave height, H, while distance between two successive crests is the wave length, L. We define the period as the time taken by the wave to traverse a distance of one wave length, which is denoted by T. It's reciprocal $f = T^{-1}$ is the wave frequency measured in cycles per kilo second. The ratio H/L is known as the wave steepness. When the steepness exceeds one-seventh, wave becomes unstable and breaks. Two other associated quantities are the wave number $K = 2\pi/L$ and the angular velocity $\omega = 2\pi/T$. The vertical distance between from crest to mean sea level or from trough to mean sea level is the wave amplitude denoted by a. There is a simple relationship $C = LT^{-1}$ connecting the wave velocity C with the wave period T and length L. On the other hand, we also have

$$C = \frac{gL}{2\pi} \tanh \left(\frac{2\pi d}{L}\right),$$

where g is the acceleration due to gravity and d, the depth of water.

The above definitions relate to simple sinusoidal progressive wave. For the actual ocean waves the wave parameters will be introduced in a subsequent section.

1.1.3. Waves in ocean

Sinusoidal waves are not found in the ocean. Ocean waves occur as wave trains where the individual waves constituting the wave group travel with velocity corresponding to their own wave length. The individual wave moving with its phase velocity advances through the group because it moves with a speed double that of the group. Finally it disappears at the front of the wave train, to be followed by the others. In shallow water (depth $< \frac{L}{2}$) individual waves are progressively slowed down and their phase velocity equals the group velocity.

1.1.4. Important wave theories

The wave theories describing the ocean waves are mainly classified as small amplitude wave theory and finite-amplitude wave theory, the former being considered as a first approximation of the latter.

According to the small amplitude wave theory, the orbital motion of particles becomes negligible at a depth $h = \frac{-L}{2}$. In the case of shallow water waves, the particles generally exhibit an elliptical motion. The horizontal displacement remains constant whereas the vertical displacement is equal to the amplitude at the surface and zero at the bottom. Deep water wave particles exhibit circular motion. The radii decrease exponentially with depth. The vertical displacement is equal to the wave amplitude at the surface.

The wave celerity is given by the relation

$$C^2 = k^{-1} g \tanh (kh)$$

Wave energy is expressed in terms of average energy over a wave length per unit surface area. The total energy of a wave system consists of components of the potential and kinetic energies, the average potential and kinetic energy density being given by the relation,

$$P.E. = \frac{1}{4} \rho g a^2$$

and

$$K.E. = \frac{1}{4} \rho g a^2$$

where ρ is density of the fluid. For a small amplitude wave, both the quantities are same and hence the total energy,

$$E = \frac{1}{2} \rho g a^2$$

Wave energy travels with the group velocity and is transported in the direction of wave propagation.

If the wave amplitude is large, a first approximation to the theoretical explanation to the wave behaviour, as was done in the case of small amplitude wave theory is no longer true. For finite amplitude waves, four theories have been proposed in literature as will be explained below.

The first theory related to finite amplitude waves was propounded by Gerstner (1802) and is applicable only to deep water waves. The essential features of his theory are irrotational motion, trochoid free surface and exactly circular orbits for the particles which decreases exponentially with depth. On account of these, the theory does not allow for mass transport.

Stokes (1847) brought forward his second-order theory for the case of a nonlinear wave progressing over still water of finite depth. According to his wave form, the crest is more peaked and shorter than the trough and the phase velocity C is given by

$$C^2 = K^{-1} g \tanh (kh)$$

The motion of the particle is irrotational and the orbit is not closed, with a little forward shift in the direction of the profile motion and a slight net transport of mass which is known as Stokes drift. His investigation also includes wave theory for water of finite depth.

The cnoidal wave theory applies over the range $\frac{1}{50} < \frac{h}{L} < \frac{1}{10}$ and is developed using elliptic functions. This theory suffers from the limitation that cnoidal wave functions are difficult to apply and therefore not generally used in practice.

Russell (1838, 1845) introduced a wave form which lies above the still water level, propagates at constant velocity and remains unaltered in form. These conditions are generally satisfied in the case of very long waves.

As an oscillatory wave moves into shallower water, the crests become shorter and steeper, while the troughs become longer and flatter. Theoretical findings on solitary wave characteristics are more or less similar to those of the long waves mentioned earlier.

The celerity is given by the solitary wave theory as

$$C = [\ g(H+h)\ ]^{1/2}$$

1.1.5. <u>Wave generation</u>

The generation of wind waves depends on the transfer of energy from the wind to the sea. A brief exposition of the important theories in this connection is given below.

The sheltering theory of Jeffreys (1925) assumes that the air flow is laminar over the windward slope of the wave and turbulent on the lee slope, with a tangential friction that can be neglected. The parameter involved here is the sheltering coefficient, S, which is estimated as 0.27. Although this theory offers a satisfactory explanation of the initial generation of waves, as the waves increase in steepness the value of S often appears to be underestimated.

Sverdrup and Munk (1947) uses as the basis of their theory, rough turbulent flow which occurs when the wind speed exceeds 7m/S. While the air flow is similar to that of Jeffreys with a sheltering coefficient of 0.013, here the tangential stress is considered to be a significant factor. An important feature of this theory is that it provides a basis for forecasting wave heights.

A third approach is that of Eckart (1953) applicable to fully turbulent flow. Sheltering coefficient is not considered in this theory. In the absence of a proper accounting of the normal pressure, this theory does not provide accurate results.

In another significant contribution, Phillips (1957) introduced the assumption of random distribution of pressure on the surface. According to him the fluctuating pressure upon the water surface is responsible for the birth and early growth of wave and the motion is irrotational.

Miles combined two theories of wave generation, the turbulent pressure fluctuations and the shear-flow instability. The initial disturbance of the water surface is due to turbulent pressure. Miles's shearing flow is important in the main stage of wave growth.

1.1.6. Wave reflection, refraction and diffraction

Perroud (1957) made laboratory studies on the reflection of solitary waves from a vertical wall and found that there are three types of reflection patterns. When the incident angles are greater than forty five degrees the reflection was found to be normal. In this case the angle of reflection is equal to the angle of incidence. For angles of incidence less than twenty degrees, the wave crest bends so that it becomes perpendicular to the wall and no reflected wave appears. In cases where the angle of incidence is greater than twenty degrees but less than forty five degrees, three waves are present, the incident wave, a reflected wave and a wave approximately perpendicular to the wall.

When the waves from the deep water move into shallow water of the nearshore regions, they are influenced by the topography of this region. The wave crest in shallow water moves at a slower speed than the portion in deep water. This results in the bending of wave crest and this process is known as wave refraction, which leads to a local increase or decrease in wave energy. The refraction coefficients are determined from refraction diagrams using one of the two methods available for the purpose viz. the wave front method and the direct orthogonal method.

Wiegel (1964) gave a description of wave diffraction phenomena. When a wave system incident on a structure such as a breakwater, a portion of the wave will be reflected or break and the portion moving past the tip of the structure is the source of a flow of energy into the region in the lee of the structure. The two sets of waves, reinforce and cancel each other in such a manner as to cause an irregular wave height in this region. This phenomenon is known as diffraction.

1.1.7. Wave measurements

The accurate measurement of wave parameters at sea is not an easy task. The wave periods are the easiest to be measured as by using a dye marker and a stop watch. By having a painted scale along the side of a ship the wave lengths can be estimated. The simplest way of estimating wave heights is to mount a vertical scale in the water and record the wave heights. For deep water waves, floats can be used. Wave records can be obtained by using pressure transducers along with suitable electronic circuits and recorders. Such wave recorders are widely and successfully employed for obtaining accurate information on wave parameters. The failure of these instruments are often due to lack of proper inspection and service after installation than to weakness in design. Stereophotogrammetric methods can also be used for wave measurements to cover large areas to provide clear information on waves.

Draper (1966) has discussed the problems in the recording of sea waves through the existing techniques for measuring waves in the open sea and close to the shore. It is rarely possible to satisfy all the requirements of the user because of technical, operational and fundamental difficulties and all wave recorder installations for engineering purposes are the result of compromise. Wave measurement as a science, is still in its formative stages with only a history of about twenty years and accordingly the different techniques applied and many useful instruments devised, are still far from being perfect.

Cavaleri (1980) has analysed the drawbacks of wave measurement using pressure transducers. The major drawback of investigating wave motion with a submerged pressure transducer is the bias in its output resulting from the dynamical effect of the relative motion of water particles. Tucker (1983) has discussed the potential of a microwave precision radar altimeter and a synthetic aperture radar carried aboard a satellite to provide information on ocean waves. The system is useful for open ocean areas to within $\sim$ 10 km of the coast. Sampling variability, interpretation problems and the capabilities and limitations of each sensor still remain as subjects of serious concern.

The instruments presently available for measurements on waves can be broadly classified as surface, subsurface and above surface types. The wave staff, spar buoys, step-resistance and capacitance gauges, inverted echo sounders and the different types of accelerometer buoys fall in the surface measuring devices category. Examples of subsurface devices are pressure type recorders and the N.I.O (U.K.) ship-borne wave recorder. Remote sensing methods from spacecrafts, aircrafts and radars are examples for above-surface measuring techniques.

The swell wave direction at the recording point can be taken using a Brunton compass.

Information on tidal level fluctuations along with wave data are available from a pressure type wave and tide telemetering system. The wave and tide recording system consists of a wave and tide telemeter (Sivadas, 1981), a wave recorder, a tide printer, a timer and power supply and control units. The functions of the unit is given by Baba and Kurian (1988). The response is greater than 95% for wave periods greater than 3 S.

A wave rider system consists of a moored buoy which transmits wave data, a WAREP receiver, which receives and records the data on paper charts and a DIMA unit, capable of recording the digitised data in magnetic cassettes. The wave rider gives 100% response for wave periods between 2 S and 10 S and it is above 95% upto 18 S.

Wave record analysis can be made by the three methods available at present viz. Tucker method, wave-by-wave analysis and spectral analysis. For details we refer to Baba and Kurian (1988).

1.2. Wave research along Indian coasts

The wave research along Indian coasts is only a recent activity with most of the work carried out on the west coast of India. This section looks into the available information on this aspect.

Dattatri, Raman and Jothi Shankar (1979) studied the height and period distributions for waves off Mangalore harbour by utilising ocean wave data off Mangalore harbour on the west coast of India. The study indicated the validity of Rayleigh distribution for wave heights well beyond the narrow band assumption on the basis of which it is derived.

The main sources of long-term wave data are the atlases prepared using wave data reported by ships and provided by the Naval Physical and Oceanographic Laboratory (1978) and National Institute of Oceanography (1982).

Kesava Das et. al. (1981) had computed the wave power around the Indian coasts using the Indian Daily Weather Reports published by the India Meteorological Department for the period from 1968 to 1973. Of the 5 grids of 5^o squares (A,B,C,D and E), B and C cover stations off Mangalore and Trivandrum respectively where recorded wave information are available.

The average wave power potential along the Indian coasts was found to be 23 kw/m. The highest average wave power potential is on the eastern side of the Atlantic and the Pacific oceans and is about 2.5 times that of the Indian seas.

For grid B the wave power ranges from a minimum of 4.45 kw/m in April to a maximum of 61.15 kw/m in July. The average wave power for annual, fair weather (November to April) and rough weather (May to October) seasons were found to be 22.86 kw/m, 9.76 kw/m and 35.97 kw/m respectively. In the case of grid C, wave ranges from a minimum of 5.29 kw/m in February to a maximum of 43.05 kw/m in June. The average wave power for annual, fair weather and rough weather seasons were found to be 21.40 kw/m, 14.11 kw/m and 28.69 kw/m respectively. The reliability of these results are to be checked with the wave power obtained from recorded wave information from these grids.

Thomas (1988) described the various wave parameters of shallow water waves off Valiathura. The waves were always above 0.5 m in height and the maximum wave height (H_{max}) observed was 6.0 m during 1980-1984.

The zero-crossing period varied between 5 and 18 S. Long period waves (10 to 16 S) dominate during October-December. Short period sea waves of 3 - 6 S were observed during January-May.

The wave direction was dominated by waves from 190° to 210° during October–May. With the onset of monsoon, waves from 250° to 270° became prominent. The breaker characteristics and the beach profiles at Valiathura were also described by him.

Shahul Hameed (1988) studied the wave climatology and littoral processes at Alleppey. The maximum wave height recorded in the nearshore off Alleppey was 3.8 m during the peak monsoon. The maximum significant wave heights recorded were 3.0 m and 1.4 m during the rough and fair seasons respectively. The wave periods were 8–9 S during rough season and 9–11 S during fair season. The wave directions, breaker characteristics, longshore currents, beach characteristics etc., were also studied.

Waves and littoral processes at Calicut were examined by Kurian (1988). Harish (1988) studied these characteristics at Tellicherry. Shallow water wave spectral and probabilistic characteristics along the southwest coast of India were examined by Baba, Shahul Hameed and Harish (1988) using wave information at Alleppey. Most of the spectra examined had multiple peaks. The southern part of the coast shows the highest energy level almost throughout the year. A new theoretical spectral form (PMK), combining the models of Pierson–Moskowitz and

Kitaigorodskii was proposed for shallow water wave spectrum. It was found that in high energy conditions, the PMK spectrum slightly underestimated the peak energy density. The shallow water wave height distribution was represented by the simple function of Gluhovski. No satisfactory model was proposed by them for the wave period. The joint distribution of heights and periods was explained by the CNEXO function.

Kurian and Shahul Hameed (1988) discussed the wave transformations in shallow water. An important draw back in the study of wave transformation is the lack of measured data in synchronised deep water and shallow water. Characteristics of wave height and spectral transformation as observed for the southwest coast of India and other parts of the world are discussed. There is an attenuation in wave height and energy which varies from location to location.

The TMA spectrum simulated the observed shallow water spectra when the scale and shape parameters were derived from the observed. The heights were found to follow the Gluhovski distribution. The joint distribution of heights and periods followed the CNEXO group.

The different wave transformation processes are refraction, shoaling, wave breaking and non-linear dissipation processes. Reflection and diffraction were not considered for general cases because the coasts are straight with no coastal structures or offshore islets. The paper also presents a review of the available models used in literature for prediction of shallow water wave height.

Kurian and Baba (1988) studied the applicability of a model proposed by Dobson (1967) with certain modifications for predicting shallow water waves and established the universal applicability of the Dobson model.

Baba and Joseph (1988) gave a picture of deep water wave climate off Cochin and Trivandrum. The wave climate based on a year-round observation off Cochin and some intensive monsoonal observations off Trivandrum were reported. The intensity of wave action is higher at Trivandrum than at Cochin. The spectra at both locations are multipeaked throughout the year. The low frequency swell component is prominent off Trivandrum throughout the year.

Baba (1988) has given a description on the wave characteristics and beach processes of the southwest coast of India. The wave climate along this coast was subjected to both temporal and spatial variations. A long-term wave data for a given location will increase the confidence in the selection of design wave parameters. The Trivandrum coast due to its high wave power potential is suitable for a wave power development programme.

Muraleedharan, Nair and Kurup (1988) has observed the averaged visual wave statistics for the southwest coast of India. Long-term distributions of wave height (H_s), direction and power obtained from grid No.17 (5°-9°N, 73°-77°E) of the wave atlas published by the Naval Physical and Oceanographic Laboratory and grid No.I (5°-10°N, 75°-80°E) of the atlas published by the National Institute of Oceanography (These grids overlap over a rectangular area measuring $4^\circ \times 2^\circ$. The wave recording stations off Trivandrum and Valiathura are located in this overlapping area of the two grids.) were examined in the light of recorded wave information off Trivandrum. The distributions of wave height were tested with the Weibull, Rayleigh and exponential distributions. They found that the best fit was obtained for the Weibull probability density function.

The predominant wave directions obtained from the grids were in agreement with the recorded information off Trivandrum (20 m) during most of the months. Recorded wave directions at 5 m agreed with the atlases during monsoon and post-monsoon periods. The wave power computed for yearly, fair weather and rough weather periods from the sea and swell wave statistics (N.P.O.L) provided very low values while the swell data (N.I.O) showed good agreement in wave power derived from recorded wave statistics.

Ravindran and Raju (1988) discussed the wave energy utilisation prospects and problems in India. Among the various forms of Ocean Energy, Tidal Energy, Wave Energy, Ocean Thermal Energy are promising in the near future.

The annual average energy potential along our coast varied from about 3 kw/m to about 13 kw/m. The corresponding wave energy potential in the North Sea varied from 25-60 kw/m. Therefore in India, the wave energy plants is not going to be economical for a longer period. Wave energy group at I.I.T, Madras after studying the wave power for more than 5 years concluded that the barrier type wave energy device incorporating Oscillating Water Column principle will be more suitable for our country.

Baba (1988) gave a description on wave power potential of India with special reference to islands. The recorded 5-year data off Trivandrum at Valiathura showed that the mean monthly wave power varied between 4 and 25 kw/m. Here the average wave power was 17.5 kw/m during monsoon (May-October) and 5.3 kw/m during the non-monsoon season. He also pointed out that the reliability of the predictions with the ship data can be examined with recorded data. At present the only source for a preliminary examination of the wave power potential was obtained from the ship-data for Lakshadweep and Andaman and Nicobar Islands.

Deo (1988) has given a description of directional spectrum and its application. The representation of the sea surface spectral density function S(f) against various wave frequencies, f, constitutes the wave spectrum. If this representation is categorised into various directions of wave propagation (O), then directional spectrum, S(f,o) is obtained.

The surface spectral density function is proportional to the energy of the waves. Similarly the directional spectrum also gives the energy of the waves (per unit plain area) against various frequencies as well as direction.

In many ocean engineering studies, directional spectrum forms an essential input. Some cases in point are (1) problems pertaining to refraction of waves in the shoaling water (2) studies about growth and decay of waves (3) hindcasting and forecasting of waves in which directional spectrum gives origin of swells and its path, (4) determination of the spectra of motion of ships, moorings, floating vessels as well as of buoys, (5) diffraction of waves from an object, (6) studies pertaining to littoral drift, (7) response analysis of off-shore structures in which the directional spectrum is used in the wave forcing function to obtain the response spectra and (8) studies pertaining to erosion and siltation.

Kurian and Shahul Hameed (1989) studied the effects of shallow water transformation on the distribution of wave heights and periods using synchronised deep and shallow water data and a transformation model.

In order to study the wave transformation in Mirya Bay, Ratnagiri using wave data recorded by CWPRS at Mirya Bay, Ratnagiri during 1985-1986, Gadre and Kanetkar (1989) considered the changes in statistical characteristics of waves such as wave height, wave period, groupiness, band width etc. and also the transformation in spectral characteristics.

Kiran Kumar et. al. (1989) suggested that the procedure to estimate the long-term design wave heights at a sight was basically empirical in nature and involved alternative modelling and fitting techniques. Discrepancies were likely to occur in the predicted values in a particular analysis. He examined such variations with the help of the wind data collected for one year in the Bombay High region. The variations in short-term predictions were not reflected in the corresponding long-term predictions.

Muraleedharan, Kurup and Nair (1989) utilised the long-term wave data published in the atlases (N.P.O.L, 1978; N.I.O, 1982) to study the wave climatology off Mangalore.

Wave parameters obtained from grid No.9 of the N.P.O.L atlas and grid No.VII of the N.I.O atlas were used in this work. These grids overlap over a square area measuring $2^{\circ} \times 2^{\circ}$. The wave recordings off Mangalore at 10m depth were carried out in this overlapping area. Wave climatology off Mangalore was analysed utilising long-term (visual) and short-term (recorded) information. Observed long-term wave height distributions were tested with the Weibull, Rayleigh, Gumbel, log-normal and exponential curves. The best fit was obtained for the Weibull probability density function. Methods for computing maximum wave height and most probable maximum wave heights were suggested. A mathematical expression was derived for predicting the maximum wave height of a predetermined magnitude and also the probability of realising a wave height less than a designated value in a given period of time. The decennial wave heights so obtained were comparable with those predicted from recorded wave information. Of the various ratios of standard wave height parameters computed and predicted using theoretical Weibull distribution, $H_{1/3}/\bar{H}$ and $H_{1/10}$ / $H_{1/3}$ seem to be relatively more consistent.

In another investigation, Muraleedharan, Nair and Kurup (1990) tried to study the long-term wave statistics off Goa. Long-term wave statistics from grid No.9 (N.P.O.L atlas) and grid No.XIII(N.I.O atlas) off Goa were examined and compared with recorded wave information. Wave directions and average monthly frequency of waves in the period 5 to 8 S (Zero-crossing period) from grid No.XIII were comparable with recorded information at Goa. The theoretical and calculated values of significant wave heights were in agreement for grid No.9. The wave power averaged from swell statistics (grid No.XIII)were found to be much higher than that averaged from sea and swell statistics (grid No.9). They came to the conclusion that the degree of accuracy of the visually estimated wave data were sufficient for wave climatological studies provided it should be calibrated with recorded wave information.

Muraleedharan, Nair and Kurup (1990) observed the long-term wave characteristics off Trivandrum. The available atlases of averaged visual wave statistics (N.P.O.L, N.I.O) of the Arabian sea provided wave information which differ from one another. A comparative study of the long-term distributions of significant wave heights obtained from these atlases was made for an area off Trivandrum. The long-term distributions of significant wave heights were tested with Weibull, Gumbel, Rayleigh, exponential and log-normal models. The best fit was obtained for Weibull probability density function. Over estimates of peak percentage frequency of occurrence of wave heights amount to less than 11% and under-estimates less than 13%. The return period of the maximum significant wave height (7.5 m) obtained from N.P.O.L atlas was 2.27 years and that from N.I.O atlas (5.0 m) was 1.71 years. Average maximum significant wave heights to occur in a 5 year period were computed using Weibull model for combined sea and swell statistics separately. Nearly 95% waves lied in the height range 0 - 3.25 m. The most frequently occuring wave height for overall and monsoon data were 0.75 and 1.00 m (grid No.17, N.P.O.L), 1.33 and 1.75 m (grid No.I, N.I.O) respectively.

1.3. Scope of the present work

Whenever structures have been built in exposed locations failures are bound to come that must have been too expensive to remedy and often it will be in excess of the likely cost of any wave climate study. (Draper, 1970).

Ploeg (1968) suggested that there is a fairly sharp optimum cost of design for coastal structures, so that without a fairly good estimate of wave conditions, which are major parameters, it would be nearly impossible to come close to the optimum, and the cost would necessarily increase. Accurate wave information alone will help a designer to have estimate of having required precision. In addition, the results of a comprehensive wave climate study is highly essential for the assessment of utilisation of all kinds of surface vehicles, ships, drilling and for other civil and military purposes. Draper (1964) gave information on freak ocean waves. Estimates of the heights of the highest waves which could be encountered at sea vary widely. Thom (1971) had reported that there had been many reports of huge waves in the open oceans, and these might be considered as waves of extreme height. Draper (1973) suggested that information on extreme wave conditions is needed in the design of offshore structures. Although such events happen only rarely, this does not mean that their likelihood of occurrence is not predictable. This problem is discussed in chapter 2 with the aid of some theoretical formulae derived for the purpose. The only way to have reliable information of wave climate is to study them instrumentally and theoretically in all geographical areas.

The peculiar geographic set-up of the southwest coast which stretches from Cape Comorin to Mangalore has invited considerable developmental activities along the region. The adjoining sea is rich in fisheries. Two major ports (Cochin and Mangalore), and a large number of fishing harbours and fish landing centres are established along this coast. This coast lies along the major marine thoroughfare across the Arabian Sea between the Gulf countries and the Far East.

Coastal erosion and flooding are annually recurring problems along this coast. Siltation of harbours also poses another serious problem. A detailed understanding of wave climate is required to solve the above problems and for the planning of coastal developmental activities. The wave power potential of this coast is also high compared to the other coasts of the country.

The present work is an attempt to examine the reliability of the available averaged visual wave information. It is proposed to assess the degree of accuracy of the visually estimated wave data for application in wave climatological studies and to calibrate these data with recorded wave information.

1.3.1. Wave climate study using visual observations reported by ships of opportunity.

In the present section we discuss the reliability of the visual observations of wave information and their importance in wave climatological studies.

Cross (1980) attempted to summarise the reliability of the various data on wave climate study. Data bases used to analyse the offshore wave climate (San Francisco) were published ship's reports, hindcast studies by National Marine Consultants (NMC), and hindcasts based on U.S. Navy archives (1951-1974, FNWC-Fleet Numerical Weather Central). The first of these two were judged as more valid and were suggested for further project analyses.

Goldsmith, Victor and Sofer (1983) after studying the wave climatology of the Southeastern Mediterranean, came to the conclusion that of the wave climate developed from a variety of sources including visual ship observations and directional wave gauge measurements, the visual observations formed a reasonable representation.

Assessing the wave observations from ships in Southern Oceans, Laing (1985) found that there is very little consistency in the reporting of wind wave and swell periods and swell directions compared to heights which fared considerably better. Despite these inconsistencies, the intercomparisons showed that the data was representative of many of the physical characteristics of wave fields, and therefore could be useful in climatological studies.

Soares (1986) reported that visual observations of wave heights were still the main source of statistical information available for the prediction of extreme wave conditions to be used in the design of ship structures. He also suggested that visual observations of wave properties, especially mean wave periods, were an important source of statistical information needed for the prediction of design and operational conditions of ocean structures. But the observations were to be calibrated with measurements.

The importance of visual observations on wave climate study were also emphasised by Kumar, Sarkar and Dattatri (1989) by comparing it with satellite information. They dealt with the analysis of wave and wind statistics off the West Coast of India using SEASAT altimeter data. The wave data interpreted from SEASAT observations was found to be in good agreement with the averaged data from ships observations as published in the Wave Atlas by N.P.O.L , N.I.O and Monthly Meteorological Charts.

1.4. Materials and methods

1.4.1 Available wave information sources

The available sources of wave information for the seas around India consist of

(i) Wave information from satellites

(ii) Wave data recorded by wave recorders

(iii) Wave information hindcast from meteorological parameters, and

(iv) Visual observations on waves reported by ships of opportunity.

Sarkar (1988) reviewed the presently available remote sensing systems and their possible uses in the Indian context. The satellite derived oceanographic information are very much useful in maritime activities. The feasibility of detecting the oceanic waves on the satellite imageries has been evaluated by Nath and Rao (1989). A single satellite cannot meet all sampling conditions. Atleast two or three satellite systems are needed for wind and wave measurements. At present India does not have such a facility and satellite oceanography is only in the preliminary stage of development. Recorded wave data are very scanty due to obvious reasons. Wave forecast as obtained using the existing forecasting techniques that differ from one another due to limitations of the theories involved. Visual observations on waves reported in I.D.W.R compiled by different agencies also differ from one another depending on the temporal spread and method of analysis of the data.

1.4.2. Wave atlases

The scientists of N.P.O.L made use of wave data reported in the Daily Weather Reports of India Meteorological Department for the preparation of the wave statistics.

About 33,000 data from weather reports spread over ten years have been considered in this publication. For the preparation of the wave statistics, the part of the Arabian Sea, north of 5°N latitude and East of 61°E longitude has been divided into 17 zones of 4° squares. Two sets of tables are prepared, one showing the distribution of data irrespective of the direction and the other with the break-up of direction in sectors of 30° for each zone and month. Wave roses representing the direction of the waves, predominant direction and percentage of calm conditions are given for each zone and month. Wave data (direction, period and height of the wave) have been compiled from the weather charts for the area under reference for 10 years from 1960 to 1969. This compilation is published as an atlas entitled "Wave statistics of the Arabian Sea" (Fig. 1(a)).

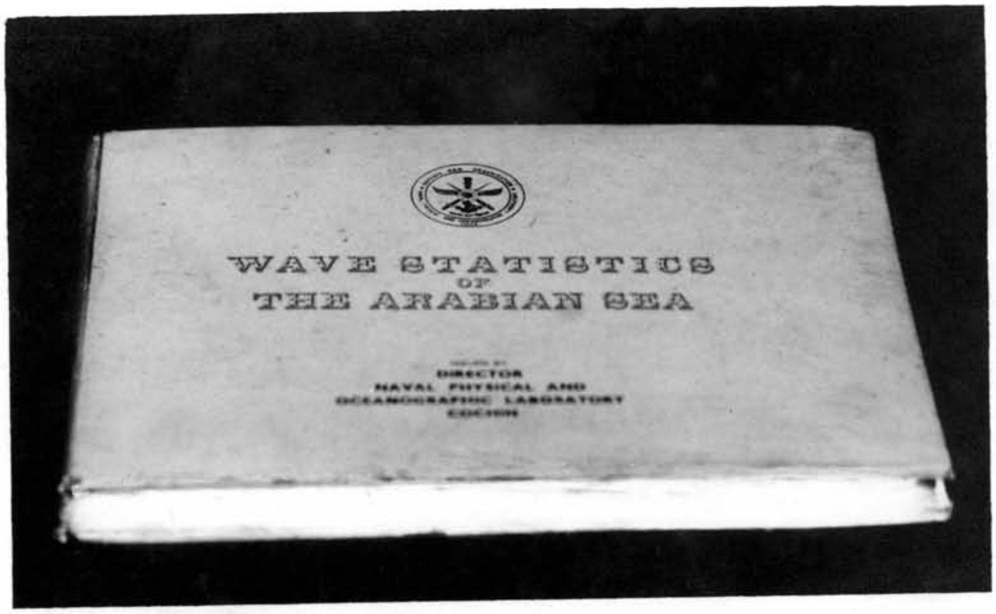

Fig. 1(a) N.P.O.L wave atlas.

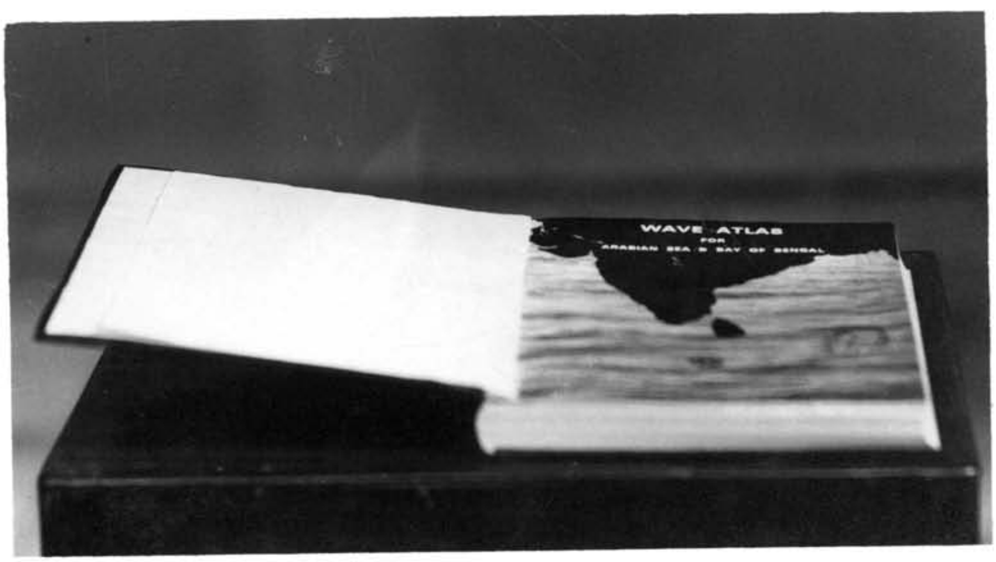

Fig. 1(b) N.I.O wave atlas.

With a view to provide a comprehensive information on swell characteristics, the National Institute of Oceanography prepared a swell atlas for the Northern Indian Ocean with equator, Asiatic land mass, 60°E meridian and 95°E meridian as the boundaries. This area was divided into twentynine 5° lat: longitude squares and the swell characteristics pertaining to each square are presented monthwise in polar diagrams.

The data on swell characteristics for the period 1968-1973 published in the Indian Daily Weather Reports were utilised for the preparation of this atlas, " Wave (swell) atlas for Arabian Sea and Bay of Bengal" (Fig.1(b)).

Published information on wave climate in limited regions along the Indian coasts are available in various journals. They are however, of limited, temporal and spacial coverage. The wave statistics (Wave height, wave period and wave direction) obtained from N.P.O.L atlas (1978), N.I.O atlas (1982) and published information are utilised in this study to clear the wave climate along the southwest coast of India.

1.4.3. <u>Methodology</u>

Gouveia and Mahadevan (1983) have pointed that many natural processes including waves are random in nature. Any statistically meaningful understanding of such phenomena requires particular system of analyses through some appropriate statistical techniques. Following are some of the important statistical functions used to describe the basic properties of a random process.

(i) Probability density function
(ii) Mean values
(iii) Auto correlation function
(iv) Spectral density function

After bringing logical and experimental support for the validation of using the probability density functions for modelling waves, certain theoretical aspects are investigated. The wave statistics computed from visual wave observations are compared with those from recorded wave measurements and these are then utilised to infer the wave climate along the south-west coast of India.

1.4.3.1. Long-term distributions of wave heights

At present main source of long-term distributions of wave heights are either the ship observations reported by IMD or the extrapolations of waves recorded for one year or hind-casts from storms known to have occurred in the area and their extrapolation (Baba, 1985). The probability distributions used in literature to model wave heights are generally the log-normal, exponential, Weibull and Gumbel distributions (Baba, 1985; Dattatri, 1981). Rayleigh distribution was also tried for long-term distributions of wave heights after accommodating a relative height factor, $\bar{H}/d$ in Rayleigh distribution as recommended by Gluhovski in 1968 (Baba, 1985). For deep water conditions $\bar{H}/d \longrightarrow 0$ and the Gluhovski distribution assumes the form of Rayleigh distribution (Shahul Hameed and Baba, 1985). In other words, in deep water the Gluhovski distribution behaves as a Rayleigh distribution. The data obtained from the west coast of India near Mangalore over a period of 18 months during 1968-1969 were also utilised for examining the fitness of the Rayleigh distribution with the distributions of wave heights obtained from recorded information (Dattatri, Sankar and Raman, 1976). The present study attempts to use the Weibull distribution for modelling wave height and to establish that it is much superior to the available competing models described earlier. The principal motivations for using the Weibull model are explained in chapter 2. The model was fitted with long-term distributions of wave heights (H_s) obtained from 17 grids of the N.P.O.L atlas and 12 grids of the N.I.O atlas which cover nearly the same part of the Arabian Sea. The larger and more obvious waves in a chaotic sea condition is known as significant wave and the evaluation of significant wave height (H_s) from actual wave records was given by Draper (1966). Significant wave height is nearly equal to that height reported from visual observations by ships.

The properties of the Weibull model and the methods of estimating its parameters are explained in section 2.2 of chapter 2. Since it was seen that there is considerable experimental support for the Weibull distribution for explaining the long-term distributions of wave heights, a plausible theoretical explanation is given in section 2.2 of chapter 2.

After observing that there is both experimental and logical support for the Weibull distribution as a reasonable model for wave heights on the basis of wave height information from 29 grids of N.P.O.L and N.I.O atlas, certain theoretical aspects such as formulae for computing the mean wave height, coefficient of variation, median, significant wave height (H_s), one-tenth of the highest wave height ($H_{1/10}$), maximum wave height, most probable maximum wave height are also derived. Also included in this connection are certain equations that enable the prediction of the return period of a maximum wave height of a predetermined magnitude and also the probability of realising a wave height less than a designated value in a given period of time.

The long-term distributions of wave heights obtained from the coastal grids (17, 9) of N.P.O.L atlas and coastal grids (I and VII) of N.I.O atlas are tested with Weibull, Gumbel, log-normal, Rayleigh and exponential models. Grid 17 (N.P.O.L) and grid I (N.I.O) overlap over a rectangular area measuring $4^o \times 2^o$ (Fig.2). The wave recording stations off Trivandrum and Valiathura are located in this overlapping area of the two grids. At Valiathura (off Trivandrum), since it has a steep offshore, there is a proximity to the waves generated in the deeper ocean (Baba, 1985). Also grid 9 (N.P.O.L) and grid VII (N.I.O) overlap over a square area measuring $2^o \times 2^o$ (Fig.3). Published wave statistics obtained from wave recordings off Mangalore were from this overlapping area. Dattatri and Renukaradhya (1971) suggested that the deep water waves are directly comparable to shallow water waves off Mangalore since the crests travel parallel to the coast, the bottom contours being practically parallel to the coast, the coast being a very flat one and the refraction and shoaling coefficients are very nearly unity. The appropriateness of the various models tested in this connection are assessed in sections 2.2 and 2.3.

Draper (1973) had pointed the importance that, before the construction of any structure it is necessary to undertake a detailed study covering a large area around the site to ensure that no focussing of waves, even from large distances or confused seas are likely to occur at the site.

Accordingly, wave statistics obtained from grid 17 (N.P.O.L) and grid I (N.I.O) are compared with those obtained from wave recordings in the overlapping area of these grids to clear the wave climate. Similarly wave statistics obtained from grid 9 (N.P.O.L) and grid VII (N.I.O) are also compared with those from wave recordings off Mangalore.

1.4.3.2. Wave power

Wave power is defined as the rate of energy transfer per unit area per unit crest width across a plane normal to wave propagation (Thomas et.al. 1986). For deep water

$$P = \frac{\rho g^2 H_s^2 T_z}{64\pi} \text{ Watts } m^{-1}$$

where 'P' is the wave power, ρ - water density, g - acceleration due to gravity, H_s - significant wave height and T_z - the zero-crossing wave period. (Salter, 1974). For intermediate depths the wave power is estimated as

$$P = \frac{\rho g^2 H_s^2 T_z}{64\pi} \left[1 + \frac{4\pi d/L}{\mathrm{Sinh}(4\pi d/L)}\right] \tanh(2\pi d/L)$$

where d - water depth and L - the wave length at this depth.

The wave power available in a random sea is given by the relation $P = 0.55\ H_s^2\ T_z$ (Raju and Ravindran, 1987). This expression is considered in the present work. T_z is computed using the relation obtained by Dattatri (1971) for swell prevailed sea state as

$$T_s = 1.3T_z - 2.5,$$

where T_s is the significant wave period.

The wave power computed from grid 17 (N.P.O.L) and grid I (N.I.O) are compared with the wave power computed from recorded wave information at Valiathura. The wave power computed from grid 9 (N.P.O.L) and grid VII (N.I.O) is to be compared with those obtained from recorded data from the overlapping area of these grids for emphasizing reliability on the results.

1.4.3.3. Wave direction

The predominant wave directions published in the atlases for grid 17 and grid I were compared with directions obtained at Valiathura (5m) and off Trivandrum (20 m). The directions obtained from grid 9 and grid VII are to be compared with measured wave directions at the overlapping area of these grids.

1.4.3.4. Long-term distributions of wave periods (T_s)

The wave periods published in the atlases are considered as significant wave periods (T_s). It is the mean period of the highest one-third wave height in a wave record. The long-term distributions of wave periods published in the atlases by N.P.O.L (grid 17, grid 9) and N.I.O (grid I, grid VII) were compared with Bretschneider distribution, gamma distribution, exponential distribution and Rayleigh distribution. The parameters of these models are estimated by the method of maximum likelihood. Bretschneider (1959) had showed that the distributions of the square of the wave periods could be represented approximately by a distribution with density function

$$P(\frac{T}{\bar{T}})\ d(\frac{T}{\bar{T}}) = 2.7 \quad \frac{T^3}{(\bar{T})^4} \quad \exp^{-0.675(\frac{T}{\bar{T}})^4}\ dT$$

where ($\bar{T}$) is the mean wave period.

Putz (1952) had obtained a gamma-type distribution function to represent wave periods. Based on these investigations, in the present work, the Bretschneider and gamma distributions were fitted for the wave periods. Also by examining some monthly data on visually averaged long-term distributions of wave periods (N.P.O.L, N.I.O), the exponential model also was tried, as another possible alternative. Further, consequent on the suggestion of Baba and Harish (1985) that the swell wave periods fit closer to the Bretschneider distribution and that the sea wave periods to the Rayleigh distribution of the form

$$P(T) = \exp\left(- \frac{\pi}{4} \left(\frac{T}{\bar{T}} \right)^2 \right),$$

the Rayleigh distribution has also been fitted for explaining the long-term wave period distributions. The details of these investigations are reported in chapter 4.

Chapter-2

DISTRIBUTION OF WAVE PARAMETERS

Chapter-2

DISTRIBUTION OF WAVE PARAMETERS

2.1. Introduction

The focal theme of the present study as defined in section 1.3 is to critically examine the reliability of the available averaged visual wave information; which is achieved here by first establishing an appropriate long-term distribution for wave heights. As has been described earlier, our choice of the long-term distribution for wave heights is Weibull. Accordingly in the next section we look at the properties of the Weibull distribution and some of the reasons for it being a versatile model that can represent many natural phenomena.

2.2. The Weibull distribution

The Weibull distribution was discovered as early as the latter half of the twenties in a discussion relating to the asymptotic distribution of the extreme values in sample. The richness in flexibility enjoyed by this model through a judicious choice of values of its parameters has made it a favourable distribution in many areas of practical application. A random variable X possesses a Weibull distribution if it has a probability density function of the form

$$f(x;\ a,b) = \frac{b}{a} \left(\frac{x}{a} \right)^{b-1} \exp\left(-\left(\frac{x}{a} \right)^{b} \right) \qquad (2.1)$$

$$x,a,b > 0$$

The cumulative distribution function is

$$F(x;\ a,b) = 1-\exp\left(- \left(\frac{x}{a} \right)^{b} \right) \qquad (2.2)$$

Notice that a functions as the scale parameter and b as the shape parameter of the model. By assigning appropriate values of b we can generate L-shaped, skew or symmetric curves from equation (2.1). Further when b = 1

$$f(x,a) = \frac{1}{a} \exp - \left(\frac{x}{a} \right),$$

the exponential distribution and when b = 2

$$f(x;a) = \frac{2}{a} \left(\frac{x}{a} \right) \exp \left(- \left(\frac{x}{a}\right)^{2} \right), \qquad (2.3)$$

the Rayleigh distribution, which is widely used as the model for wave heights. When X follows Weibull, it can be shown that Y = - log x has the Gumbel's extreme value distribution. There is also some approximations available between the Weibull and the gamma and lognormal distributions. It is thus evident that the Weibull fits all data that follows the exponential or Rayleigh and approximately fits several types of data that represents positively skewed distributions such as gamma and lognormal.

The mean and variance of the distribution (Johnson and Kotz, 1970) are respectively,

$$m = a\,\Gamma(1 + b^{-1}) \tag{2.4}$$

and

$$\sigma^2 = a^2\,(\Gamma(1+2b^{-1}) - \Gamma^2(1+b^{-1})) \tag{2.5}$$

where $\Gamma(p)$ is the usual gamma function defined by

$$\Gamma(p) = \int_0^\infty e^{-x}\,x^{p-1}\,dx, \; p > 0$$

In order to fit the distribution in actual practice one needs the estimates of the parameters in terms of the observations.

In the present study we have used the following method of estimation. From the expressions for the mean and variance in equations (2.4) and (2.5) we find that coefficient of variation is

$$\frac{\sigma}{m} = \Gamma(1+2b^{-1}) - \Gamma^2(1+b^{-1}) \,/\, \Gamma(1+b^{-1}) \tag{2.6}$$

Equating σ/m with the coefficient of variation of the sample viz. $S/\bar{x}$, where S and $\bar{x}$ are respectively the standard deviation and mean of the sample, we find

$$S/\bar{x} = \Gamma(1+2b^{-1}) - \Gamma^2(1+b^{-1}) / \Gamma(1+b)^{-1} \qquad (2.7)$$

The parameter b is estimated from the last equation, using the table of b values corresponding to the coefficients of variation given in Sinha (1986). New, equating the same and population means

$$\bar{x} = a\Gamma(1+b^{-1}) \qquad (2.8)$$

which provides the value of a as

$$\hat{a} = \bar{x} / \Gamma(1+\hat{b}^{-1})$$

where b is obtained from equation (2.7).

The estimates $\hat{a}$ and $\hat{b}$ thus obtained can be used as starting values in obtaining the more accurate maximum likelihood estimates which has many optimal properties. The new accurate estimates are the solutions of the equations,

$$\Sigma\left(\frac{X_i}{a}\right)^b = n \qquad (2.9)$$

and

$$\Sigma \left(\frac{X_i}{a} \right)^b \log x_i - \Sigma \log x_i = \frac{n}{b} = 0 \qquad (2.10)$$

by trial and error, after renaming a^b as p and then solving for a from p using $\log a = b^{-1} \log p$.

2.3. Motivations for using Weibull distribution

The motivations for using the Weibull distribution for modelling wave heights in the present investigation are as follows.

Of the various models used in literature for modelling wave heights only the Rayleigh distribution seems to have been derived mathematically on the basis of the physical characteristics governing wave heights. The conditions under which such a model arises are

(i) Spectrum of the waves consist of a single narrow frequency band and the disturbance is made up of a number of random components.

(ii) Each generating area is sufficiently large compared with a wave length so that the phases of contributions from different regions are independent enabling to write the enveloping function as

$$B = b_1 + b_2 + \dots + b_n$$

(iii) Each component b follows exponential distribution such that $\Sigma bj^2 = b^2$ (fixed) and $bj^3 \longrightarrow 0$ as $n \longrightarrow \infty$. Longuet-Higgins (1952) derived the distribution of wave heights H as

$$f(h;a) = (2h/a^2) \exp - (h/a)^2 \qquad (2.11)$$

This is a particular case of the Weibull distribution for b=2. Empirical studies reveal that the Rayleigh distribution does not provide a good fit to many data.

For the short-term wave height distribution, Longuet-Higgins (1952) has shown that the probability density function of individual wave heights is represented by a typical Rayleigh distribution, if (i) the distribution of instantaneous surface elevations are assumed as Gaussian normal, (ii) wave energy is confined to a narrow range of frequencies, and (iii) ocean waves are assumed as the result of superposition of many sinusoidal components in random phase. These conditions are not satisfied in many situations as was reported by Baba (1985) who found that most of the data deviate from Rayleigh. The main reasons can be attributed to natural conditions that do not meet the assumptions (i), (ii) and (iii) specified above. Contributions from the different parts of the generating area are to be super posable means that the mechanical system we are dealing with is linear, which is true generally for low waves in deep water and not for waves tending to attain maximum height. Hence we need a model that can meet the twin objectives of

(a) accommodating the Rayleigh distribution whenever the basic assumptions that justify it are satisfied, and

(b) fitting data situations under more general conditions.

One way of achieving this is to make equation (2.11) more flexible by adding one more parameter to it. The universal constant 2 in the factor exp $-(h/a)^2$ in (2.11) means that the curve can provide only the same shape irrespective of the values of 'a' which changes only the scale. This motivates the use of an arbitrary positive quantity 'b' in the place of 2 in the exponent in equation (2.11) to arrive at equation (2.1).

Thus the modified curve becomes Rayleigh whenever b=2 and our twin objectives stated above are satisfied.

Apart from accommodating curves of different shape in the modification suggested above, another possible explanation for the Weibull curve can be offered in terms of the intensity function described below.

Let H be the continuous random variable representing the wave height in a specified region taking values in the interval (O,W) where W is the maximum height to which wave can rise. For a given height h, the probability that H exceeds h is

$$P\ (H > h)\ =\ 1-F(h) \qquad (2.12)$$

where F(h) is the distribution function of H. The probability that a wave of height h decays before height h+dh is attained (the decay takes place within an infinitesimal height dh) is

$$P(h < H < h+dh \mid H > h) = \frac{P(h < H < h+dh)}{P(H > h)}$$

$$= \frac{f(h)\ dh}{1-F(h)} \qquad (2.13)$$

where f(h) is the density function of H. If the right side of (2.13) is denoted by k(h)dh, k(h) represents the intensity at which a wave of height h begins to decay. From a knowledge of the form of the function, one can determine the distribution of H as (Gumbel, 1954)

$$f(h)\ =\ k(h)\ \exp\left(-\int_0^h k(t)\ dt\right) \qquad (2.14)$$

For the Longuet-Higgins (1952) model of wave heights

$$k(h) = 2h/a^2 \qquad (2.15)$$

So that the intensity of decay is directly proportional to the height of the wave. On the other hand for the Weibull model

$$k(h) = (b/a^b)\ h^{b-1};\ a,b > 0 \qquad (2.16)$$

The rate at which the intensity changes is $\frac{dk(h)}{dh}$. So that for the Rayleigh distribution it is $2a^{-2}$, which is a constant. In the Weibull case it becomes $b(b-1)a^{-b}\ h^{b-2}$, which varies with h.

The main point here is that the proportion of waves that decays when they passes height h, increases as the value of h increases in both the models. While for Rayleigh model this increase proportion for unit change in height remains the same, for the Weibull case the proportion decaying increases at a faster rate. (Here we assume that the parameter $b>1$, which is justified empirically). In other words the proportion decaying at high values of h is much greater than the proportion of waves decaying at smaller heights. This appears to be more realistic than a uniform increase in proportion according to the Rayleigh model, especially when the narrow band assumption does not hold.

In any case, it is important to note that the assumption of Weibull law does not contradict the Longuet-Higgins conditions, which is automatically satisfied in situation favourable to it, but only supplements it by extending the condition to more general situations. The empirical findings in the later chapters also supports the same view point.

Once the long-term distribution of wave heights is assumed to be Weibull, it is possible to have specific expression for the different wave parameters. In the following sections we derive some formulae in this connection.

2.4. Significant wave height

If $h_1, h_2, \ldots, h_N$ form a sequence of wave heights that are arranged in descending order of magnitude, $h^{(p)}$ stands for the mean of the first pN values where $0 \leqslant p \leqslant 1$. We shall first derive a formula for $h^{(p)}$ and then deduce the significant wave height and mean of all waves.

The probability that the wave height H should be larger than an observed value h is obtained from equation (2.2) as

$$
\begin{aligned}
1-F(h) &= P(H > h) \\
&= \exp(-(\frac{h}{a})^b) \qquad (2.17)
\end{aligned}
$$

Since this should be the theoretical equivalent of p,

$$p = \exp\left(-\left(\frac{h}{a}\right)^b\right)$$

or

$$h_p = a(-\log p)^{1/b} \qquad (2.18)$$

The mean value $h^{(p)}$ of those H's that are larger than h is

$$h^{(p)} = E(H \mid H > h)$$

$$= E(H-h \mid H > h_p)+h \qquad (2.19)$$

where E stands for the usual expectation operator. Now,

$$E(H-h|H > h_p) = (1-F(h)^{-1}) \int_o^h (x-h)f(x)dx$$

$$= R(h) \int_h^\infty (x-h) \left(\frac{-dR}{dx} \right)dx$$

$$= R(h) \int_h^\infty R(x)dx \qquad (2.20)$$

where $R(x) = 1-F(x)$. Using equation (2.17) for R(h),

$$E(H-h|H > h_p) = \exp\left(\frac{h}{a}\right)^b \int_h^\infty \exp\left(-\left(\frac{x}{a}\right)^b\right)dx$$

$$= \exp\left(\frac{h}{a}\right)^b \frac{a}{b} \int_{\left(\frac{h}{a}\right)^b} e^{-y}\, y^{\frac{1}{b}-1}\, dy$$

$$= p^{-1}\, ab^{-1} \int_{\left(\frac{h}{a}\right)^b} e^{-y}\, y^{\frac{1}{b}-1}\, dy$$

Thus from (2.19)

$$h^{(p)} = h_p + p^{-1} ab^{-1} \int_{-\log p}^{\infty} e^{-y} y^{\frac{1}{b}-1} dy$$

$$= a(-\log p)^{1/b} + p^{-1} ab^{-1} I_{-\log p}(b^{-1}) \quad (2.21)$$

where $I_t(p) = \int_t^{\infty} e^{-x} x^{p-1} dx$ is the incompleted gamma function. The significant wave height is obtained when $p = \frac{1}{3}$, as

$$h^{(1/3)} = a(\log 3)^{1/b} + 3ab^{-1} I_{\log 3} (b^{-1}) \quad (2.22)$$

and the average of all waves,

$$h^{(1)} = ab^{-1} \Gamma(b^{-1})$$

Since the incomplete gamma function is tabulated for all ranges of b^{-1} it is easy to apply (2.22).

It is to be noted in this connection that the formula (2.22) refers to the population of all waves while the actual $h^{(1/3)}$ refers to the significant wave height in a sample of N wave heights. Strictly speaking, these two values should be different, especially when N is small. However, when N is large, the deviations between the two will not be significant and can therefore, be neglected.

2.5. Maximum wave height

If $H_1, H_2, \ldots, H_n$ is a sample of n wave heights, the probability for the largest of them should not exceed h is

$$\begin{aligned} P(\max H_i \leqslant h) &= P(H_1 \leqslant h,\ H_2 \leqslant h,\ \ldots,\ H_n \leqslant h) \\ &= P(H_1 \leqslant h)\ P(H_2 \leqslant h)\ \ldots\ P(H_n \leqslant h) \\ &= (F(h))^n \\ &= (1-\exp[-\ (\tfrac{h}{a})^b\ ])^n \end{aligned}$$

Accordingly, the density of max H_i is

$$\begin{aligned} f_1(h) &= \frac{d}{dh}\left\{1-\exp[-(\tfrac{h}{a})^b]\right\}^n \\ &= n\left\{1-\exp[-(\tfrac{h}{a})^b]\right\}^{n-1} \exp[-(\tfrac{h}{a})^b]\ \frac{b}{a}\ (\tfrac{h}{a})^{b-1} \end{aligned} \tag{2.23}$$

From equation (2.2) the mean value of maximum wave height is

$$\begin{aligned} E(\max H_i) &= \int h\ f_1(h)\ dh \\ &= \int_0^\infty h\ \frac{nb}{a}\left\{1-\exp[-(\tfrac{h}{a})^b]\right\}^{n-1} \exp[-(\tfrac{h}{a})^b](\tfrac{h}{a})^{b-1}\ dh. \end{aligned}$$

To evaluate the integral, we introduce the transformation $y = (\frac{h}{a})^b$ to obtain

$$E(\max H_i) = na \int_0^\infty (1-e^{-y})^{n-1} e^{-y} y^{1/b} dy$$

Integrating the last expression by parts

$$= ab^{-1} \int_0^\infty [1-(1-e^{-y})^n] y^{\frac{1}{b}-1} dy \qquad (2.24)$$

Using the binomial expansion

$$(1-e^{-y})^n = \sum_{r=o}^{n} (-1)^{r-1} \binom{n}{r} e^{-ry}$$

(2.24) reduces to

$$E(\max H_i) = ab^{-1} \sum_{r=1}^{n} \binom{n}{r} (-1)^{r-1} \int_0^\infty e^{-ry} y^{\frac{1}{b}-1} dy$$

$$= ab^{-1} \sum_{r=1}^{n} \binom{n}{r} (-1)^{r-1} \Gamma(\frac{1}{b}) / r^{1/b} \qquad (2.25)$$

Formula (2.25) can be used to tabulate the mean maximum wave heights.

2.6. Most probable maximum height

Once the distribution of H is taken to be Weibull, the most probable wave height in the region is given as the median of the distribution. This is

$$H_o = (\log 2)^{1/b} \text{ for } b > 1$$

However, more interest will be on the maximum height that is most likely, which is by the reasoning as above, the mode of the distribution $f_1(h)$ in equation (2.2). Differentiating (2.2) with respect to h, the mode is obtained as the solution of the equation

$$(1-e^{-y})(b-1)-(1-e^{-y})yb + (n-1)e^{-y} by = 0 \qquad (2.26)$$

where $y = (h/a)^b$

or

$$e^{-y} = \frac{(b-1) - yb}{(b-1) - nyb}$$

The last equation can be solved by numerical methods like the Newton-Raphson technique. If y_o is an approximate solution

$$y_o = \left(\frac{h}{a} \right)^b$$

or

$$h = a{y_o}^{1/b}$$

which is the most probable maximum height.

2.7. Analysis of return periods

The wave heights observed daily in a particular grid can be thought of as a random variable following Weibull law. It has been shown in section 2.4 that the distribution of the maximum wave height is specified by

$$G(h) = (F(h))^n = (1-\exp[-(\frac{h}{a})^b])^n$$

Therefore, the probability that a specified value h_m is exceeded is

$$P(H_{max} > h_m) = 1-G(h_m)$$

$$= 1-(1-\exp[-(h_m/a)^b])^n$$

In a series of observations on the daily maximum height the probability that the n^{th} observation is the first value that exceed h_m is $(1-G)G^{n-1}$, $n = 1,2,3,\ldots$. The expected value of n is

$$E(n) = (1-G)^{-1}$$

$$= \left\{ 1-(1-\exp(-(h_m/a)^b))^n \right\}^{-1}$$

Obviously E(n) is greater than 1 since $0<G<1$. The average number of observations included between two adjacent wave heights that exceed h_m is E(n). As we are observing the largest wave height that occurs every day, the number of observations E(n) equals the number of days that lies between the appearance of maximum wave heights that exceeds h_m. Thus E(n), infact represents a period in which a maximum wave height larger than h_m is observed. In other words denoting this period by

$$t(h_m;a,b) = \left\{1-(1-\exp[-(h_m/a)^b]^n\right\}^{-1}$$

or

$$(1-\exp[-(h_m/a)^b])^n = (1-(1/t))$$

or

$$\exp[-(h_m/a)^b] = 1-(1-(1/t))^{1/n}$$

or

$$h_m = a\left\{-\log\left[1-(1-(1/t))^{1/n}\right]\right\}^{1/b} \qquad (2.27)$$

Equation (2.27) provides a fundamental relation that connects a prescribed maximum wave height and its average return period or time of re-occurrence.

Another question that is of interest at this juncture is given a period of time t, what is the probability that level h_m is never realised in m years.

For this we assume that P is the probability that a level larger than h_m will not be realised in 'm' consecutive years.

$$P = (1-G)^m = (1-(1/t))^m$$

Note that t increases if h_m increases. Hence when wave heights anticipated are larger and larger, the return periods also become larger. ie, usually large wave heights are realised only over longer periods of time. Since t is larger than 1, binomial expansion is valid at as a first approximation.

$$P = 1 - (m/t)$$

$$P = 1 - m \exp - [n(h_m/a)^b]$$

The probability of realising a height of h_m during any one of the m years is 1-p = q.

2.8. Other models

The wave height models for examining the long-term distributions of wave heights are mainly Weibull, Gumbel, log-normal and exponential. Rayleigh model is also recommended by many researchers for this purpose. A brief review on the above mentioned models, will now be made.

Depending on the nature of constants used there are three types of extreme value distributions, viz. Type-I (Gumbel), Type-II (Cauchy) and Type-III (Weibull).

The Probability density function of the Type-I distribution is given as

$$P(x) = \frac{1}{\Theta} \exp(- \frac{(x-u)}{\Theta}) \exp (-e^{-\frac{(x-u)}{\Theta}}); \Theta > 0$$

where Θ and u are the parameters of the model. In order to estimate these parameters we use the method of moments to obtain estimators

$$\Theta = (\sqrt{6}/\pi).S$$

where S - sample standard deviation

and

$$\hat{U} = \bar{x} - r\Theta$$

where r is the Euler's constant given by

$\underset{n \to \infty}{Lt} (1 + \frac{1}{2} + \frac{1}{3} + \ldots \frac{1}{n} - \log n) = 0.5772157 \ldots$ and $\bar{x}$ is the sample mean. The mean and variance are respectively $u + 0.57722\Theta$ and $\frac{1}{6}\pi^2\Theta^2$.

The lognormal distribution in its simplest form may be defined as the distribution of a variate whose logarithm obeys the normal law of probability. (Aitchison and Brown, 1957). It is also known as Galton-McAlister, Kapteyn or Gibrat distribution, and the logarithmico-normal.

It arises from a theory of elementary errors combined by a multiplicative process.

McAlister is the first person to set down explicitly a theory of the lognormal distribution.

$$f(x) = \frac{1}{x\sigma\sqrt{(2\pi)}} \exp\left\{-\frac{1}{2\sigma^2}(\log x-\mu)^2\right\} dx; \ x > 0$$

is the probability density function of the lognormal distribution. μ and σ are parameters. The distribution is positively skewed and it has positive kurtosis. The mean and variance are respectively

$$e^{\mu+\frac{1}{2}\sigma^2} \quad \text{and} \quad e^{2\mu+\sigma^2}(e^{\sigma^2}-1)$$

The exponential distribution is a univariate continuous model with density function

$$f(x) = \frac{1}{\theta} e^{-x/\theta}; \ 0 < x < \infty, \ \theta > 0$$

$$= 0, \text{ elsewhere}$$

where θ is a parameter to be estimated as $\Sigma \frac{x}{n} = \theta$ where θ is the sample mean. The mean of this distribution is θ and variance is θ^2.

2.9. Models for long-term wave period (T_s) distributions

The gamma distribution has density function

$$f(x) = \begin{cases} \frac{1}{\beta^{\alpha}\ (\alpha)} x^{\alpha-1} e^{-x/\beta}; & x>0,\ \alpha>0,\ \beta>0, \\ 0 & , \text{elsewhere} \end{cases}$$

where α and β are parameters.

For different values of α and β we get a family of distributions, called the gamma family of distributions. $\alpha\beta$ is the mean value and $\alpha\beta^2$ is the variance of this distribution. The Probability density function P(T) of Bretschneider (1959) distribution for the square of the wave periods (T^2) is given to be

$$P(T) = 2.7\ (T^3/\bar{T}^4)\exp[-0.675(T/\bar{T})^4\ ]$$

where $\bar{T}$ is the mean wave period. This distribution explains the wave periods satisfactorily when dominated by swells (Baba and Harish, 1985). The strong base of this function is on the narrow bandedness of the wave spectrum, which can be observed in the swell dominated sea-state.

The exponential and Rayleigh models are also suggested for long-term wave period distributions after examining certain wave period distributions obtained from N.P.O.L atlas and N.I.O atlas.

Chapter-3

ANALYSIS OF WAVE CLIMATE OFF TRIVANDRUM AND MANGALORE

Chapter-3

ANALYSIS OF WAVE CLIMATE OFF TRIVANDRUM AND MANGALORE

3.1. Introduction

In the preceding chapter we have examined reasons for preferring the Weibull model over other competing alternatives for describing long-term distributions of wave heights and also obtained mathematical relations for significant wave heights, maximum wave height, most probable maximum wave height and period of re-occurrence of wave height of a pre-determined magnitude. The analyses of the wave height distributions (visual) in comparison with the available theoretical models are carried out in the present chapter. In addition, the reliability of the theoretically obtained parametric relations are tested with the help of available recorded wave information off Trivandrum and Mangalore.

3.2. Weibull model for modelling long-term wave height distributions

It has been explained that the available models for explaining long-term wave height distributions are mainly four. The Rayleigh distribution has also been tried for this purpose. (Dattatri, Sankar and Raman, 1976; Baba, 1985). The experimental results obtained by various researchers for recorded wave information led to the conclusion that there is no reason to prefer any one model over the others. (Dattatri, 1978; Baba, 1985).

In the light of the strong case that has been advanced over its choice, the Weibull model is fitted for the long-term distributions of wave heights obtained from 17 grids of the N.P.O.L sea and swell atlas and 12 grids of the N.I.O swell atlas. First, the model is fitted for approximate values of a* and b*. After ascertaining experimental evidence in support of the model using such approximate values, more accurate values of the parameter were redetermined using the method explained in section 2.2. The approximate and revised values of a and b for various months and grids are given in tables I and II. The results obtained for approximate a and b and, revised a and b are given in tables III(a,b) and tables IV(a,b). The agreement between theory and observations were finally checked with the aid of the χ^2 goodness of fit test at 5% level of significance. The relative gain obtained after revising the estimates of a and b are exhibited in tables III(a,b) and IV(a,b). The grids where χ^2-test failed have been deleted from the total number of grids considered. The χ^2 test was carried out to ascertain whether there is any seasonal pattern exist as regards the appropriateness of

Table I

Approximate (scale parameter-a*, shape parameter-b*) and revised (scale parameter-a, shape parameter-b) parameters of Weibull model for N.P.O.L wave height data.

Month	JANUARY				FEBRUARY				MARCH				APRIL			
Grids	a*	b*	a	b	a*	b*	a	b	a*	b*	a	b	a*	b*	a	b
1	0.88	1.08	0.92	1.21	0.76	1.03	0.80	1.22	0.91	1.10	0.95	1.28	0.80	1.16	0.84	1.49
2	0.84	1.32	0.86	1.58	0.79	1.24	0.81	1.36	0.97	1.26	0.99	1.41	1.01	1.47	1.01	1.57
3	1.07	1.53	1.07	1.59	0.86	1.05	0.92	1.35	0.66	1.07	0.68	1.18	0.69	1.19	0.71	1.39
4	1.24	1.43	1.26	1.57	0.95	1.40	0.97	1.54	0.82	1.13	0.86	1.30	0.65	1.13	0.68	1.35
5	1.15	1.47	1.16	1.59	0.91	1.18	0.94	1.36	0.96	1.54	0.96	1.58	0.90	1.41	0.91	1.51
6	1.21	1.85	1.21	1.85	1.19	1.33	1.19	1.39	0.56	1.02	0.59	1.21	0.55	1.04	0.58	1.21
7	1.23	1.51	1.24	1.62	1.01	1.75	1.01	1.81	0.96	1.45	0.97	1.51	1.04	1.20	1.03	1.15
8	1.13	1.85	1.13	1.91	0.71	1.52	0.72	1.70	0.93	1.37	0.94	1.49	0.87	1.46	0.88	1.51
9	0.89	1.23	0.91	1.37	0.82	1.63	0.82	1.71	0.99	1.21	1.02	1.41	0.67	1.02	0.71	1.21
10	1.26	2.56	1.26	2.67	1.11	2.20	1.11	2.03	0.75	1.01	0.79	1.14	0.92	1.04	0.97	1.19
11	1.19	2.04	1.19	2.03	1.01	1.55	1.02	1.65	0.81	1.36	0.81	1.40	0.69	1.05	0.73	1.25
12	1.00	1.53	1.01	1.62	0.85	1.59	0.85	1.72	0.72	1.23	0.73	1.36	0.79	1.38	0.80	1.48
13	0.77	1.04	0.82	1.30	0.63	1.27	0.64	1.46	0.77	1.36	0.78	1.51	0.67	1.15	0.70	1.42
14	1.32	1.69	1.33	1.75	1.26	2.56	1.26	2.74	1.17	1.86	1.16	1.57	0.83	1.29	0.84	1.39
15	1.23	3.05	1.24	1.75	0.90	1.56	0.90	1.62	0.81	1.34	0.81	1.43	0.71	1.18	0.73	1.39
16	0.97	1.62	0.98	1.71	0.77	1.18	0.80	1.38	0.58	1.08	0.61	1.28	0.70	1.02	0.74	1.19
17	0.98	1.08	1.01	1.18	1.06	1.28	1.07	1.38	0.74	1.09	0.76	1.24	0.60	1.08	0.62	1.24

contd...

Month	MAY				JUNE				JULY				AUGUST			
Grids	a*	b*	a	b	a*	b*	a	b	a*	b*	a	b	a*	b*	a	b
1	1.27	1.42	1.27	1.42	2.09	1.67	2.10	1.72	2.22	1.38	2.26	1.55	1.79	1.69	1.78	1.66
2	1.24	1.55	1.26	1.72	1.84	1.69	1.84	1.68	2.11	2.11	2.11	2.06	1.84	1.67	1.93	1.63
3	1.38	1.29	1.39	1.37	2.25	2.16	2.25	2.16	3.13	1.85	3.13	1.88	2.47	2.03	2.47	1.99
4	1.24	2.24	1.22	1.52	2.18	1.77	2.18	1.80	2.90	2.02	2.90	2.03	2.43	2.03	2.43	2.03
5	1.09	1.29	1.11	1.44	1.79	1.81	1.79	1.87	2.49	1.83	2.49	1.87	2.05	1.58	2.06	1.66
6	1.11	1.23	1.13	1.36	2.36	1.87	2.36	1.88	3.44	2.49	3.44	2.30	2.70	1.88	2.70	1.87
7	1.03	1.16	1.07	1.34	2.33	1.83	2.33	1.87	2.85	1.94	2.85	1.88	2.32	1.79	2.32	1.79
8	1.11	1.45	1.13	1.60	1.90	1.63	1.91	1.69	2.64	1.79	2.64	1.83	2.07	1.94	2.08	1.98
9	1.03	1.13	1.07	1.33	1.64	1.57	1.63	1.53	2.05	1.63	2.05	1.68	1.65	1.77	1.65	1.81
10	1.29	1.27	1.32	1.39	2.11	2.34	2.11	2.21	2.74	1.56	2.75	1.62	2.08	1.77	2.08	1.78
11	1.22	1.41	1.23	1.52	1.82	1.87	1.83	1.91	2.03	1.81	2.03	1.88	1.73	1.95	1.73	1.95
12	1.02	1.39	1.03	1.49	2.10	1.72	2.10	1.74	2.12	1.76	2.12	1.74	1.61	1.73	1.61	1.83
13	1.04	1.22	1.07	1.41	1.36	1.36	1.38	1.57	1.90	1.61	1.90	1.63	1.37	1.50	1.38	1.53
14	1.48	1.63	1.47	1.61	1.87	2.63	1.87	2.60	2.27	1.80	2.28	1.94	2.00	2.70	2.01	1.90
15	1.15	1.57	1.15	1.64	1.67	1.93	1.67	1.93	1.95	1.96	1.95	2.16	1.48	1.40	1.49	1.47
16	1.24	1.09	1.28	1.21	1.73	1.86	1.73	1.86	1.67	1.60	1.69	1.68	1.44	1.54	1.44	1.55
17	1.22	1.41	1.23	1.53	1.44	1.74	1.44	1.81	1.51	1.85	1.51	1.90	1.39	1.23	1.41	1.31

contd...

Month	SEPTEMBER				OCTOBER				NOVEMBER				DECEMBER			
Grids	a*	b*	a	b	a*	b*	a	b	a*	b*	a	b	a*	b*	a	b
1	1.40	1.93	1.39	1.69	0.71	1.06	0.73	1.15	0.75	1.06	0.78	1.21	0.83	0.98	0.91	1.28
2	1.28	1.73	1.28	1.77	0.96	1.28	0.98	1.43	0.97	1.47	0.98	1.56	0.99	1.17	1.03	1.38
3	1.50	1.64	1.50	1.69	0.66	1.02	0.69	1.22	0.99	1.33	1.00	1.40	1.14	1.34	1.16	1.46
4	1.42	1.52	1.43	1.60	0.93	1.32	0.95	1.52	1.09	1.37	1.11	1.50	1.24	1.19	1.27	1.34
5	1.31	1.35	1.32	1.43	0.91	1.12	0.94	1.32	0.80	1.01	0.85	1.22	0.98	1.22	1.01	1.39
6	1.94	2.25	1.93	1.74	1.02	1.51	1.03	1.58	1.33	1.43	1.34	1.51	1.58	1.75	1.58	1.78
7	1.60	1.63	1.60	1.68	1.09	1.03	1.15	1.20	1.05	1.23	1.08	1.46	1.04	1.14	1.08	1.37
8	1.31	1.50	1.32	1.58	0.82	1.54	0.83	1.68	0.88	1.12	0.91	1.25	1.02	1.41	1.04	1.56
9	1.13	1.31	1.14	1.41	0.75	1.34	0.76	1.49	0.72	1.05	0.76	1.20	0.64	1.26	0.66	1.46
10	1.62	1.77	1.62	1.81	0.80	1.20	0.82	1.38	0.96	1.67	0.96	1.67	1.14	1.13	1.18	1.31
11	1.42	1.63	1.42	1.68	0.76	1.21	0.77	1.35	0.86	1.20	0.88	1.31	1.13	1.28	1.15	1.44
12	1.26	1.07	1.31	1.26	0.79	1.20	0.81	1.36	0.77	1.25	0.79	1.39	1.00	1.27	1.02	1.39
13	1.17	1.09	1.22	1.27	0.94	1.02	0.95	1.04	0.64	1.07	0.66	1.18	0.95	1.14	0.94	1.10
14	1.39	1.37	1.41	1.53	0.94	1.09	0.96	1.18	1.53	1.23	1.49	1.11	1.13	2.31	1.13	1.99
15	1.22	1.52	1.22	1.57	0.84	2.04	0.84	2.11	0.81	1.07	0.83	1.17	0.97	1.41	0.98	1.58
16	1.29	1.26	1.32	1.44	0.91	1.05	0.94	1.19	0.73	1.17	0.74	1.27	0.89	1.02	0.92	1.11
17	1.31	1.20	1.35	1.38	0.90	1.05	0.95	1.27	0.92	1.06	0.93	1.19	0.76	1.04	0.80	1.20

Table II

Approximate (scale parameter-a*, shape parameter-b*) and accurate (scale parameter-a, shape parameter-b) parameters of Weibull Model for N.I.O. wave height data.

Month	JANUARY				FEBRUARY				MARCH				APRIL			
Grids	a*	b*	a	b	a*	b*	a	b	a*	b*	a	b	a*	b*	a	b
XVII	1.10	1.29	1.09	1.21	1.07	1.28	1.07	1.28	1.18	1.57	1.16	1.37	1.07	1.43	1.07	1.49
XVIII	1.31	1.38	1.31	1.38	1.14	1.41	1.15	1.48	1.32	1.48	1.32	1.50	1.32	1.69	1.33	1.77
XI	1.29	2.14	1.29	2.14	1.26	1.39	1.25	1.30	1.13	1.20	1.14	1.25	0.87	1.21	0.86	1.14
XII	1.56	2.33	1.57	2.36	1.05	1.94	1.05	1.87	1.21	1.77	1.21	1.77	0.96	1.11	0.98	1.20
XIII	1.30	2.04	1.30	2.02	1.14	1.64	1.14	1.64	1.06	2.10	1.06	2.06	1.37	1.25	1.40	1.38
V	1.85	2.07	--	--	2.17	1.84	--	--	1.14	2.03	--	--	0.79	1.92	--	--
VI	1.54	1.90	1.54	1.84	1.69	1.83	1.64	1.35	1.08	2.10	1.08	2.10	1.03	1.48	1.02	1.40
VII	1.25	2.72	1.25	2.75	1.38	2.51	1.37	2.54	0.96	1.80	0.95	1.68	0.81	1.52	0.81	1.46
XXVII	1.93	4.15	--	4.15	1.76	2.79	--	2.75	1.39	1.38	--	1.52	1.11	1.67	--	1.57
XXVIII	1.51	3.05	--	--	1.54	1.87	1.54	1.69	1.32	2.04	--	--	1.42	2.55	--	--
XXIX	1.36	2.54	1.37	2.42	1.26	1.75	1.25	1.62	1.03	1.60	1.02	1.50	1.36	1.76	1.26	1.12
I	1.82	2.69	1.83	2.60	1.09	1.37	1.08	1.30	1.04	1.87	1.03	1.78	1.31	1.85	1.31	1.83

Contd...

Month	MAY				JUNE				JULY				AUGUST			
Grids	a*	b*	a	b	a*	b*	a	b	a*	b*	a	b	a*	b*	a	b
XVII	2.04	2.31	2.04	2.25	3.24	2.58	3.24	2.54	3.59	2.62	3.59	2.60	3.01	3.24	3.02	3.18
XVIII	2.13	1.83	2.12	1.74	2.87	2.39	2.87	2.30	3.41	3.56	3.41	3.60	3.18	2.19	3.18	2.19
XI	1.30	1.53	1.32	1.88	4.32	2.73	4.32	2.73	4.90	2.70	4.91	2.60	3.89	3.91	3.92	3.40
XII	1.54	1.47	1.55	1.60	3.46	2.44	3.46	2.45	4.25	3.62	4.26	3.51	3.53	4.09	3.54	3.79
XIII	1.52	2.54	1.52	2.53	3.19	2.45	3.19	2.36	3.69	3.55	3.70	3.39	2.91	3.81	2.92	3.64
V	1.66	1.18	--	--	4.07	2.43	--	--	3.84	1.93	--	--	2.67	5.39	--	--
VI	1.77	1.55	1.77	1.56	3.30	3.23	3.31	3.08	3.70	2.87	3.71	2.75	3.13	3.46	3.13	3.46
VII	1.50	2.23	1.50	2.20	2.94	2.71	2.93	2.75	3.02	3.29	3.03	3.18	2.58	2.87	2.58	2.87
XXVII	2.25	1.75	--	1.78	3.16	2.36	--	2.30	2.98	5.54	--	--	2.94	3.14	--	--
XXVIII	1.66	1.01	--	--	3.11	3.88	--	--	3.22	4.89	--	--	2.57	2.12	--	--
XXIX	1.93	2.55	1.93	2.55	1.68	1.32	1.73	3.28	2.40	2.60	2.40	2.57	2.58	2.65	2.58	2.68
I	1.98	2.59	1.98	2.48	2.53	2.73	2.53	2.73	2.33	3.44	2.32	3.65	2.18	3.04	2.18	3.04

Contd...

Month	SEPTEMBER				OCTOBER				NOVEMBER				DECEMBER			
Grids	a*	b*	a	b	a*	b*	a	b	a*	b*	a	b	a*	b*	a	b
XVII	2.22	1.81	2.22	1.88	1.13	1.71	1.13	1.61	0.94	1.44	0.93	1.35	1.11	1.45	1.10	1.34
XVIII	1.85	2.59	1.85	2.53	1.36	1.26	1.34	1.19	0.70	1.14	0.69	1.08	1.00	1.44	1.00	1.39
XI	2.26	2.08	2.26	2.11	1.01	1.34	1.00	1.29	1.46	2.16	1.46	2.11	1.24	1.42	1.24	1.39
XII	1.87	2.22	1.87	2.16	0.98	3.53	0.98	1.61	1.22	1.84	1.21	1.69	1.27	1.33	1.27	1.74
XIII	1.68	2.49	1.68	2.53	1.05	1.46	1.06	1.53	0.98	1.32	0.97	1.27	1.65	2.39	1.65	2.30
V	1.82	1.39	--	--	1.26	3.42	--	--	1.62	2.73	--	--	1.36	1.56	--	--
VI	2.09	2.11	2.09	2.02	1.36	1.45	1.37	1.53	1.45	2.22	1.34	1.84	1.13	1.65	1.14	2.02
VII	1.63	2.86	1.63	2.82	1.23	2.81	1.22	2.83	1.03	2.99	1.03	2.99	1.31	3.01	1.31	2.99
XXVII	1.87	1.56	--	--	1.26	2.28	--	--	1.78	1.91	--	--	1.78	2.80	--	--
XXVIII	2.23	3.13	--	--	1.65	2.17	--	--	1.45	1.73	1.45	1.80	1.43	1.71	--	--
XXIX	2.14	2.41	2.14	2.42	1.52	2.23	1.52	2.30	1.46	3.09	1.46	3.19	1.42	2.66	1.42	2.68
I	1.87	3.09	1.87	3.00	1.56	2.73	1.56	2.75	1.44	2.83	1.44	2.83	1.68	2.03	1.68	2.02

the Weibull model. In other words, whether the Weibull distribution fits the data for any particular month better than any other. The hypothesis formulated is that the model does not prefer any individual month, according to which the frequency of grids where the fit is good should be equal for all months. For e.g. in the N.P.O.L data the total frequency of 124 grids should be equally distributed among the 12 months at 10.33 grids a month, and this value form the expected frequency. The χ^2 calculated in this way were not significant (e.g. for the N.P.O.L data the calculated value was 9.16 against a 5% χ^2 value 19.77) confirming the fact that seasonality does not affect the Weibull law.

From table III(a) and III(b) it can be seen that the Weibull model fits better by about 15% more of the cases to the long-term wave height distributions of combined sea and swell sea-state (N.P.O.L) than the swell dominated condition (N.I.O). This variation can be attributed to the broad spectrum associated with sea and swell sea-state than the swell prevailed state. In tables III(b) and IV(b) the number of data when χ^2-test fails has been deleted from the total number of data. From the overall percentages cited in the tables it is evident that the results are much improved when the revised estimates of the shape and scale parameters are employed. It may also be noted that the data on wave

Table III(a)

Number and percentage of months for which Weibull distribution fits in various grids for N.P.O.L sea and swell height data, with approximate and revised scale and shape parameters.

Grid No.	approximate a*,b*		revised a,b	
	No. of months	Percentage	No. of months	Percentage
1	6	50.0	10	83.3
2	5	41.7	5	41.7
3	7	58.3	9	75.0
4	3	25.0	3	25.0
5	1	8.3	4	33.3
6	6	50.0	9	75.0
7	6	50.0	8	66.7
8	4	33.3	7	58.3
9	8	66.7	11	91.7
10	7	58.3	10	83.3
11	7	58.3	9	75.0
12	9	75.0	10	83.3
13	3	25.0	8	66.7
14	4	57.1	7	77.8
15	8	72.7	8	72.7
16	1	8.3	5	41.7
17	2	16.7	3	25.0
Overall percentage		44.4		63.3

Table III(b)

Number and percentage of months for which Weibull distribution fits in various grids for N.I.O swell height data with approximate and revised scale and shape parameters.

Grid No.	approximate a*,b*		revised a,b	
	No. of months	Percent-age	No.of months	Percent-age
17	7	58.3	7	58.3
18	6	50.0	6	50.0
11	4	36.4	4	36.4
12	4	36.4	6	50.0
13	7	63.6	8	72.7
5	-(test fails)	-	-(test fails)	-
6	4	40.0	6	54.6
7	2	18.2	3	27.3
27	-(test fails)	-	-(test fails)	-
28	1	50.0	1	50.0
29	4	36.4	4	40.0
I	6	50.0	6	50.0
Overall percentage		43.93		48.93

Table IV(a)

Monthly variation in number and percentage of grids for N.P.O.L sea and swell height data fitting Weibull distribution with approximate and revised scale and shape parameters.

Months	approximate a*,b*		revised a,b	
	No. of grids	percent-age	No. of grids	percent-age
January	8	50.0	13	76.5
February	10	62.5	14	87.5
March	7	41.2	8	47.1
April	6	37.5	12	70.6
May	4	23.5	10	58.8
June	11	64.7	13	76.5
July	12	70.6	13	76.5
August	7	41.2	12	70.6
September	7	41.2	7	41.2
October	3	18.8	5	29.4
November	8	50.0	10	62.5
December	4	25.0	7	43.8

Table IV(b)

Monthly variation in number and percentage of grids for N.I.O swell height data fitting Weibull distribution with approximate and revised scale and shape parameters.

Months	approximate a*, b*		revised a,b	
	No. of grids	percentage	No. of grids	percentage
January	6	66.7	6	66.7
February	4	44.4	4	44.4
March	3	42.9	3	42.9
April	3	37.5	5	62.5
May	4	44.4	4	44.4
June	4	44.4	5	55.6
July	5	55.6	6	66.7
August	2	22.2	2	22.2
September	5	55.6	6	66.7
October	3	42.9	3	42.9
November	3	33.3	3	33.3
December	3	33.3	4	44.4

information is visual and therefore it is quite probable that many of them may be under or over estimated. In either case, there is the possibility of unusually high or low observations to be included in the data thereby contaminating the true distribution to a large extend. This often complicates the problem of identifying the real distribution, and it is for no other reason that researchers are led to seek and try several alternatives. Some proposals to identify discordant observations that had crept into the data and to eliminate them will be pointed out in the concluding chapter.

3.3. Visual wave statistics vis-a-vis recorded waves

A detailed study is made for grid 17(5°-9°N, 73°-77°E) and grid 9 (13°-17°N, 73°-74.7°E) of the sea and swell atlas (N.P.O.L, 1978) and, grid I (5°-10°N, 75°-80°E) and grid VII (10°-15°N, 70°-76°E) of the swell atlas (N.I.O, 1982). Grid 17 (N.P.O.L) and grid I(N.I.O) overlap over a rectangular area measuring $4^{\circ} \times 2^{\circ}$ (Fig.2). Trivandrum and Valiathura where recorded wave information are available are located in this common portion. This overlapping area will hereafter be referred as the "Trivandrum grid" for convenience. Also grid 9 (N.P.O.L) and grid VII (N.I.O) have a common square area of dimension $2^{\circ} \times 2^{\circ}$ (Fig.3). Published recorded wave statistics off Mangalore are available for this overlapping grid which will be termed as "Mangalore grid" in the present study.

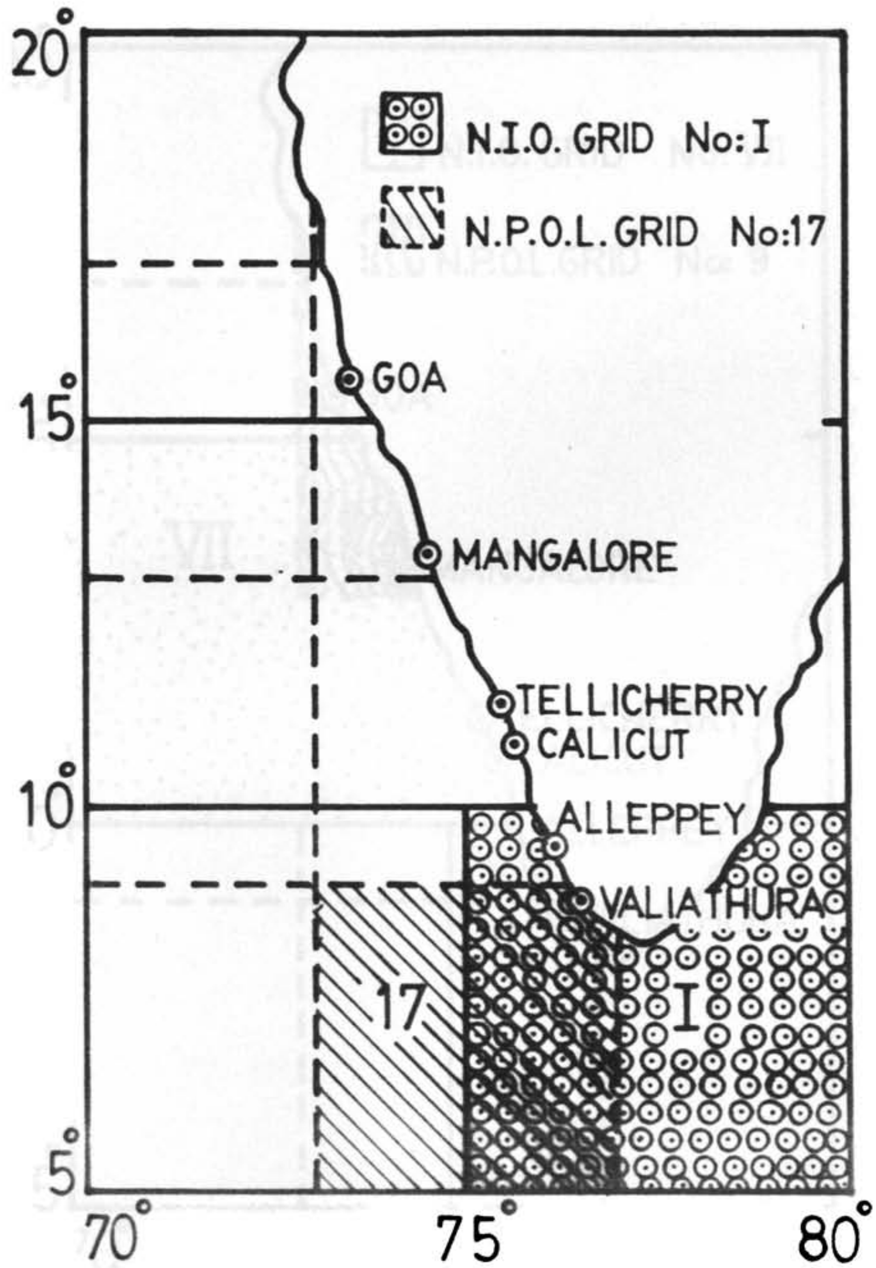

Fig.2. Map showing grid 17 of N.P.O.L atlas and grid I of N.I.O atlas used in present study.

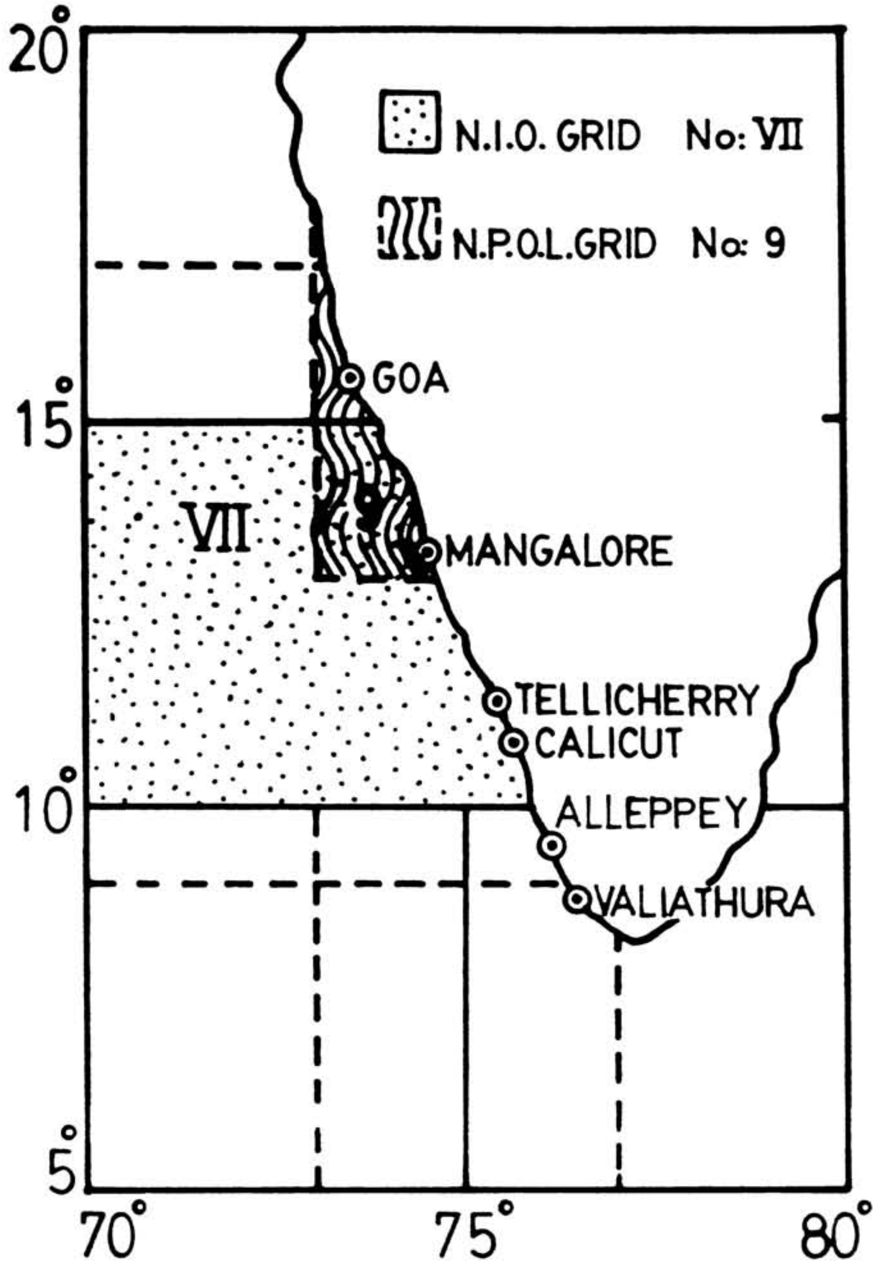

Fig.3. Map showing grid 9 of N.P.O.L atlas & grid VII of N.I.O atlas used in present study.

Visual wave statistics computed for grid 17 and grid I are compared with the recorded wave information available for the Trivandrum grid. Visual statistics for grid 9 and grid VII are compared with recorded information for Mangalore grid. These comparisons help to test the reliability of wave climatological studies based on visually averaged wave information.

3.3.1. Long-term wave height distributions off Trivandrum

Long-term wave height distributions obtained from grid 17 (N.P.O.L) and grid I(N.I.O) are examined with Weibull, Gumbel, log-normal, exponential and Rayleigh models. The goodness of fit is tested using χ^2-test at 0.05 level of significance. The method of maximum likelihood has been used for all the models except in the Gumbel for estimating the distribution parameters. A comparative study of the observed percentage frequency of occurrence of wave heights with the theoretical curves is made (Fig.4(a-f)). A comparison of the visual wave height distributions with the theoretical distributions as shown as in Fig.4(a-f) indicates that the Weibull model effectively explains the different sea-states. For both the sea and swell dominated conditions (grid 17, N.P.O.L), Weibull conforms to the wave patterns observed in February, April, June, July, September and November and of

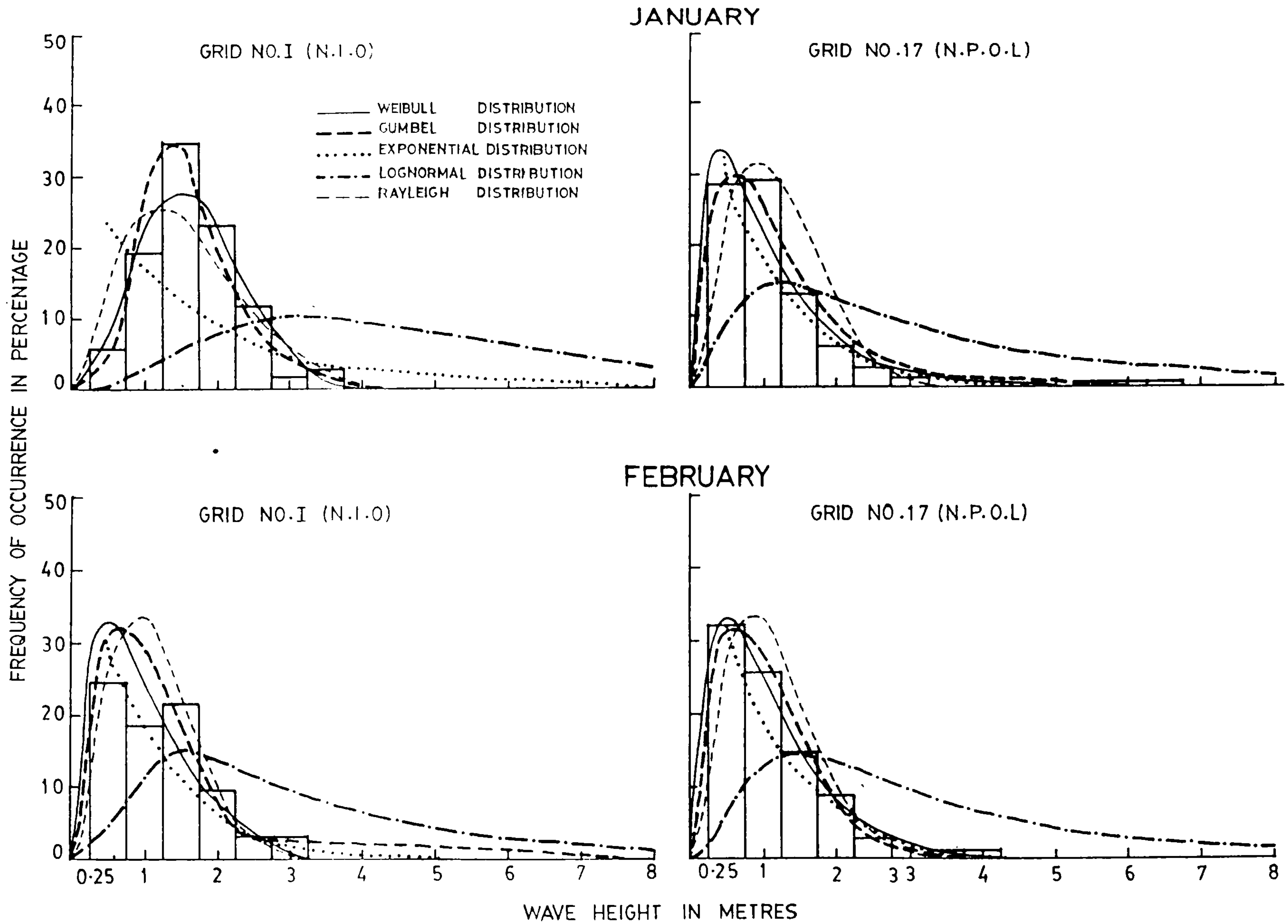

Fig.4(a) Comparison of the distributions of observed wave heights (Histograms) with theoretical distributions off Trivandrum.

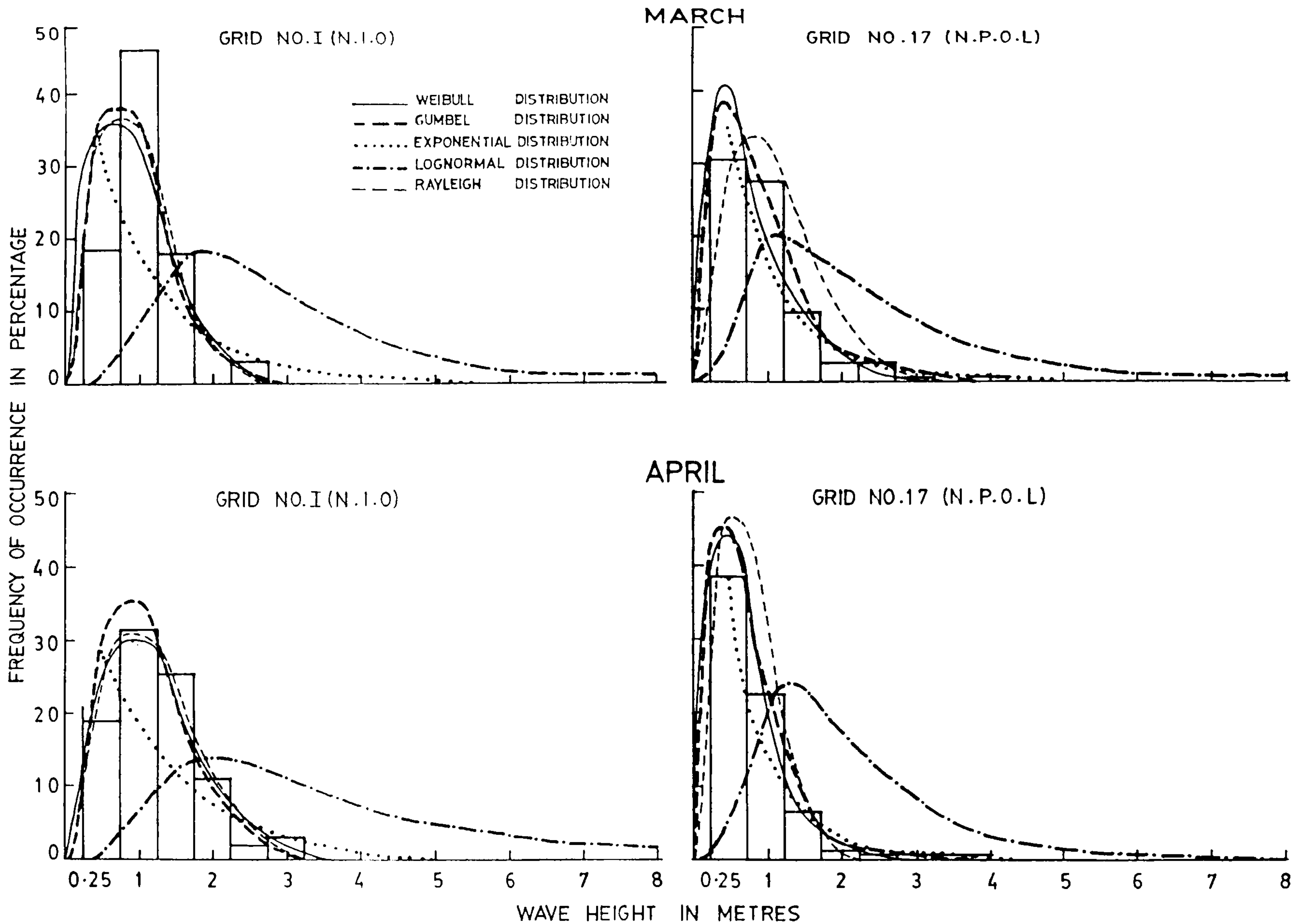

Fig. 4(b) Comparison of the distributions of observed wave heights (Histograms) with theoretical distributions off Trivandrum.

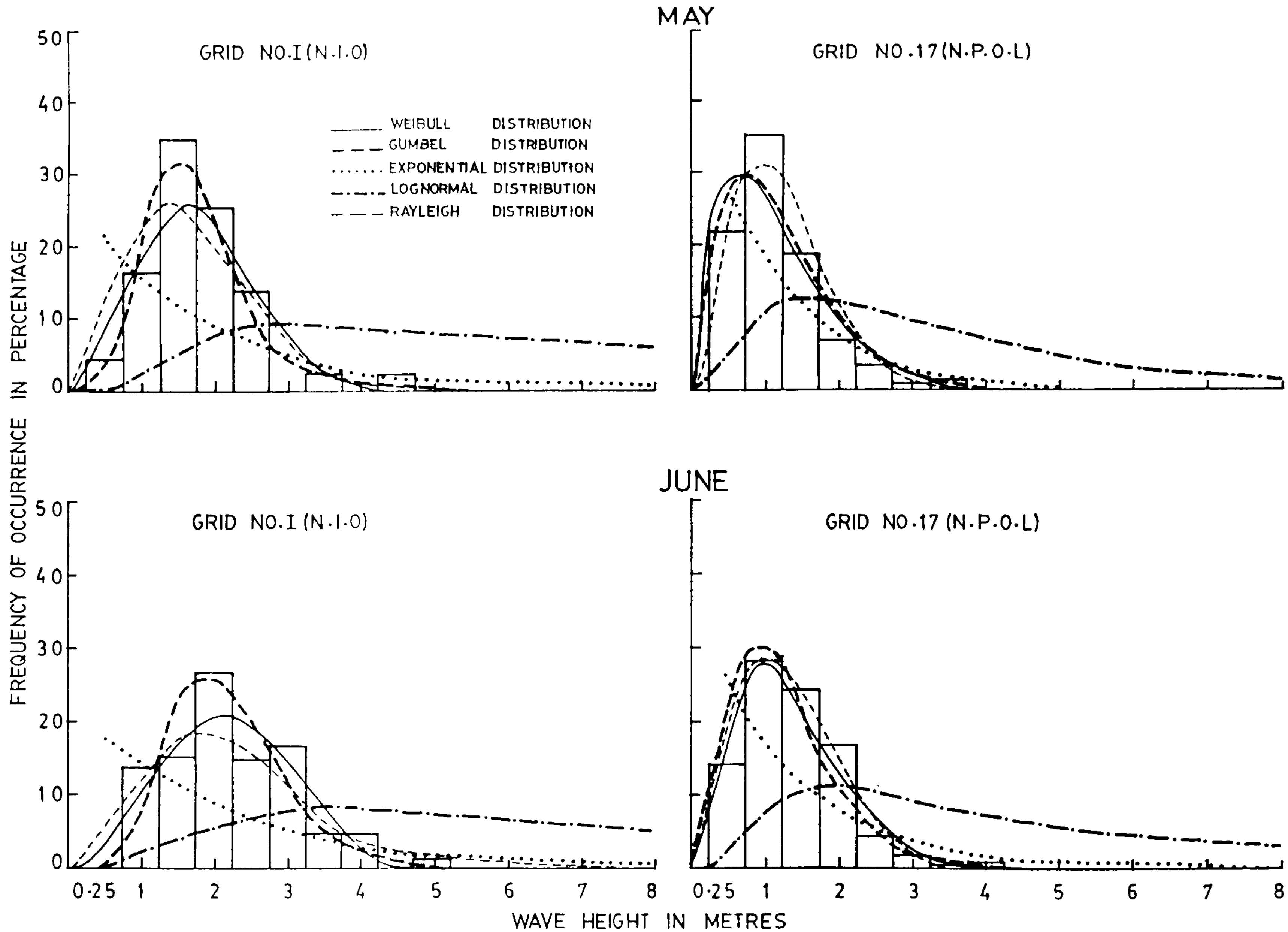

Fig: 4(c) Comparison of the distributions of observed wave heights (Histograms) with theoretical distributions off Trivandrum.

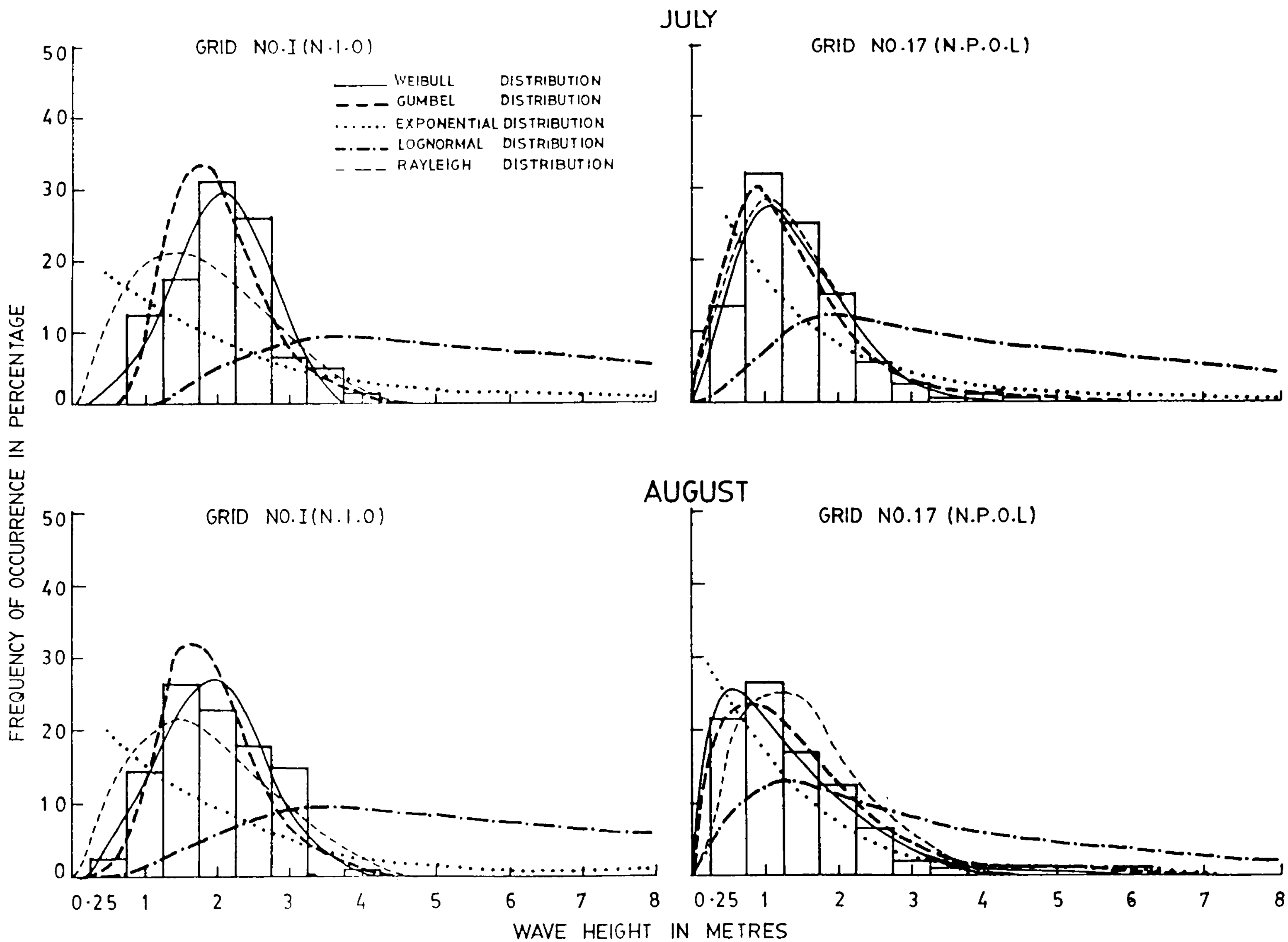

Fig. 4(d) Comparison of the distributions of observed wave heights (Histograms) with theoretical distributions off Trivandrum.

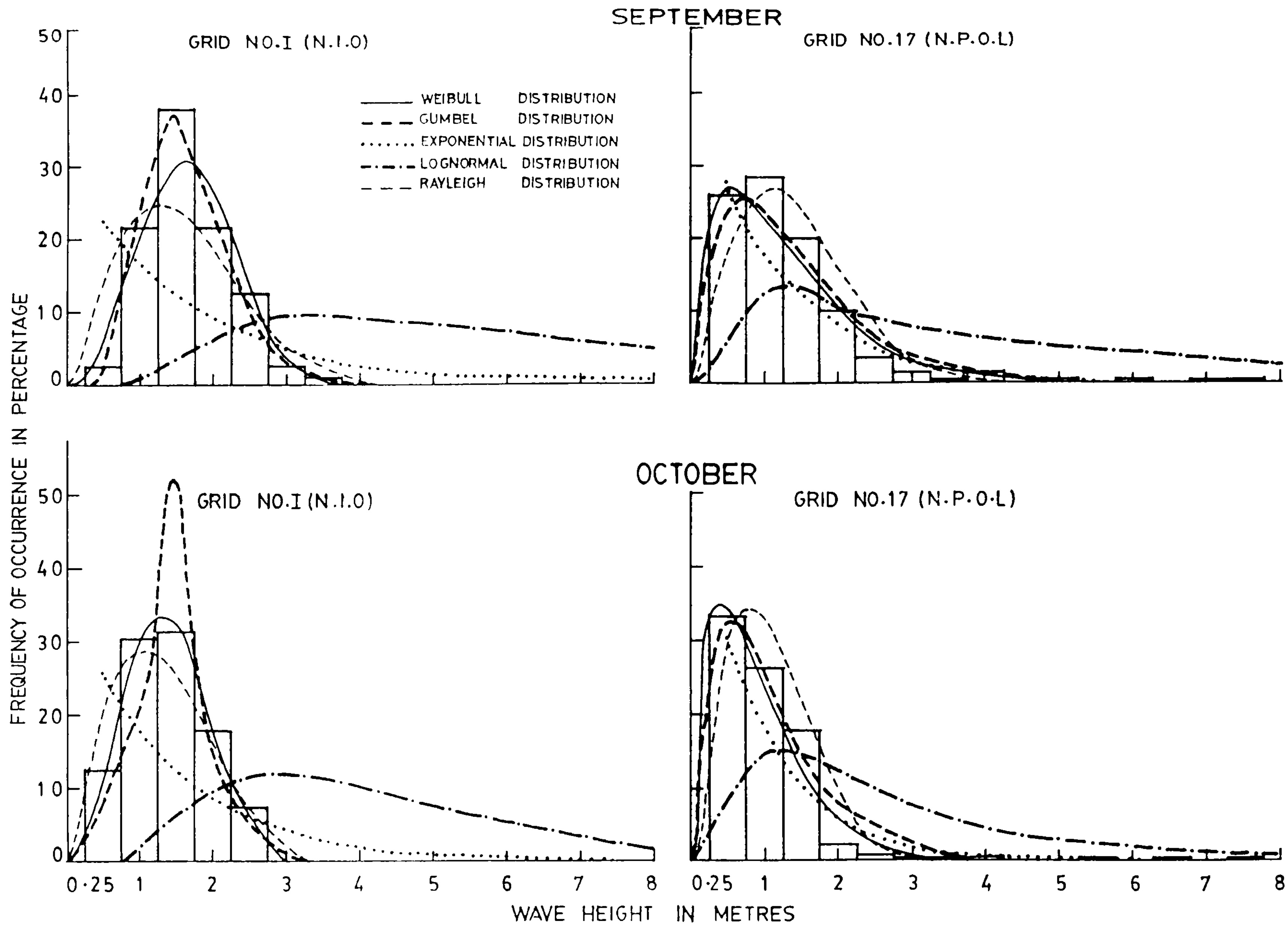

Fig. 4(e) Comparison of the distributions of observed wave heights (Histograms) with theoretical distributions off Trivandrum.

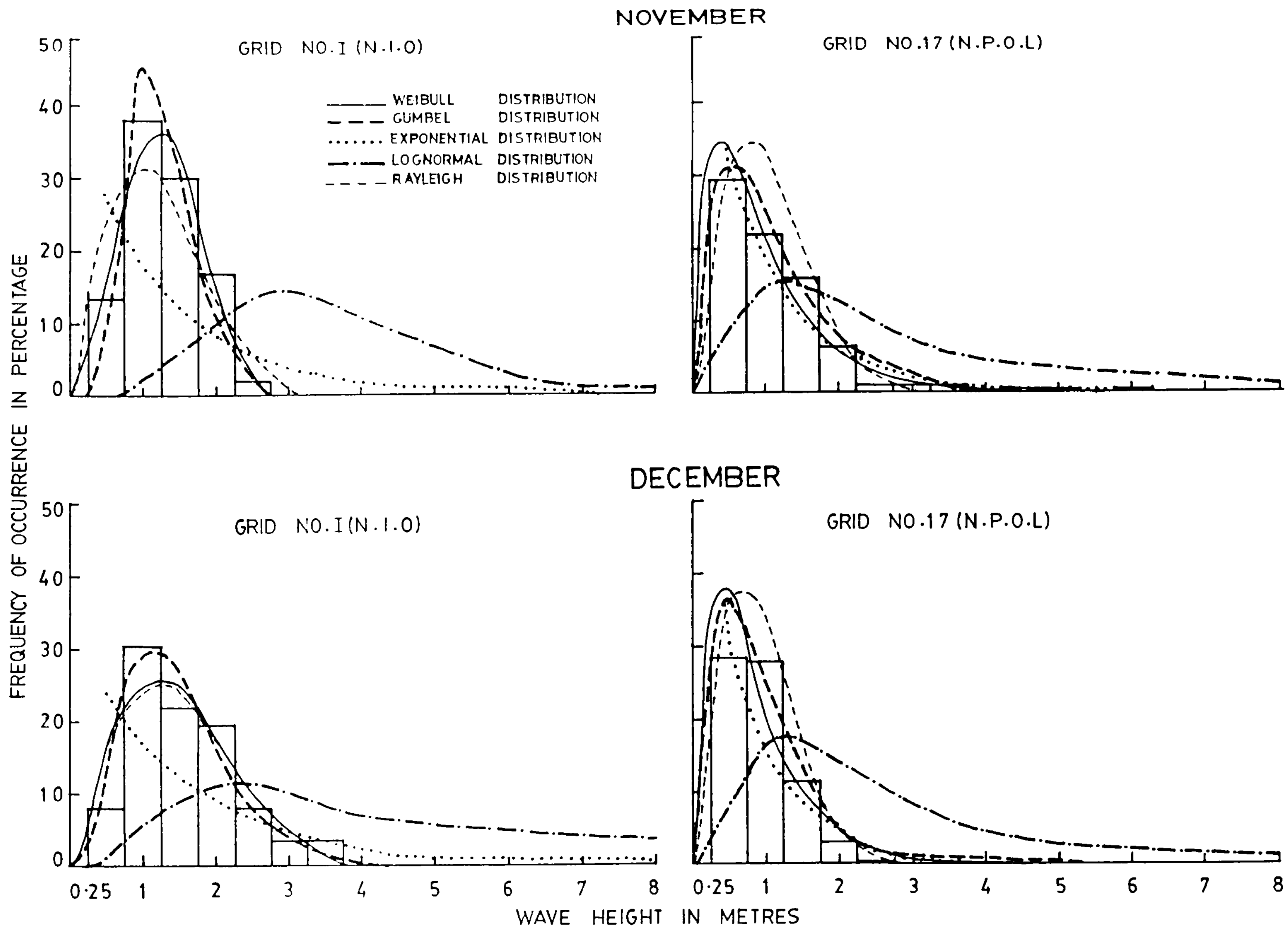

Fig.4(f) Comparison of the distributions of observed wave heights (Histograms) with theoretical distributions off Trivandrum.

swell prevailed sea conditions (grid I, N.I.O), in January, March to August, October and November. At the same time the Gumbel distribution provides a better explanation than the other curves for the rest of the monthly wave height formations in both cases.

In the case of the swell prevailed state (grid I, N.I.O), the Weibull model fits in 50% of the cases followed by Gumbel in 41.5% and Rayleigh in 8.5% of the cases. On the other hand, for the combined sea and swell data (grid 17) adequate fit could be realised only in 58.5% of the total cases. Of these, 25% each accounts for the Weibull and Gumbel models and 8.5% for the Rayleigh. Even in data where the Weibull fit was rejected, it was due to the presence of one or two abnormal observations rather than the incomparability of the model with the whole data set. Such discordant values may be the result of bias in visual observations. The overall analysis suggests that the Weibull distribution offers a uniformly good fit. The appearance of unusually larger or smaller values in the data suggests that the analysis of data requires more sophisticated tools than mere fitting of models. One has to test whether these observations are outliers and can be rejected. If the answer to this question is in the affirmative, then the data is to be cleared and the fitting re-done for the cleaned data. This problem requires extensive analysis and therefore, will be considered only in a future work.

From Fig.4(a-f) it is seen that Weibull overestimates and underestimates the peak percentage frequencies of wave heights (histograms) to a maximum of 10.5% and 12.5% respectively. The respective figures for Gumbel and Rayleigh are 20.5% and 10.0%, 8.0% and 14.0%. While the Gumbel distribution estimates the peak frequency with a higher kurtosis; Rayleigh curves are seen to underestimate the peak frequencies.

It could be observed that the distribution of the reported percentage frequency of occurrence of wave heights show a broad band of wave heights for swell dominated conditions than that for sea and swell combined sea-state. A change to broad band is observed during southwest monsoon season (grid 17, Fig.4(a-f)). The Weibull model explains the varying wave patterns (Fig.4(a-f)). In view of the fact that of all the models, the Weibull distribution provided the closest fit for the long-term distributions of wave heights (H_S) in a majority of cases, there is a strong case for using it as the basic model for wave heights (H_S). With this point of view, several wave parameters of interest are derived using this particular model.

3.4. Wave statistics off Trivandrum from Weibull model

Since Weibull model gives the closest fit to the long-term distributions of wave heights, certain wave statistics are derived from it and are compared with those obtained from available recorded wave information off Trivandrum.

3.4.1. Ratios of standard wave height parameters off Trivandrum

The mean values of some standard ratios and their standard deviation are computed from the visual observations from grid 17 (N.P.O.L) and grid I (N.I.O) and are compared with those predicted from Weibull model. The results are given in table V.

Of the various ratios of standard wave height parameters computed and predicted, $\bar{H}/\eta$, $H_{1/3}/\bar{H}$ and $H_{1/10}/H_{1/3}$ seem to be relatively more consistent and can be used for practical purposes. $H_{max}/H_{1/3}$, $H_{1/10}/\eta$ and H_{max}/η show comparatively less consistency. The inconsistencies of these ratios may be due to the bias in reporting high waves by merchant ships, since they usually avoid rough sea conditions.

3.4.2. Averaged maximum wave height off Trivandrum

The averaged maximum wave heights to occur within 5, 10 and 100 years are computed from Weibull model for grid 17 (N.P.O.L) and grid I (N.I.O) using the formula (2.27),

with t = 5, 10, 100 years,

n = 1 month

a and b are parameters of the Weibull model.

Table V

Averaged computed (C) and predicted (P) ratios of standard wave height parameters

Ratio	Grid No.17		Grid No.I	
	C	P	C	P
$H_{max}/H_{1/3}$				
Mean	3.04	---	1.53	--
S.D.	0.68	--	0.15	--
$H_{1/3}/\eta$				
Mean	2.22	3.31	3.43	6.87
S.D.	0.25	0.79	0.49	2.35
H_{max}/η				
Mean	6.63	--	5.19	--
S.D.	0.99	--	0.63	--
$\bar{H}/\eta$				
Mean	1.25	1.38	2.34	2.32
S.D.	0.24	0.24	0.48	0.57
$H_{1/10}/\eta$				
Mean	3.34	6.36	4.20	14.86
S.D.	0.24	2.22	0.47	7.73
$H_{1/10}/H_{1/3}$				
Mean	1.51	1.89	1.23	2.42
S.D.	0.13	0.24	0.06	0.11
$H_{1/3}/\bar{H}$				
Mean	1.82	2.38	1.49	2.88
S.D.	0.20	0.22	0.14	0.40

These are compared with that obtained from recorded wave data off 'Trivandrum grid'. The averaged maximum wave heights to occur in 5 years, 10 years and 100 years are given in table VI, for both sea and swell combined sea-state (grid 17) and swell prevailed state (grid I).

In a period of 5 years, the maximum wave height obtained from recorded wave information at Valiathura (Baba, 1985) for overall data is 6.02 m. This result is comparable with those obtained from swell data (grid I) while that computed from sea and swell statistics give much higher values (Table VI). From table VI, it can also be seen that grouping of data into annual or monsoonal (June-September) does not show significant variation in the results. Dattatri (1981) arrived at similar results using recorded wave data off Mangalore Harbour.

3.4.3. Return periods of maximum wave height off Trivandrum

The re-occurrence of maximum wave heights obtained from N.P.O.L atlas (grid 17) and that from N.I.O atlas (grid I) are calculated using the relation given in section 2.7 which is derived from the Weibull model.

t = return period

n = one month

h_{max} = maximum wave height

a, b = parameters of Weibull distribution

Table VI

Averaged maximum wave height for grid 17 and grid I

Averaged maximum wave height	grid 17(N.P.O.L)		grid I (N.I.O)	
	overall	monsoon	overall	monsoon
5 year wave (m)	9.60	9.63	6.19	6.00
Decennial wave (m)	12.56	12.60	7.31	6.61
Centennial wave (m)	21.21	20.14	10.16	8.31

The maximum wave height reported for the sea and swell combined conditions as given in N.P.O.L data is 7.5 m, and considering the overall data the return period (median) is found to be 3.40 years. For the swell dominated sea-state as presented in N.I.O atlas, a maximum wave height of 5.0 m (grid I) is observed and its re-occurrence is computed as 2.88 years.

From 5 years wave recording (1980-1984) at Valiathura (Trivandrum grid),(Baba,1985) a maximum wave height of 6.02m was recorded. This duration can be considered as its return period. The re-occurrence (median) of this height considering overall data for sea and swell combined state (grid 17) is 2.52 years and that for swell prevailed sea-state is 6.27 years. The return period of 6.02 m wave height obtained from N.I.O data (grid I) is comparable with the duration (5 years) of wave recording.

3.4.4. Probability of realising a wave height greater than a designated value in a given period of time off Trivandrum

Probability of realising a wave height greater than a designated value in a given period of time is found out using the relation given in section 2.7 which has been derived from Weibull model in the previous chapter. Here m denotes the period of time proposed for re-occurrence. The maximum wave height given in the N.P.O.L atlas is 7.5 m (grid 17)and its return period is found to be 3.40 years. The probability of this height to occur within one year is calculated to be 29.41%. But the maximum wave height is given to be 5.0m in N.I.O atlas (grid I) and its re-occurrence is computed as 2.88 years. This height will return within a year with 34.72% probability. The recorded maximum wave height at Valiathura (Trivandrum grid) is 6.02m and the duration of wave recording is 5 years. This maximum wave height is recorded on the third year of wave recording (Baba, 1985). Therefore the probability of this height to occur within 3 years is found to be 60%. Using N.P.O.L data (grid 17) this height will return within 3 years with 100% probability whereas from N.I.O data it is found to be with 47.85% probability which is nearer to that computed from recorded information.

3.5. Comparison of wave directions off Trivandrum

Table VII gives comparison of the wave directions published in the atlases for grid 17 (N.P.O.L) and grid I (N.I.O) with measured wave directions obtained off Trivandrum (20 m) (Narayana Swamy et. al. 1979) and Valiathura (5 m) (Baba et.al. 1983). By studying the average wind pattern over the seas around India for fifty years, Srivastava et.al. (1970) grouped the twelve months into the following four seasons for the study of

Table VII

Comparison of monthly predominant wave directions

Month	Grid No.17 N.P.O.L atlas	Grid No.I N.I.O atlas	Recorded off Trivandrum (20m)	Recorded Valiathura (5m)
January	030 (NNE)	030 (NNE)	061 (ENE)	SSW
February	060 (ENE)	330 (NNW)	016 (NNE)	SSW
March	360 (N)	330 (NNW)	030 (NNE)	SSW
April	360 (N)	180 (S)	222 (SW)	SW
May	270 (W)	270 (W)	250 (WSW)	WSW
June	270 (W)	270 (W)	256 (WSW)	WSW
July	270 (W)	270 (W)	260 (W)	W
August	270 (W)	270 (W)	246 (WSW)	WSW
September	270 (W)	270 (W)	252 (WSW)	WSW
October	270 (W)	270 and 180 (W and S)	231 (SW)	SW
November	300 (WNW)	360 and 180 (N and S)	150 (SSE)	SW
December	360 (N)	030 (NNE)	051 (NE)	SW

waves. Pre-monsoon (March-April), Southwest monsoon (May-September), Post-monsoon (October), and Northeast monsoon (November-February). These seasons are considered here for wave directions study.

It is seen that during the southwest monsoon season, both atlases indicate predominantly westerly waves which turn to westsouthwesterly on approaching the shallow regions.

Post-monsoon (October) is characterised by westerly or southwesterly waves. During the northeast monsoon period, northerly or northeasterly components are predominantly indicated by the atlases as well as the measured wave directions at 20 m. The pre-monsoon season manifests variable wave directions. Near the shore, at 5 m depth, the swells approach from directions between west and southwest throughout the year.

3.6. Long-term wave height distributions off Mangalore

Long-term distributions of wave heights obtained from grid 9 (N.P.O.L) and grid VII (N.I.O) are examined with the available theoretical models. The χ^2-goodness of fit test is employed at 0.05 level of significance. The sea and swell data in grid 9 are found to follow Weibull in 92.8%, Gumbel in 58.8%, Rayleigh in 25.8%, exponential in 8.8% and log-normal in none of the cases. For the swell data (grid VII), Weibull fits in 27.0% , Gumbel in 36.0%, Rayleigh, exponential and log-normal curves in none of the cases. The comparatively lesser number of good fits provided by Weibull curve in grid VII can be attributed to the dominance given for swell conditions while reporting. Apart from the fit being good for both sea and swell combined conditions, it also explains the observed wave height patterns for swell dominated sea-state.

Fig.5(a-f) gives a comparative study of the observed percentage frequency of occurrence of wave heights with the theoretical curves. The various diagrams in Fig.5(a-f) indicate that the Weibull model agrees with the changing wave patterns in different months. For both the sea and swell combined state (grid 9), Weibull explains the wave patterns observed in January, February, March, May, June and September. Gumbel follows the wave patterns observed in April, October, November and December whereas Rayleigh provides a better fit for the rest of the months. For swell dominated conditions (grid VII), the observed wave patterns (histograms) take the form of Weibull curve in January, April to August and November and that of Gumbel in the remaining months. The Weibull model offers a uniformly good fit for the annual data.

From Fig.5(a-f) it is seen that Weibull overestimates and underestimates the peak percentage frequencies of wave heights

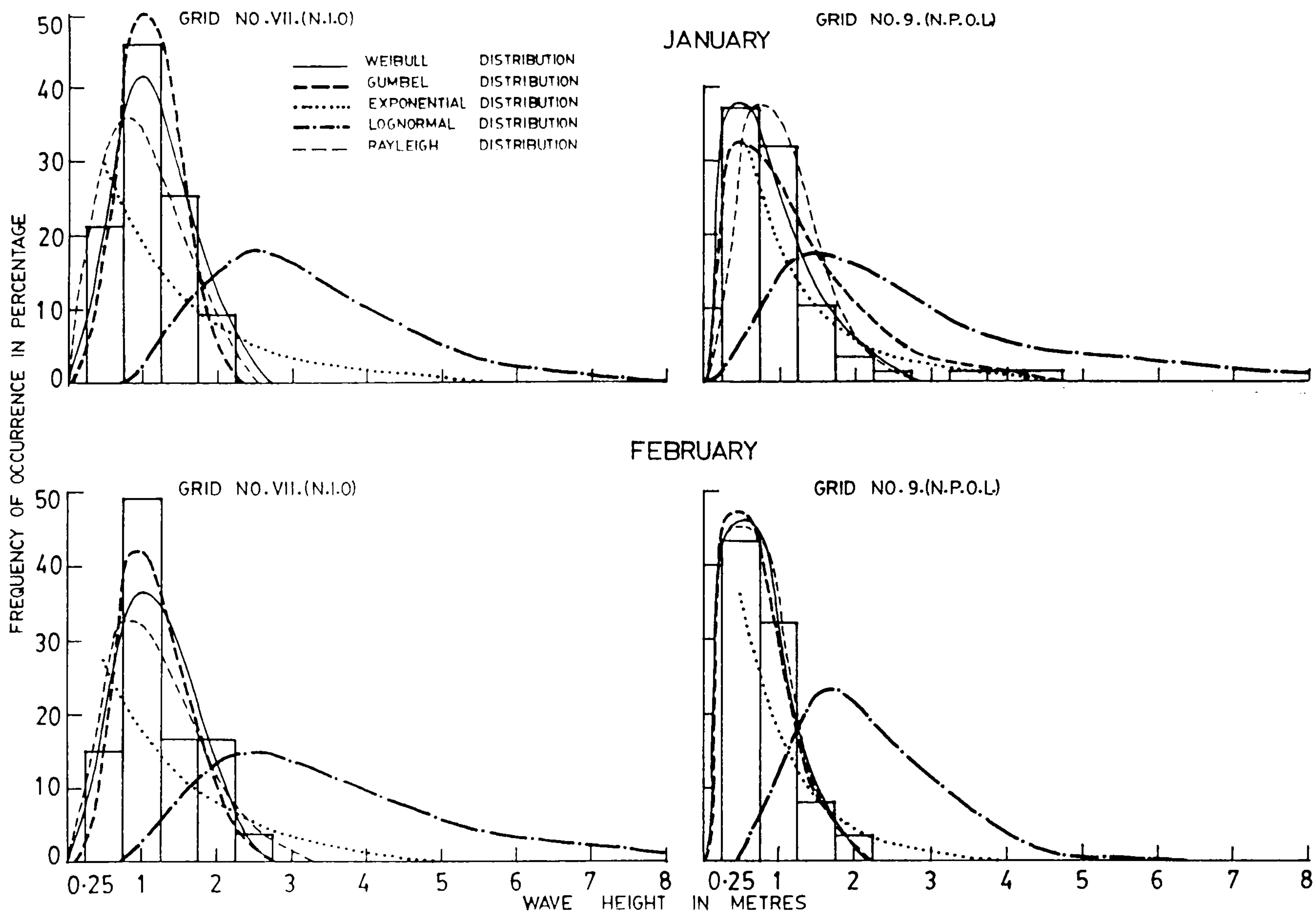

Fig.5(a) Comparison of the distributions of observed wave heights (Histograms) with theoretical distributions off Mangalore.

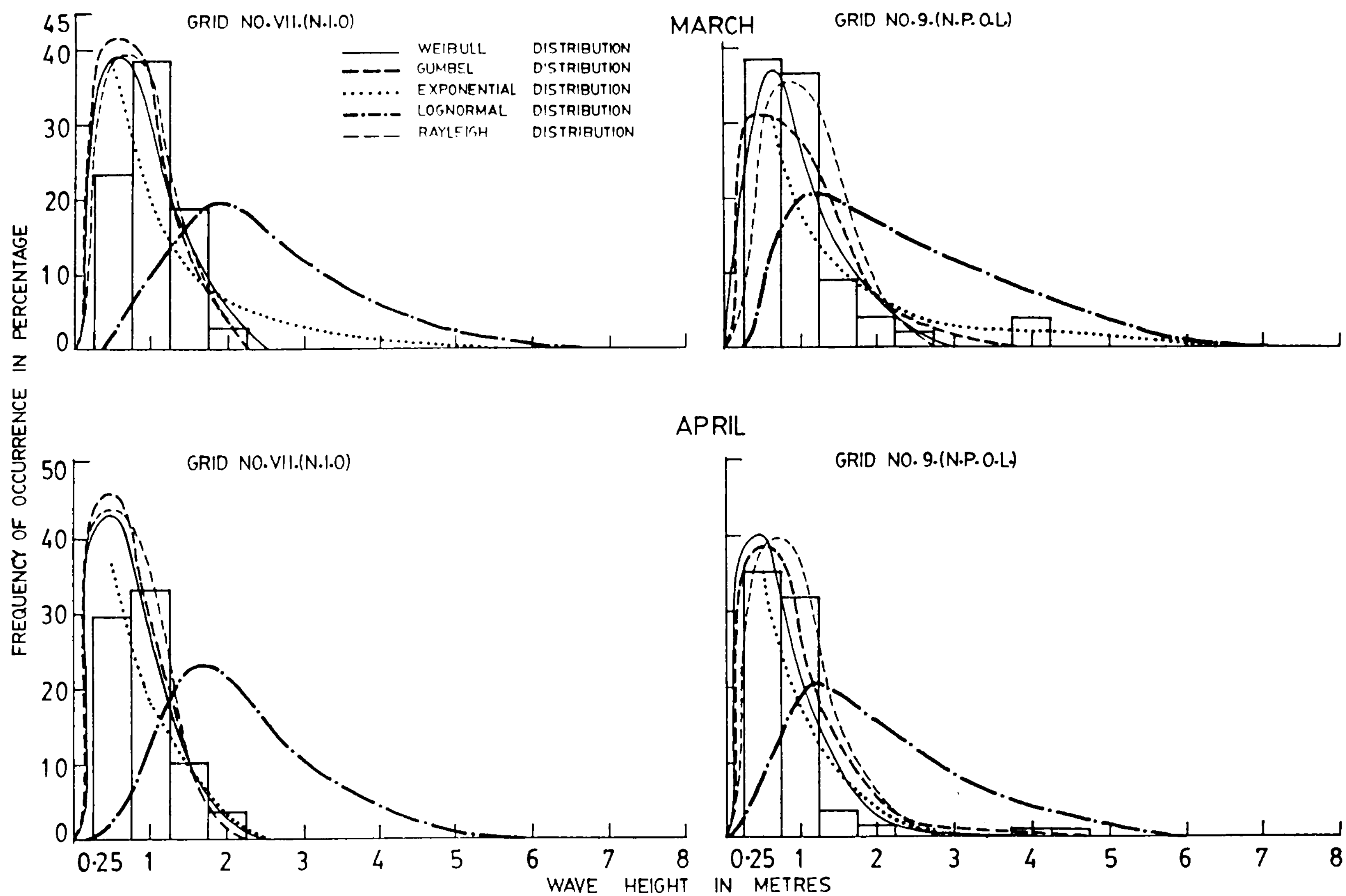

Fig. 5(b) Comparison of the distributions of observed wave heights (Histograms) with theoretical distributions off Mangalore.

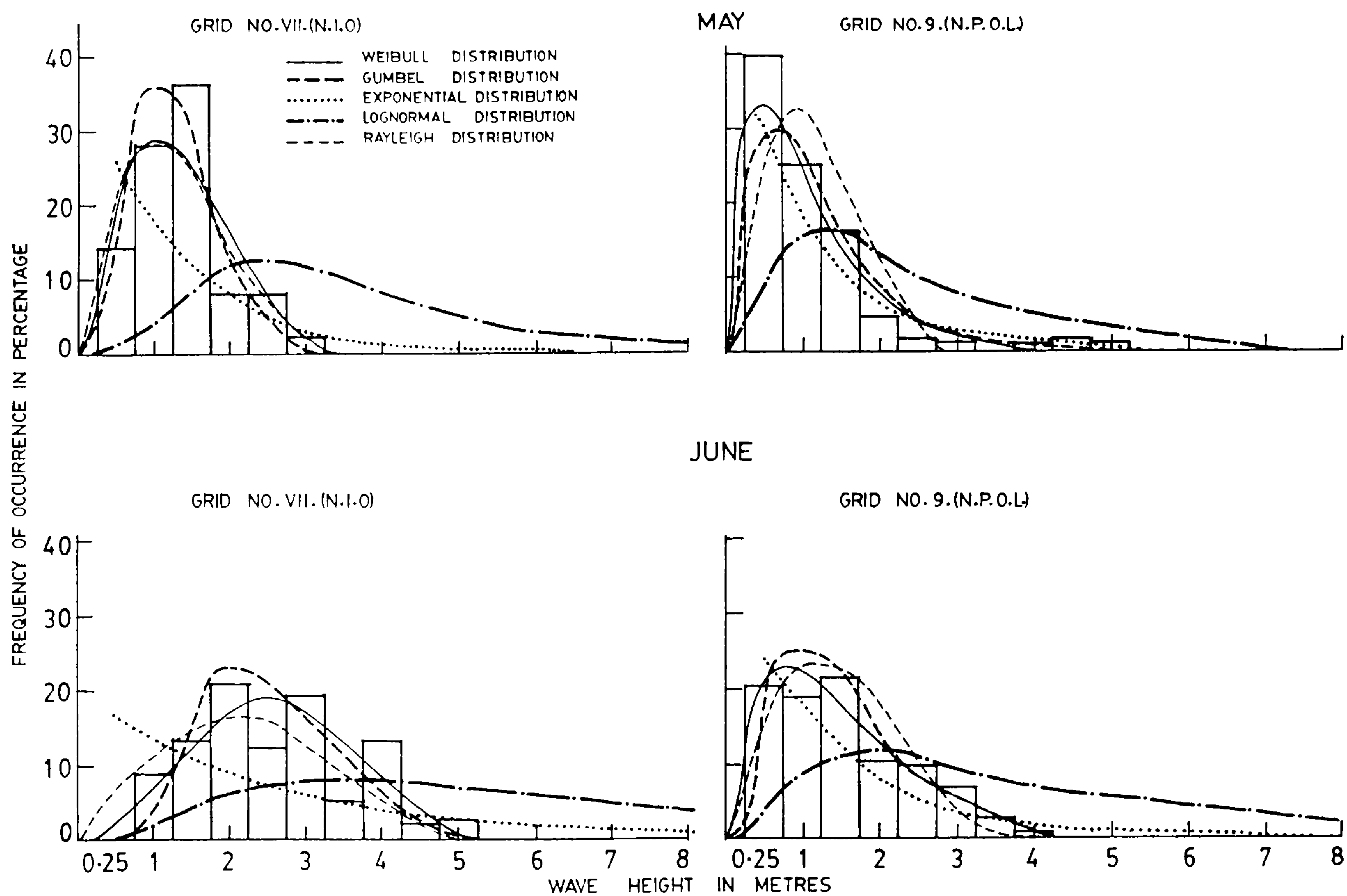

Fig. 5(c) Comparison of the distributions of observed wave heights (Histograms) with theoretical distributions off Mangalore.

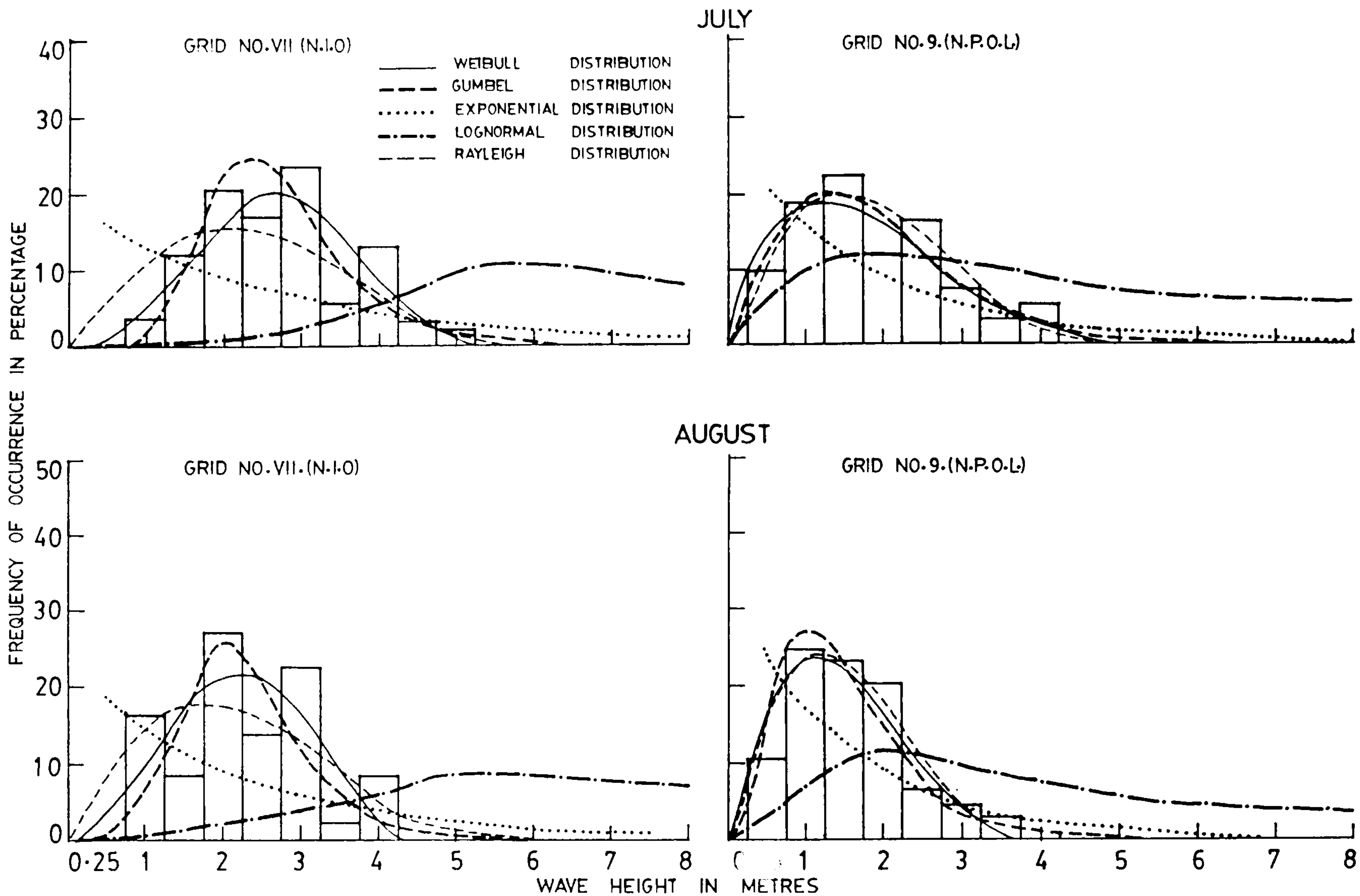

Fig. 5(d) Comparison of the distributions of observed wave heights (Histograms) with theoretical distributions off Mangalore.

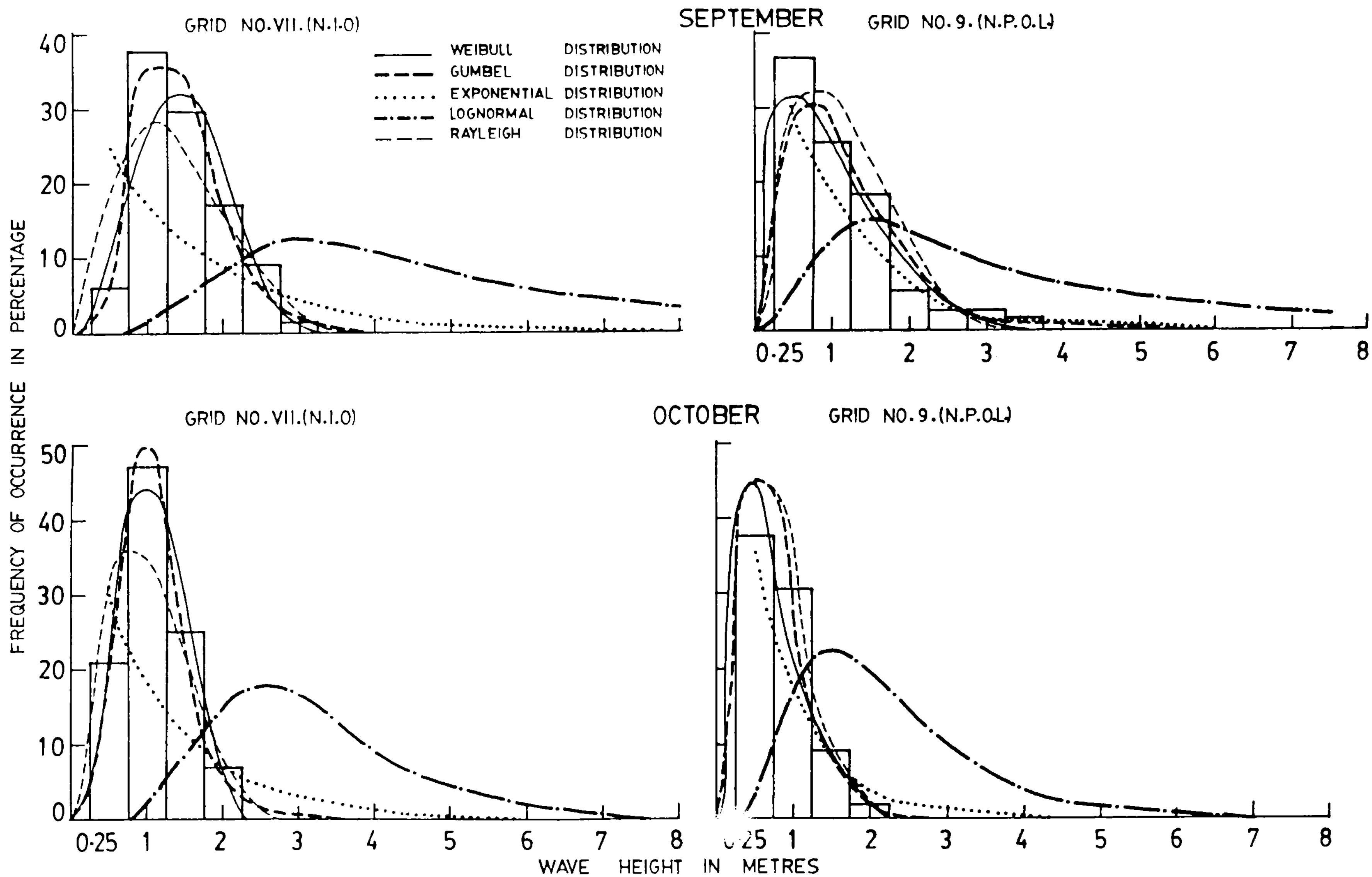

Fig. 5(e) Comparison of the distributions of observed wave heights (Histograms) with theoretical distributions off Mangalore.

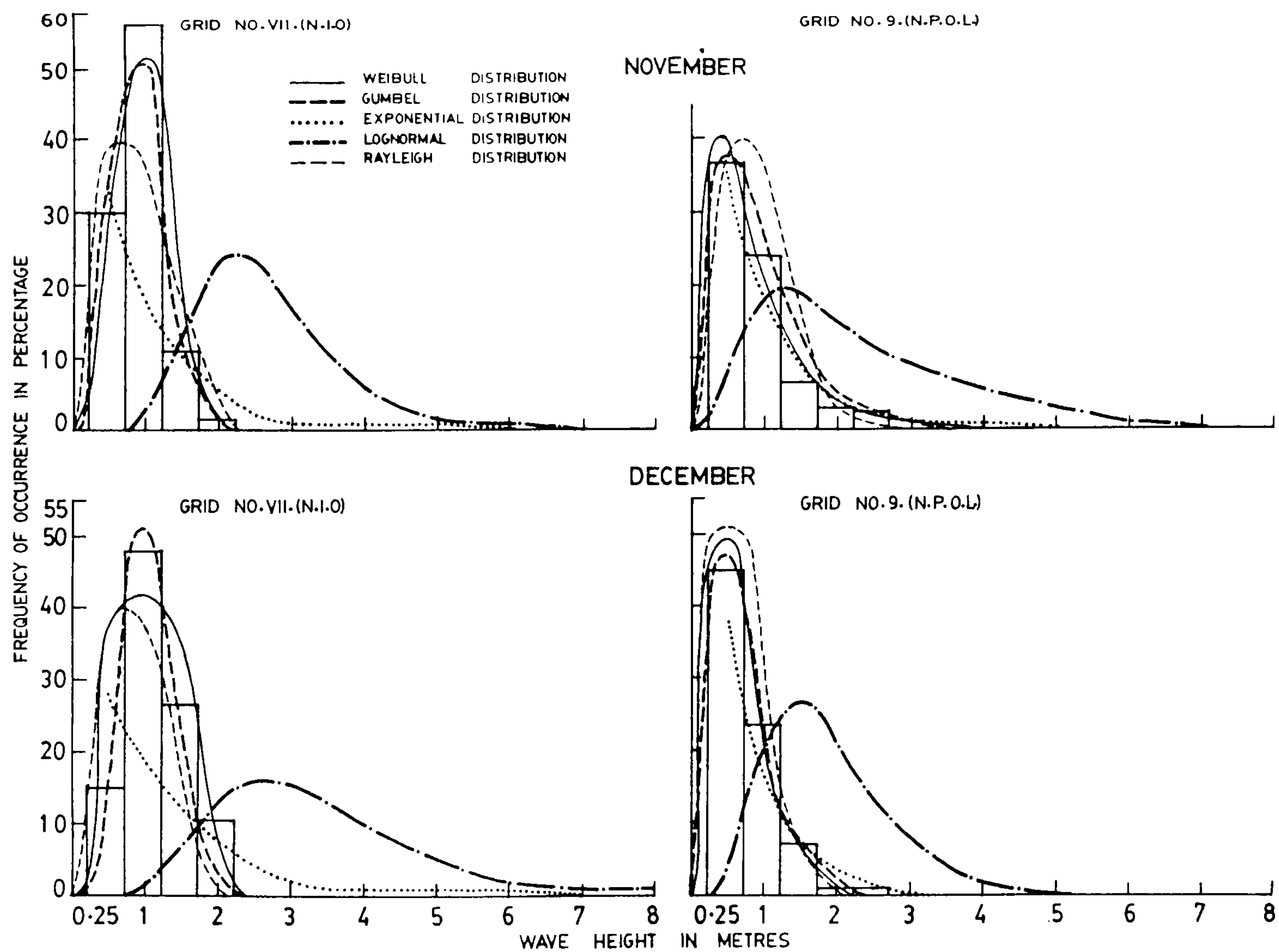

Fig. 5(f) Comparison of the distributions of observed wave heights (Histograms) with theoretical distributions off Mangalore.

to a maximum of 10.0% and 12.5% respectively. The respective values for Gumbel and Rayleigh are 7.5% and 11.0%, 7.0% and 21.5% . The peak percentage frequencies of observed wave heights of sea and swell combined sea-state is more effectively estimated by Weibull than Gumbel whereas in the case of swell dominated state, the estimation by Gumbel is more effective. For the sea and swell prevailed sea-state, the Weibull, Gumbel and Rayleigh models overestimate the peak percentage frequencies of wave heights in half of the cases and underestimate in the other half. The three models underestimate the peak percentage frequencies of occurrence of wave heights of swell dominated conditions in majority of the cases.

The distribution of the visually obtained percentage frequency of occurrence of wave heights show a narrow band of wave heights for both swell and, sea and swell combined conditions. A change to broad band is observed during southwest monsoon season.

3.6.1. Wave statistics off Mangalore from Weibull model

Since Weibull model is considered as a basic model for modelling the long-term distributions of wave heights, the wave statistics computed from the model using the wave height parameters from these grids are compared with those obtained from available recorded wave information off Mangalore.

Table VIII

Averaged computed (C) and predicted (P) ratios of standard wave height parameters

Ratio	Grid 9		Grid VII	
	C	P	C	P
$H_{max}/H_{1/3}$				
Mean	2.40	--	1.38	--
S.D.	0.52	--	0.14	--
$H_{1/3}/\eta$				
Mean	2.37	3.53	3.52	7.14
S.D.	0.27	0.58	0.44	1.68
H_{max}/η				
Mean	5.56	--	4.82	--
S.D.	0.68	--	0.51	--
$\bar{H}/\eta$				
Mean	1.33	1.44	2.42	2.38
S.D.	0.22	0.18	0.41	0.42
$H_{1/10}/\eta$				
Mean	3.41	7.02	4.28	17.56
S.D.	0.19	1.67	0.45	4.87
$H_{1/10}/H_{1/3}$				
Mean	1.45	1.97	1.23	2.42
S.D.	0.12	0.14	0.06	0.23
$H_{1/3}/\bar{H}$				
Mean	1.81	2.58	1.47	2.96
S.D.	0.11	0.54	0.10	0.25

3.6.2. Ratios of standard wave height parameters off Mangalore

Table VIII gives the mean and standard deviations of certain standard wave height ratios calculated from the visual observations from grid 9 and grid VII in comparison with the values predicted from Weibull model.

Among the various ratios computed $H_{1/3}/\bar{H}$ and $H_{1/10}/H_{1/3}$ show maximum consistency while H_{max}/η, (η- S.D) shows relatively minimum consistency. This may be due to the missing of reporting of high waves because merchant ships usually avoid rough sea conditions. This may also be the reason for the predicted values being higher than the computed values. The reliability of these ratios has to be checked with that obtained from long-term recorded wave information, at present which is not available.

3.6.3. Averaged maximum wave height off Mangalore

The averaged largest wave heights to return within 5, 10 and 100 years are computed from Weibull model (2.27) and are presented in table IX. These values are compared, with available results obtained from recorded wave information off Mangalore. (Dattatri, 1973, 1981).

Dattatri (1973) obtained 10 year maximum wave height to be 8.0 m. Also he got a value of 7.506 m by the method suggested

Table IX

Averaged maximum wave heights for overall data and monsoon data for grid 9 and grid VII

Averaged maximum wave height	Grid 9		Grid VII	
	overall data	monsoon data	overall data	monsoon data
5 year wave (m)	8.29	10.25	5.29	7.05
Decennial wave (m)	10.64	12.84	6.14	7.97
Centennial wave (m)	17.26	19.88	8.23	10.13

by Jean Larras (1970). The 10 year maximum wave extrapolated from overall and monsoon data for the Weibull distribution is 7.20 m and 6.40 m respectively (Dattatri, 1981). The results are comparable with those obtained from swell data (grid VII) while that from sea and swell statistics (grid 9) give much higher values (Muraleedharan et. al. 1989). This is because the recorded waves are mainly swells over shallow depths while the wave statistics is averaged over wider deep sea area.

3.6.4. Return periods of maximum wave height off Mangalore

The return periods of maximum wave heights given in grid 9 and grid VII are computed using the relation derived from Weibull (sec. 2.7). The maximum wave height reported for sea and swell prevailed condition was 6.5 m (grid 9) and its return period (median) considering overall data is found to be 3.05 years. But the maximum wave height reported for swell dominated condition (grid VII) is only 5.0 m and taking yearly data into account its re-occurrence (median) is computed to be 4.20 years. The reliability of these findings is to be checked with recorded wave information. It is to be noted that the maximum wave height reported for sea and swell combined condition returns earlier than the maximum height reported for swell dominated condition though it is higher. The reason is evident that swell waves are much regular whereas sea waves are irregular and chaotic and are frequently characterised by high waves.

3.6.5. Probability of realising a wave height greater than a designated value in a given period of time off Mangalore

The chances for a wave height greater than a designated value to occur in a given period of time was determined. (sec. 2.7). The maximum wave height is reported to be 6.5 m for sea and swell prevailed sea-state (grid 9) and its re-occurrence is seen to be 3.05 years. The probability of this height and higher to occur within 1 year is 32.77% and within 2 years is 65.57%. The maximum wave height reported for swell dominated condition (grid VII) is 5.0 m and its return period is seen to be 4.20 years. The chance of wave height greater than or equal to this to occur within a year is 23.81% and within 2 years is 47.62%. The recorded information for this purpose are not available and hence the reliability of these findings are uncertain due to the limitations of the data involved in this work.

3.7. Comparison of wave directions off Mangalore

A comparison of monthly predominant wave directions of sea and swell combined condition (grid 9) and swell prevailed condition (grid VII) are given in table X.

Table X

Comparison of monthly predominant wave directions

Month	Grid 9	Grid VII
January	360 (N)	330 and 360 (NNW and N)
February	330 (NNW)	330 (NNW)
March	360 (N)	330 (NNW)
April	300 (WNW)	330 (NNW)
May	300 (WNW)	270, 300 and 330 (W, WNW and NNW)
June	270 (W)	270 (W)
July	240 (WSW)	270 (W)
August	270 (W)	270 (W)
September	270 (W)	270 (W)
October	330 (NNW)	180 and 330 (S and NNW)
November	360 (N)	330 and 360 (NNW and N)
December	360 (N)	360 (N)

During southwest monsoon season, the waves approach from directions ranging from westsouthwest and westnorthwest for sea and swell combined state. For the swell prevailed condition, waves approach from a direction between west and northnorthwest. Post-monsoon season is characterised by southerly or northnorthwesterly waves. During the northeast monsoon period, northerly or northnorthwesterly directions of approach are indicated in both the atlases. Pre-monsoon is characterised by waves from northnorthwest to north. A comparison of the monthly predominant wave directions given in the atlases for sea and swell combined sea-state and swell dominated conditions indicates that the predominant wave directions are more or less the same for both state. At present no measured information are available on wave directions for shallow waters in this region.

Chapter-4

LONG-TERM DISTRIBUTIONS OF WAVE PERIODS AND WAVE POWER

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Chapter-4

LONG-TERM DISTRIBUTIONS OF WAVE PERIODS AND WAVE POWER

4.1. Introduction

While there is an abundance of literature on long-term distributions of wave heights, there is a paucity of literature on the long-term distributions of wave periods. A few studies have been reported on the short-term distributions of wave periods. (Longuet-Higgins, 1975; Dattatri et. al. 1979; Deo and Narasimhan, 1979; Baba and Harish, 1985). This chapter attempts to explain the long-term distributions of wave periods in terms of probability distributions using visual data on wave periods reported in the atlases of N.P.O.L. (1978) and N.I.O(1982).

The monthly distributions of the zero-crossing wave periods computed from the averaged significant wave periods given in the atlases are compared with those calculated from the available recorded wave information for the regions considered. The monthly percentage frequency of occurrence of wave periods obtained from the atlases are compared with the percentage frequencies obtained from the probability distributions suggested for long-term distributions of wave periods. The monthly distributions of wave power is computed using visual wave statistics and compared with wave power calculated from the available recorded wave information.

4.2. Long-term distributions of wave periods off Trivandrum

The long-term distributions of wave periods obtained from N.P.O.L data (grid 17) and N.I.O data (grid I) are presented in Fig.6(a-f). In these diagrams the histograms represent the observed frequency of occurrence of wave periods and the curves provide the theoretical models. Four theoretical models are made use of for this purpose. They are gamma, Bretschneider, exponential and Rayleigh distributions. The goodness of fit of these distributions are tested visually with the observed percentage frequency of wave periods. From these diagrams, revealing the monthly observed wave period pattern and the theoretical curves, two theoretical models are suggested for the two different sea-states, viz, the sea and swell combined state and the swell prevailed state. For the forms of the densities of the above models, and the methods of estimators of the parameters there of, we refer to section 1.4.3.4.

The sea and swell prevailed condition is evidenced by the broad band of wave periods in grid 17. The wave periods range from less than or equal to 5 seconds to more than 21 seconds. From Fig.6(a-f), it can be seen that gamma distribution explains the changing wave period patterns more accurately than the other three curves. The observed peak percentage frequency of occurrence of wave periods lies in the period range 0.5 S - 5.5 S in majority of the cases. The second peak is observed at 5.5 S -

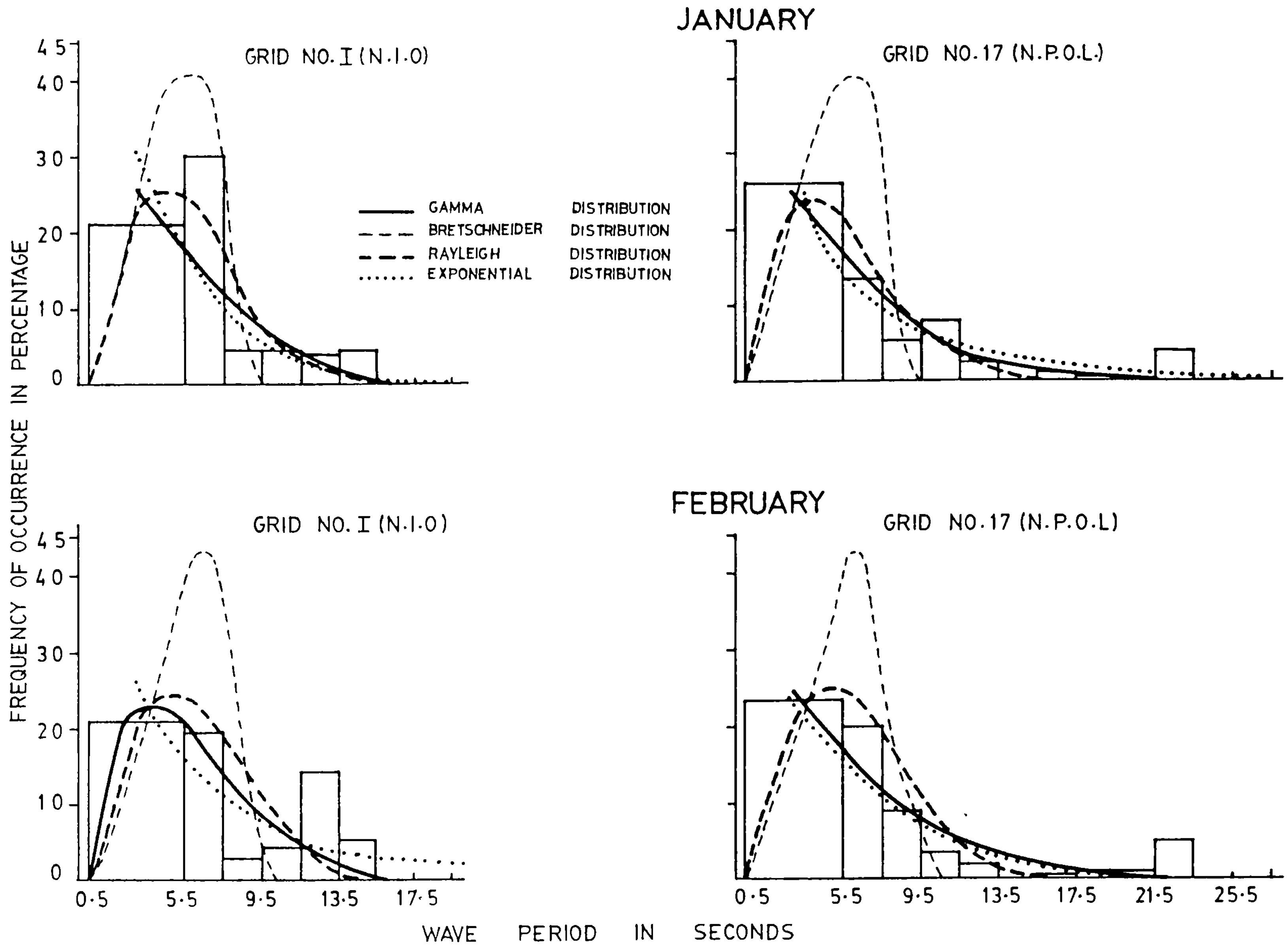

Fig. 6(a) Comparison of the distributions of observed wave periods (Histograms) with theoretical distributions off Trivandrum.

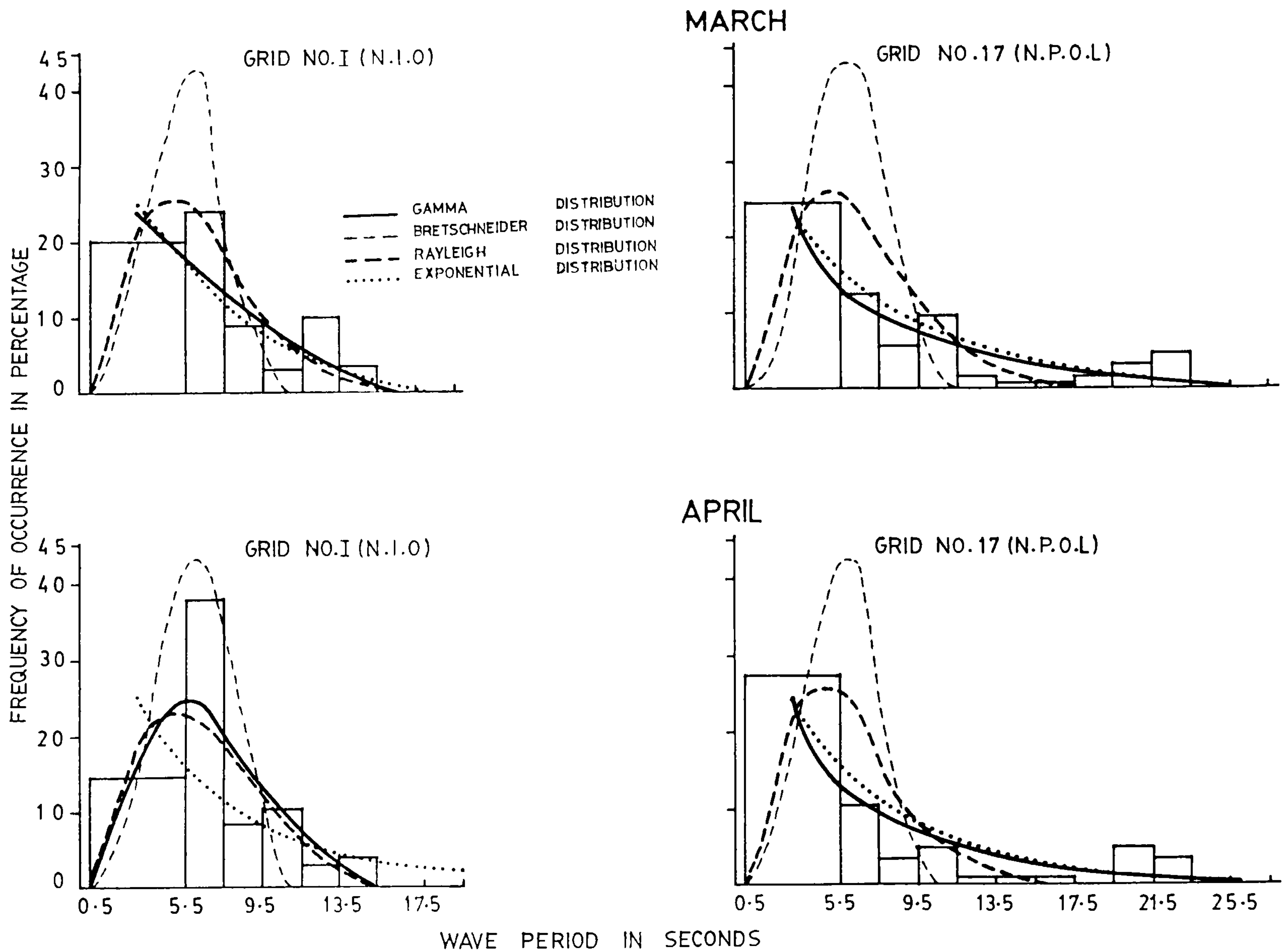

Fig. 6(b) Comparison of the distributions of observed wave periods (Histograms) with theoretical distributions.off Trivandrum.

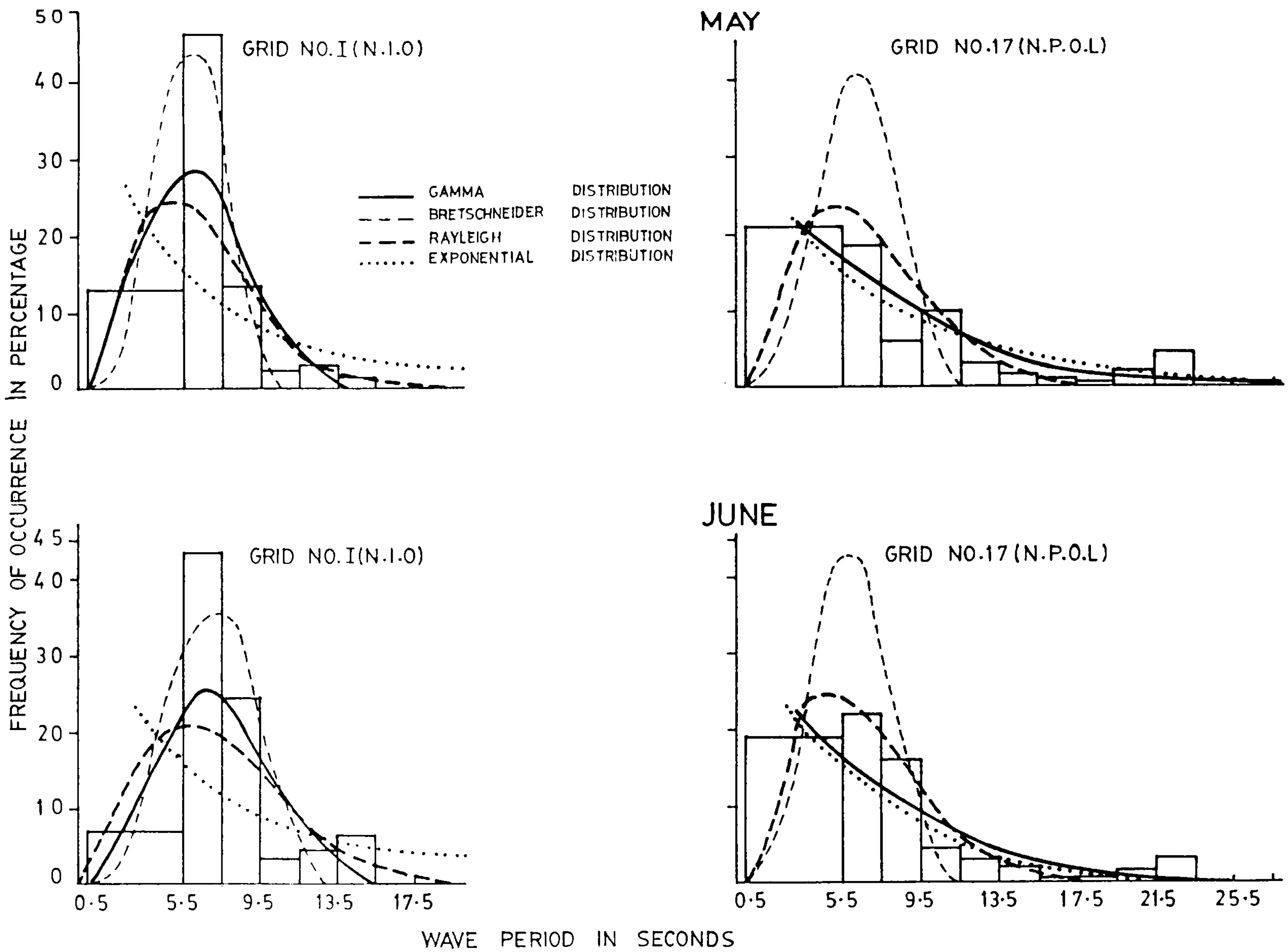

Fig. 6(c) Comparison of the distributions of observed wave periods (Histograms) with theoretical distributions off Trivandrum.

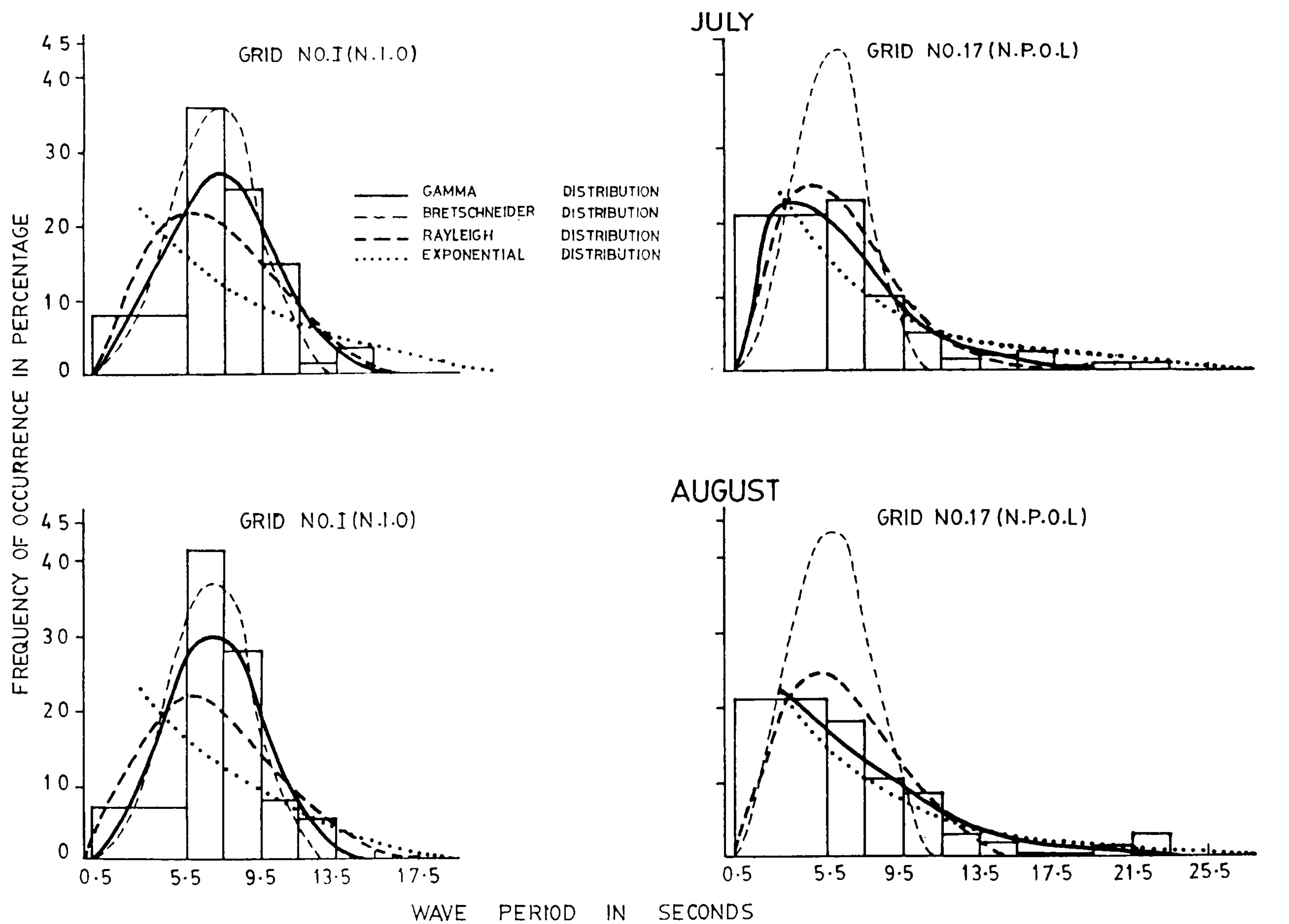

Fig.6(d) Comparison of the distributions of observed wave periods (Histograms) with theoretical distributions off Trivandrum.

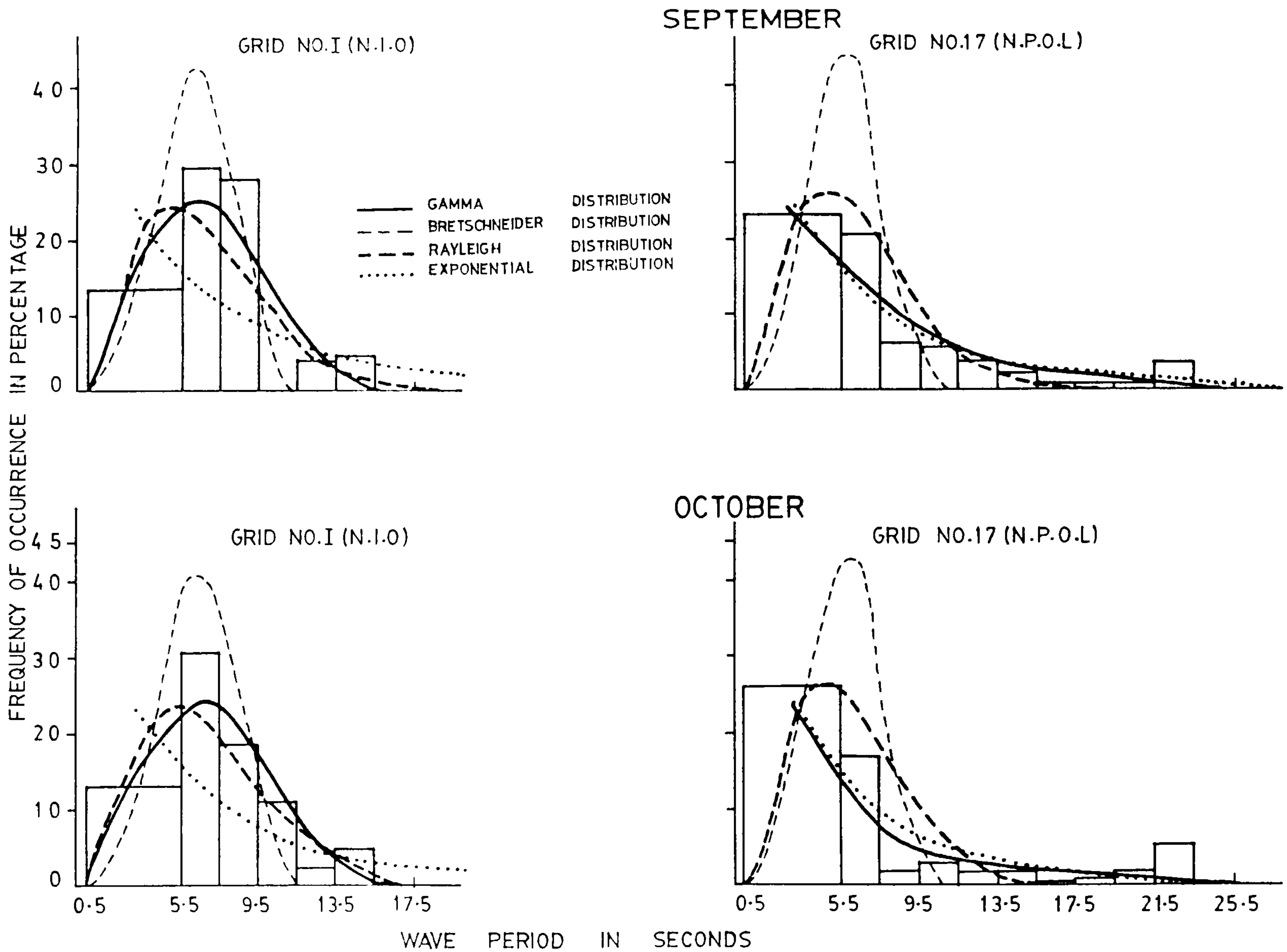

Fig.6(e) Comparison of the distributions of observed wave periods (Histograms) with theoretical distributions off Trivandrum.

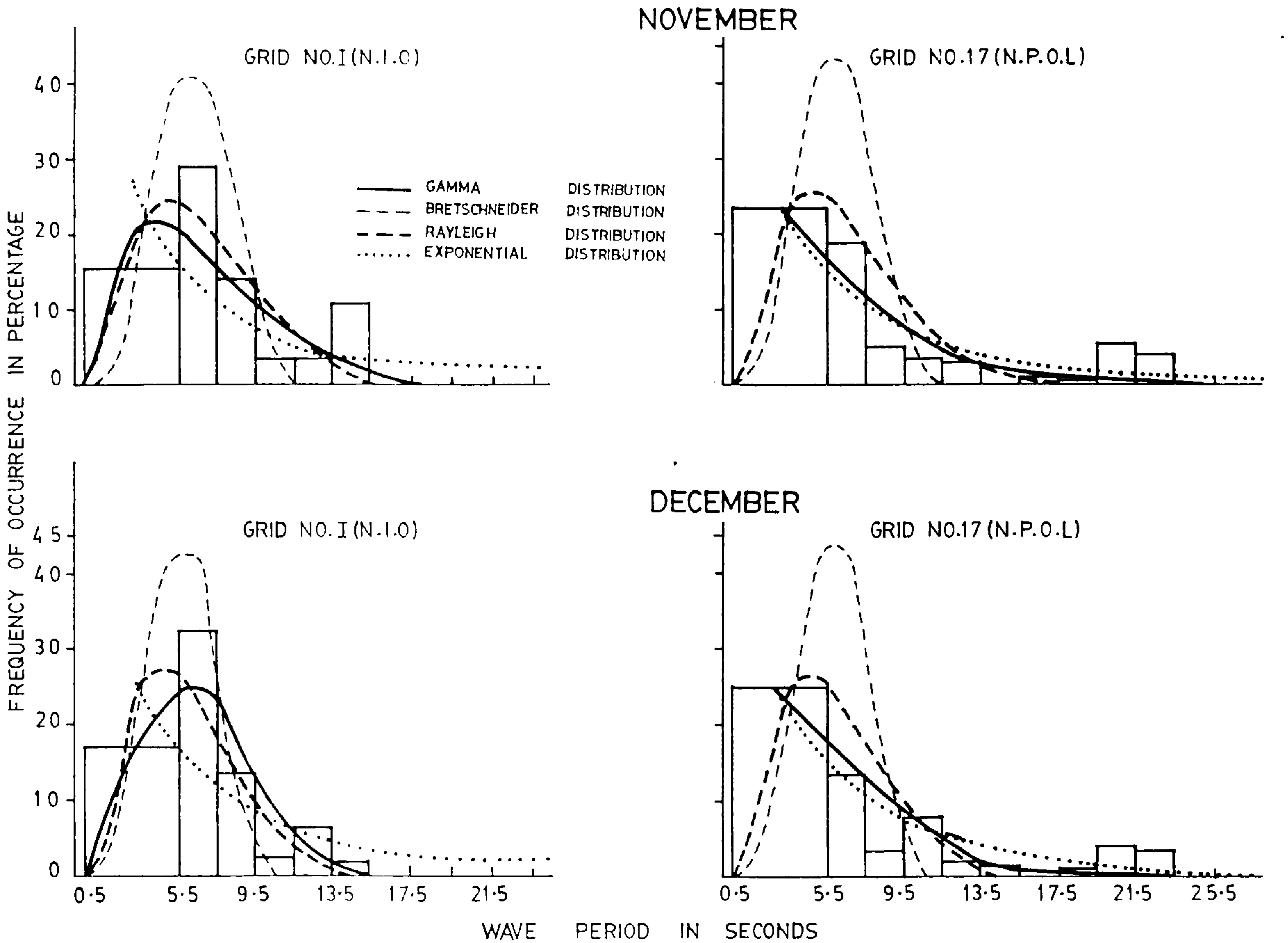

Fig.6(f) Comparison of the distributions of observed wave periods (Histograms) with theoretical distributions of Trivandrum.

7.5 S. The wave period patterns do not show any noticeable monthly variations. The gamma distribution more or less correctly estimates the observed peak percentage frequency. It underestimates the second peak percentage frequency to a maximum of 8.0%. The exponential distribution explains the observed wave period patterns better than the Bretschneider and Rayleigh distributions. In many of the cases the gamma distribution shows a closeness to the exponential curve. It is to be noted that exponential curve is a special case of the gamma family of curves for $\alpha = 1$, where α is a parameter of the gamma model. The Bretschneider and Rayleigh distributions totally fail in explaining the long-term distributions of wave periods. The Bretschneider distribution shows very high kurtosis and a very narrow band of wave periods.

The swell prevailed sea-state is characterised by a narrow band of wave periods compared to sea and swell combined condition. Wave periods ranging from less than or equal to 5 S to 15 S are observed under this condition. The observed peak percentage frequency which is prominent during the south-west monsoon season lies in the period range 5.5 S to 7.5 S. A second peak percentage frequency lies in the period range 7.5 S to 9.5 S during the rough weather season and in the 0.5 S to 5.5 S range always in the fair weather season.

The Bretschneider distribution explains the long-term distributions of swell wave periods better than the gamma, Rayleigh and exponential models. This is because the function has a strong base on the narrow bandedness of the wave periods which is observed in the swell dominated sea-state (Baba, 1985). Still it fails to explain the higher side of the wave periods ranging from 11.5 S to 15.5 S. This part is estimated by the gamma distribution better than the other models. As a whole, the Bretschneider distribution gives visually a good fit to the observed distributions of long-term wave periods. In certain cases the Bretschneider distribution shows a high kurtosis. The exponential curve completely fails in explaining the distribution patterns of swell wave periods.

Monthly percentage frequency of occurrence of waves in the period range less than or equal to 5 S to 7 S (T_S)obtained for sea and swell combined state (grid 17) and swell prevailed state (grid I) are compared with that obtained from the theoretical models suggested for the long-term distributions of wave periods (T_S). (Table XI).

The percentage frequency of occurrence of significant wave periods estimated from Bretschneider model is higher than that obtained from grid I(N.I.O) for swell prevailed condition whereas gamma model estimates are more or less equal to those

Table XI

Comparison of percentage frequency of occurrence of significant period in the range $\leqslant$ 5 S to 7 S obtained for swell prevailed state (grid I) and sea and swell combined condition (grid 17) with those from theoretical models.

Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Swell												
Visual (grid I)	82.0	72.5	74.5	74.0	79.5	61.0	55.5	59.0	63.5	63.5	67.5	75.5
Bretschneider (theoretical)	93.0	82.5	87.0	77.5	83.0	54.5	55.5	59.0	75.0	69.5	69.0	86.5
Sea and Swell												
Visual (grid 17)	78.0	78.5	73.5	79.0	71.0	69.5	76.0	70.5	77.5	82.0	78.0	76.0
Gamma (theoretical)	76.0	75.5	69.5	72.0	69.0	69.5	72.5	69.5	71.5	70.0	70.5	71.0

obtained from grid 17 (N.P.O.L) for sea and swell combined sea-state. As a whole the estimations by the two theoretical models for two different sea-states are comparable with those obtained from visually gathered information. For the swell dominated condition the Bretschneider model overestimates the observed percentage frequency of occurrence of wave periods during various months to a maximum of 12.5% and for the sea and swell combined sea-state, the gamma model underestimates to a maximum of 12.0%.

4.3. Distributions of zero-crossing wave periods

The zero-crossing wave period is the average of the zero-up crossing wave period (The time difference between two consecutive points at which the wave crosses the mean sea level in the upward direction) and zero-down crossing wave period (The time difference between two consecutive points at which the wave crosses the mean sea level in the downward direction).

The monthly distributions of the zero-crossing wave periods computed from averaged significant wave periods obtained (sec. 1.4.3.2) from the N.P.O.L atlas (grid 17) and N.I.O atlas (grid I) are compared, with that calculated for Valiathura (Trivandrum) from recorded wave statistics (Baba, 1985). These three distributions are given in Fig.7.

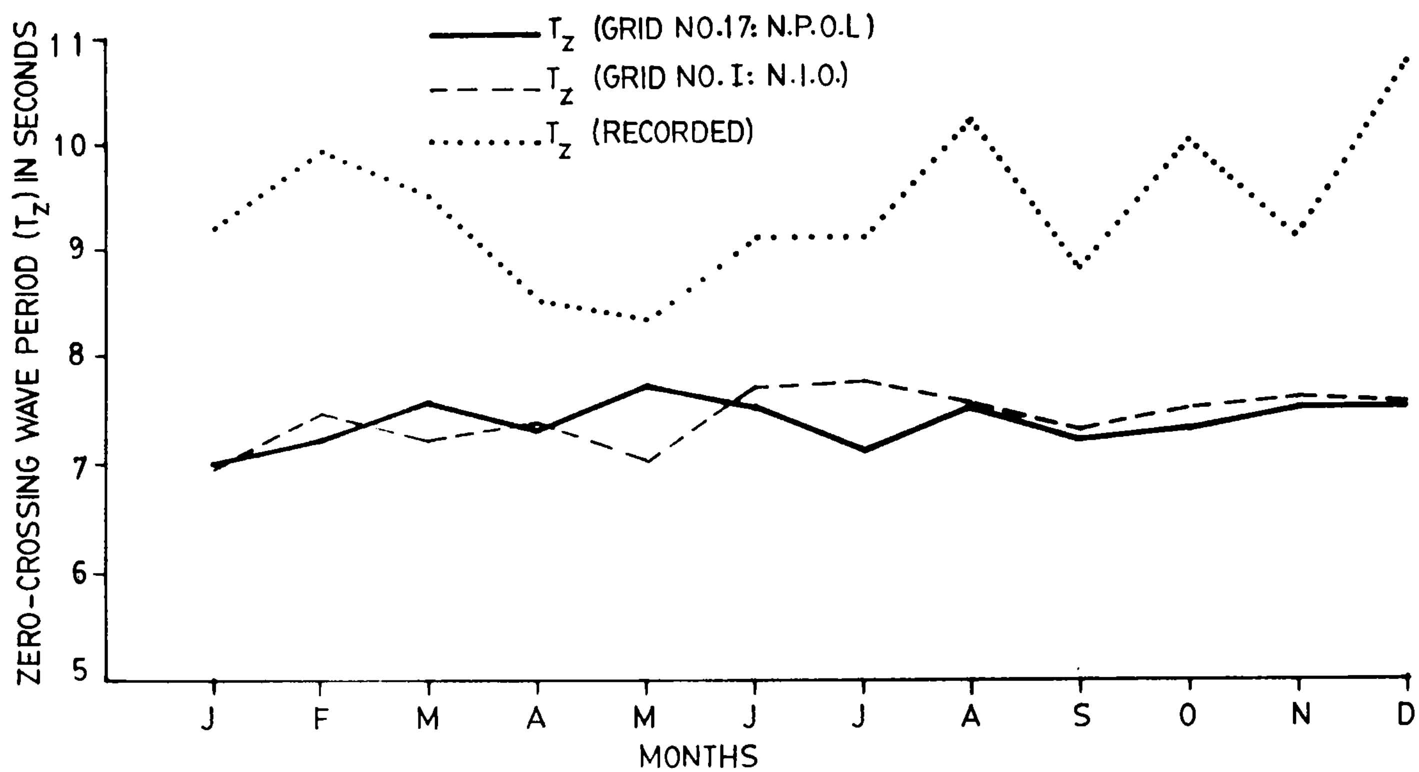

Fig.7. Comparison of the monthly distributions of wave periods (T_z) off Trivandrum.

The recorded waves show an average monthly zero-crossing period ranging from a minimum of 8.3 S in May to a maximum of 10.7 S in December. The sea and swell combined state provides a monthly distribution of zero-crossing wave periods having a minimum of 7.0 S in January and a maximum of 7.7 S in May. For the swell prevailed condition the monthly distributions of wave periods gives a minimum of 6.9 S in January and a maximum of 7.7 S in June and July. For both the sea and swell combined sea-state and the swell prevailed sea-state, the consistency in the monthly distributions of zero-crossing periods is equally higher than for the short-term monthly distributions of zero-crossing periods derived from recorded wave data off Valiathura (Trivandrum).

The monthly distributions of the wave periods obtained for sea and swell combined condition, swell prevailed sea-state and recorded information do not show any similarity in trend. Some trend is observed (Fig.7) during August to December for grid 17 and grid I. The average zero-crossing periods for various months computed from recorded information (Baba, 1985), show higher values throughout the year than those from grid 17 and grid I. Calibration of the visually obtained periods would require recorded information on long-term distributions of wave periods.

4.4. Distribution of wave power off Trivandrum

The monthly distribution of wave power computed for swell prevailed condition (grid I) and sea and swell combined sea-state (grid 17) using the relation given in section 1.4.3.2, are given in Fig.8. These are compared, with the wave power calculated from recorded wave information off Trivandrum (Thomas et. al. 1986).

The sea and swell statistics (grid 17) show an annual variation of wave power ranging from a minimum of 1.35 kwm^{-1} during April to a maximum of 7.03 kwm^{-1} during July. The swell statistics on the other hand, show larger monthly variation ranging from a minimum of 3.35 kwm^{-1} during March to a maximum of 21.50 kwm^{-1} during June. The averages of wave power for the annual, fair weather (November to April) and rough weather (May to October) periods are given in table XII.

The sea and swell statistics (grid 17) provide lower values of wave power while the swell statistics (grid I) provide values comparable with wave power obtained from nearshore recordings.

Average wave power is maximum (23 kwm^{-1}) during June and July (Thomas et. al. 1986). The wave power computed from sea and swell statistics for these months are 6.69 kwm^{-1} and

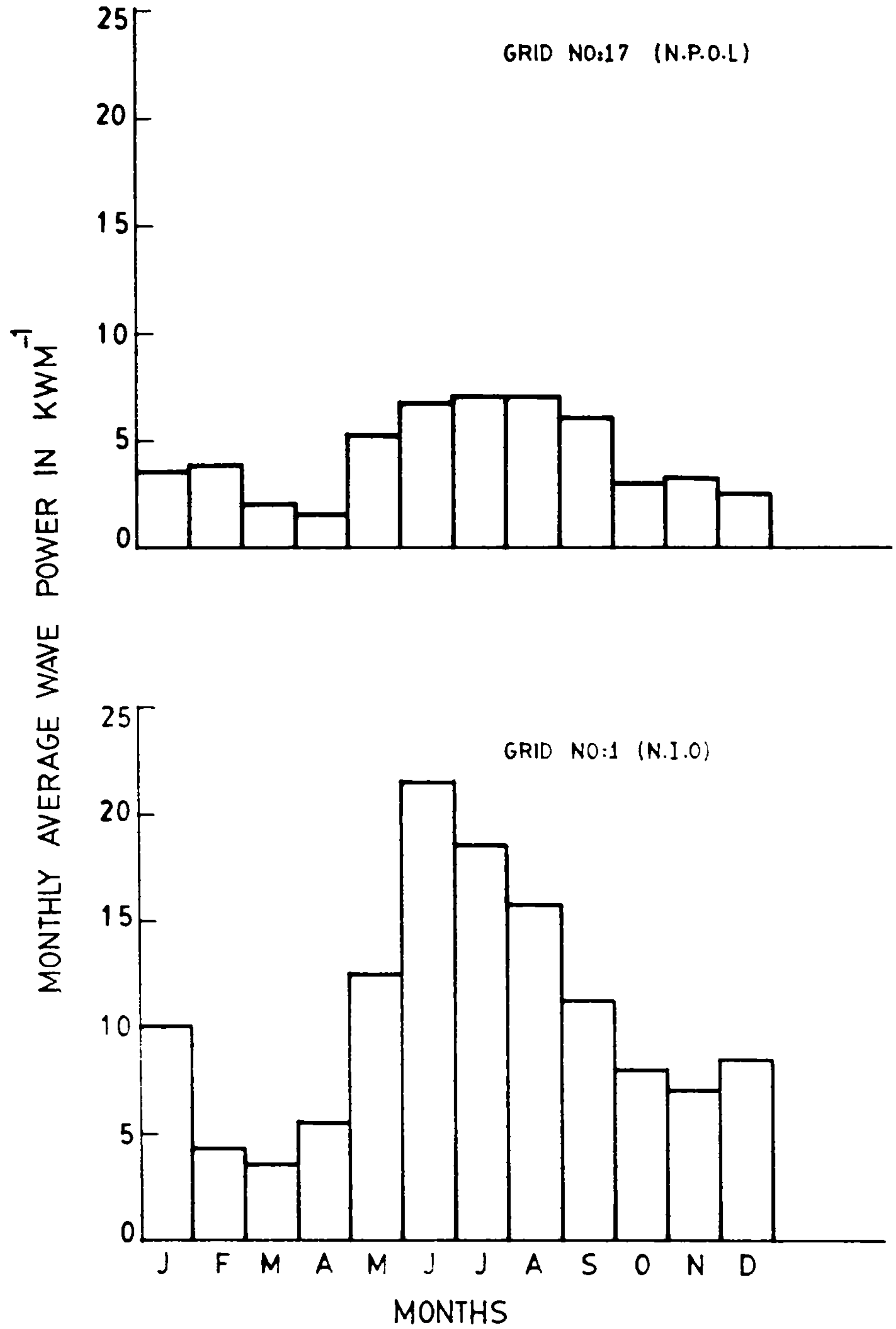

Fig.8 Distribution of monthly average wave power off Trivandrum

Table XII

Comparison of wave power for annual, fair weather and rough weather periods.

Data	Wave power kwm^{-1}		
	Annual	Fair Weather	Rough Weather
Sea and Swell	4.26	2.70	5.82
Swell	10.45	6.42	14.49
Nearshore (off Trivandrum)	10.00	4.52	15.50

7.03 kwm^{-1} respectively which are very low estimations than those from recorded wave information. The respective values for swell prevailed conditions are 21.50 kwm^{-1} and 18.57 kwm^{-1}.

Thomas et. al. (1986) arrived at the conclusion that wave power along Trivandrum coast is usually less than 10 kwm^{-1} during fair weather seasons. During rough weather time wave power usually exceeds 10 kwm^{-1}. This is true for swell prevailed condition (grid I) but the values are very low in the case of combined sea and swell wave statistics for both fair and rough weather seasons. (Fig.8). The monthly distributions of the wave power obtained from recorded information off Trivandrum (Thomas et. al. 1986) resemble the distribution of wave power averaged from swell statistics especially during rough weather season.

5.1. Long-term distributions of wave periods off Mangalore

The long-term distributions of wave periods for grid 9 (N.P.O.L) and grid VII (N.I.O) are visually examined (Fig.9 (a-f)). After examining the monthly distributions of the percentage frequency of occurrence of wave periods it is seen that of the four models suggested for this purpose, the Bretschneider model explains the long-term distributions of the wave period patterns of swell prevailed condition and the gamma model explains the wave period patterns of sea and swell combined conditions.

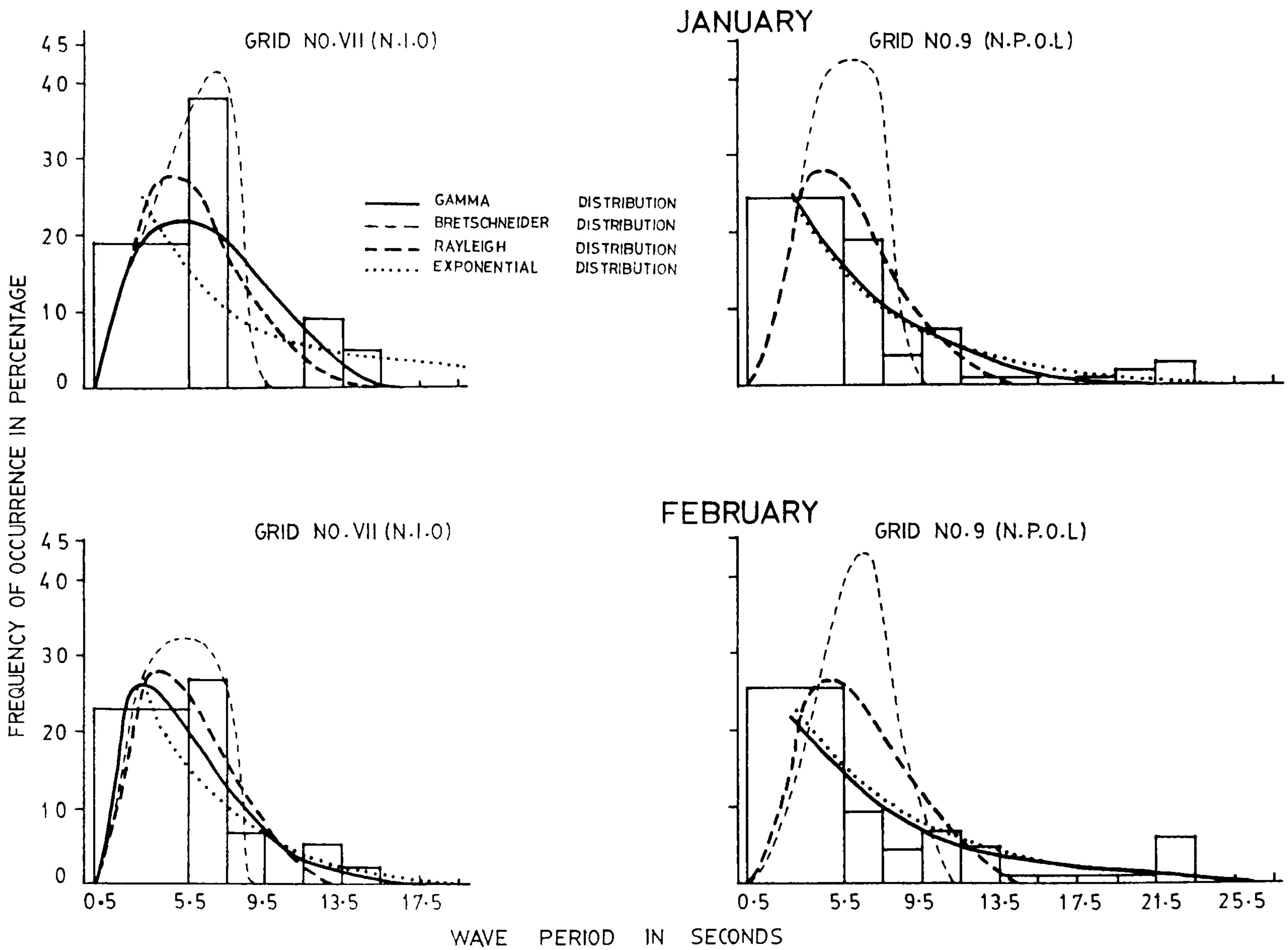

Fig.9(a) **Comparison** of the **distributions** of **observed wave periods (Histograms) with theoretical** distributions **off Mangalore.**

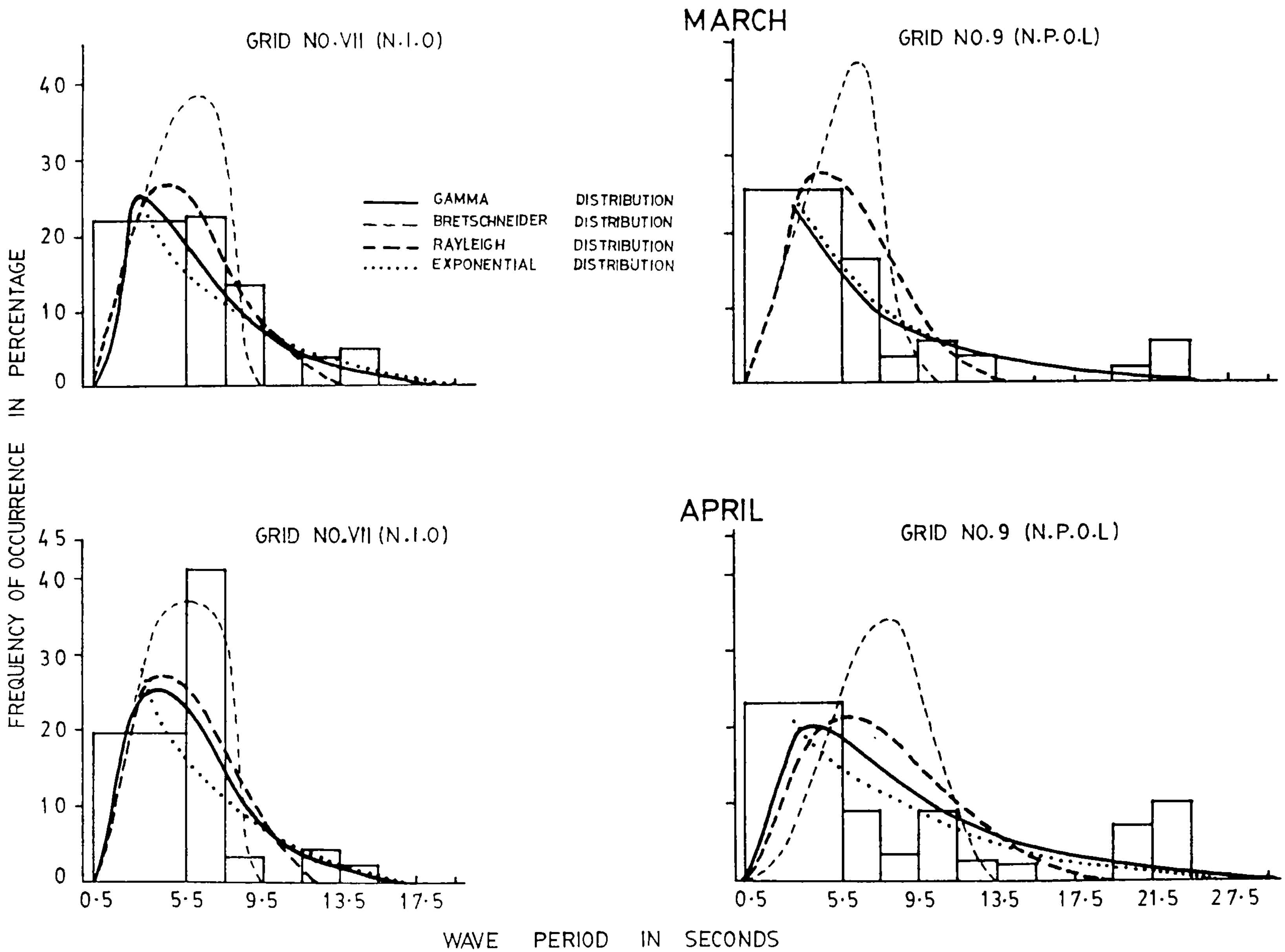

Fig. 9(b) Comparison of the distributions of observed wave periods (Histograms) with theoretical distributions off Mangalore.

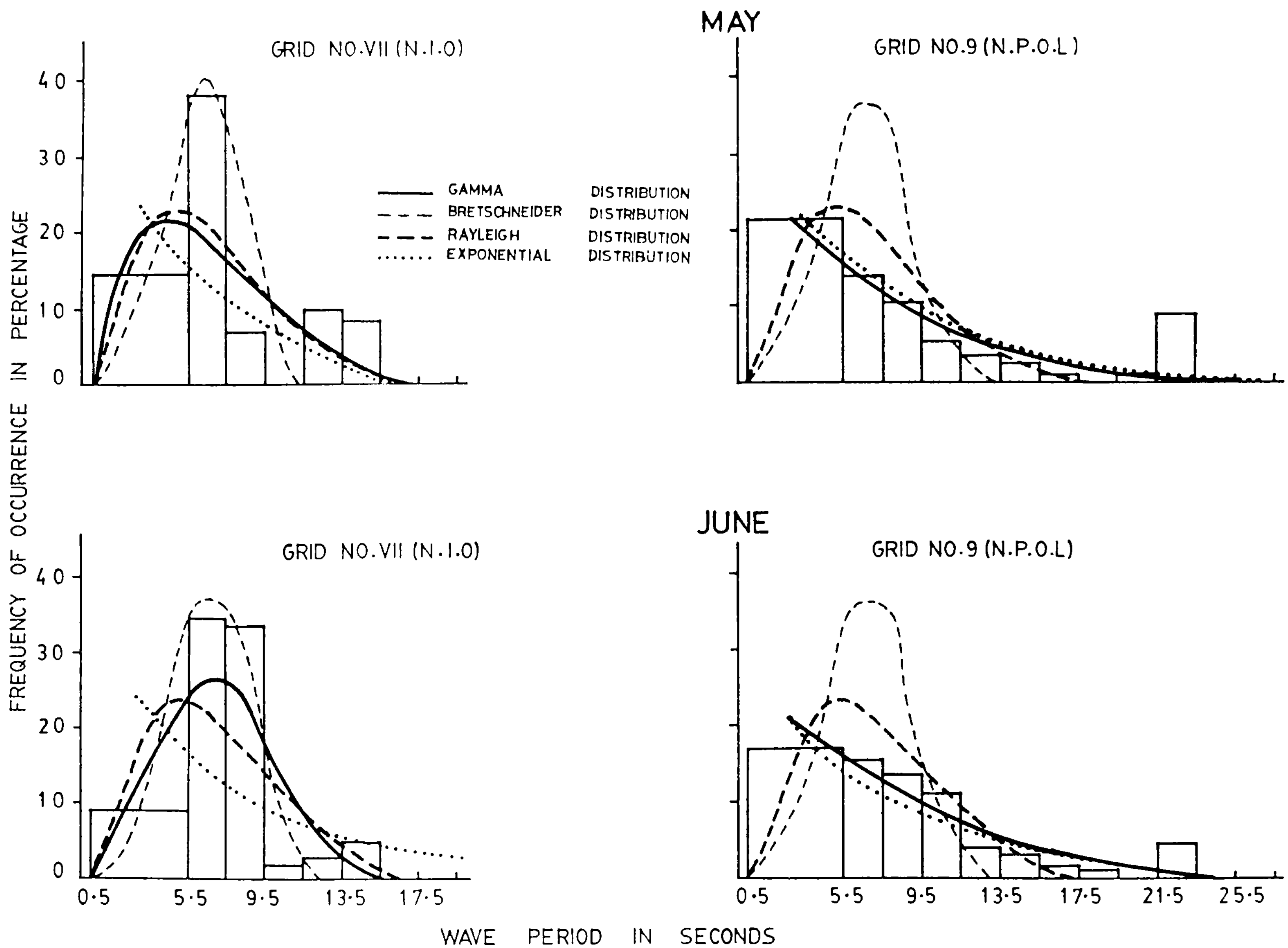

Fig.9(c) Comparison of the distributions of observed wave periods (Histograms) with theoretical distributions off Mangalore.

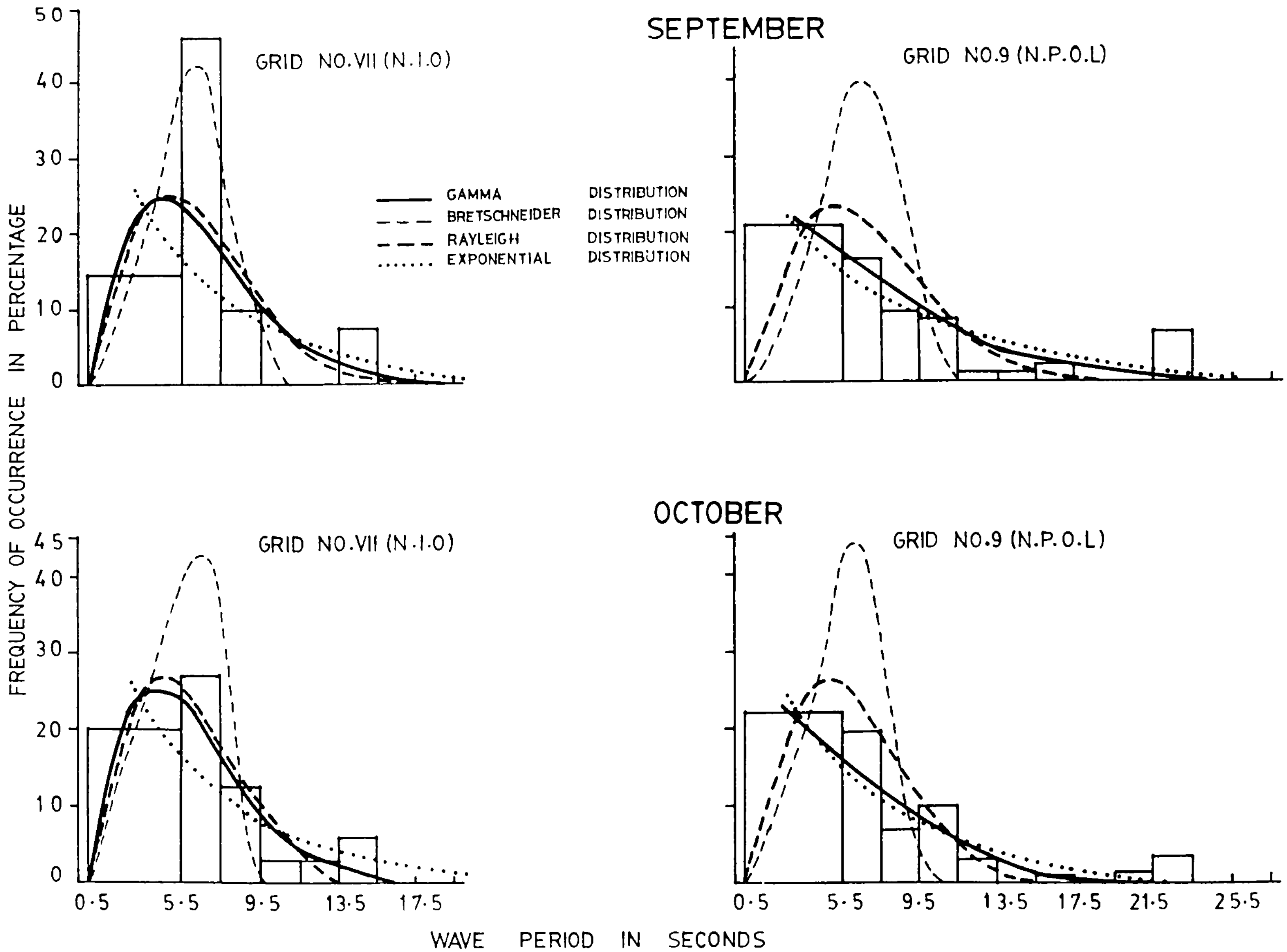

Fig.9(e) Comparison of the distributions of observed wave periods (Histograms) with theoretical distributions off Mangalore.

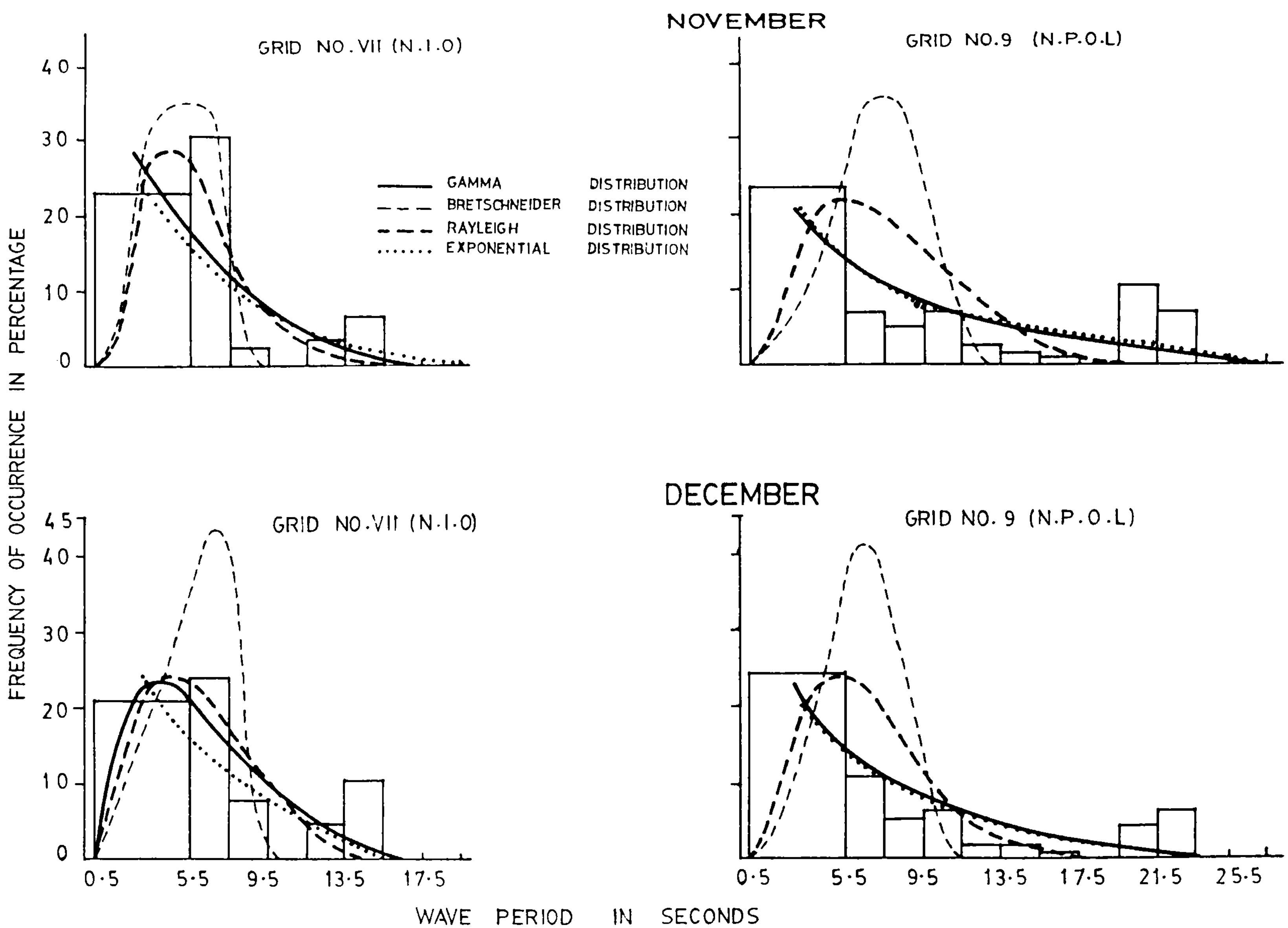

Fig.9(f) Comparison of the distributions of observed wave periods (Histograms) with theoretical distributions off Mangalore.

The broad band of wave periods reveal the presence of sea and swell combined sea-state (Fig.9, histograms). The wave periods range from less than or equal to 5 S to more than 21 S. The gamma model corporates with the changing wave period patterns more effectively than the other three models. The peak percentage frequency of occurrence of wave periods lies in the period range 0.5 S to 5.5 S except in July and August when it lies in the period range 5.5 S to 7.5 S. The maximum of the peak is found to be 26.0% in the period range 5.5 S to 7.5 S, in August and, the minimum of the peak is 17.0% in the period range 0.5 S to 5.5 S, in June. The second peak is observed at 5.5 S to 7.5 S except in July and August when it is in the range 0.5 S to 5.5 S. The maximum of the second peak is found to be 19.5% in October and the minimum of the second peak is found to be 9.5% in February. The observed wave period patterns do not show any considerable variations during the year. The gamma distribution estimates the observed peak percentage frequency more or less correctly. It overestimates and underestimates the peak percentage frequency to a maximum of 3.0% and 8.5% respectively. It overestimates and underestimates the second peak percentage frequency to a maximum of 7.0% and 8.5% respectively.

Swell prevailed sea-state (grid VII) is evident from the presence of a narrow band of wave period compared to the band of periods of sea and swell combined condition (grid 9). Wave periods of less than or equal to 5 S to 15 S are observed under this sea-state. The peak percentage frequency lies in the period range 5.5 S to 7.5 S and it is prominent during May to September.

A second peak frequency is observed between 7.5 S to 9.5 S from June to August. It shifts to 0.5 S to 5.5 S from September to May. The maximum and the minimum of peak frequencies are found to be 46.0% in September and 22.5% in March respectively. The maximum and the minimum of the second peak frequencies are 38.0% in August and 14.5% in May and September respectively.

The Bretschneider model is the best among the four distributions tried for describing the long-term distributions of swell wave periods. But it does not give a good fit on the higher side of the wave periods ranging from 11.5 S to 15.5 S. This portion is estimated from the gamma distribution better than the other three. The exponential curve fails in describing the long-term distributions of wave periods in almost all cases. The Bretschneider model gives a uniformly good visual fit to the observed distributions of long-term swell wave periods.

Table XIII

Comparison of percentage frequency of occurrence of significant period in the range $\leq$ 5 S to 7 S obtained for swell prevailed state (grid VII) and sea and swell combined condition (grid 9) with those from theoretical models.

Data	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Swell												
Visual (grid VII)	86.0	85.0	77.0	90.0	74.5	56.5	53.0	61.0	82.0	76.5	87.5	76.0
Bretschneider (theoretical)	90.0	98.5	94.5	95.5	70.0	60.0	55.0	69.0	83.0	90.5	96.5	86.0
Sea and Swell												
Visual (grid 9)	80.0	73.0	80.0	66.0	67.5	57.5	57.0	63.5	69.0	74.5	66.0	72.0
Gamma (theoretical)	75.5	65.0	72.5	60.5	65.0	67.0	57.5	63.5	64.5	71.0	64.5	66.5

The Bretschneider model overestimates the percentage frequency of occurrence of significant wave periods of swell dominated condition (grid VII) whereas gamma model estimates more or less correctly those observed for sea and swell combined condition (grid 9) (Table XIII). In general, the estimation by the two theoretical models for two different sea-states are comparable with visually obtained information. The Bretschneider model overestimates the percentage frequency of occurrence of wave periods ($\leqslant$ 5 S to 7 S) during various months to a maximum of 17.5% for swell prevailed state and the gamma model underestimates to a maximum of 9.5% for sea and swell combined sea-state.

5.2. <u>Distribution of zero-crossing wave periods off Mangalore</u>

The monthly distributions of the zero-crossing wave periods computed from averaged significant wave periods for grid 9 (N.P.O.L) and grid VII (N.I.O) are shown in Fig.10.

The monthly distributions of the wave periods (T_z) for sea and swell combined condition show a minimum of 6.4 S in January and a maximum of 8.0 S in April.

For the swell prevailed sea-state a maximum of 7.7 S in June and a minimum of 6.7 S in February and April are observed. For the swell prevailed conditions, the distributions of the

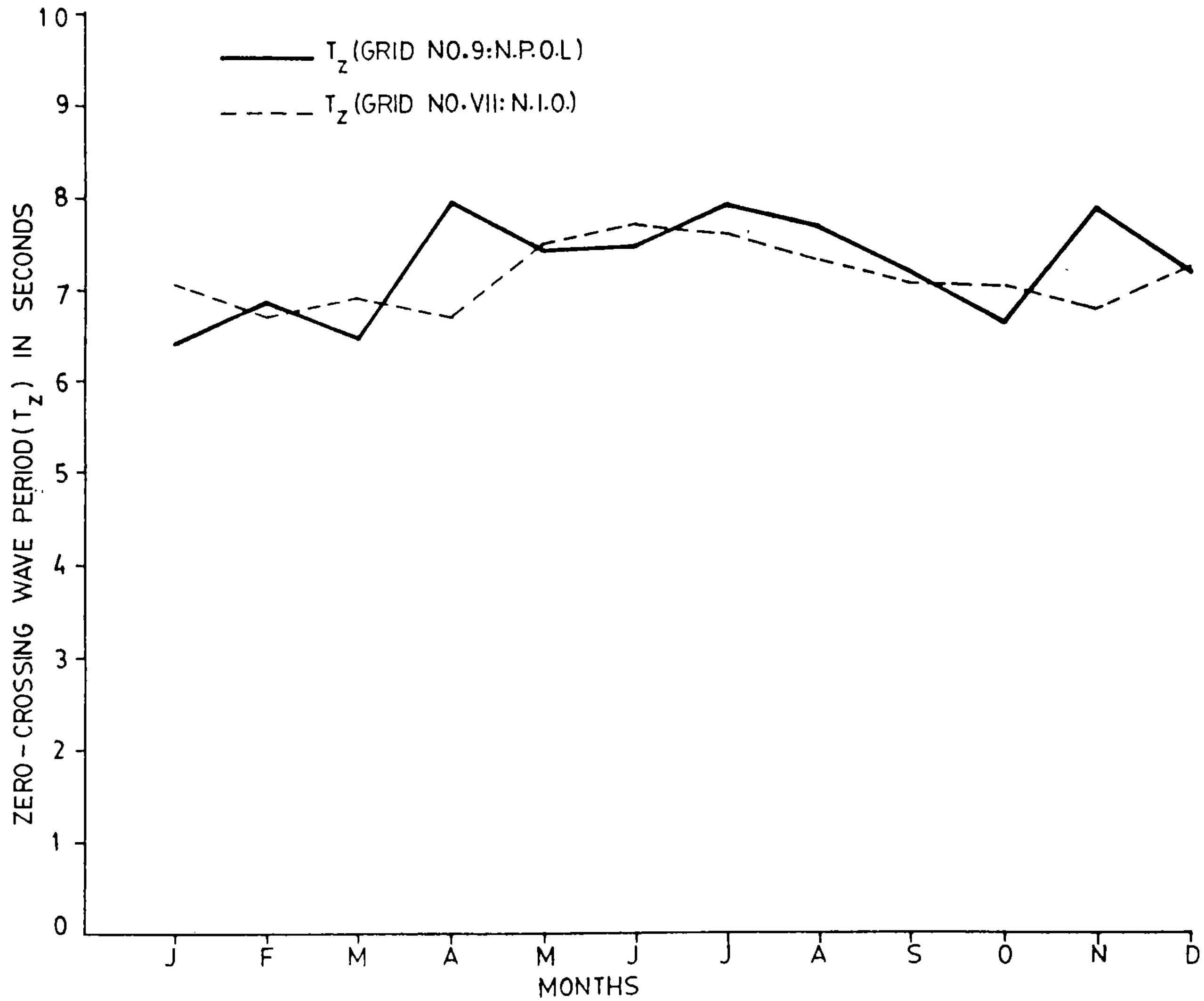

Fig.10 Comparison of the monthly distributions of wave periods (T_z) off Mangalore.

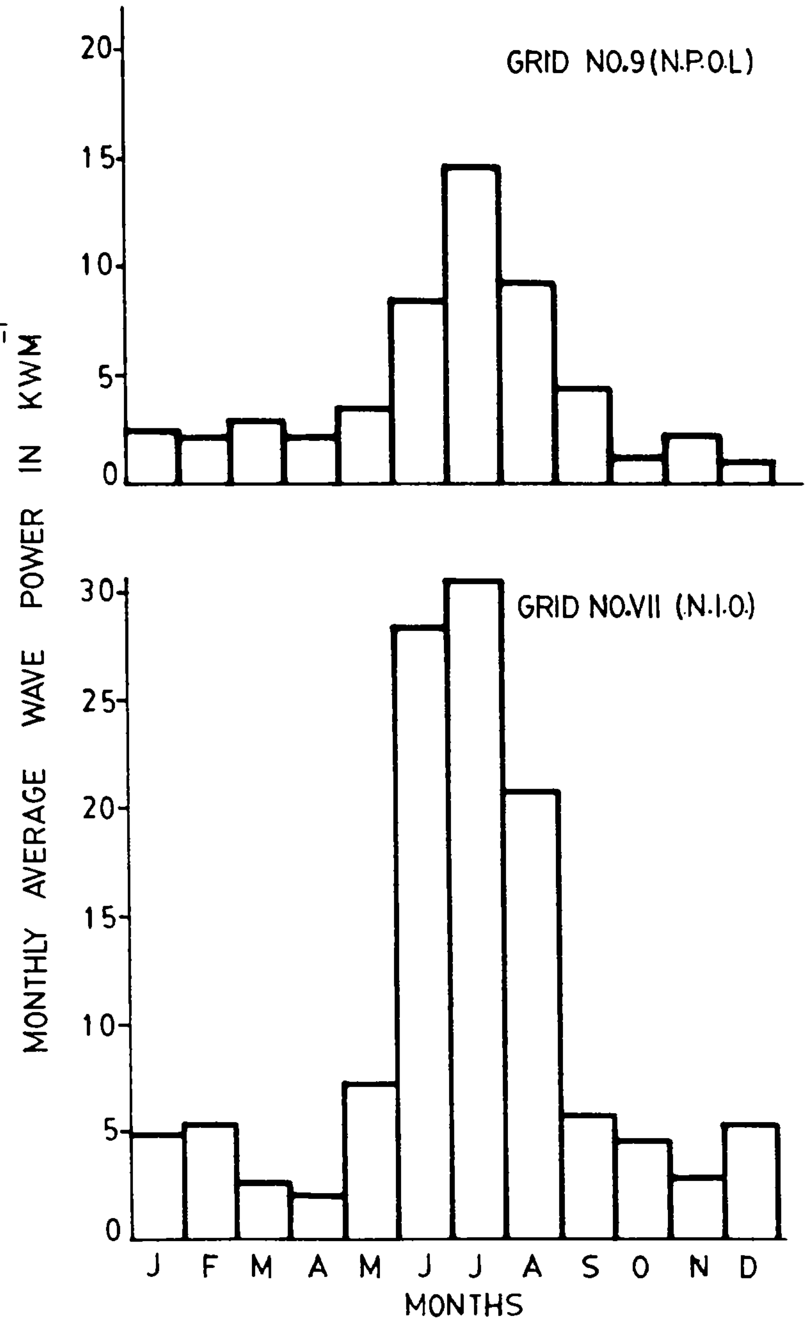

Fig.11 Distribution of monthly average wave power off Mangalore.

wave periods (T_z) are found to be more consistent than for sea and swell combined condition.

The distributions of the wave periods for sea and swell combined state and swell dominated sea-state do not show any similar trend (Fig.10). Calibration of the visually averaged wave periods could not be attempted for want of recorded wave information.

5.3. Distribution of wave power off Mangalore

The monthly distributions of wave power for swell dominated sea-state (grid VII) and sea and swell combined sea-state (grid 9) are shown in Fig.11.

The annual variation of wave power for sea and swell statistics ranges from a minimum of 1.41 kwm^{-1} during December to a maximum of 14.55 kwm^{-1} during July. For swell prevailed state, a larger monthly variation ranging from a minimum of 1.96 kwm^{-1} during April to a maximum of 30.78 kwm^{-1} during July is observed. A comparison of averages of wave power for the annual, fair weather (November to April) and rough weather (May to October) periods is given in table XIV. The sea and swell statistics (grid 9) provide lower values of wave power compared to the swell statistics (grid VII).

The reliability of this information could not be checked for want of values obtained from recorded information.

Table XIV

Comparison of wave power for annual, fair weather and rough weather periods.

Data	Wave power kwm^{-1}		
	Annual	Fair Weather	Rough Weather
Sea and Swell	4.63	2.18	7.07
Swell	10.19	3.92	16.45

Chapter-5

SUMMARY AND CONCLUSIONS

In this thesis, we have made an attempt towards understanding the wave climate along the southwest coast of India with the aid of some of the available statistical techniques and various parametric relations based on a model that appeared to be empirically valid. The wave climate parameters computed using visually averaged wave information published in N.P.O.L (1978) and N.I.O (1982) atlases have been compared with the wave climate parameters calculated from available recorded wave information off Trivandrum and Mangalore.

The first chapter of the thesis described briefly the importance of the study of waves and reviewed the literature on wave research carried out in Indian Ocean. The scope of the work, materials used and the methodologies adopted have also been presented in this context.

The various models tried for modelling long-term distributions of wave heights and wave periods have been reviewed in chapter 2. A mathematical explanation for the validity of Weibull model for describing the long-term wave height distributions and the reasons for preferring this over other available models for this purpose were also discussed.

Certain parametrical relations from Weibull distribution have been derived. Also the motivations for using Weibull distribution for modelling wave heights have been discussed.

From the mathematical justification brought out for the validity of Weibull distribution for modelling wave heights, it has been concluded that the rate of change of decay of wave is a more rapidly increasing function of wave height rather than a linear increase as contemplated in the case of Longuet-Higgins distribution. The Weibull distribution can be proposed for any sea conditions, where the shape parameter b takes care of the prevailing sea conditions, and being able to provide different shapes for different values of b it is more flexible than the other models in use. This distribution fits for all data that follow exponential or Rayleigh exactly and fits approximately for data that follow gamma, log-normal, extreme value etc. The motivation for using Weibull distribution is to meet the twin purposes of accommodating the Rayleigh distribution whenever it holds and also to provide adequate fit in data situations when the latter appears to be inappropriate.

The Weibull model was fitted to the visually averaged wave height data obtained from 17 grids of the N.P.O.L atlas and 12 grids of the N.I.O atlas for approximate parameters a* and b* in the third chapter. From the results obtained we were led to conclude that there is sufficient experimental support for using the Weibull distribution for modelling wave heights. Hence using a* and b* as pilot estimates, more accurate estimates of a and b were calculated and the distribution was fitted with these values. This gave considerably improved fits in many of the cases. From these results one could easily see that the long-term wave height distributions in the regions under investigation followed the Weibull better than any other competing models. A detailed wave climate study is made for grid 17 and grid 9 of the N.P.O.L atlas (1978), and grid I and grid VII of the N.I.O atlas (1982). Recorded wave information off Trivandrum (overlapping portion of grid 17 and grid I) and off Mangalore (overlapping portion of grid 9 and grid VII) are available. To emphasize reliability on wave climatological studies based on visually averaged wave information, the wave statistics computed for these grids have been compared with the available recorded wave information off Trivandrum and Mangalore. The wave statistics considered in this connection were long-term wave height distributions, ratios of standard wave height parameters, averaged maximum wave heights to occur within 5, 10 and 100 years, return periods of maximum wave height, probability of realising a wave height greater than a designated value in a given period of time and wave directions.

Long-term wave height distributions obtained from grid 17 (N.P.O.L) and grid I (N.I.O) have been examined with the available theoretical models for this purpose and the goodness of fit was tested using χ^2- test at 0.05 level of significance. For both the sea and swell combined condition (grid 17, N.P.O.L) Weibull distribution explains the wave patterns observed in February, April, June, July, September and November and of swell prevailed sea-state in January, March to August, October and November. The Weibull over-estimates and underestimates the peak percentage frequencies of wave heights to a maximum of 10.5% and 12.5% respectively. The model explains the varying wave patterns and the long-term wave height distributions obtained from grid 9 (N.P.O.L) and grid VII (N.I.O) better than the other available models. The sea and swell data for grid 9 have been found to follow Weibull in 92% cases. In this case, the Weibull explains the wave patterns observed in January, April to August and November. The overall analysis suggests that the Weibull distribution offers a uniformly good fit.

From the various ratios of standard wave height parameters computed and predicted using Weibull model for grid 17 (N.P.O.L) and grid I (N.I.O), $\bar{H}/\eta$, $H_{1/3}/\bar{H}$ and $H_{1/10}/H_{1/3}$ are relatively more consistent and can be used for practical purposes. The inconsistencies of $H_{max}/H_{1/3}$, $H_{1/10}/\eta$ and H_{max}/η may be due to the bias in reporting high waves by merchant ships. In the case of grid 9 and grid VII, a maximum consistency is seem to be associated with $H_{1/3}/\bar{H}$ and $H_{1/10}/H_{1/3}$ while H_{max}/η shows the least consistency. The reliability of these ratios has to be checked with the help of long-term recorded wave information which, at present, is not available.

The averaged maximum wave height to occur within 5 years from Weibull model is computed to be 6.19 m considering overall data in the case of swell prevailed state (grid I) and it is found to be comparable with that calculated from recorded wave information at Valiathura (off Trivandrum). The averaged maximum wave heights to return within 5, 10 and 100 years are also computed for grid 9 and grid VII and are compared, with those calculated from available recorded wave information off Mangalore. The decennial waves computed from Weibull model for swell data (grid VII) are found to be 6.14 m and 7.97 m using overall data and monsoon data respectively and are comparable with those obtained from recorded data off Mangalore.

The return periods of the maximum wave heights obtained from grid 17 (N.P.O.L) and grid I (N.I.O) are calculated using the relation derived from the Weibull model. The maximum wave height reported for sea and swell combined condition (grid 17) is 7.5 m and its averaged return period is found to be about 3.40 years. For the swell dominated sea-state (grid I), the maximum wave height is obtained as 5.0 m and period of its re-occurrence is approximately 2.88 years. The return period of the recorded maximum wave height of 6.02 m at Valiathura (off Trivandrum) is found to be 5 years. Considering overall data it is expected that this height will re-occur within 2.52 years in the case of sea and swell combined condition (N.P.O.L), and within 6.27 years for swell prevailed state (N.I.O). This return period (6.27 years) is comparable with the re-occurrence of the recorded maximum wave height (6.02m).

The averaged return periods computed for the averaged maximum wave heights obtained from grid 9 (6.5m) and grid VII (5.0 m) taking into account the overall data are respectively 3.05 years and 4.20 years. These results could not be checked because recorded wave information are at present not available for these region.

Thus it is seen that high waves reported for sea and swell combined condition are more frequent than the high waves reported for swell prevailed state. This is true since the ocean characterised by sea and swell are chaotic and irregular and are frequently influenced by high waves.

The maximum wave height is found to be 6.02 m from wave recording at Valiathura (off Trivandrum) and the duration of recording (5 years) can be considered as its return period. But this maximum wave height is recorded on the 3rd year of wave recording. Hence the chance of this height to occur within 3 years is seen to be 60.0%. Considering the sea and swell combined condition (grid 17) the probability of this height to occur within 3 years is computed to be 100.0% and for the swell dominated state (grid I) it is 47.9% which is nearer to the probability of this height obtained from wave recordings at Valiathura.

The maximum wave height reported for sea and swell combined state is 7.5 m (grid 17) and the probability of this height to occur within one year is calculated to be 29.4%. But the maximum wave height published in the N.I.O atlas (grid I) is 5.0 m and the chance of this height to re-occur within a year is calculated as 34.7%.

For sea and swell combined condition (grid 9) the maximum wave height is reported to be 6.5 m and the probability of its re-occurrence within a year is 32.8% and within 2 years, 65.6%. On the other hand, for the swell prevailed state, the maximum wave height is obtained as 5.0 m (grid VII) and the chance of this height and higher to occur within a year is computed to be 23.8% and within 2 years to be 47.6%. The reliability of these results are to be checked with the results obtained from recorded wave information, which are at present not available.

A comparison of the wave directions published in the atlases for sea and swell combined state (grid 17) and swell prevailed state (grid I) with measured wave directions obtained off Trivandrum (20 m) and Valiathura (5 m) was made. Both the sea and swell combined sea-state and swell prevailed state are predominantly characterised by westerly waves during southwest monsoon period which deviate to westsouthwesterly on approaching the nearshore regions. Westerly or southwesterly waves dominate during post-monsoon season in the case of both the sea-states. Both the atlases and also the measured wave directions at 20 m indicate northerly or northeasterly components during the northeast monsoon. Variable wave directions are experienced in pre-monsoon season. The swells (5 m) approach from directions between west and southwest throughout the year. There is no correlation between the wave directions obtained for the wider deep sea area covering grid 17 and grid I and the nearshore regions (5 m).

The monthly predominant wave directions obtained from grid 9 (N.P.O.L) and grid VII (N.I.O) atlas have also been compared. For sea and swell combined condition (grid 9), the waves approach from directions ranging between westsouthwest and westnorthwest during southwest monsoon season while for swell prevailed condition, the waves approach from directions between west and northnorthwest. Southerly or northnorthwesterly waves are predominant during post-monsoon season. In both the atlases, during the northeast monsoon period, northerly or northnorthwesterly directions of wave approach are indicated. Waves from northnorthwest to north are indicated during the pre-monsoon season. From this comparative study, it can be seen that the predominant wave directions for both sea-states are nearly the same during different seasons. However, off Mangalore, a comparative study is not possible at present for want of measured information on wave directions.

The fourth chapter tries to explain statistically the long-term distributions of wave periods (T_s) obtained from N.P.O.L atlas (grid 17, grid 9) and N.I.O atlas (grid I, grid VII) by comparing them with statistical probability distributions. The monthly distribution of the zero-crossing wave periods (T_z) computed for the above mentioned grids are compared with those computed from available recorded wave data. The monthly distribution of wave power is computed from visually averaged wave information (grid 17 and grid I) and compared with wave power calculated from recorded wave statistics off Trivandrum. The wave power is also calculated for grid 9 and grid VII.

The long-term distributions of wave periods obtained from the N.P.O.L (grid 17) and N.I.O (grid I) atlases are compared with four theoretical models, ie. gamma, Bretschneider, exponential and Rayleigh distributions. The goodness of fit of these curves is tested visually and two models are suggested for two different sea-states, the gamma for sea and swell combined state (grid 17) and the Bretschneider for swell dominated state (grid I).

The sea and swell prevailed condition is characterised by the broad band of wave periods. The range is from less than or equal to 5 S to more than 21 S. In most of the cases, the observed peak percentage frequency lies in the period range 0.5 S - 5.5 S. A second peak is at 5.5 S - 7.5 S. The gamma distribution estimates the observed peak percentage frequency comparatively more accurately. A maximum of 8.0% underestimation is noted for the second peak percentage frequency. The exponential distribution is the second suitable model for explaining the observed wave period pattern.

The swell prevailed state (grid I) is characterised by a narrow band of wave periods ($\leqslant$ 5 S to 15 S). During the southwest monsoon season, the peak percentage frequencies are prominent and lies between 5.5 S to 7.5 S. During the rough weather season, a second peak percentage frequency is observed in the period range 7.5 S to 9.5 S and during the fair weather season, it is in 0.5 S to 5.5 S range.

The Bretschneider distribution appears to be the best among the four models considered in the present study, to describe the long-term distributions of swell wave periods (grid I). It fails to explain the higher side of the wave periods and that part is estimated better by the gamma distribution. The Bretschneider distribution gives uniformly a good visual fit to the visually averaged long-term distributions of wave periods.

The long-term distributions of wave periods off Mangalore obtained from grid 9 (N.P.O.L) and grid VII (N.I.O) are also examined. A comparison of the above models firmly suggests that the Bretschneider distribution describes the long-term distribution of the wave period pattern of swell dominated state and the gamma model explains the wave period patterns of sea and swell combined conditions.

The dominance of sea and swell combined sea-state is evidenced by the broad band of wave periods ($\leqslant$ 5 S to more than 21 S). The peak percentage frequency lies in the period range 0.5 S to 5.5 S except in July and August when it lies between 5.5 S to 7.5 S. The maximum of the peak lies at 26.0% in August in the range 5.5 S to 7.5 S and the minimum of the peak at 17.0% in June in the period range 0.5 S to 5.5 S. A second peak is seen in the range 5.5 S to 7.5 S for all the months except in July and August when it is in the range 0.5 S to 5.5 S. The gamma distribution takes the form of the visually averaged wave period patterns and it estimates the first and the second peak percentage frequencies more or less correctly.

The narrow band of wave periods ($\leqslant$ 5 S to 15 S) is characterised by swell dominated state (grid VII). The peak percentage frequency is prominent during May to September and it lies in the period range 5.5 S to 7.5 S. A second peak frequency is noticed in the range 7.5 S to 9.5 S from June to August and in the range 0.5 S to 5.5 S from September to May.

The Bretschneider distribution describes the long-term distributions of wave periods better than the other three models. The higher ranges of the wave periods (from 11.5 S to 15.5 S) are estimated more effectively by the gamma distribution. Thus the gamma distribution can be suggested for explaining the long-term distributions of wave periods for sea and swell combined state and the Bretschneider distribution for the long-term distributions of periods of swell dominated state.

The monthly percentage frequency of occurrence of wave periods lying in the range less than or equal to 5 S to 7 S obtained for sea and swell combined state (grid 17, grid 9) and swell prevailed state (grid I, grid VII) is compared with that obtained from the theoretical models suggested for the two different sea-states. It is seen that the estimated values from Bretschneider model are higher than the values obtained for swell dominated state and the estimations made from gamma model are nearly equal to the values obtained for sea and swell combined state.

The monthly distributions of the zero-crossing wave periods for sea and swell combined state (grid 17) and swell dominated condition (grid I) are compared, with those obtained from wave recordings off Valiathura (Trivandrum) (Baba, 1985). The distribution of wave periods for grid 17 (N.P.O.L) and grid I (N.I.O) seem to be more consistent than those derived from recorded wave statistics off Valiathura (Trivandrum). No similarity in trend is observed among the three distributions. The values obtained from grid 17 and grid I are lower than the values obtained from recorded information throughout the year.

The long-term wave period (T_z) distributions for grid 9 and grid VII show no similar trend. The distribution for swell prevailed condition is more consistent than for sea and swell combined condition. The visually averaged long-term distributions of wave periods are to be checked with the recorded information on long-term distributions of periods for emphasizing reliability of these statistics.

The monthly distribution of wave power computed for grid I and grid 17 are examined and compared with the wave power computed from recorded wave statistics off Trivandrum. For the sea and swell statistics (grid 17), a minimum power of 1.35 kwm^{-1} during April and a maximum power of 7.03 kwm^{-1} during July are observed. On the other hand, the swell information (grid I) show a larger variation (3.35 kwm^{-1}during March and 21.50 kwm^{-1} during June). The wave power calculated from nearshore recordings (off Trivandrum) are comparable with the values computed from the swell wave statistics. During rough weather season (May to October) the monthly distribution of wave power computed from swell wave statistics (grid I) and the wave power obtained from recorded wave information off Trivandrum (Thomas et. al. 1986) show a similar trend. The recorded waves are mainly swells and this may be the reason for the nearness of values of wave power calculated from swell wave statistics (grid I) and from wave recordings (off Trivandrum).

The monthly distributions of wave power are also computed from wave statistics obtained from grid 9 (N.P.O.L) and grid VII (N.I.O). A minimum wave power of 1.41 kwm^{-1} during December and a maximum wave power of 14.55 kwm^{-1} during July are observed for sea and swell combined state (grid 9). For swell dominated state, a minimum of 1.96 kwm^{-1} during April and a maximum of 30.78 kwm^{-1} during July are indicated which give a larger variation compared to sea and swell combined sea-state. The wave power estimated for sea and swell dominated state provides lower values compared to the wave power calculated from swell prevailed condition (grid VII).

By examining the various wave statistics obtained and computed for sea and swell combined state (N.P.O.L atlas) and swell prevailed state (N.I.O atlas) in the light of available recorded wave information, it can be concluded that the visually averaged wave statistics can be used for wave climatological studies provided the information is calibrated with recorded wave information for emphasizing reliability of the data.

Problems for future work

In the present and concluding section we look at the problems that have come to the fore as a result of the investigations so far carried out and provide some proposals for the future course of action in this regard.

The first of these concerns with the Weibull model itself. Although the empirical support that has been received from the data strongly favours this model and a plausible analytical argument given in section 2.3 supports this conjecture, a formal derivation of the Weibull distribution based on the physical conditions that govern the formation of wave heights is still lacking. The main difficulty that arises in providing such a rigorous theoretical derivation is the inherent complications that arises when one attempts to relax the narrow band assumption of Longuet-Higgins model and the multiplicity of facts to be taken into consideration in such an event. An investigation in the theory of extremes that explains the conditions for a limit law to be Weibull that parallels the result of Longuet-Higgins to arrive at the Rayleigh distribution could be an answer to this problem. Some attempts are being made in this direction.

Although the data that has been subjected to scrutiny so far indicates the validity of the model and conclusions derived therefrom, its acceptance and reproducibility to other regions need further probe and extensive data analyses. Even from what has been examined already one has to look back at the situations where the Weibull law failed to provide an adequate fit. The problem in this connection appears to be more with the data rather than in the endurance of the model. The legitimacy of our claim stems from the fact that even when the theoretical conditions under which the Rayleigh model is derived is reasonably met, there is lack of fit to that model as evidenced from tables of b values given in tables III & IV. Majority of estimates are far off the ideal value which is two. The reason that can be attributed to such inconsistencies, is the high subjectivity and bias involved in assessing the visual observations. It is common tendency to view low values as still lower and high values as still higher and this creates a few extreme observations that are discordant with the moderate observations which form the majority. Such unusually small or large observations will naturally be fewer in a data set, nevertheless they are enough to contaminate the model. It has been detected during the course of our analysis that in quite a few cases where Weibull distribution proved inadmissible, observations that could be suspected as discordant were indeed present in the data. The identification of such observation as 'outliers' from the hypothesised model requires special tests for the purpose. Once these observations are detected by statistical techniques, the data could be cleaned off them and revised estimates of the parameters would give better fits and thereby more accurate conclusions.

The data arising from the two atlases we have used (N.P.O.L and N.I.O) did not provide the same amount of reliability as basically they were representing different conditions (sea, sea and swell). Since the data pertaining to sea and swell conditions could be slightly different from that arriving out of the swell condition alone, it is preferable to introduce variations in the basic model that can accommodate such differences. One way to do this is to use a simple Weibull model for the N.I.O data and a mixture of Weibull models to the N.P.O.L data so that the mixing constant measures the influence of the sea and swell components on the final observation. This can also pave way for isolating the effect of the sea component in the N.P.O.L atlas and therefore its elimination would make the two data sets comparable. Needless to say that, this would lead to more accurate visual observations.

On the basis of the literature survey in chapter 4, we have remarked earlier that very little work has been done in finding a suitable model to represent the wave periods. The present thesis also could not accomplish anything more than a comparison of the existing models based on some visual data. The picture that has emerged from the investigations so far is that, all the models tried have been tentative in their action and that a suitable law valid over time and space is yet to be found. Some work towards this direction is also in progress. It is hopefully wished to present the results of these investigations in a future work.

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APPENDIX

PAPERS PUBLISHED BASED ON THE PRESENT STUDY

1. Averaged visual wave statistics for southwest coast of India.

2. Wave climatology off Mangalore.

3. Long-term wave characteristics off Trivandrum.

4. Long-term wave statistics off Goa.

AVERAGED VISUAL WAVE STATISTICS FOR SOUTHWEST COAST OF INDIA

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INTRODUCTION

Wind waves provide the major dynamic forces causing changes in physiography of the nearshore regions. Increased maritime activities like offshore mineral and oil exploration, utilisation of wave energy, construction of marine structures and harbours, shipping and naval activities require accurate information on wave characteristics.

Wave information is obtained through visual observations and use of a variety of wave gauges and recorders. Goldsmith et al. (1983) studied the wave climatology of the Southeastern Mediterranean using a variety of sources including visual observations and directional wave gauge measurements and suggested that visual observations provided a reasonable representation. Laing (1985) based on an assessment of wave observations from ships in Southern Oceans concluded that there was very little consistency in the reporting of swell periods and swell directions. Reporting of heights, however, provided considerably better reliability. Despite the inconsistencies, intercomparisons show that visual data are, in general, representative of many of the physical characteristics of wave field and, therefore, can be useful in climatological studies. Visual observations of wave heights are still the main source of statistical information available for the prediction of extreme wave conditions (Soares, 1986).

MATERIALS AND METHODS

Ship-based visual observations reported by the India Meteorological Department in the daily weather reports for 0830 and 1730 *IST* have

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CESS, Trivandrum, 1989.

been compiled in the wave atlases prepared by the Naval Physical and Oceanographic Laboratory using data for 1960-1969 (N.P.O.L.,1978) and by the National Institute of Oceanography using data for the period 1968-1973 (N.I.O., 1982). The N.P.O.L. wave atlas includes both sea and swell statistics and the N.I.O. atlas provides swell information. The wave parameters provided in these atlases are height, period and direction. In the atlas compiled by N.P.O.L., the part of the Arabian Sea north of 5°N and east of 61° E has been divided into 17 zones of 4° squares and in the N.I.O. atlas this area is divided into 12 zones of 5° squares. Wave statistics for each square has been presented month-wise in both atlases. Long term distributions of wave height, direction and power obtained from Grid No. 17 (5° - 9°N, 73° - 77° E) of the N.P.O.L. atlas and Grid No. I (5° - 10° N, 75° - 80° E) of the N.I.O. atlas are used in the present study (Fig. 1). Recorded wave information obtained at 20 m off Trivandrum using *OSPOS* wave recorder (Narayanaswamy et al., 1979) and at 5 m off Valiathura using pressure type recorder (Baba et al., 1983) are used for comparison with wave statistics computed from visual observations. The long-term distributions of wave heights are tested with the theoretical

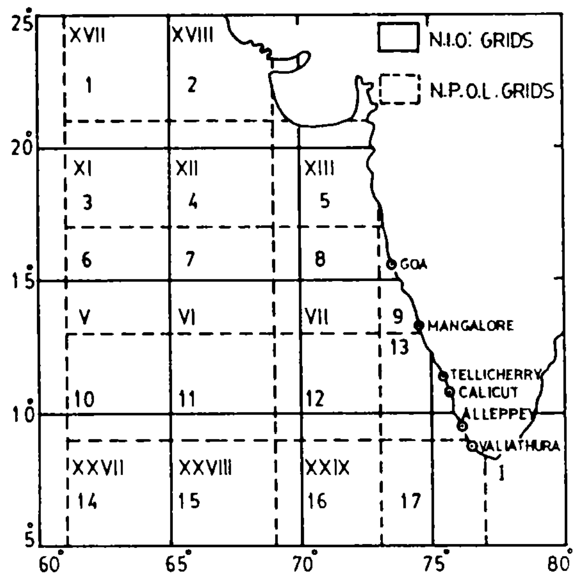

Fig. 1 Map showing Grid No. 17 of N.P.O.L. atlas and Grid No. I of N.I.O. atlas used in the present study.

Weibull, Rayleigh and exponential distributions. The directions of wave approach are also compared with published information. Wave power is computed monthwise for both the grids and compared with power calculated from recorded information (Thomas et al., 1986). Wave power is calculated using the equation $P = 0.55 H_s^2 T_z$ kW/m which is the power available in random sea (Salter, 1974; Raju and Ravindran, 1987). T_z is obtained from the relation $T_s = 1.3 T_z - 2.5$ (Dattatri and Renukaradhya, 1971).

RESULTS AND DISCUSSION

Comparisons of observed wave height distribution with Weibull, Rayleigh and exponential distributions during different months are made. A typical example is given in Fig. 2. Rayleigh distribution agrees with the observed distribution during March, April and December in the N.I.O. grid and during April, May, June and July in the N.P.O.L. grid. The exponential distribution fits only during February in the N.I.O. grid and during January, November and December in the N.P.O.L. grid. In both

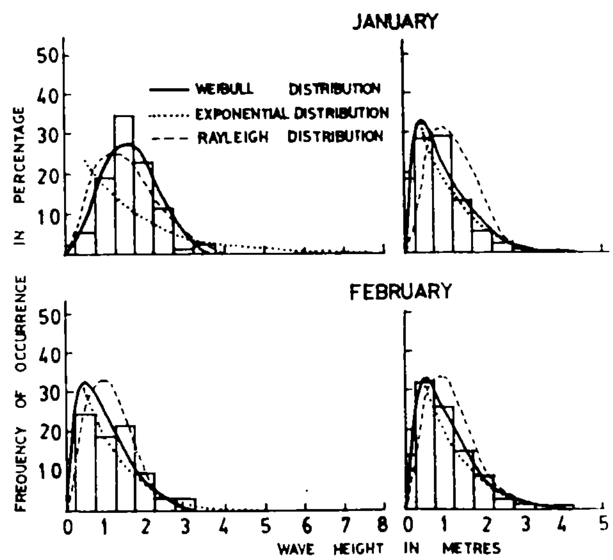

Fig. 2 Comparison of the distribution of observed wave heights with theoretical distributions.

grids, the exponential distribution underestimates the percentage of frequency of occurrence of wave heights during most of the months. Rayleigh distribution overestimates in half of the cases and underestimates in the other half. The best fit is provided by the Weibull dis tribution. It fits for all the data that follow either Rayleigh or exponential distributions since they are special cases of Weibull for λ=2 and λ=1 respectively, where λ is the shape parameter of the Weibull curve. For the sea and swell statistics (N.P.O.L.), the Weibull distribution overestimates the maximum frequency of occurrence of wave heights during March (10.5%), April (5.5%), November (5.5%) and December (3%). For the swells (N.I.O.), the Weibull distribution provides underestimates during January (7%), March (12.5%), May (9%), June (6%), September (8%), November (4%) and December (6%).

Table 1 gives comparison of wave directions obtained from the wave atlases with recorded information off Trivandrum (Narayanaswamy et al., 1979) and Valiathura (Baba et al., 1983). By studying the average wind pattern over the seas around India for fifty years, Srivastava et al. (1970) grouped the twelve months into the following four seasons for the study of waves in seas around India: pre-monsoon (March-April), southwest monson (May-September), post-monsoon (October) and northeast monsoon (November-February).

Table 1 Comparison of monthly predominant wave directions.

Month	Grid No. 17 N.P.O.L. atlas	Grid No. I N.I.O. atlas	Recorded off Trivandrum (20 m)	Recorded off Valiathura (5 m)
Jan	030(NNE)	030(NNE)	061(ENE)	SSW
Feb	060(ENE)	330(NNW)	016(NNE)	SSW
Mar	360(N)	330(NNW)	030(NNE)	SSW
Apr	360(N)	180(S)	222(SW)	SW
May	270(W)	270(W)	250(WSW)	WSW
Jun	270(W)	270(W)	256(WSW)	WSW
Jul	270(W)	270(W)	260(W)	W
Aug	270(W)	270(W)	246(WSW)	WSW
Sep	270(W)	270(W)	252(WSW)	WSW
Oct	270(W)	270 and 180 (W and S)	231(SW)	SW
Nov	300(WNW)	360and180 (N and S)	150(SSE)	SW
Dec	360(N)	030(NNE)	051(NE)	SW

It is seen that during the southwest monsoon season, both atlases indicate predominantly westerly waves which turn to west-southwesterly on approaching the shallow regions. Post-monsoon is characterised by westerly or southwesterly waves. During the northeast monsoon period, northerly or northeasterly components are predominantly indicated by the atlases as well as the recorded information at 20 m. Pre-monsoon season manifests variable wave directions. Near the shore, at 5 m depth, the swells approach from directions between west and southwest throughout the year.

Fig. 3 shows monthly distribution of wave power for Grid No.17 of N.P.O.L. and Grid No.I of N.I.O. atlases. The sea and swell statistics show an annual variation of wave power ranging from a minimum of 1.35 kW/m during April to a maximum of 7.03 kW/m during July. The swell statistics, on the other hand, show larger monthly variation ranging from a minimum of 3. 35 kW/m during March to a maximum of 21.50 kW/m during June. A comparison of averages of wave power for the annual, fair weather (November to April) and rough weather (May to October) periods are given in Table 2. The sea and swell statistics (N.P.O.L.) provides lower

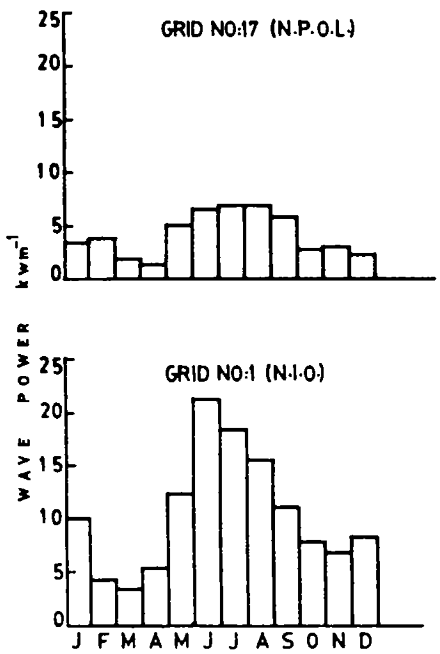

Fig. 3 Distribution of monthly average wave power.

values of wave power while the swell statistics (N.I.O.) provides values comparable with wave power obtained from nearshore recordings.

The comparability of the various sources of wave information used above, namely, sea and swell statistics for Grid No.17 (N.P.O.L.), swell statistics for Grid No. I (N.I.O.), recorded wave information at 20 m off Trivandrum and wave recordings at 5 m at Valiathura, may, however, be examined with caution. Grid No.I and Grid No.17 overlap over a rectangular area measuring $4^0 \times 2^0$. The wave recording stations off

Table 2 Comparison of wave power for anual, fair weather and rough weather periods.

Data	Wave power (kw/m)		
	Annual	Fair weather	Rough weather
Sea and swell	4.26	2.70	5.82
Swell	10.45	6.42	14.49
Nearshore	10.00	4.50	15.50

Trivandrum and Valiathura are located in this overlapping area of the two grids. The recorded waves are, however, swells over shallow depths while the wave statistics is averaged over wider deep sea area. Ships usually avoid rough seas and thus miss observations on sea waves. This contributes to comparatively lower values obtained on averaging sea and swell statistics. The good agreement in wave power computed from swell data and that derived from recorded data may particularly be noted.

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WAVE CLIMATOLOGY OFF MANGALORE

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ABSTRACT

Wave Climatology Off Mangalore is analysed utilising long-term (visual) and short-term (recorded) information. Observed long-term wave height distributions are tested with the theoretical Weibull, Rayleigh, Gumbel, Lognormal and Exponential curves. The best fit is obtained for the Weibull probability density function. Methods for computing maximum wave height and most probable maximum wave heights are suggested. A mathematical expression is derived for predicting the maximum wave height of a predetermined magnitude and also the probability of realising a wave height less than a designated value in a given period of time. The decennial wave heights so obtained are comparable with those predicted from recorded wave information. Of the various ratios of standard wave height parameters computed and predicted using theoretical Weibull distribution, $H_{1/3}/\bar{H}$ and $H_{1/10}/H_{1/3}$ seem to be relatively more consistent.

INTRODUCTION

Knowledge of wave climate in Indian Coastal Waters is essential from strategic, economic and commercial points of view. Wave information is obtained through visual observations and use of a variety of wave gauges and recorders. From a cross comparison of the wave climate of the Southeastern Mediterranean, developed from various sources including visual ship observations, several authors (Goldsmith, Victor and Stan Sofer 1983), suggested that visual observations provide a reasonable representation. Laing (1985) observes that despite the inconsistencies on wave observations from ships, the data is representative of many of the physical characteristics of wave fields and therefore can be useful in climatological studies. Visual observations still remain to be the main source available for the prediction of freak ocean waves (Soares. 1986), and therefore such data are highly relevant in modelling wave heights.

MATERIALS AND METHODS

At present the main sources of long-term distributions of wave parameters in Indian Ocean are the wave atlases compiled by Naval Physical and Oceanographic Laboratory (N.P.O.L. 1978) and National Institute of Oceanography (N.I.O. 1982) using ship based visual observations. Wave parameters obtained from grid no. 9 (13°-17°N, 73°-74.7°E) of the swell atlas (N.I.O) are used in the present study. (Fig. 1). These grids overlap over a square area measuring 2° x 2°. The wave recordings off Mangalore at 10m depth were carried out in this overlapping area. Dattatri and Renukaradhya (1971) suggested that the deep water waves are directly comparable to shallow water waves off Mangalore since the crests travel parallel to the coast, the bottom contours being practically parallel to the coast, the coast being a very flat one and the refraction and shoaling coefficient are very nearly unity. The available recorded wave measurements in shallow waters are used for calibration of the statistics obtained from visual observations. For the long-term distributions of wave heights, the models generally used in literature are Lognormal, Gumbel, Weibull and Exponential (Baba. 1985). Rayleigh distribution is recommended for broad band spectra by several researchers. (Longuet-Higgins. 1975; Chakraborthy and Snider. 1974; Dattatri, Raman and Jothi Sankar. 1979). In view of several competing models available for the purpose, this paper attempts to find the best fit for the long-term visual observation data on wave heights against the above mentioned theoretical distributions. The goodness of fit is ascertained by the X^2-test at .05 level of significance.

Of these models, the Weibull distribution specified by $f(h) = \frac{\lambda}{\sigma} \times (\frac{h}{\sigma})^{\lambda-1} \times \exp\left[-(\frac{h}{\sigma})^{\lambda}\right]$. $h > 0$. $\lambda, \sigma > 0$ h - wave height, λ, σ - parameters, appears to be more versatile for the following reasons. Exponential and Rayleigh distributions are particular cases of Weibull when $\lambda = 1$ and 2 respectively and therefore should naturally fit well when the first two are appropriate. For data that follow positively skewed distributions such as Gamma, Lognormal, extreme value etc., the Weibull generally provides a very good approximation. Empirical validation of this fact is given in the next section. Weibull distribution being the best model for wave height patterns, some theoretical calculations using the distribution seem to be in order.

Mean wave height, $\bar{H} = \sigma \Gamma(1+\frac{1}{\lambda})$ where $\Gamma(P) = \int_0^{\infty} e^{-h} \times h^{P-1} \times dh$ the well known gamma function.

If $h_1, h_2, \ldots\ldots h_n$ are a sequence of wave heights that are arranged in descending order of magnitude and $h^{(P)}$ the mean of the first P.n of these values, where $0 \leq P \leq 1$, the significant wave is $h^{1/3}$ and is derived as

$$H_S = \sigma (\log 3)^{1/\lambda} + \left(\frac{\sigma}{\lambda}\right) \times 3 \times \int_{\log 3}^{\infty} e^{-y} \times y^{(1/\lambda)-1} \times dy$$

Similarly

$$H_{1/10} = \sigma (\log 10)^{1/\lambda} + \left(\frac{\sigma}{\lambda}\right) \times 10 \times \int_{\log 10}^{\infty} e^{-y} \times y^{(1/\lambda)-1} \times dy$$

Where $y = \left(\frac{h}{\sigma}\right)^{\lambda}$

The probability density of the maximum wave heights in a sample of size n is

$$f(h_{max}) = n \times F(h)^{n-1} \times f(h). \qquad F(h) = 1 - \exp\left[-\left(\frac{h}{\sigma}\right)^{\lambda}\right]$$

Accordingly, the most probable maximum wave height is mode of $h_{max} = \sigma\left[1+\frac{1}{n\lambda}\right]^{1/\lambda}$ and the mean maximum wave height is $E(h_{max}) = \frac{\sigma}{\lambda}\int_0^{\infty}\left[n e^{-y} - - - (-1)^{n-1} \times e^{-ny}\right] y^{(1/\lambda)-1} \times dy$

Thom (1971) reports that there have been many instances of huge waves in the open oceans and these may be considered as waves of extreme heights. The time of occurrence and magnitude of such unusually large waves are of considerable importance in many areas of application. Using Weibull model we can arrive at expressions for predicting these wave heights considering the wave heights (h) observed daily in a particular grid as a random variable following that law. The largest height H_L that appears in a period of time will follow the distribution $G(h) = \exp[-n (\frac{h}{\sigma})^{\lambda}]$ In a series of observations, the probability that the n^{th} observation is the first value that exceed H_L is $(1-G)^{n-1} \times G$, where $n = 1,2,3, \ldots\ldots\ldots$ On the average the number of observations included between two adjacent values that exceed H_L is $t(H_L, \lambda, \sigma) = e^{n(H_L/\sigma)^{\lambda}}$. This function t can be interpreted as a period representing a re-occurrence of H_L. Therefore $H_L = \sigma \times (\log t^{1/n})^{1/\lambda}$, gives the fundamental relation connecting a prescribed large wave height H_L and its return period. Considering n as one month and t as 10 or 100 years, the decennial and centennial waves are presented in Table - 1 for grid no. 9 and grid no. VII for overall data and monsoon data and these are compared with information obtained from recorded wave measurements.

Given a period of time t, the probability P that a wave height larger than H_L will not be realised in m consecutive years is $P = (1 - \frac{1}{t})^m$. Note that t increases if H_L increases. Hence when wave heights anticipated are larger the return periods also become larger ie. unusually large waves are realised only over longer periods of time.

The mean and root mean square (S.D) of certain standard ratios of wave height parameters are computed using observed visual wave statistics and are compared with those obtained from theoretical Weibull model.

RESULTS AND DISCUSSIONS

The wave heights in grid no. 9 are found to follow Weibull in 92%, Gumbel in 58%, Rayleigh in 25%, Exponential in 8% and Lognormal in none of the cases. For the Swell data (grid no. VII) Weibull fits in 27%, Gumbel in 36%, Rayleigh, Exponential and Lognormal curves in none of the cases. The comparatively lesser number of good fits provided by Weibull curve in grid no. VII can be attributed to the dominances given for swell conditions while reporting. Apart from the fit being good for both sea and swell conditions, it also explains the observed wave height patterns for swell dominated sea state.

The average decennial and centennial waves computed from swell statistics (grid no. VII) and sea and swell statistics (grid no. 9) for overall data and monsoon data (June to September) are tabulated (Table - 1). Dattatri (1973) derived 10 year maximum wave height to be 8 m. Also he got a value of 7.506 m by the method suggested by Jean Larras (1970). The 10 year design wave extrapolated from overall and monsoon data for the Weibull distribution is 7.20 m and 6.40 m respectively. (Dattatri. 1981). The results are comparable with those obtained from swell data while the sea and swell statistics give much higher values. This is because the recorded waves are swells over shallow depths while the wave statistics is averaged over wider deep sea area.

Among the various ratios computed $H_{1/3}/H$ and $H_{1/10}/H_{1/3}$

show maximum consistency while H_{max}/σ, (σ - S.D) shows relatively minimum consistency. (Table - 2). This may be due to the missing of reporting of high wave because merchant ships usually avoid rough sea conditions.

The most probable maximum wave heights obtained for overall data and monsoon data are 1.10 m, 1.62 m (grid no. 9) and 1.77 m, 2.55 m (grid no. VII) respectively.

Table - 1

Averaged maximum wave heights for overall data and monsoon data for grid no. 9 and grid no. VII

	grid no. 9		grid no. VII	
	overall data	monsoon data	overall data	monsoon data
Decennial wave (m)	10.64	12.84	6.14	7.97
Centennial wave (m)	17.26	19.88	8.23	10.13

Table - 2

Averaged computed (C) and predicted (P) ratios of standard wave height parameters

Ratio	grid no. 9		grid no. VII	
	C	P	C	P
$H_{max}/H_{1/3}$				
Mean	2.40	-	1.38	-
S.D.	0.52	-	0.14	-
$H_{1/3}/\sigma$				
Mean	2.37	3.53	3.52	7.14
S.D.	0.27	0.58	0.44	1.68
H_{max}/σ				
Mean	5.56	-	4.82	-
S.D.	0.68	-	0.51	-
$\bar{H}/\sigma$				
Mean	1.33	1.44	2.42	2.38
S.D.	0.22	0.18	0.41	0.42
$H_{1/10}/\sigma$				
Mean	3.41	7.02	4.28	17.56
S.D.	0.19	1.67	0.45	4.87
$H_{1/10}/H_{1/3}$				
Mean	1.45	1.97	1.23	2.42
S.D.	0.12	0.14	0.06	0.23
$H_{1/3}/\bar{H}$				
Mean	1.81	2.58	1.47	2.96
S.D.	0.11	0.54	0.10	0.25

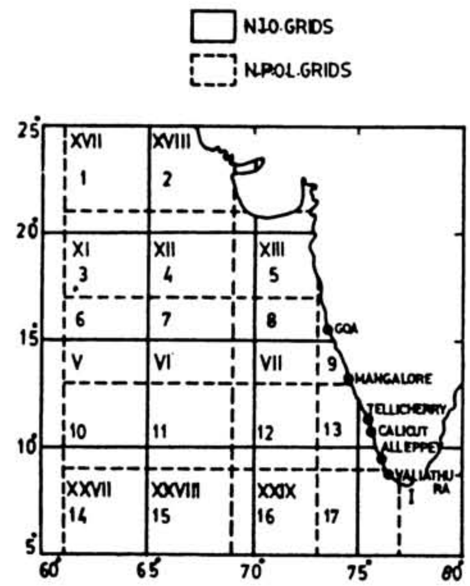

Fig. 1. Map showing grid no. 9 of N.P.O.L. atlas and grid no. VII of N.I.O. atlas used in present study.

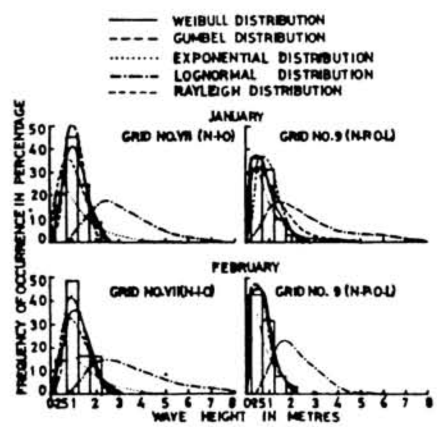

Fig. 2. A typical example of observed (Histograms) and theoretical wave height distributions.

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LONG-TERM WAVE CHARACTERISTICS OFF TRIVANDRUM

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ABSTRACT

The available atlases of averaged visual wave statistics of the Arabian Sea provide wave information which differ from one another. A comparative study of the long-term distributions of significant wave height obtained from these atlases is made for an area off Trivandrum. The long-term distributions of significant wave height are tested with Weibull, Gumbel, Rayleigh, Exponential and Log-normal models. The best fit is obtained for Weibull probability density function. Over estimates of peak percentage frequency of occurrence of wave heights amount to less than 11% and under estimates less than 13%. The return period of the maximum significant wave height (7.5 m) obtained from N.P.O.L. atlas is 2.27 years and that from N.I.O. atlas (5.0 m) is 1.71 years. Average maximum significant wave heights to occur in a 5 year period are computed using Weibull model for combined sea and swell statistics separately. Nearly 95 % waves lie in the height range 0 - 3.25 m. The most frequently occurring wave heights for overall and monsoon data are 0.75 and 1.00 m (grid 17), 1.33 and 1.75 m (grid I) respectively.

Key-words : Wave statistics, long-term wave data, wave climatology.

INTRODUCTION

Wind waves provide the major dynamic forces causing changes in physiography of the nearshore regions. Increased marine activities like offshore mineral and oil exploration, utilisation of wave energy, construction of marine structures and harbours, shipping and naval activities require accurate information on wave climatology. Visual observations of wave heights form a good source of statistical information available for the prediction of extreme wave conditions.

Ship based visual observations reported by the India Meteorological Department in the Daily Weather Reports for 0830 and 1730 IST were used in the wave atlases prepared by the Naval Physical and Oceanographic Laboratory (N.P.O.L.) using data for the periods 1960-1969 (Anonymous, 1978) and by the National Institute of Oceanography (N.I.O.) for the period 1968-1973 (Anonymous, 1982). The N.P.O.L. wave atlas includes both sea and swell statistics while the N.I.O. atlas provides swell information only. The wave parameters provided in these atlases are height, period and direction. Long-term distributions of wave height and

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direction, obtained from grid 17 (5°-9°N, 73°-77°E) of the N.P.O.L. atlas and grid 1 (5°-10°N, 75°- 80°E) of the N.I.O. atlas were compared by Muraleedharan, Nair and Kurup (1990). The present paper tries to study the monthly variations of long-term wave height (H_s) distributions and the return periods of the maximum significant wave height off the Trivandrum coast.

MATERIAL AND METHODS

Long-term wave statistics obtained from grid 17 (N.P.O.L) and grid I (N.I.O) enclosing the area off the Trivandrum coast are considered in this work (Fig.1). The monthly observed long-term wave height (H_s) distributions are examined and compared with the available theoretical models. Weibull, Gumbel, log-normal and exponential distributions are generally used for this purpose. Rayleigh distribution has also been suggested as a useful model for long-term distributions (Dattatri, Raman and Jothi Sankar, 1979; Baba, 1985). In this paper emphasis is placed on fitting the Weibull curve for all data, the motivation being that wherever the data follow exponential or Rayleigh exactly, the Weibull also does so and moreover fits

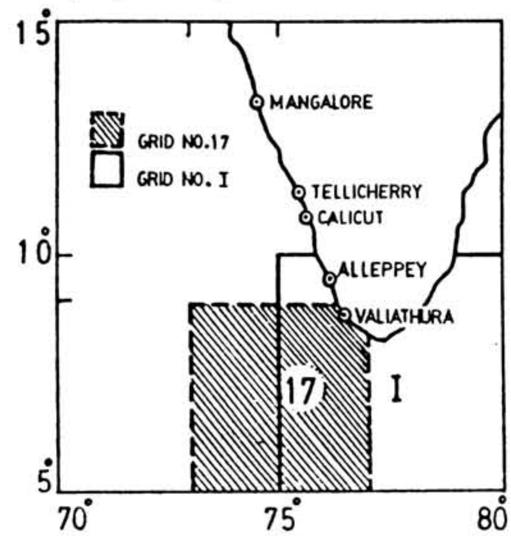

Fig. 1. Map showing grid 17 of N.P.O.L. atlas and grid 1 of N.I.O. atlas used in present study.

Table I. Monthly percentage frequency of occurrence of waves in the height range 0-3.25 m

Sea/Swell	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Swell												
Visual	97.5	100.0	100.0	100.0	95.5	88.5	93.5	99.5	98.5	100.0	100.0	96.5
Weibull	99.5	100.0	100.0	100.0	97.5	86.0	97.0	96.0	99.5	100.0	100.0	98.5
Sea & Swell												
Visual	98.0	98.0	100.0	99.0	97.5	98.5	98.5	96.0	96.0	98.5	98.5	99.5
Weibull	98.5	99.0	100.0	100.0	99.0	99.0	99.0	95.0	96.0	99.0	99.0	99.5

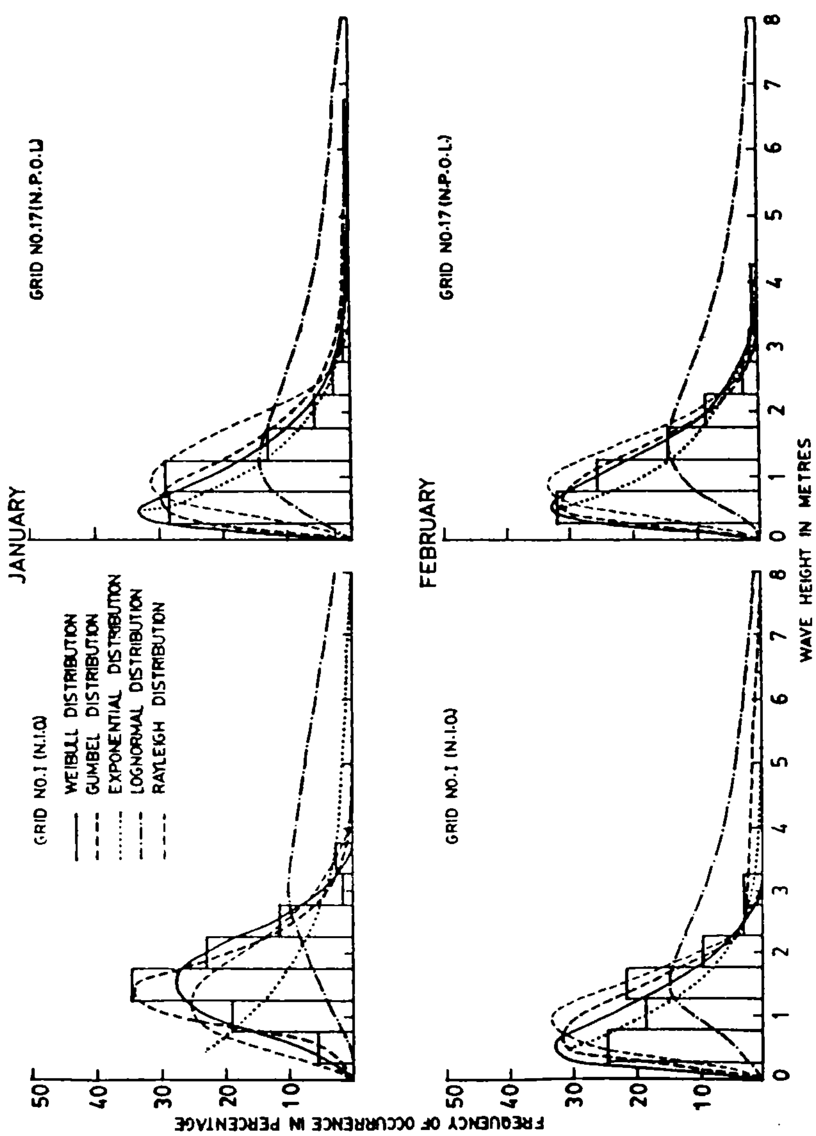

Fig. 2a. Comparison of the distribution of observed wave heights (Histograms) with theoretical distributions.

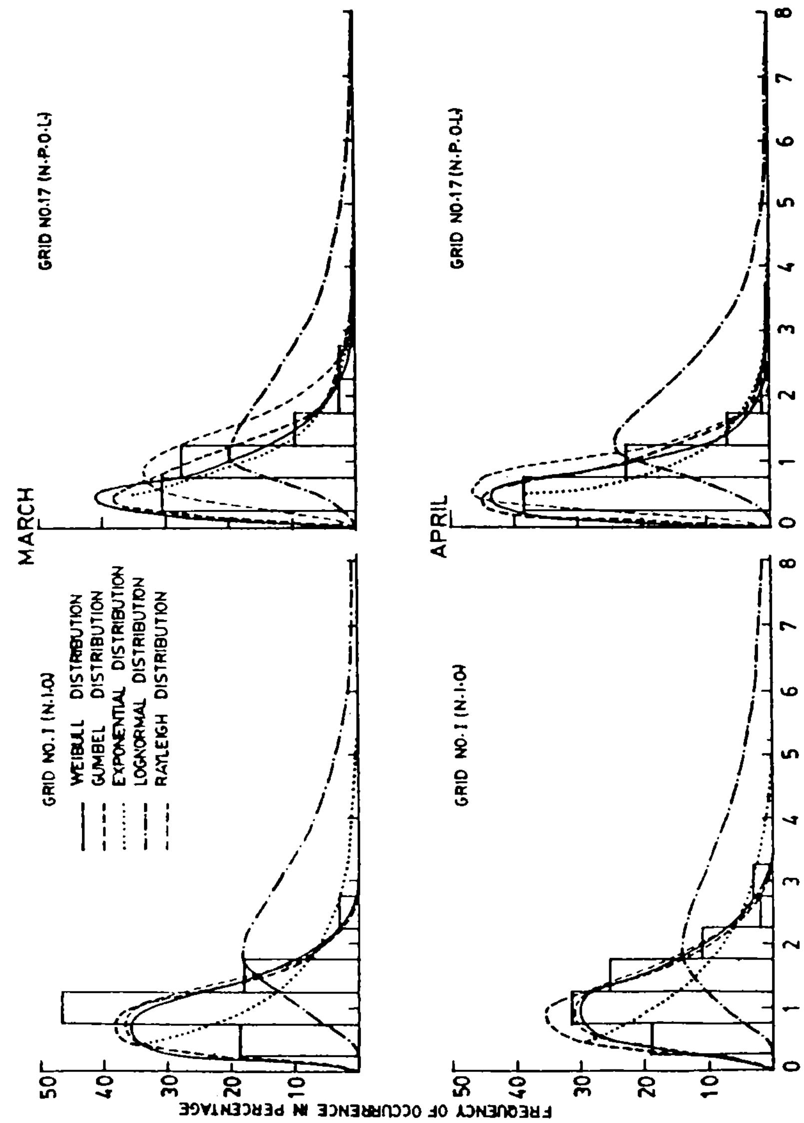

Fig. 2b. Comparison of the distribution of observed wave heights (Histograms) with theoretical distributions.

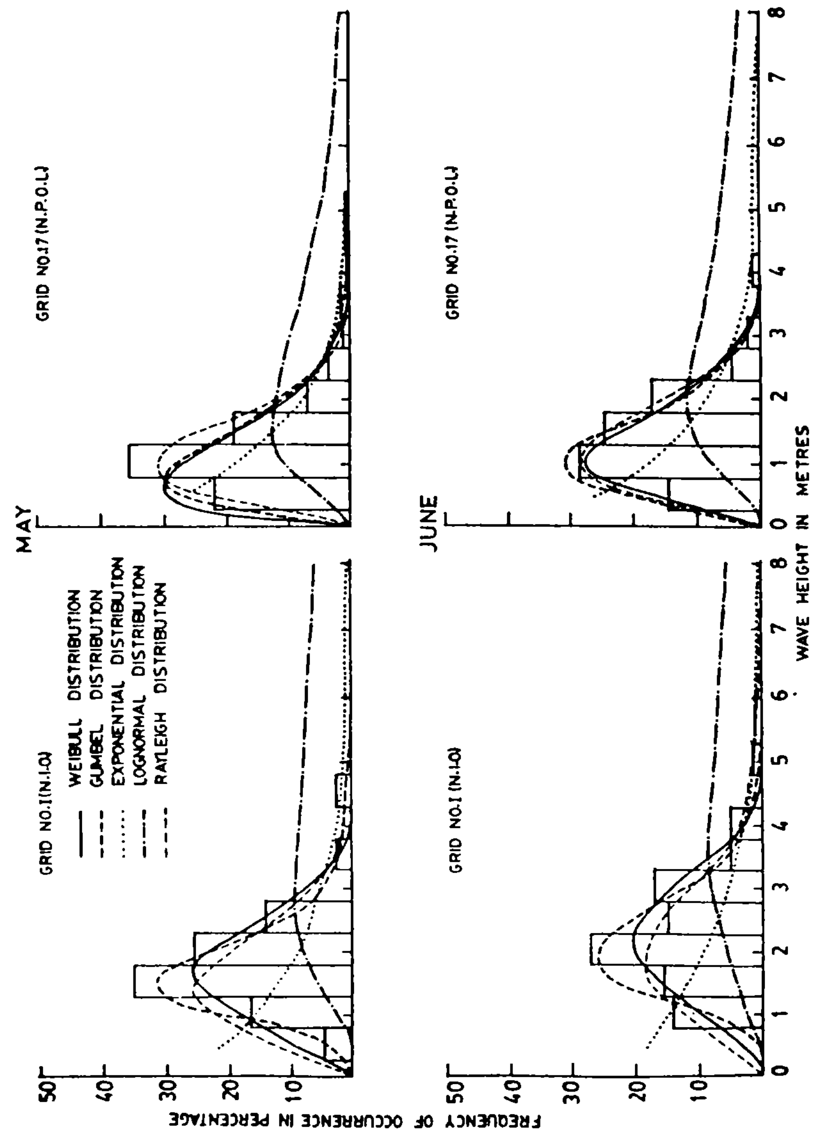

Fig. 2c. Comparison of the distribution of observed wave heights (Histograms) with theoretical distributions.

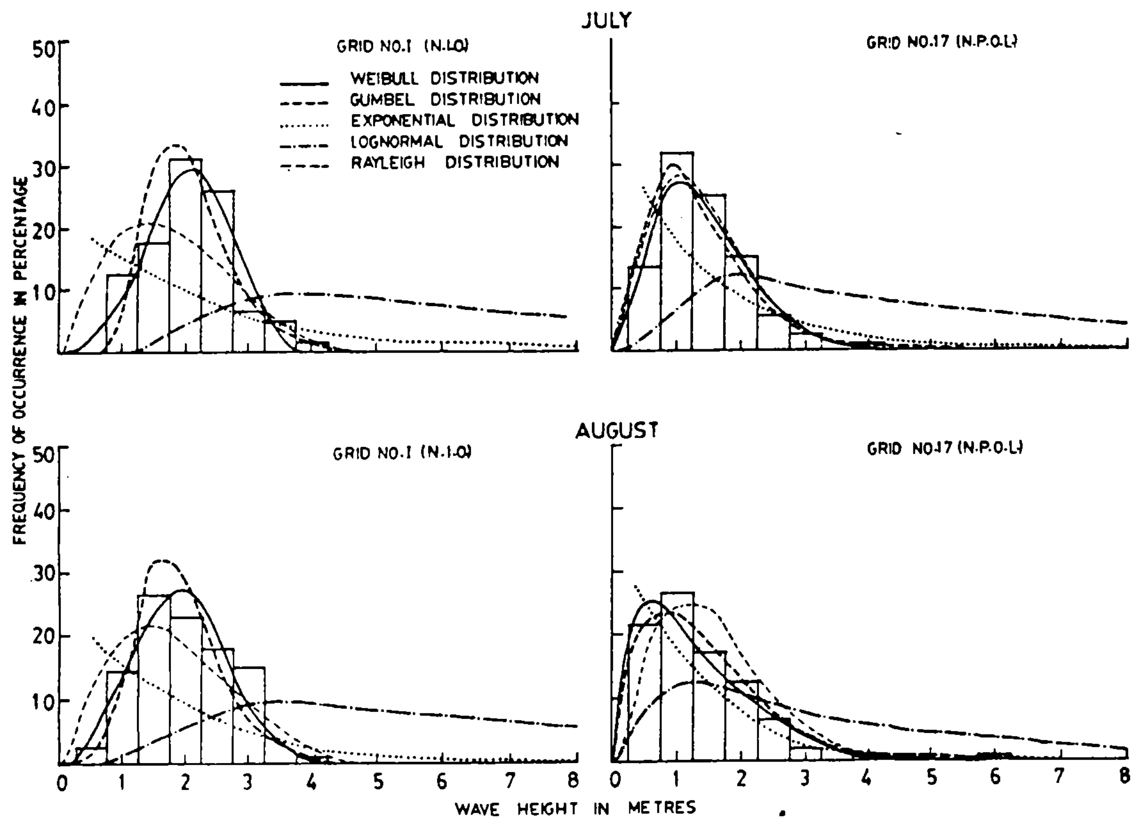

Fig. 2d. Comparison of the distribution of observed wave heights (Histograms) with theoretical distributions.

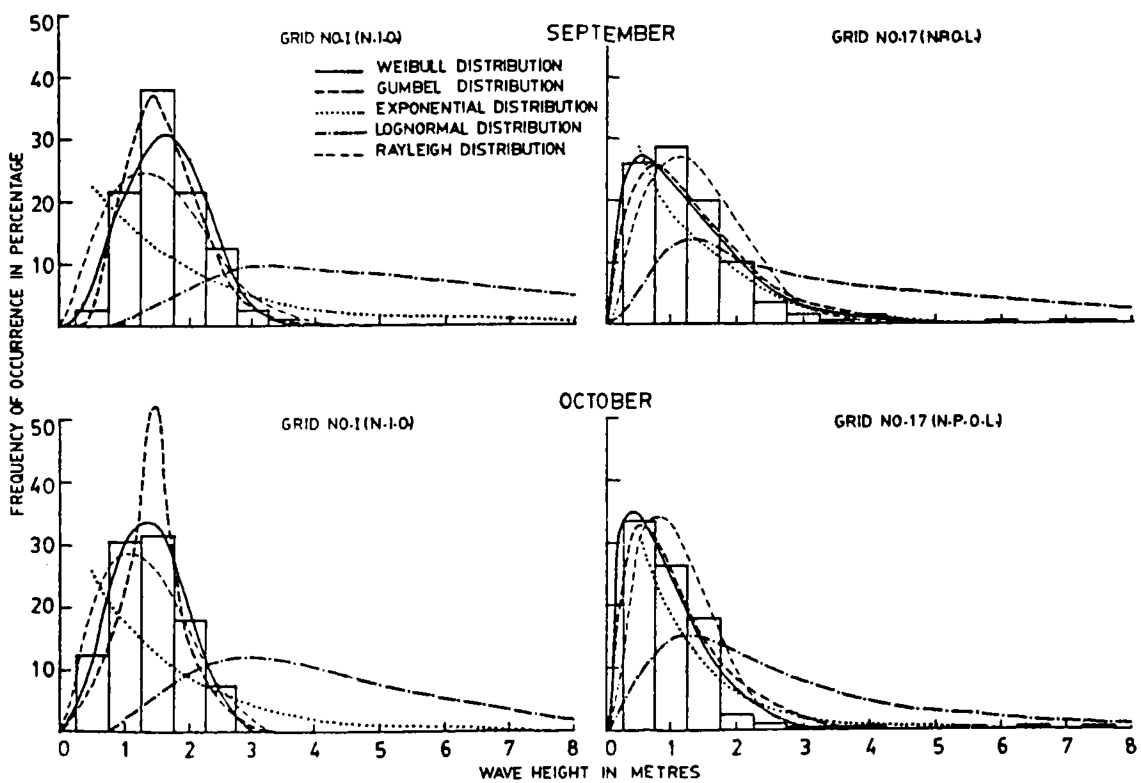

Fig. 2e. Comparison of the distribution of observed wave heights (Histograms) with theoretical distributions.

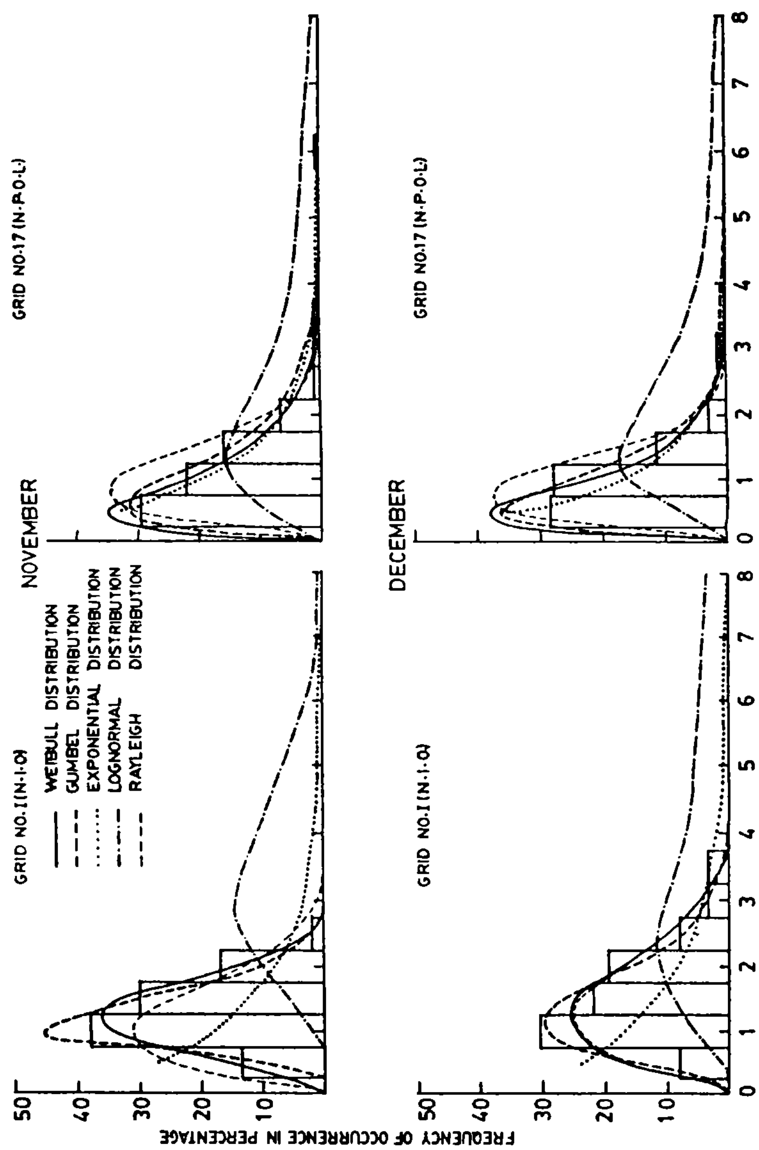

Fig. 2f. Comparison of the distribution of observed wave heights (Histograms) with theoretical distributions.

reasonably well for observations that follow other positively skewed distributions such as gamma, log-normal, extreme value etc.

In the present investigation, the long-term distributions of wave height (H_s) obtained from grid 17 (N.P.O.L.) and grid 1 (N.I.O.) are tested with Weibull, Gumbel, log-normal, exponential and Rayleigh models. The method of maximum likelihood has been used in estimating the parameters and the goodness of fit is ascertained using X^2-test at 0.05 level of significance. A comparative study of the observed percentage frequency of occurrence of wave heights with the theoretical curves is made (Fig. 2). Monthly percentage frequency of occurrence of waves in the height range 0-3.25 m is estimated for the visual and theoretical (Weibull) curves for the above grids (Table I).

In view of the fact that of all the models, the Weibull distribution provided the closest fit for H_s in majority of cases in both deep and shallow water conditions, there is a strong case for using it as the basic model for wave heights (H_s). With this point of view, several wave parameters of interest are derived using this particular model. Accordingly, the chances of average maximum significant wave heights to occur in a period of 5 years are computed for both the grids with respect to annual and monsoon seasonal data using the relation,

$$H_s\,(\max) = \sigma(\log t^{1/n})^{1/\lambda}$$

where t=5 years, n=1 month and σ and λ, parameters of the Weibull distribution specified by the density function,

$$f\,(h;\,\sigma,\lambda)=(\lambda/\sigma)\,(h/\sigma)^{\lambda-1}.\exp[-(h/\sigma)^{\lambda}],\; h>0$$

Apart from likely maximum heights, represented by H_s (max) it is of interest to calculate the probabilities of such wave heights to re-occur in designated periods of time. This is provided by the formula

$$q = m \times e^{-n}\,[H_s(\max)/\sigma]^{\lambda}$$

where m is the periods of time proposed for a re-occurrence. The derivation of the expressions is given in the appendix.

RESULTS AND DISCUSSION

In respect of the swell statistics (Anonymous, 1982), the Weibull model fits in 50% of the cases followed by Gumbel in 41.5% and Rayleigh in 8.5% of the cases. On the other hand, for the N.P.O.L data (Anonymous, 1978), adequate fit could be realised only in 58.5% of the total cases. Of these, 25% each accounts for the Weibull and Gumbel models and 8.5% for the Rayleigh. Even in data where the Weibull fit was rejected, it was due to the presence of one or two abnormal observations, rather than the incomparability of the model with the whole data set. Such discordant values may be the result of bias in visual observations. The overall analysis suggests that the Weibull distribution offers a uniformly good fit.

A comparison of the visual wave height distributions with the theoretical distributions as shown in Fig. 2a-f indicates that the Weibull model effectively explains the different sea states. For both the sea and swell dominated conditions, Weibull conforms to the wave patterns observed in February, April, June, July, September and November and of swell prevailed sea conditions, in January, March to August, October and November. At the same time, the Gumbel distribution provides a better explanation than the other curves for the rest of the monthly wave height informations in both cases.

From Fig. 2, it is seen that Weibull overestimates and underestimates the peak percentage frequencies (difference in observed and theoretical peak percentage frequencies) of wave heights to a maximum of 10.5% and 12.5% respectively. The respective figures values for Gumbel and Rayleigh are 20.5% and 10.0%, 8.0% and 14.0%. While the Gumbel distribution estimates the peak frequency with a higher kurtosis, Rayleigh curves underestimate the peak frequencies.

It could be observed that the distribution of the reported percentage frequency of occurrence of wave heights show a broad band of wave heights for swell dominated conditions than that for sea and swell combined sea state. A change to broad band is observed during southwest monsoon season. (grid 17, Fig. 2). The Weibull model explains the varying wave patterns (N.P.O.L., N.I.O. atlases). The values obtained from this model for the monthly percentage frequency of occurrence of wave heights less than 3.25 m are in accordance with that obtained from the atlases (Table I). Nearly 95% of waves have heights less than 3.25 m for both combined swell and sea, and swell data.

The maximum wave height reported for the sea and swell combined conditions as given in N.P.O.L. data is 7.5 m and the return period is found to be 2.27 years. For the swell dominated sea state as presented in N.I.O. atlas, a maximum wave height of 5.0 m is observed and its re-occurrence is given as 1.71 years. The probability of a 7.5 m wave (N.P.O.L.) to occur within one year is 44% and a wave of height 5 m (N.I.O.) will return within a year with 59% probability. The averaged maximum significant wave heights to occur in a period of 5 years calculated from Weibull model for sea and swell (N.P.O.L.) statistics (grid 17) for annual and monsoon seasonal data (June-September) are 9.60 m and 9.63 m respectively. The respective values are 6.19 m and 6.00 m for swell information (N.I.O.) (grid I). Grouping of data into annual or monsoonal does not show significant variation in these results. Dattatri (1981) arrived at similar results using recorded wave data off Mangalore harbour. The most frequently occurring wave heights for the annual and monsoon data are obtained as 0.75 m and 1.00 m respectively from the combined sea and swell statistics. For the swell statistics they are 1.33 m and 1.75

m respectively. Wave power off Trivandrum estimated using recorded data (Thomas, Baba and Ramesh Kumar, 1986) showed better agreement with that derived from swell data than from the combined sea and swell data (Muraleedharan, Nair and Kurup, 1990). Visually observed wave information can thus be effectively used in wave climatological studies provided that the wave parameters are statistically treated and theoretically obtained wave statistics are checked with those obtained from recorded wave information.

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APPENDIX

Analysis of return periods:

The largest significant wave height $(H_s)_L$ that appears in a period of time will follow the distribution specified by

$G(h) =$ ~~$\exp - n(h/\sigma)^{\lambda}$~~ $\left[1-\exp-\left(\frac{h}{\sigma}\right)^{\lambda}\right]^{n}$

The probability that a specified value (Hs)max is exceeded is therefore

$P[(H_s)_L > (H_s)_{max}] = 1 - G[(H_s)_{max}] =$ ~~$1 - \exp - n[(H_s)_{max}/\sigma]^{\lambda}$~~ $1-\left[1-\exp\left(-H_s/\sigma\right)^{\lambda}\right]^{n}$

In a series of observations the probability that the nth observation is the first value that exceed $(H_s)_{max}$ satisfies the geometric law,

$(1-G)^{n-1} \times G, \quad n=1,2,3 \ldots\ldots$

The mean of this distribution is

$m =$ ~~$1/G = \exp n[(H_s)_{max}/\sigma]^{\lambda}$~~ $= 1/(1-G) = \left\{1-\left[1-\exp-\left(\frac{H_s}{\sigma}\right)^{\lambda}\right]^{n}\right\}^{-1}$

Thus on the average the number of observations included between two adjacent values that exceed $(H_s)_{max}$ is

$t\,[(H_s)_{max}, \lambda, \sigma] =$ ~~$1/G = \exp n[(H_s)_{max}/\sigma]^{\lambda}$~~ $1/(1-G) = \left\{1-\left[1-\exp-\left(H_s/\sigma\right)^{\lambda}\right]^{n}\right\}^{-1}$

This function t can be interpreted as a period representing a re-occurrence of the maximum wave height $(H_s)_{max}$. This is the fundamental relation connecting a prescribed maximum wave height $(H_s)_{max}$ and its return period.

Given a period of time t, then the probability of realising a height larger than $(H_s)_{max}$ in the first m consecutive years is given by

$q = 1-(1-G)^{m} = 1-(1-1/t)^{m}$

Note that t increases if $(H_s)_{max}$ increases. Hence when wave heights anticipated are larger and larger, the return periods also become larger, i.e., unusually large wave heights are realised only over longer periods of time. Since t is larger than 1, binomial expansion is valid and as a first approximation,

$q = 1-(1-m/t)$

$q =$ ~~$m \times \exp - n[(H_s)_{max}]$~~ $= m \cdot \exp\left[-n\left(\frac{(H_s)_{max}}{\sigma}\right)\right]^{\lambda}$

Long-term wave statistics off Goa

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Long-term wave statistics from grid 9 (NPOL Atlas) and grid XIII (NIO Atlas) off Goa were examined and compared with recorded wave information. Wave directions and average monthly frequency of waves in the period 5 to 8 sec (zero-crossing period) from grid XIII were comparable with recorded information at Goa. The theoretical and calculated values of significant wave heights were in agreement for grid 9. The wave power averaged from swell statistics (grid XIII) was found to be much higher than that averaged from sea and swell statistics (grid 9).

A knowledge of wave climate is important from the strategic, economic and commercial points of view. Different workers[1,2] have pointed out that visual observations suggest a reasonable representation for wave climatological studies. Here an attempt was made to study the wave climatology for an area off Goa by utilizing the available wave atlases and recorded information.

Visual wave parameters obtained from grid 9 (13°–17°N, 73°–74.7°E) (NPOL Atlas, 1978) and grid XIII (15°–20°N, 70°–74°E) (NIO Atlas, 1982) were utilized in the present work[3,4] (Figure 1). These grids overlap over an area off Goa. Wave direction, wave power and percentage frequency of occurrence of waves in the period range 5 to 8 sec (zero-crossing period) from these grids were examined in the light of recorded information off Goa[5]. Zero-crossing period is the average of zero up-crossing period (the time difference between two consecutive points at which the wave crosses the mean sea level in the upward direction) and zero down-crossing period (the time difference between two consecutive points at which the wave crosses the mean sea level in the downward direction). Wave power was calculated using the relation

$$P = 0.55 \; H_S^2 \cdot T_Z . \qquad (1)$$

where P is the power available on a random sea[6], H_S the significant wave height and T_Z the zero-crossing period, computed from the relation[7]

$$T_S = 1.3 T_Z - 2.5 . \qquad (2)$$

where T_S is the significant wave period. The wave heights

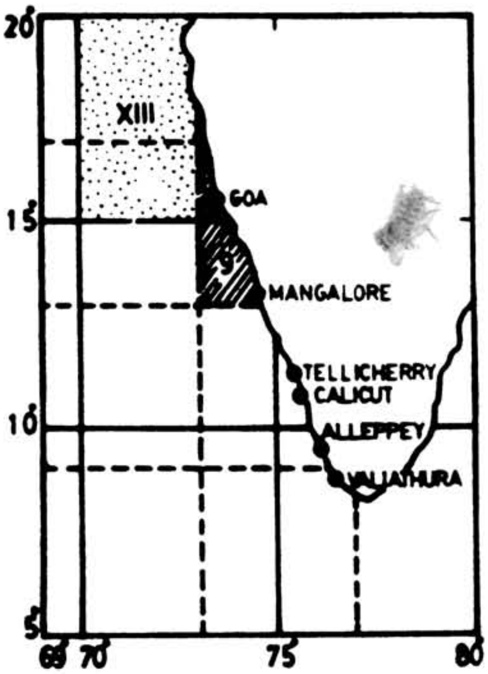

Figure 1. Orientation map showing area of study.

and wave periods published in the atlases may be considered as H_s and T_s respectively. In two recent articles[8,9], it has been confirmed by empirical evidence that the long-term frequency of wave heights follows a Weibull distribution function

$$F(x) = 1 - \exp(-H/\sigma)^{\lambda}. \quad (3)$$

where σ is the scale parameter and λ the shape parameter of the model. Accordingly, with the Weibull distribution for wave heights, the significant wave height (H_s) and one-tenth the highest wave height ($H_{1/10}$) were computed from the model and compared with values obtained from

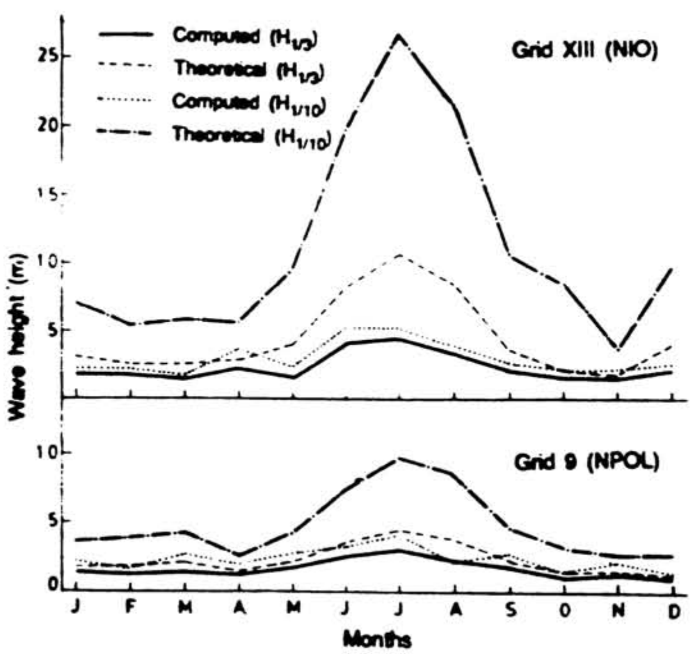

Figure 2. Monthly variations of computed and theoretical values of $H_{1/3}$ and $H_{1/10}$ wave heights (m).

Table 1. Comparison of monthly predominant wave direction off Goa

Month	Grid 9 (NPOL Atlas)	Grid XIII (NIO Atlas)	Recorded information
January	360 (N)	360 and 30 (N and NNE)	90 (E)
February	330 (NNW)	330 (NNW)	315 (NW)
March	360 (N)	330 (NNW)	315 (NW)
April	300 (WNW)	300 (WNW)	315 (NW)
May	300 (WNW)	270 (W)	315 (NW)
June	270 (W)	240 and 270 (WSW and W)	270 (W)
July	240 (WSW)	240 (WSW)	270 (W)
August	270 (W)	240 (WSW)	270 (W)
September	270 (W)	240 and 270 (WSW and W)	315 (NW)
October	330 (NNW)	240, 270 and 330 (WSW, W and NNW)	270 (W)
November	360 (N)	360 (N)	270 (W)
December	360 (N)	30 (NNE)	90 (E)

Table 2. Comparison of the average monthly percentage frequency of waves in the period range 5–8 seconds.

Data	Averaged % of occurrence of waves Nov–May	June–Oct.
Sea and Swell Atlas	77.0	75.0
Swell Atlas	86.0	86.0
Recorded	90.0	—

reported wave information (Figure 2).

The monthly wave directions published in the NPOL Atlas (grid 9) and NIO Atlas (grid XIII), and the directions obtained from recorded information[10] off Goa are given in Table 1. The directions of wave approach from both the atlases and the recorded information are in agreement during different seasons.

A comparison of the average monthly percentage frequency of waves in the range 5 to 8 sec (zero-crossing period) is given in Table 2. The values obtained from grid XIII are found to be closer to the recorded information[5].

The monthly distribution of the computed and predicted values of $H_{1/3}$ and $H_{1/10}$ are given in Figure 2. The wave heights obtained from sea and swell statistics (grid 9) provide much lower values compared to those obtained from swell statistics alone (grid XIII). It is interesting to note that the theoretical wave heights were always greater than the computed values. The theoretical values deviate much from the computed values during the southwest monsoon. This deviation is greater for $H_{1/10}$ than for $H_{1/3}$.

Figure 3 gives the distribution of monthly average wave power for two grids. The sea and swell statistics (grid 9) give an annual variation of wave power ranging from a minimum of 1.41 kW m^{-1} in December to a maximum of 14.55 kW m^{-1} in July. The swell statistics (grid XIII) give a variation ranging from a minimum of 3.15 kW m^{-1} in March to a maximum of 46.98 kW m^{-1} in July. Table 3 gives a comparison of average wave power for annual, fair-weather (November to April) and rough-weather (May to October) seasons. The swell statistics

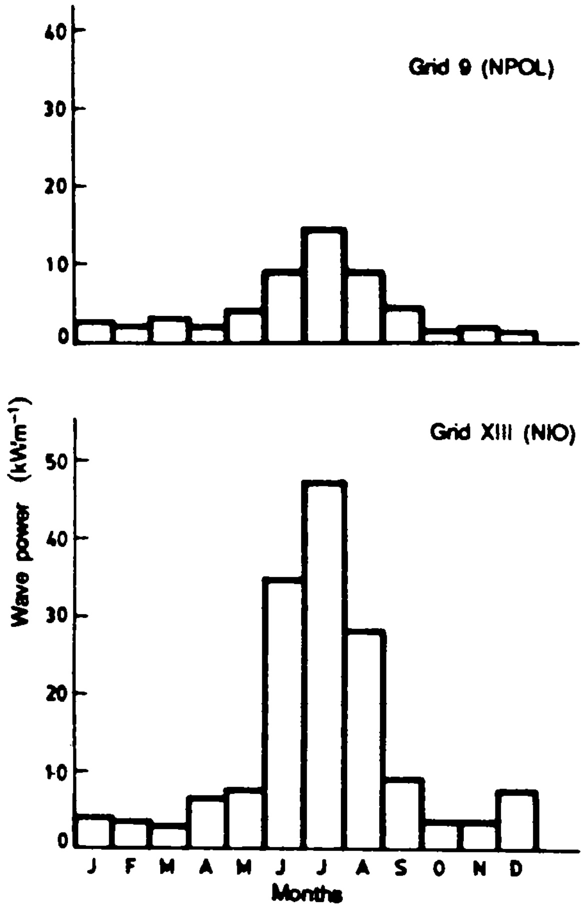

Figure 3. Distribution of monthly average wave power.

Table 3. Comparison of wave power for annual, fair-weather and rough-weather seasons

	Wave power (kW m^{-1})		
Data	Annual	Fair-weathr	Rough-weather
Sea and swell	4.6	2.2	7.1
Swell	13.1	4.6	21.6

provide much higher values of wave power than the combined sea and swell statistics. The low values obtained from sea and swell statistics may be attributed to the fact that rough seas are avoided by ships and the information is therefore absent in the data.

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