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Distribution of Deep Water Wave Power Around the Indian Coast Based on Ship Observations

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ABSTRACT

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The ship reported swell data published in the Indian Daily Weather Reports for the period from 1968 to 1983 are compiled for the seas around India which are divided into 10 grids each of 5° latitude and 5° longitude. The percentage distribution of wave power in different directions over a year for each grid is presented. The annual mean wave power along the Indian coast varies from 11.4 to 15.2 KW per metre length of wave crest with a maximum of 15.2 KW for the regions off south Kerala and south Tamilnadu coasts and a minimum of 11.4 KW off the Andhra coast. Computation based on the measured waves of one year duration show that the annual mean wave power available in the grids 3 and 9 is lower and is only about 53 and 77 percent respectively of the annual mean wave power computed based on ship reported wave data. About 55 to 65 percent of the annual total wave power is contributed during the southwest monsoon period from June to September. Wave power available in February, March and April in general is the lowest. Wave activity is found to be high both during the southwest and the northeast monsoons along the east coast bordering the Bay of Bengal whereas it is confined predominantly to the southwest monsoon period in the case of the west coast bordering the Arabian Sea.

ADDITIONAL INDEX WORDS: *Wave power, coastal process, Indian coast, wave energy, wave direction.*

INTRODUCTION

India has a vast coastal zone with about 7000 Km long shoreline bounded by the Bay of Bengal on the east, the Indian Ocean on the south, and the Arabian Sea on the west. The meteorological and oceanographic conditions in the coastal zone of India can be distinguished under the three different seasons namely, the southwest monsoon (June to September), the northeast monsoon (October to January) and the nonmonsoon or the fair weather season (February to May). The west coast of India experiences high wave activity during the southwest monsoon with relatively calm sea conditions prevailing during the rest of the year. On the east coast, the wave activity is significant both during southwest and northeast monsoons. Extreme wave conditions are, however, found to occur under severe tropical cyclones which are frequent in the Bay of Bengal during the northeast monsoon period. Knowledge of the directional distribution of mean wave power and its variation with time is important in sediment transport studies as well as in determining the potential sites for wave power plants along the coast.

Longterm data on measured waves are not available at present in India. Non-directional time series data on wave heights and periods measured by waverider buoys are available only for a limited locations and periods. In the absence of instrumentally recorded wave data, ship reported wave data can be used at least for the sake of preliminary study and evaluation. The results presented here based on such a study would be valuable in evaluating a coastal engineering problem or in identifying potential sites for wave power plants.

WAVE DATA BASE

The India Meteorological Department documents the daily sea weather reports over the Indian region classified as Zone II—A by the World Meteorological Organisation (Figure 1).

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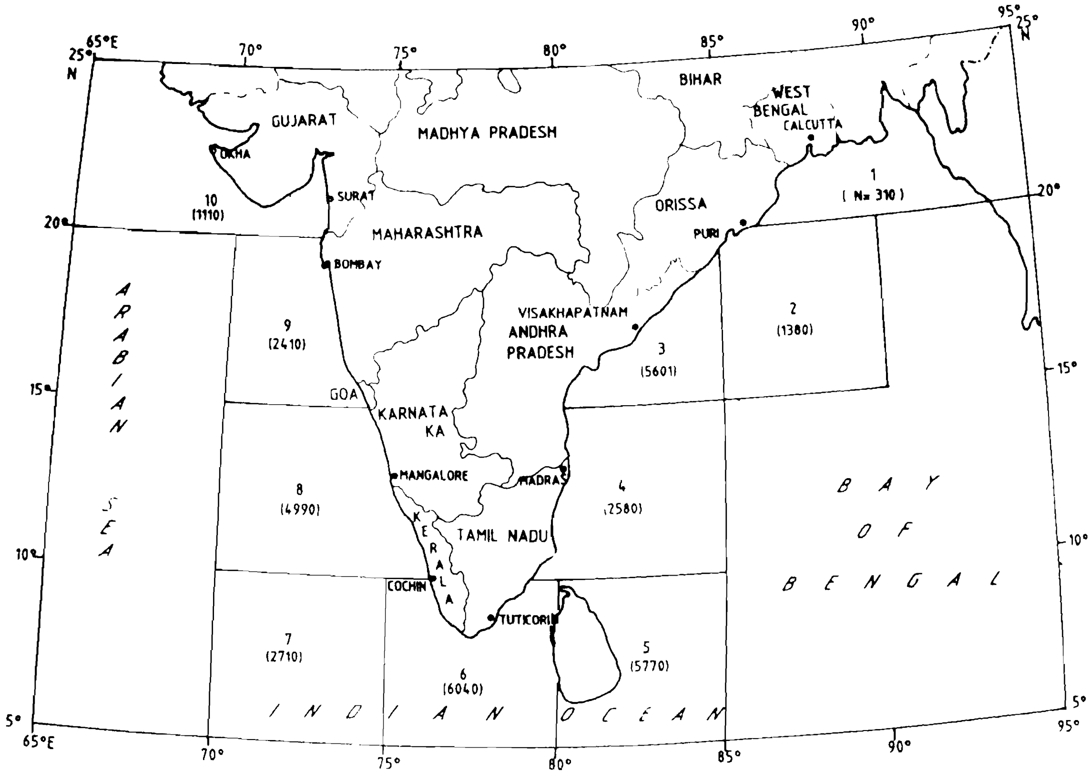

Figure 1. Location map.

Sea weather reports contain the visual information on the sea and the swell wave characteristics reported by the ships passing in the seas around India. Wave data are published in the Indian Daily Weather Reports in codes wave height in half metre intervals, wave period with an accuracy of one second, and wave direction with a resolution of ten degrees in the range 10 to 360 degrees. In the case of sea waves, only the heights and periods are reported but not the wave direction. Number of visual observations of sea waves and reported in the Daily Weather Reports are meagre and are found to be less than 5 percent of the total number of swell observations published in the report. Since sea waves are reported without information on direction and are very low in number, they are excluded from the present study and only the swell wave data are considered. The region around India is divided into 10 grids, each of size 5° latitude and 5° longitude as shown in Figure 1. The grids 1 to 4 are in the Bay of Bengal, grids 5 to 7 are in the Indian Ocean and grids 8 to 10 are in the Arabian Sea. Each grid approximately covers the shore line of one coastal state, for example, grid 1 covers West Bengal and north Orissa, grid 2 covers south Orissa, grid 3 covers Andhra Pradesh, grid 4 covers north Tamilnadu, grid 6 covers south Tamilnadu and south Kerala, grid 8 covers north Kerala and Karnataka, grid 9 covers Goa and Maharastra and grid 10 covers Gujarat. The Indian Daily Weather Reports published for a period of 16 years from 1968 to 1983 are retrieved and the swell information documented in them were compiled and stored in magnetic tapes. Number of visual wave observations (N) reported for each grid are indicated in .Figure 1. These data points, each one representing a particular wave height, period

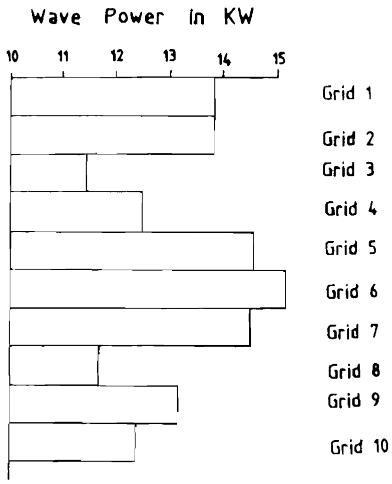

Figure 2. Average annual wave power.

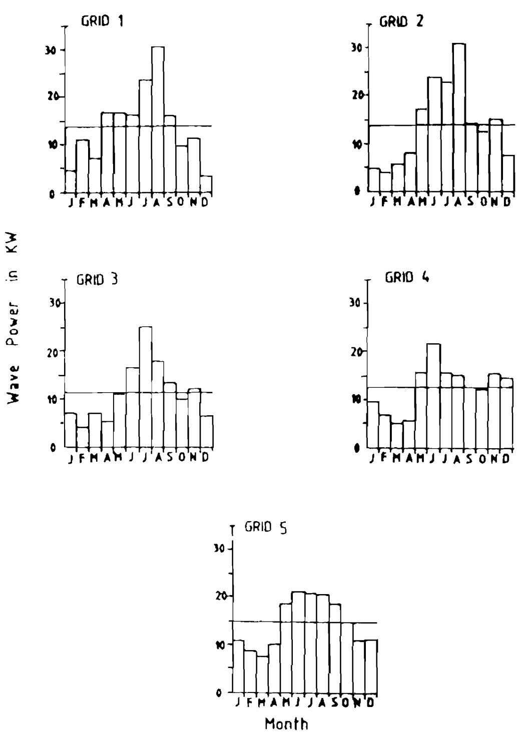

Figure 3. Monthly distribution of wave power.

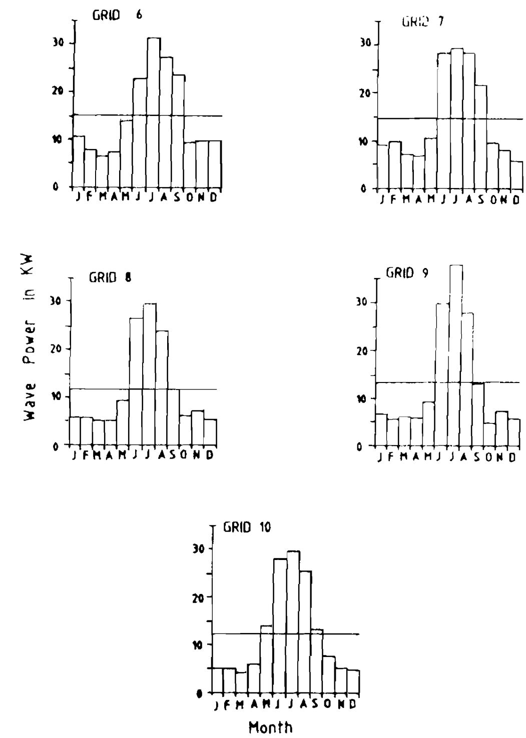

Figure 4. Monthly distribution of wave power.

and wave direction are used in estimating the wave power in the present study.

Ship reported data pertain to deep water waves. The visual estimate of wave height and period by a trained observer normally conforms to the significant wave height (H_s) and zero crossing wave period (T_z). The direct use of visually observed wave height as significant wave height is justified for most of the applications (JARDINE, 1979). In the present study, ship reported visual wave heights are considered as significant wave height (H_s) and wave periods corresponding to zero crossing wave period (T_z).

For the purpose of a comparison, wave data measured at two locations using the datawell wave rider buoy for a period of one year from June 1983 to May 1984 were also used (Figure 1). Wave measurements taken off Kakinada at 90 m water depth and that measured at Bombay High at 70 m water depth were used as that pertaining to grid 3 and grid 9, respectively. Waves were recorded for 20 minutes duration at 3 hourly intervals and each record was analysed

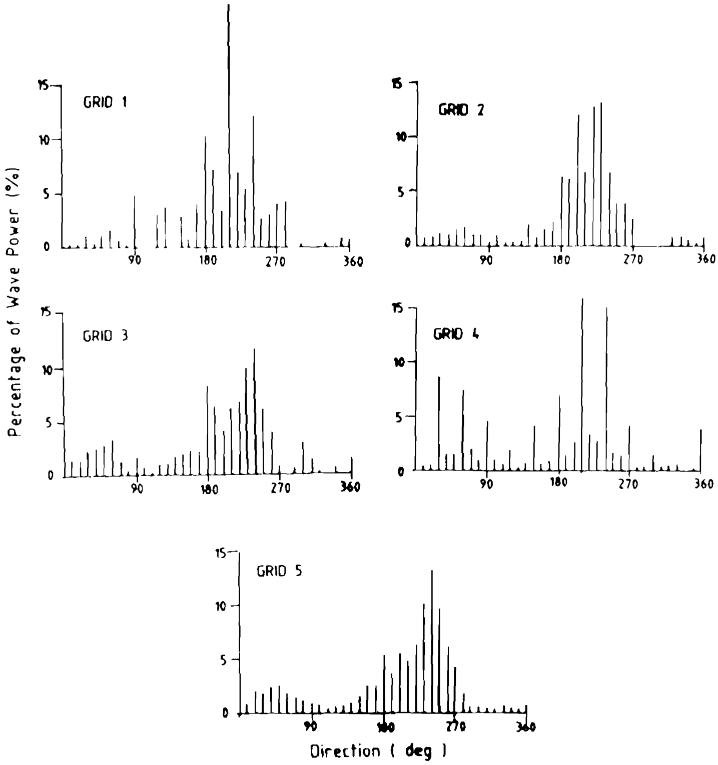

Figure 5. Directional distribution of wave power.

for the significant wave height and zero crossing wave period using Tucker's method (TUCKER, 1963).

METHOD OF STUDY

In the case of measured waves, significant wave height at the measured depth is converted to corresponding deep water wave height using the small amplitude wave theory (SVENDSON and JONSSON, 1976).

$$H_0 = H[(\tanh kh\,(1 + \frac{2kh}{\sinh 2kh})]^{0.5} \qquad (1)$$

where H_o = deep water wave height in m.
H = wave height measured at depth h in m.
h = depth of wave measurement in m.
k = wave number = $2\,\pi/L$
L = wave length in m.

Propagation of Wave Energy

For regular first order wave trains, the energy E per unit area is equal to,

$$E = \rho g H_{rms}^2/8 \qquad (2)$$

where E = Energy in Joules/m^2
ρ = Seawater density (1025 Kg/m^3)
g = Acceleration due to gravity (9.81 m/s^2)
H_{rms} = Root mean square wave height in m.

Using the small amplitude wave theory, the group velocity in deep water is given by (WEIGEL, 1964),

$$C_g = C/2 = gT/4\pi$$

where, C_g = Group velocity in m/s (3)
C = Phase velocity in m/s
T = Wave period in s.

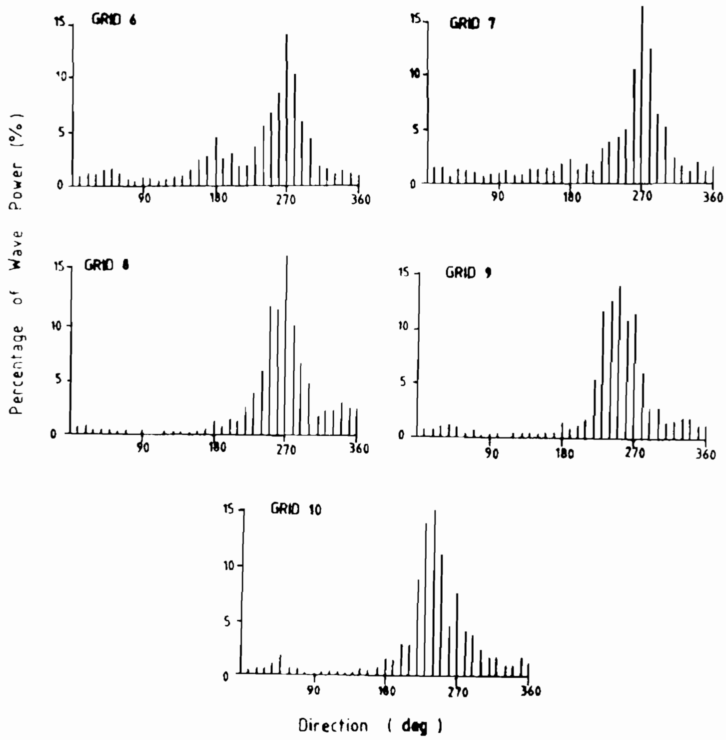

Figure 6. Directional distribution of wave power.

Using Eqns. (2) and (3), the energy flux (wave power) per metre length of wave crest is given by,

$$P = EC_g = (\rho_g H_{rms}^2/8)(gTz/4\pi) = \rho g^2 H_{rms}^2 T_z/(32\pi) = 0.980\ H_{rms}^2\ T_z\ \text{KW/m} \quad (4,5)$$

where, P = Wave power in Kilowatts per metre length of the wave crest.

Statistically, the root mean square wave height is related to the significant wave height (LONGUET-HIGGINS, 1972),

$$H_s = 1.414\ H_{rms}$$

or (6)

$$H_s^2 = 2H_{rms}^2$$

where H_s = Significant wave height.

Using Eqn. (6) in Eqn. (4),

$$P = \rho g^2 H_s^2 T_z/(64\pi) \quad (7)$$
$$P = 0.490\ H_s^2 T_z\ \text{KW/m}.$$

Wave Power Computation

Visual Waves. The ship data compiled from 1968-83 in each grid are put together to represent the variation of wave characteristics for an annual cycle in that grid. Thus, all the data points indicated in Figure 1 (*e.g.* 2580 data points for grid 4) are used in the estimation of wave power.

Considering the ship reported waves as regular waves and based on Eqn. (7), the monthly mean wave power ($\bar{P}m$) in a grid is computed by,

$$\bar{P}m = (\rho g^2/(64\pi))\ fm.H_s^2 T_z \quad (8)$$

where, fm = n/N = fraction of occurrence of a particular set of Hs and Tz for a month irrespective of wave direction.

n = number of occurrences of a particular set H_s and T_z for a given month.

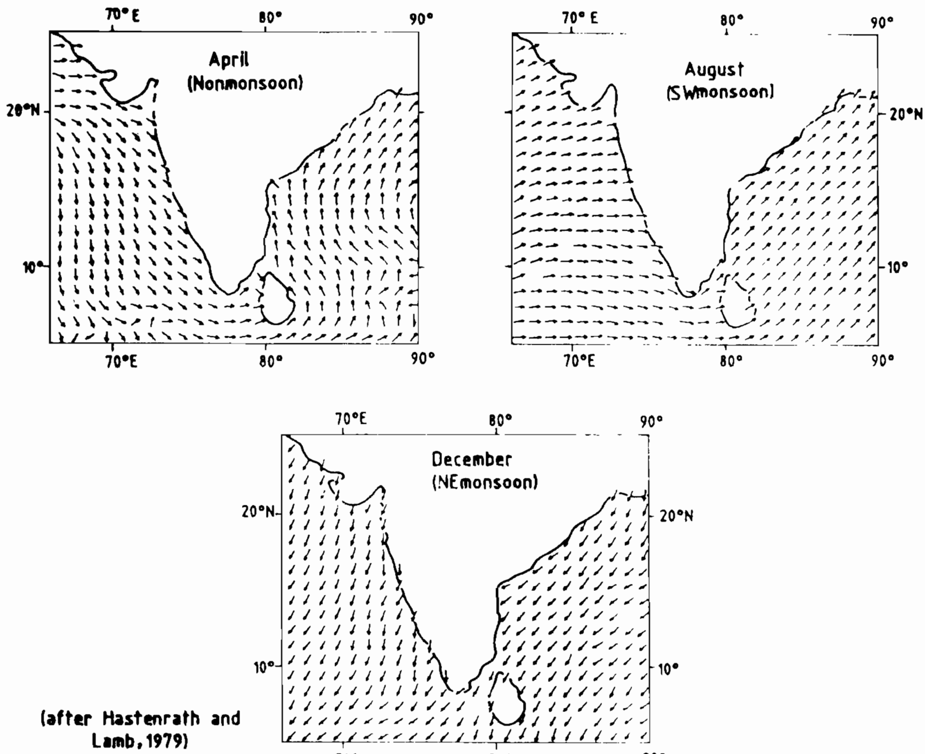

Figure 7. Seasonal wind pattern around Indian region.

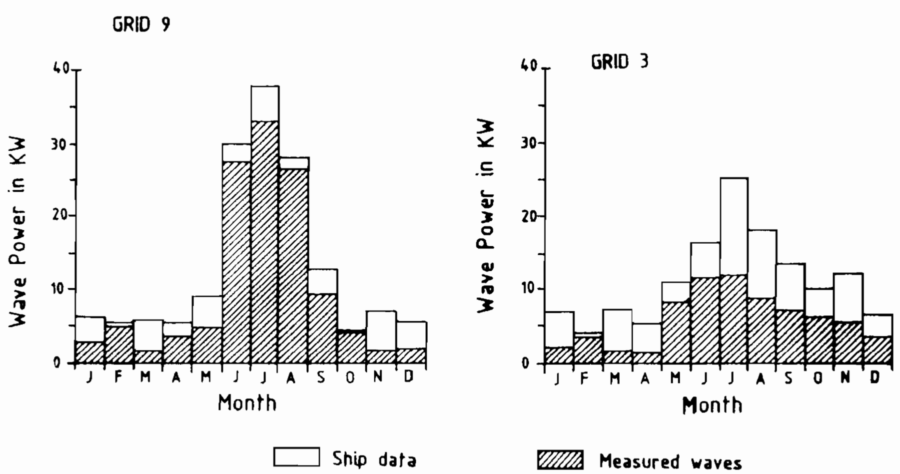

Figure 8. Comparison of wave power.

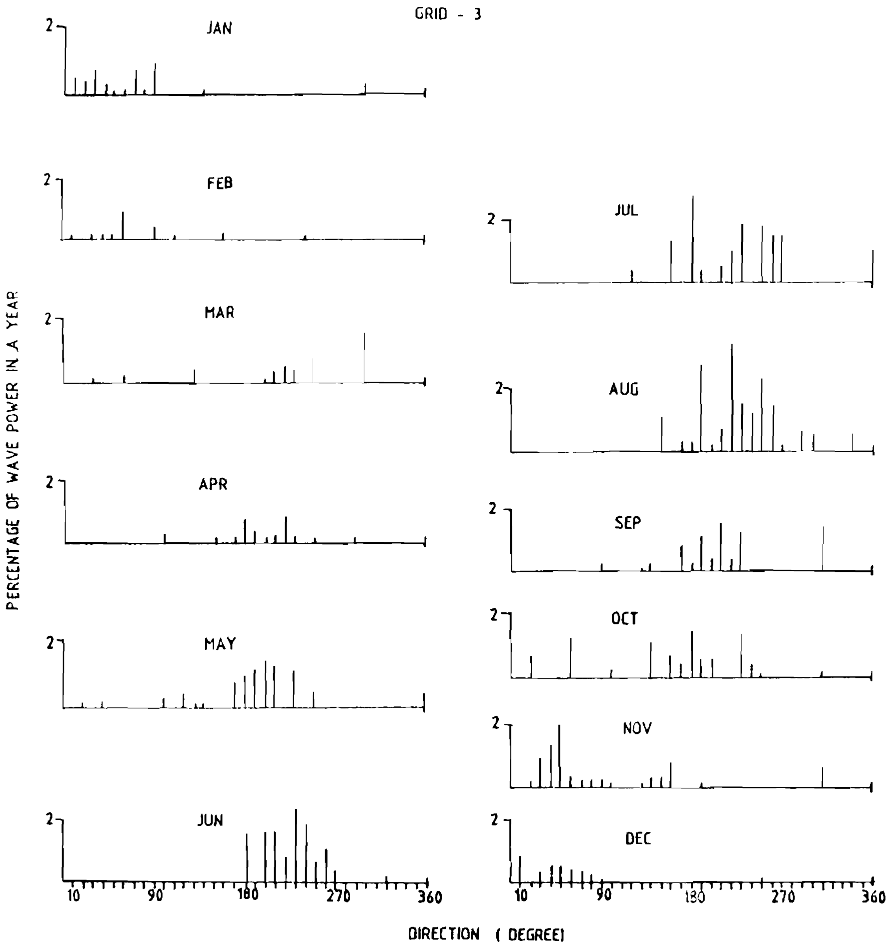

Figure 9. Percentage distribution of wave power in different directions during different months over a year.

N = Total number of visual wave data points each of H_s and T_z in a grid for a month from 1968-83.

From the monthly mean wave power obtained using Eqn. (8), the annual mean wave power ($\bar{P}y$) is computed as,

$$\bar{P}y = (1/12) \sum_{month=1}^{12} \bar{P}m \quad (9)$$

The relative percentage distribution of wave power in different directions in the deep water over an annual cycle is given by,

$$P_\theta = (\rho g^2/(64\pi))\ f_\theta(H_s^2 T_z)_\theta \quad (10)$$

where, θ = 10, 20, 30,....... 360 degrees

P_θ = the relative percentage of wave power available in direction θ over an annual cycle.

f_θ = n/N = fraction of occurrence of a particular set of H_s and T_z in direction θ over an annual cycle.

n = number of occurrences of a particular set H_s and T_z in the direction θ over an annual cycle.

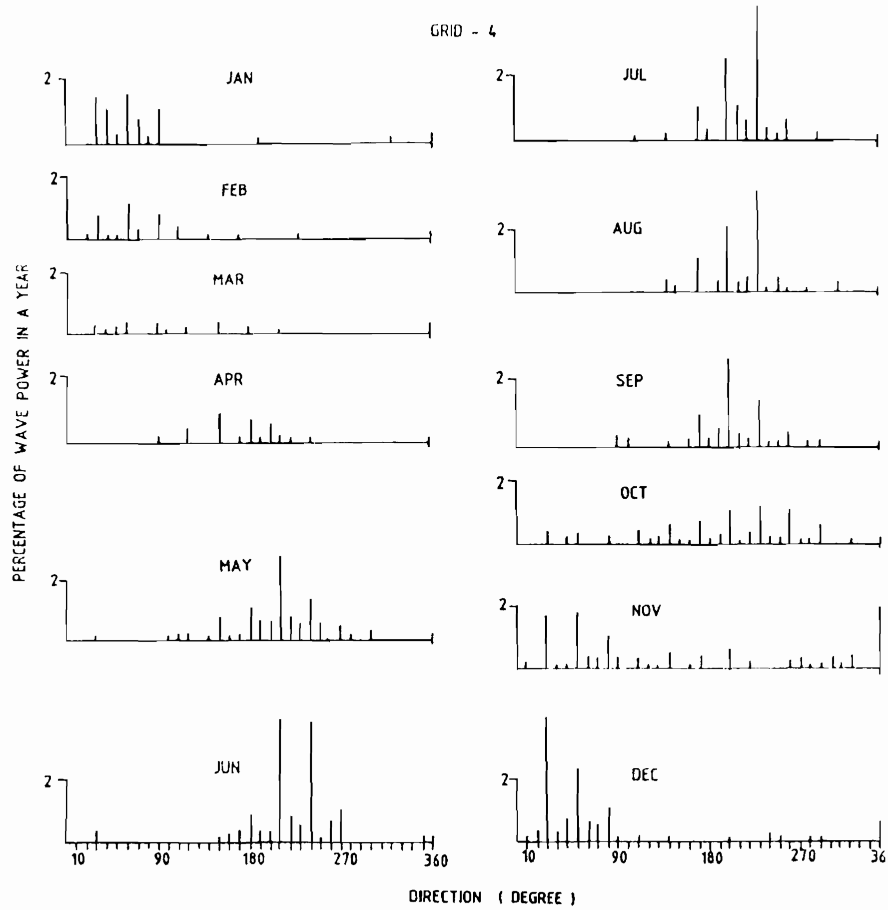

Figure 10. Percentage distribution of wave power in different directions during different months over a year.

N = Total number of visual wave data points available in a grid from 1968-83, each comprised of H_s, T_z and direction (θ) representing an annual cycle (Figure 1).

Measured Waves

The significant wave heights and the zero crossing wave periods obtained from each 20 minute wave records from June 1983 to May 1984 are used for computing the monthly mean power ($\bar{P}m$) as follows,

$$\bar{P}m = (\rho g^2/64\pi))\, f.H_s^2 \,.\, T_z \qquad (11)$$

where, f = n/N = frequency of occurrence of a particular set of H_s and T_z.

n = number of occurrence of a particular set of H_s and T_z for a given month.

N = Number of wave data set each comprised of H_s and T_z available at the measured location in a month during the measurement period from June 1983 to May 1983.

Annual mean wave power is then computed using Eqn. (9)

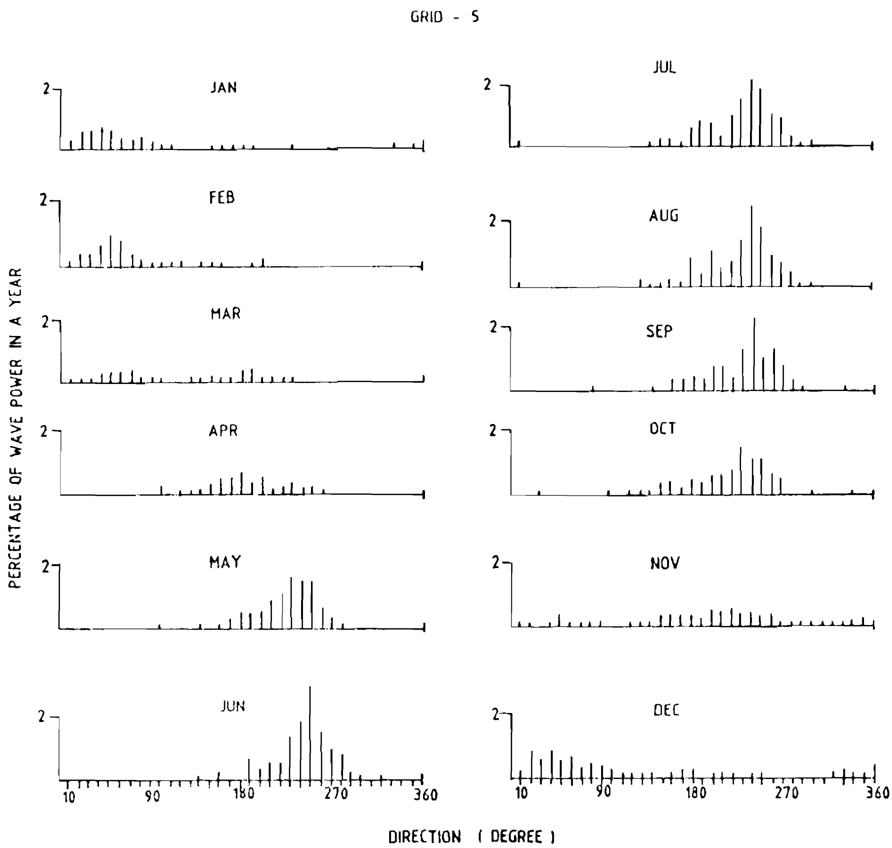

Figure 11. Percentage distribution of wave power in different directions during different months over a year.

RESULTS AND DISCUSSION

Distribution of Monthly Mean Wave Power

The monthly mean wave power per metre length of wave crest estimated using Eqn. (8) for the regions covered by different grids are shown in Figures 2 and 3. The monthly mean wave power is higher during the southwest monsoon (June to September) which comprises of about 55 percent of the annual total wave power in grids 1 to 5 and 65 percent of the annual total wave power in grids 6 to 10. During the northeast monsoon (October to January), the mean wave power contribution is only about 15 percent of the annual total wave power in grids 6 to 10 whereas it is about 25 percent of the annual total wave power in grids 1 to 5. The non-monsoon period of February to May is generally calm contributing to only about 20 percent of the annual total wave power in all the grids. In July, mean wave power is the highest and is about 20 KW in grids 1 to 5 and 30 KW in grids 6 to 10, whereas in the month of March, mean wave power is the least and is only about 5 KW in almost all the grids. The study also indicates that the wave activity is stronger during the southwest monsoon (June to September) along the Indian coast. Though the wave activity is comparatively less during the rest of the year, the Bay of Bengal experiences considerable wave activity during the northeast monsoon period (October to January) during which time the Arabian Sea is fairly calm. Frequent occurrence of cyclones in the Bay of Bengal during the northeast monsoon period leads to the generation of extreme wave conditions along the east coast of India, though for a shorter period of time.

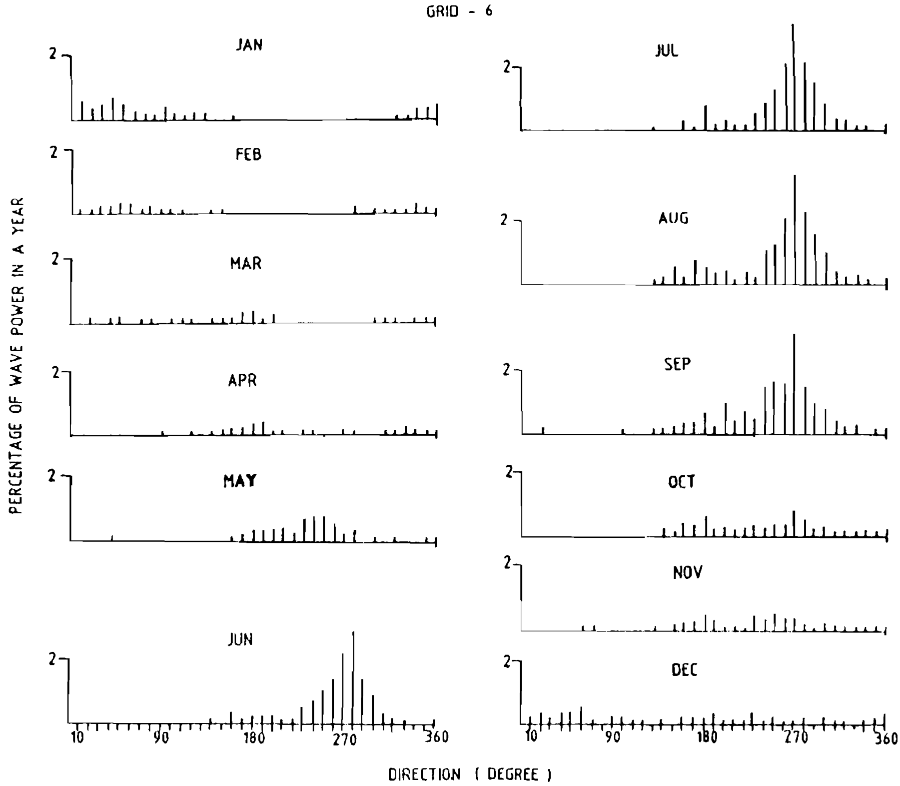

Figure 12. Percentage distribution of wave power in different directions during different months over a year.

Annual Mean Wave Power

The annual mean wave power per metre length of the wave crest around the Indian coast varies between 11.4 and 15.2 KW and their gridwise distribution based on Eqn. (9) is presented in Figure 4. Maximum mean wave power of 15.2 KW is available in grid 6 (off south Kerala and southernmost region of Tamilnadu) followed by 14.6 KW in grid 5. Minimum annual mean wave power of 11.4 KW is available in grid 3 (off Andhra Pradesh) followed by 11.7 KW in grid 8 (North Kerala and Karnataka). The annual mean wave power of 13.8, 13.8, 12.5, 14.5, 13.2, and 12.4 KW. are estimated for the grids 1,2,4,7,9 and 10, respectively. The above values indicate that the southernmost region of the Indian Peninsula namely the grids 5, 6 and 7 have comparatively higher wave power potential since they are exposed to the waves from the Indian Ocean. Grids 1 and 2 come next in the availability of higher mean wave power. The probable reason for this seems to be the fact that this region lies in the convergence zone of the funnel shaped Bay of Bengal. The middle regions of the east and west coasts of India (grids 3 and 8) are exposed to the least mean wave power.

NARASIMHA RAO and SUNDAR (1982), have reported availability of annual mean wave power of about 20 KW in grid 3 as the highest. The method employed in their study was very approximate, since the wave power was computed based on the mean wave height and period computed for each of the seasons, namely, the southwest, the northeast and the non-monsoon seasons of the year. Further these values were computed based on only 6 years of ship reported data from 1968 to 1973 and the ship reported wave heights were treated as equivalent to the root mean square wave height (H_{rms}) rather than the significant wave height (H_s) which is not correct. A similar computation

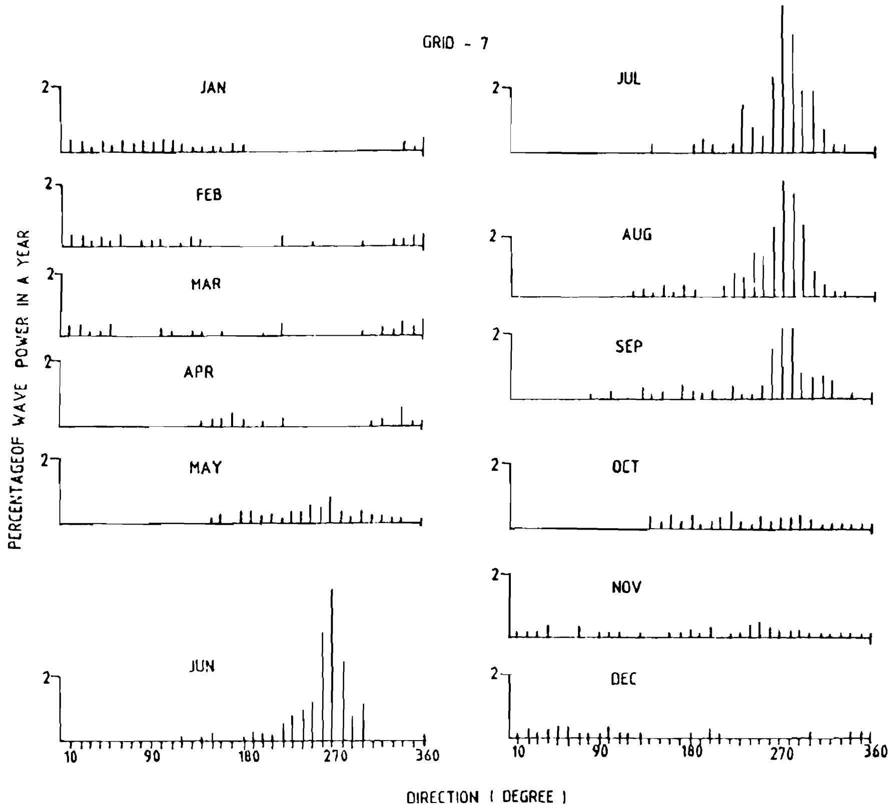

Figure 13. Percentage distribution of wave power in different directions during different months over a year.

from the ship reported data compiled for only 6 years from 1968 to 1973 have been made (ANONYMOUS, 1981) which showed annual mean wave power of about 25.1, 20.7, 24.2, 21.4, 22.9 and 23.1 KW for grids 1, 3, 4, 6, 8 and 9, respectively. Here, again, the mean wave height and period for each of the months in the year were used in the estimate of the annual mean power.

Directional Distribution of Wave Power

The relative values of the wave power in different directions are more interesting than the absolute values, since they yield dominant directions contributing the wave power (DE GRAAUW, 1986). Accordingly, the relative percentage of wave power available over an year from different directions computed based on the ship data from 1968-83 using Eqn. (10) is shown in Figures 5 and 6. The grids 1 to 5 covering the Bay of Bengal show that the mean wave power comprising of about 65 percent of the total wave power is contributed by waves approaching from the south and the southwest. Only about 15 percent of the total wave power is contributed by the waves approaching from the north and the east. The grids 7 to 10 in the Arabian Sea show a maximum of about 85 percent of the total wave power being contributed from the sector between the southwest and the northwest directions.

The above relative percentage of wave power in different directions over an annual cycle having distributed monthwise are shown in Figures 7 to 16. They indicate that the directional distribution of waves around the Indian coast is greatly influenced by the three different seasons namely, the southwest monsoon from June to September, northeast monsoon from October to January and non-monsoon period from February to May. Figures 7 to 16 indicate that during the southwest monsoon period, the wave

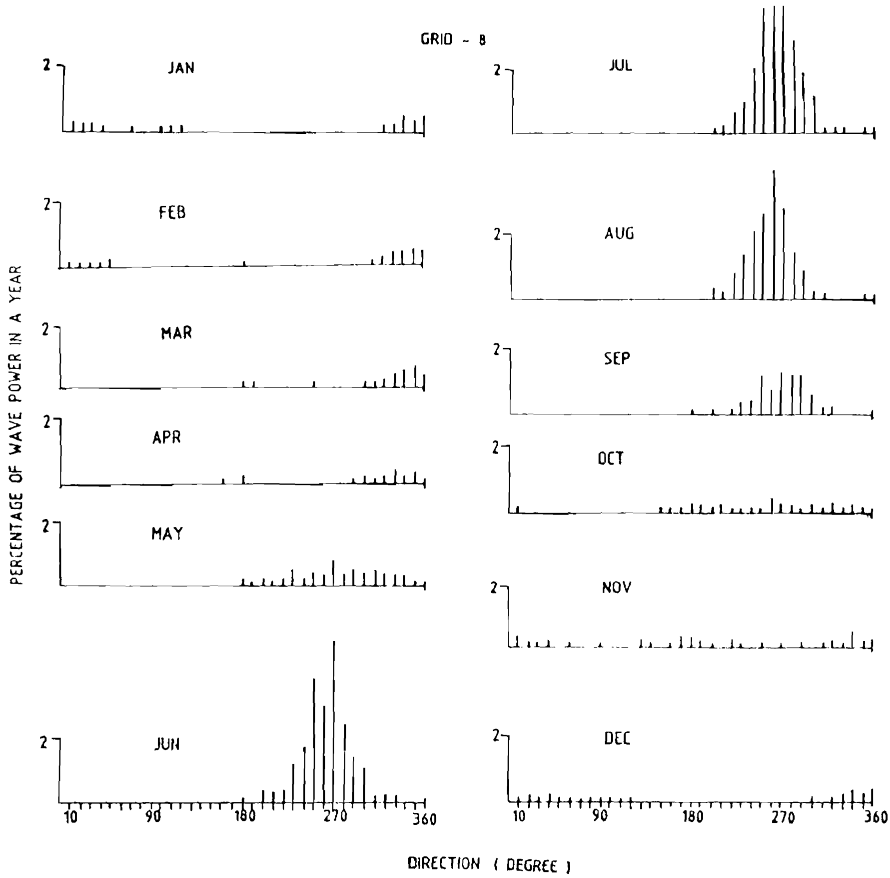

Figure 14. Percentage distribution of wave power in different directions during different months over a year.

directions are predominantly from the sector between 180° and 270° in grids 1 to 5 (in Bay of Bengal) and from the sector between 220° and 310° in the remaining grids (in Arabian Sea). Complete shift in the wave direction is observed during the northeast monsoon showing predominantly between 10° and 90° in grids 3 to 5 and it is scattered with less contribution of wave power in the remaining grids. Though the wave direction is found to be scattered during the non-monsoon period, a slight concentration of direction is found between 270° and 350° in grids 7 to 10. Typical wind pattern during the three seasons around India is shown in Figure 17 (HASTENRATH and LAMB, 1979) and it indicates that the wind distribution has a close relationship with the directional distribution of the ship reported waves.

Comparison of Results Between Visual and Measured Waves

Monthly mean wave power per metre length of the wave crest estimated from the measured waves using Eqn. (11) at grids 3 and 9 are presented in Figure 18. Wave power at grid 3 during the northeast monsoon (October to January) is higher than that observed in grid 9 indicating that the wave activity is relatively high during the northeast monsoon in the Bay of Bengal than in the Arabian Sea. The mean annual wave power based on measured waves at grids 3 and 9 are 6.0 and 10.1 KW respectively whereas the estimate based on ship reported data shows 11.4 and 13.2 KW, respectively. The estimate based on measured waves at grids 3 and 9 is lower comprising only about 53 and 77

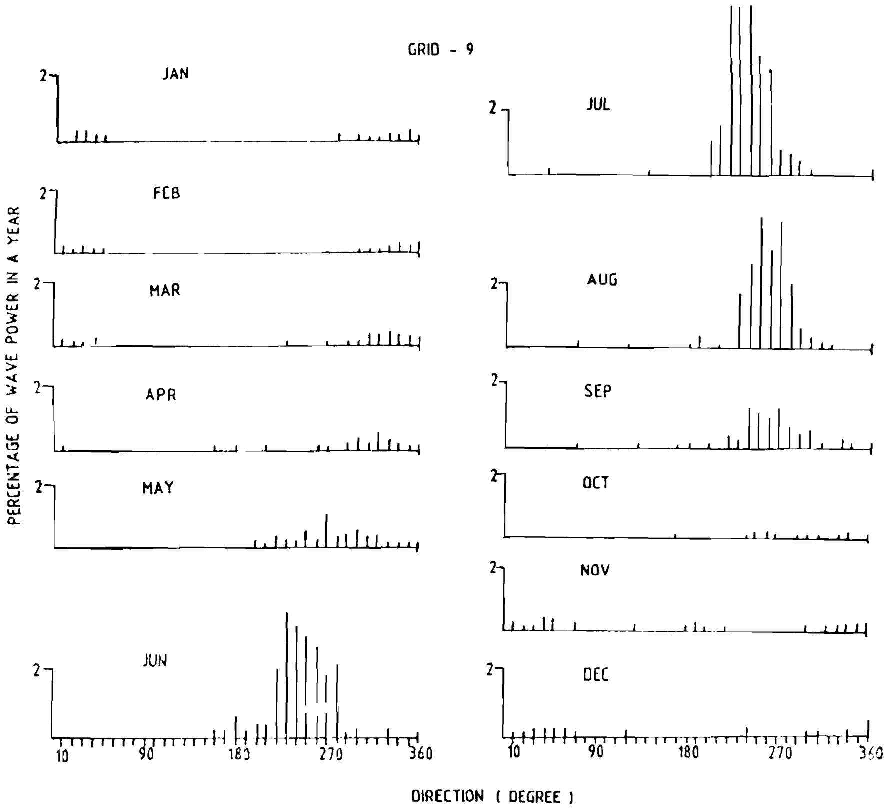

Figure 15. Percentage distribution of wave power in different directions during different months over a year.

percent respectively of the values estimated based on the ship reported data. Due to the failure of monsoon during the wave measurement period, no cyclone or stormy weather prevailed which otherwise are common and this had attributed partly the measured waves to be on the lower side. Further, the measured waves in the present study represent only the deep water waves propagating towards the coast whereas the ship reported wave includes all directional spread in the deep water.

CONCLUSIONS

The application of ship reported wave data for the estimation of the mean wave power around the Indian coast has its inherent limitation. The ship reported wave information is approximate since it is measured by simple means and is in general biased towards unsqually weather. Further, in the present study only the swell informations are compiled and the results might to some extent be altered if the sea wave informations are also considered. However, in the absence of longterm instrumental data on waves, the present study based on the ship reported swell waves would certainly give a better picture of the wave climate and the wave power distribution around the Indian coast.

The study indicates that the annual mean wave power around the Indian coast varies between 11.4 and 15.2 KW per metre length of the wave crest. The highest mean wave power of 15.2 KW is available in grid 6 for the region off south Kerala and the southern most region off Tamilnadu. The grid 3 off Andhra coast shows the availability of the least wave power of about 11.4 KW. The seasonal distribution of mean wave power shows that the wave power potential is higher during the southwest monsoon period contributing to about 55 to 65 percent of the total wave power available in a year.

The estimation based on the measured waves in grids 3 and 9 shows that the annual mean

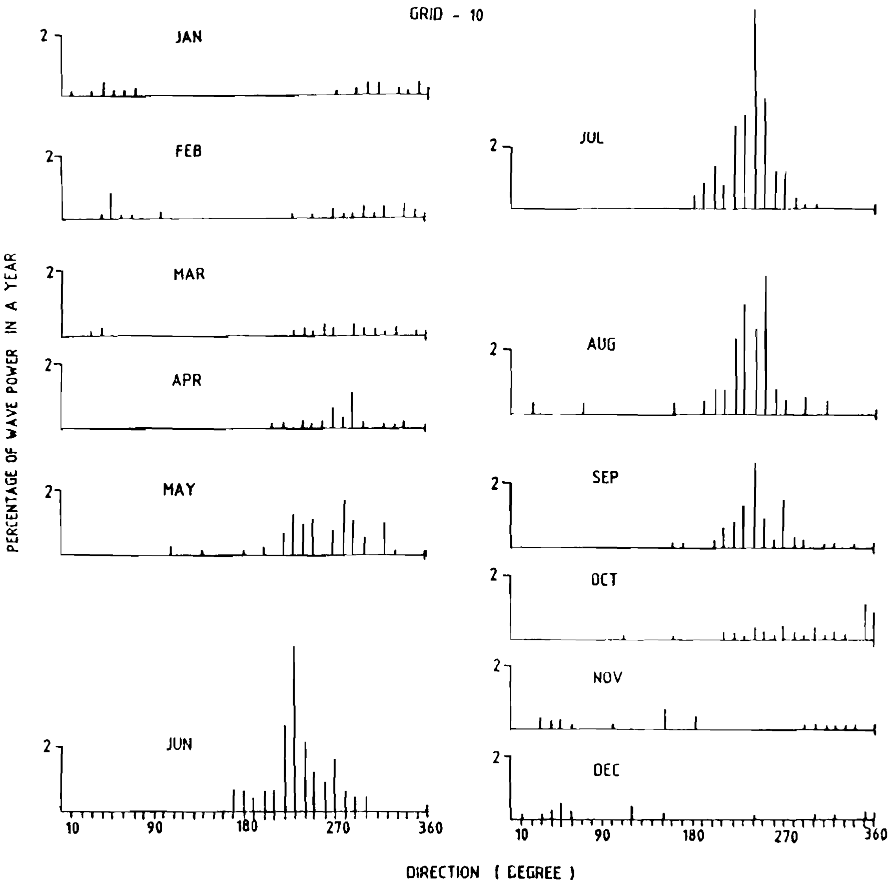

Figure 16. Percentage distribution of wave power in different directions during different months over a year.

wave power is lower and is only about 53 and 77 percent of the values estimated based on the ship reported wave data. It is noted here that during the period in which wave measurement was investigated, no cyclone or storms occurred which is quite common during monsoon periods along the Indian coast. Further, the measured waves in the present study accounts only the waves approaching the coast, whereas the ship reported waves include a spread in all directions in deep water. However, a reasonable comparison can be made with instrumentally measured waves covering for a larger period of at least about 5 to 10 years.

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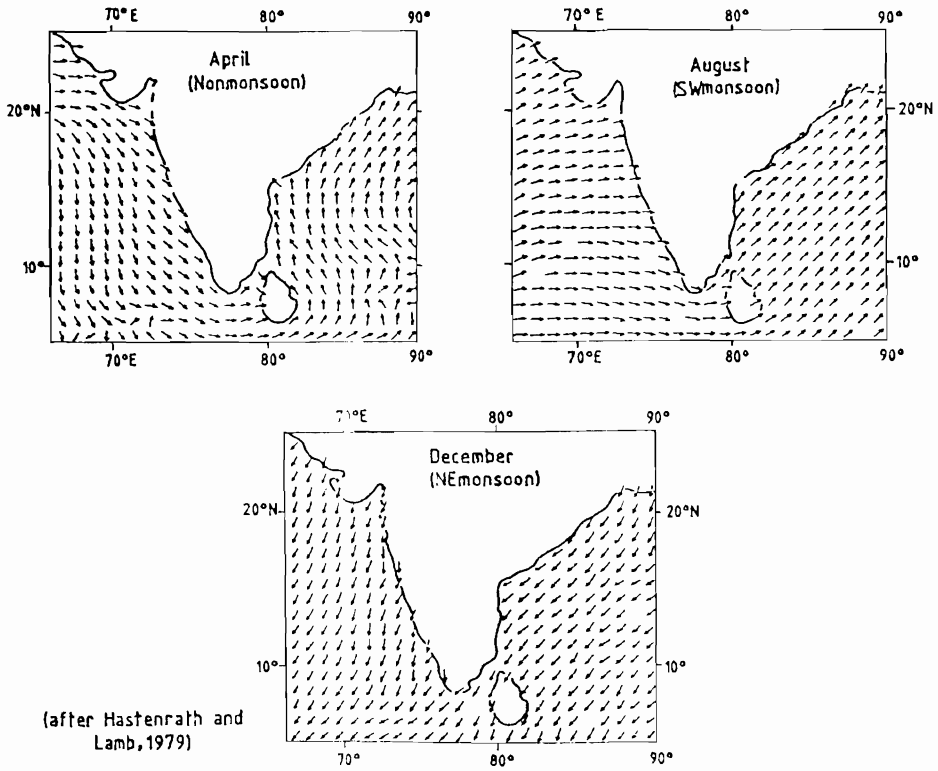

Figure 17. Seasonal wind pattern around Indian region.

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□ RESUMEN □

Los datos de swell visuales dados por barcos publicados en el diario indio "Weather Reports" para el periodo de 1968 a 1983, se encuentran recopilados para los mares alrededor de La India los cuales están divididos en 10 mallas cada una de 5° de latitud y 5° de longitud. Se presenta la distribución porcentual de la energia del oleaje en diferentes direcciones a lo largo de un año. El valor medio anual de energia del oleaje a lo largo de la costa india varia de 11.4 a 15.2 KW por metro de longitud con un máximo de 15.2 KW para las regiones fuera de las costas del Sur de Krala y Sur de Tamilnadu y un minimo de 11.4 KW fuera de la costa de Andwa. La computación basada en las olas medidas a lo largo de un año muestra que la energia del oleaje media en las mallas 3 y 9 es inferior a es aproximadamente entre un 53% y un 77% inferior al valor medio de energia del oleaje computado basándose en los datos de oleaje visuales dados por los barcos, respectivamente. Entre un 55% y un 65% de la energia total anual del oleaje es debido al monzón del Suroeste entre Junio y Septiembre. La energia del oleaje en Febrero, Marzo y Abril es en general las más baja. La actividad del oleaje es mayor durante los monzones del Suroeste y Nordeste a lo largo de la costa Este que bordea la Bahia de Bengala mientras que está confinado predominantemente durante el periodo del monzón del Suroeste en el caso de la costa Oeste que bordea el Mar de Araba.—*Department of Water Sciences, University of Cantabria, Santandes, Spain.*

□ RÉSUMÉ □

Les données de houle publiées dans l'Indian daily Weather Report de 1968 à 1983 ont été compilées pour toutes les mers baignant l'Inde, divisées en grilles de 5° de longitude et de latitude. Présente la fréquence de la puissance des vagues sur un an pour différentes directions, et pour chaque grille. La puissance annuelle varie le long des côtes indiennes de 11,4 à 15,2 KW/m de longueur de crête, avec un maximum de 15, 2 KW au large du Sud Kerala et sur les côtes du Sud Tamilnadu. Le minima de 11,4KW est enregistré sur la côte de l'Andhra. Le calcul basé sur la houle mesurée sur un an montre que la puissance moyenne annuelle disponible des grilles 3 et 9 est plus faible (53 et 77% de celle reportée à bord du navire); 55 à 65% de la puissance totale annuelle est exercée pendant la mousson de juin à septembre. La puissance disponible en février, mars et avril est plus faible. L'activité des vagues est élevée pour les moussons du SW et du NE sur la côte Est bordant le golfe du Bengale; elle se limite à la période de mousson du SW le long de la côte Ouest, bordant la mer d'Arabie.—*Catherine Bressolier, Laboratoire de Géomorphologie EPHE, Montrouge, France.*

□ ZUSAMMENFASSUNG □

Verteilung der Wellenstärke im tiefen Wasser vor den indischen Küsten aufgrund von Schiffsbeobachtungen. Die von de Schiffen gemeldeten Dünungsdaten, welche in den täglichen indischen Wetterberichten für die Zeit von 1968-1983 publiziert wurden, sind für die Seegebiete um Indien in 10 Testgebieten von je 5 Längen-und Breitengraden zusammengestellt. Präsentiert wird die prozentuale Verteilung der Wellenstärke aus verschiedenen Richtungen über 1 Jahr und für jedes Gebiet. Die mittlere jährliche Wellenstärke um Indien variert zwischen 11,4 und 15,5 kW/m Länge des Wellenkammes mit einem Maximum von 15,2 kW für die Gebiete vor Kerala und Süd-Tamilnadu und einem Minimum von 11, 4 kW vor der Andhra-Küste. Sammelanalysen der gemessenen Wellen über 1 Jahr zeigen, daβ die mittlere verfügbare Wellenstärke in den Gittern 3 und 9 niedriger ist, und zwar nur ca. 53% bzw. 77% derjenigen beträgt, welche von Schiffen gemeldet wurden. Ca. 55%-65% der gesamten jährlichen Wellenstärke wird in der Periode des Südwestmonsuns zwischen Juni und September erzeugt. Am geringsten ist die Wellenstärke generell im Februar, März und APril. Es ergab sich, daβ die Wellenaktivität sowohl während des SW- wie auch des NE-Monsuns entlang der Ostküste der Bucht von Bengalen relativ groβ ist, während sie vorwiegend auf den Südwestmonsun an der westküste, also entlang des Arabischen Meeres beschränkt ist.—*D. Kelletat, Essen.*

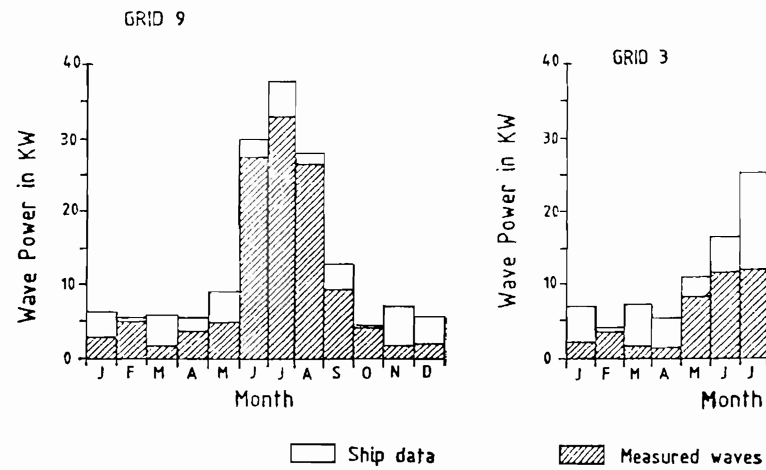

Figure 18. Comparison of wave power based on visual and measured waves.