

Short-term statistics of waves measured off Ratnagiri, eastern Arabian Sea

M.M.Amrutha, V. Sanil Kumar*

Ocean Engineering, CSIR-National Institute of Oceanography (Council of Scientific & Industrial Research), Dona Paula, Goa - 403 004 India

*Corresponding author. Tel: 0091 832 2450 327 Fax: 0091 832 2450 602 E-mail: sanil@nio.org

ABSTRACT

The short-term wave characteristics are required for design and operation of industrial facilities within the coastal areas. Water surface displacement measured using waverider buoy moored at 13 m water depth in the eastern Arabian Sea off the west coast of India have been analysed to study the short-term statistics of waves covering full one year period. The study indicates that the values of the observed maximum wave height as a function of duration are not consistent with the theoretical expected value. There is significant variation (1.29-2.19) in the ratio between highest 1% wave and significant wave height compared to the theoretical value of 1.67. The data recorded at 13 m water depth indicates that the significant wave height is $\sim 8\%$ lower than that predicted by the conventional Rayleigh distribution. The theoretical bivariate log-normal distribution represents the joint distributions of wave heights and periods for the study area.

Keywords: Ocean science, significant wave height, wave statistics, Rayleigh distribution

1. Introduction

The knowledge of wave height distribution has a major role in designing the ocean structures [1]. Statistics of surface waves are generally based on the assumption that the sea surface elevation is a stationary, Gaussian process, resulting in the conventional Rayleigh distribution for wave heights [2]. The validity of the Rayleigh distribution for wave heights has been widely investigated for different climatic conditions [3]. The Rayleigh distribution is found to agree well with field observations at some locations even though the frequency spectrum is not always as narrow and the steepness is not as small as required by the theory [4, 5]. The field observations by Forristall [6] indicate that the Rayleigh distribution over predicts the significant wave height by 7 to 8%. Forristall [6] observed that over prediction of the Rayleigh distribution is the worst for the highest waves and substantial for moderate

normalized wave heights. The discrepancy is due to the effect of spectral width since the Rayleigh distribution is derived with the assumption of a narrow spectrum. Guedes Soares [7] presented a detailed review devoted to wave parameters. In shallow water, the wave behavior is complicated and hence requires site specific examination of the wave height distribution [8].

The coastal areas of the eastern Arabian Sea are being explored by the industry for minerals and energy. The offshore platforms used to exploit these resources need to be designed such that they withstand wave-induced forces. Hence, there is a need to understand the short-term statistics of the waves to plan and design the facilities. Most of the studies in eastern AS in the past were on the statistics of the bulk wave parameters [9,10]. Dattatri et al. [11] studied the height and period distribution for waves off Mangalore, west coast of India. Hameed and Baba [12] examined the probability distribution of shallow water wave heights obtained from a pressure type recorder off the south west coast of India. Kumar et al. [13] studied the joint distribution of wave height and period of waves measured at 23 m water depth off the central west coast of India during the monsoon period. Waves in the eastern Arabian Sea show a large response to seasonal variability [monsoon (JJAS), pre-monsoon (FMAM) and post-monsoon (ONDJ)] due to the reversal of the large-scale wind field over the North Indian Ocean between the boreal summer and winter [10]. Main aim of the present work is to investigate the short-term statistics of the continuous wave time series measured at 13 m water depth over a period of one year.

2. Data and methods

The vertical (heave) and horizontal (eastward and northward) displacement data obtained by the Datawell directional waverider buoy from 1 January to 31 December 2011 are used for the study. The buoy was moored at 13 m water depth (geographic position 16.9801° N; 73.2584° E) and the location is shown in Figure 1. The data were recorded continuously at 1.28 Hz for a period of one year and the data for every 30 min are processed as one record. Zero-crossing analysis of the surface elevation time series is carried out to estimate the individual wave heights and periods. Wave parameters are derived from a record by ranking the individual wave heights and averaging some fraction of the total to obtain parameter estimates. Significant wave height ($H_{1/3}$) i.e. the average of the highest 1/3 of the wave heights, 1/10 wave height ($H_{1/10}$), root-mean-square wave height (H_{rms}) and the highest individual crest to trough excursion between successive up-crossings (maximum wave height, H_{max}) for each record is estimated from the time series. Wave height with some low exceedance probability e.g. 1% and 2% are also estimated and used in the study. A total of 17,518 data records are used in the study resulting in a

total individual waves of 61,12,069 in one year. As recommended by Casas-Prat and Holthuijsen [14], to avoid excessive effects of measurement noise near the zero level, in particular on the estimation of the number of waves, we ignored all the wave heights < 0.05 m and all crest heights and trough depths < 0.025 m and periods smaller than twice the sampling interval time [14] while studying the Rayleigh and joint-distribution. The shape, size and weight of the buoy may also affect the measurement of smaller waves. Significant wave heights less than 0.2 m were also not considered in the study to prevent the dominance of transient waves such as boat wakes during low energy conditions [14]. Hence, 3.9% of the total measured data was ignored while carrying out further analysis.

The statistical distribution of individual wave height is approximated by Rayleigh distribution, which is a continuous probability distribution for positive valued random variable. Rayleigh probability density function for wave height is,

$$p(H) = \frac{2H}{H_{rms}^2} e^{-\left(\frac{H}{H_{rms}}\right)^2} \quad (1)$$

The cumulative distribution function for wave height (H) is given by,

$$F(H) = 1 - e^{-\left(\frac{H}{H_{rms}}\right)^2} \quad (2)$$

The probability density function is the derivative of probability of occurrence. Thus probability of occurrence $P(H)$ is obtained by integrating the probability density function.

$$P(H_i < H \leq H_1) = \int_{H_i}^{H_1} p(H).dH = e^{-\left(\frac{H_i}{H_{rms}}\right)^2} - e^{-\left(\frac{H_1}{H_{rms}}\right)^2} \quad (3)$$

The joint distribution of normalized wave period and normalized wave height is calculated from measured data and is compared with theoretical bivariate log-normal distribution. Ochi [15] introduced the use of bivariate log-normal distribution for wave period and wave height. The joint probability density function of this model is given by,

$$p(H, T) = \frac{0.5}{HT \pi \sqrt{1 - \alpha_{HT}^2} \sigma_H \sigma_T} \exp \frac{-0.5}{1 - \alpha_{HT}^2} \left[\frac{(\ln(H) - \mu_H)^2}{\sigma_H^2} - \frac{2\alpha_{HT} (\ln(H) - \mu_H)(\ln(T) - \mu_T)}{\sigma_H \sigma_T} + \frac{(\ln(T) - \mu_T)^2}{\sigma_T^2} \right] \quad (4)$$

Where, α_{HT} , σ_H , σ_T , μ_H , μ_T are parameters of distribution and are obtained by natural logarithms of observed values. μ_H , μ_T are expected values of natural logarithm of wave period and wave height. σ_H , σ_T are standard deviations of natural logarithm of wave period and wave height. α_{HT} is the correlation coefficient between natural logarithm of wave period and wave height. The probability distribution is given by $P(H, T) = \iint_A p(H, T) dHdT$, for any region A.

3. Results and discussion

3.1 Wave height

The number of waves measured in each month and the average, maximum and significant wave height ($H_{1/3}$) of the monthly data are presented in Table 1. The highest individual wave height in the data set used for the study is 6.97 m and the highest $H_{1/3}$ based on 30 minutes record is 4.2 m. The monthly average height of the waves varies from 0.31 to 1.35 m (Table 1). During the annual period, 84.1% of the waves measured are with height less than 1 m and 3.6% of the waves are with height more than 2 m and only 0.5% of the waves are with height more than 3 m. All the waves with height more than 3 m are during the monsoon period (June-September). If high waves persists for longer periods it causes coastal erosion and hence, the events lasting more than 6 h are examined with different threshold limits of wave height (2 and 3 m). H_s more than 2 m occurred up to 33 times and persisted up to a maximum duration of 307 h. Up to 4 events of H_s more than 3 m are observed and the maximum duration of a single event is up to 61 h.

Monthly mean $H_{1/3}$ of the 30 minutes records are slightly higher than the $H_{1/3}$ of the full one month record in few months (Table 1). The average of the highest one third wave height over a period of one year is higher (1.18 m) than the annual average value of the $H_{1/3}$ of each record (1.12 m) due to the seasonal variations in wave height as a result of the monsoon. The mean value of various wave parameters in different seasons is presented in Table 2. The seasonal average of the mean wave height of each record during the monsoon is 1.18 m and is around 3 times that in the non-monsoon period (~0.38 m) and is around 2 times of the annual average value (~0.64 m). The wave heights were slightly higher during the pre-monsoon compared to the post-monsoon. The wave spectral characteristics of the study area are presented by Kumar et al. [10].

In metocean studies, a quantile that often needs to be computed is the value of wave height that is exceeded on average once every 1000 waves. The statistical relationship between the expected maximum individual wave height (H_{\max}), and the $H_{1/3}$, in a group of N waves in deep water is; $H_{\max} = H_{1/3} \sqrt{0.5 \log(N)}$. The ratio of the H_{\max} and $H_{1/3}$ for one month long record varies from 2.8 to 4.9 with an annual average value of 3.6. To inspect the variability of the ratio of H_{\max} and $H_{1/3}$, we also computed this ratio for each individual wave record separately. The average ratio of H_{\max} and $H_{1/3}$ estimated from the 30 minutes record during the monsoon period is 1.67 and the average number of waves during this period is 272 (Table 2). Kumar et al. [16] reported the ratio of the H_{\max} and $H_{1/3}$ for waves measured off west coast of India during the monsoon period as 1.65. During the non-monsoon period, the average number of waves in 30 minutes record increased to 387 and hence the ratio of the H_{\max} and $H_{1/3}$ increased to 1.72 (Table 2). Figure 2 shows the ratio of H_{\max} and $H_{1/3}$ observed for different groups of waves with number varying from 100 to 10000 in different months along with the theoretical value. For a group of 1000 waves, in all the months, the observed maximum wave height is within 10% of the expected H_{\max} following the Rayleigh distribution. Sudden increase in the ratio is observed in June, September and October after 3-4 hr due to non-stationary wave field. Vandever et al. [17] attributed the under-prediction of $H_{\max}/H_{1/3}$ for high values of number of waves (N) to the stationary assumption inherent in the analysis or the influence of transient waves during low energy conditions.

Figure 3 shows the ratio of the height of highest 1% wave, 2% wave and 10% wave, root mean square height and mean height with $H_{1/3}$ based on 30 minutes record. If the wave heights are Rayleigh-distributed, these heights can all be converted one into another through known constants, but if the distribution is distorted due to shallow-water effects or broad banded wave spectrum, these ratios are not constants. There is large variation (1.3-2.1) in the ratio between highest 1% wave and $H_{1/3}$ compared to the theoretical value of 1.67 and the annual average value of all records is 1.57. There was no variation in the seasonal average value of the ratio between highest 1% wave and $H_{1/3}$, but there a large daily variation of this ratio (Table 2). 84% of the time, the ratio of highest 1% wave and $H_{1/3}$ is less than the theoretical value and 11% of the time, it is higher than the theoretical value and only 5% of the time, the measured value matches the theoretical value. Similarly the annual average value of the ratio between highest 2% wave and $H_{1/3}$ is 1.49 and is lower than the theoretical value of 1.56. Similar to the ratio between highest 1% wave and $H_{1/3}$, there was no significant variation in the seasonal average value (1.48 to 1.50) of the ratio between highest 2% wave and $H_{1/3}$ (Table 2). The ratio between mean of highest 10% wave and $H_{1/3}$ varied from 1.2 to 1.4 with an annual average value of 1.24 and is close to

the theoretical value (1.27). During the monsoon, the highest 1% and 2% waves will be more heavily affected by interactions with the bottom than the highest 10% waves in shallow/intermediate water depth and hence highest 1% and 2% waves disagree with the theoretical values (Figs. 4a and 4b). Also when 3 to 8 long period swells (wave period > 13 s) with relatively high H_s are present during the pre and post-monsoon period, the ratio departs from the theoretical value (Figs. 4e and 4f). Figures 4c and 4d shows the case when the highest 1% and 2% waves agree with the theoretical values.

The annual average value of the ratio of the H_{rms} and $H_{1/3}$ is the same as that of the theoretical value (0.71). The annual average value of the ratio of the mean H and $H_{1/3}$ is also similar to the theoretical value (0.63). The annual average of the significant wave height and maximum wave height based on 30 minutes record is 1.1 m and 3.7 m respectively. The ratio of the significant wave height and mean wave height varies from 0.55 to 0.63 in different months with an annual average value of 0.59.

Significant wave height can also be estimated from the wave spectrum following the conventional Rayleigh distribution as $H_s \approx 4 \sqrt{m_0}$. For deep-water narrow band spectra, wave heights have been shown to conform to the Rayleigh distribution, and $H_{1/3}$ and H_s are equivalent estimates of significant wave height [1]. The data recorded at 13 m water depth indicates that the significant wave height is ~ 8% lower than that predicted by the conventional Rayleigh distribution (Fig. 5). Forristall [6] gives $H_{1/3} = 3.77 \sqrt{m_0}$ and the present study shows $H_{1/3} = 3.67 \sqrt{m_0}$. Based on 10 million individual waves observed with buoys in deep water, Casas-Prat and Holthuijsen [14] observed that $H_{1/3} = 3.83 \sqrt{m_0}$. For the location at 15 m water depth in the northern Arabian Sea during monsoon, Kumar et al. [16] reported $H_{1/3} = 3.72 \sqrt{m_0}$. The reduction in present case is due to the presence of wind-sea and swells in the measured data, which makes the wave spectrum relatively broad banded [10]. In the northern Arabian Sea, 75% of the waves were swells for the 45 days data (June-July) reported by Kumar et al. [16] and the wave spectra were mainly single peaked, whereas in the present study area, 46% of the waves were swells over an annual cycle [10].

The agreement between H_s and $H_{1/3}$ approaches the theoretical Rayleigh distribution at narrow bandwidths, but diverges significantly as spectrum width increases (Fig. 6). In general, $H_{1/3}$ values are close to the H_s values when the wave spectra became increasingly peaked and single peak. In the study area, over an annual cycle, 54% of the wave spectra are multi-peaked and 46 % are single peaked [10]. Kumar et al. [10] observed that spectral peakedness parameter (Q_p) is a good indicator for spectral

narrowness with high values ($Q_p > 2$) for narrow band spectra and low values ($Q_p < 2$) for broad band spectra. Figure 6 shows that for narrow band spectra, H_s and $H_{1/3}$ has similar value.

The measured waves were classified into a) short period (wave period, $T < 6$ s, is dominated by local seas), b) long period ($T > 12$ s, results primarily from swell) and c) intermediate period ($6 \text{ s} \leq T \leq 12$ s, probably results from a mixture of local and regional wind forcing) following Bromirski et al. [18]. During the non-monsoon period, most of the waves (75 to 80%) were short period and during the monsoon period the short period waves reduced and intermediate and long period waves increased (Table 2).

3.2 Wave height distribution

The distribution of waves in different wave height ranges in different months is presented in Table 3. During January to April and from October to December, 40-45% of the waves are with height 0.25-0.5 m and the H_{rms} value is also between this (Table 1). In May, 64% of the waves and in September, 42% of the waves are with height 0.25-0.75 m. During June to August, the wave height is wide range. The monthly mean H_s and the monthly mean H_{rms} are close to each other in all months (percentage deviation less than 16%) except in September (percentage deviation 23%) (Table 1). The number density from measured data and Rayleigh probability of occurrence for each month is plotted and presented in Figure 7. It is observed that the wave height distribution follows the Rayleigh distribution since during the non-monsoon period 45% of the waves satisfy the deep water criteria (water depth/wave length > 0.5) and the balance are the intermediate water waves. In the monsoon months, 20% of the waves satisfy the deep water criteria and the balance is intermediate water wave. During the high wave condition, the wave height distribution is slightly deviating from the Rayleigh distribution. Mai et al. [19] observed that during extreme wind condition, the shallow water distribution differs from Rayleigh. During pre-monsoon and post-monsoon period, the number density ranges up to 0.465 and the maximum number density is for 0.25 - 0.5 m wave height, except in November during which the maximum number density (0.465) is at 0-0.25 m wave height range since 99% of waves are in 0-1 m wave height range. The calculated Rayleigh probability of occurrence is having value up to 0.472. During the monsoon period, the occurrence of high wave height is dominant; hence the number density is distributed over a wide range of wave height. The number density is up to 0.211, whereas the values based on Rayleigh distribution is up to 0.241. The strongest deviation of the observations from theory is observed in September (Figure 7). The Rayleigh distribution is a one-parameter distribution and depends

only on root mean square wave height (H_{rms}). Since in September, the percentage difference between H_{rms} and H_s is large compared to other months (Table 1), deviation from theory is observed in the distribution of H_s .

3.3 Joint distribution of wave height and period

Wave height and wave period are independent parameters, but one of the requirements of the offshore industry is to know the wave period associated with a wave height for a particular location. The joint distribution of wave height and period for one year period is presented in Table 4. The high waves ($H > 6$ m) are associated with period 8-12 s and waves with height of 4 to 6 m are associated with period 6 to 14 s. Figure 8 shows the joint distribution of normalized wave period and normalized wave height from the measured and bivariate log-normal distribution during January, April, July and October. The study shows that the bivariate log-normal distribution is similar to the distribution of wave height and period based on measured values and can be used in engineering applications. The overall agreement between the measured and theoretical distribution is good, differences appear to be more pronounced for large normalized wave heights and periods. The Pearson's linear correlation coefficient between distribution from measured data and bivariate log-normal distribution in different months varies from 0.93 (July) to 0.98 (October) with an annual average value of 0.95.

4. Conclusions

We have examined the short-term statistics of the wave time series measured at 13 m water depth in the eastern Arabian Sea. The study shows that at 13 m water depth, the significant wave height is ~ 8% lower than that predicted by the conventional Rayleigh distribution. The average number of waves present in a 30 minutes record during the monsoon period (JJAS) is 272 and that during the non-monsoon period is 387. For a group of 1000 waves, in almost all months, the observed maximum wave height is within 10% of the expected maximum wave height following the Rayleigh distribution and it deviates largely for higher group of waves (>1000). The bivariate log-normal distribution is similar to the distribution of wave height and period based on measured values and can be used in engineering applications for the study area. The ratio between mean of highest 10% wave and significant wave height varied from 1.2 to 1.4 with an annual average value of 1.24 and is close to the theoretical value (1.27), whereas the ratio of the 1% and 2% highest waves and significant wave height disagrees with theory. The studies reported in this article will help with the design and operation of industrial facilities within the coastal areas of the eastern Arabian Sea.

Acknowledgements

The authors gratefully acknowledge the financial support given by the Earth System Science Organization, Ministry of Earth Sciences and Council of Scientific & Industrial Research, Government of India to conduct part of this research. The Director of the CSIR-National Institute of Oceanography, Goa and the Director of the INCOIS, Hyderabad provided encouragement in carrying out the study. We thank Dr. T.M. Balakrishnan Nair, Head OSISG and Mr. Arun Nherakkol, Scientist, INCOIS, Hyderabad and Mr. Jai Singh, Technical Assistant at CSIR-NIO for assistance during the data collection. We thank the three reviewers for their critical comments and the suggestions which improved the scientific content of the paper. This work is NIO contribution No. 7825.

References

- [1] Sarpkaya T, Isaacson M. Mechanics of wave forces on offshore structures, Van Nostrand Reinhold, New York 1981: 491–492.
- [2] Longuet-Higgins MS. On the statistical distribution of the heights of sea waves, *Journal of Maritime Research*. Vol. XI 1952; 3:245-267.
- [3] Ochi MK. *Ocean Waves, the Stochastic Approach*. Cambridge Univ. Press; 1998, pp. 319.
- [4] Tayfun MA, Fedele F. Wave height distributions and nonlinear effects, *Ocean Engineering* 2007; 34:1631–1649.
- [5] Longuet-Higgins MS. On the distribution of the heights of sea waves: some effects of nonlinearity and finite band width. *Journal of Geophysical Research* 1980; 85(C3):1519-1523.
- [6] Forristall GZ. On the statistical distribution of wave heights in a storm. *Journal of Geophysical Research* 1978; 83(C5):2353-2358.
- [7] Guedes Soares C. Probabilistic Models of Waves in the Coastal Zone. In: Lakhan, C.(Ed.), *Advances in Coastal Modeling*. Elsevier Sciences B.V., Amsterdam, The Netherland; 2003, pp.159–187 (Chapter 6).
- [8] Nelson RC. Depth limited design wave heights in very flat regions, *Coastal Engineering* 1994; 23: 43-59.
- [9] Anoop TR, Sanil Kumar V, Shanas PR. Spatial and temporal variation of surface waves in shallow waters along eastern Arabian Sea. *Ocean Engineering* 2014; 81:150-157, DOI: 10.1016/j.oceaneng.2014.02.010.
- [10] Kumar VS, Shanas PR, Dubhashi KK. Shallow water wave spectral characteristics along the eastern Arabian Sea, *Natural Hazards* 2014; 70:377–394, DOI 10.1007/s11069-013-0815-7.

- [11] Dattatri J, Raman H, Jothi sankar N. Height and Period Distribution for Waves off Mangalore Harbour-West coast of India. *Journal of Geophysical Research* 1979; 84(C7):3767-3772.
- [12] Hameed TS, Baba, M. Wave height distribution in shallow water, *Ocean Engineering* 1985; 12:309-319.
- [13] Kumar, V. S., Kumar, K. A., Anand, N. M., Characteristics of waves off Goa, West coast of India, *J. Coast. Res* 2000; 16:782–789.
- [14] Casas-Prat M, LH Holthuijsen. Short-term statistics of waves observed in deep water, *Journal of Geophysical Research* 2010; 115, C09024, doi:10.1029/2009JC005742.
- [15] Ochi MK. *Wave statistics for ships and structures*, Proc. SNAME conf, New York; 1978.
- [16] Kumar VS, Singh J, Pednekar P, Gowthaman R. Waves in the nearshore waters of northern Arabian Sea during the summer monsoon, *Ocean Engineering* 2011; 38:382-388.
- [17] Vandever JP, Siegel EM, Brubaker JM, Friedrichs CT. Influence of Spectral Width on Wave Height Parameter Estimates in Coastal Environments, *Journal of Waterway, Port, Coastal, and Ocean Engineering* 2008; 134:197-194.
- [18] Bromirski PD, Cayan DR, Flick RE. Wave spectral energy variability in the northeast Pacific, *J. Geophys. Res.* 2005; 110, C03005, doi:10.1029/2004JC002398, 2005.
- [19] Mai S, Wilhelmi J, Barjenbruch U. Wave height distributions in shallow waters, *Coastal engineering*, 2010 (Proc. 32th Int. Conf, ASCE, Shanghai 2010), pp. 1–6.

Figure captions

Figure 1. Map showing the study location in North Indian Ocean. The contours are the depth in m. Map is plotted using ocean data viewer.

Figure 2. Ratio of Hmax and Hs for record with number of waves 100 to 10000 in different months. The ratio of Hmax and Hs based on Rayleigh distribution is also shown in black thick line along with 10% variation (dotted black line).

Figure 3. Time series plot of the ratio between a) $H_{1/100}$ and $H_{1/3}$, b) $H_{2/100}$ and $H_{1/3}$, c) $H_{1/10}$ and $H_{1/3}$, d) H_{rms} and $H_{1/3}$ and H_{mean} and $H_{1/3}$ for the 30 minutes record for one year period.

Figure 4. Plot of wave height measured and estimated using Rayleigh distribution during 30 minutes for selected time. The ratio between highest 1% wave and $H_{1/3}$ is low for a) and b), is equal to Rayleigh distribution value for c) and d) and is high for e) and f).

Figure 5. The significant wave height, $H_{1/3}$ estimated from the time records of the waves, compared with the theoretical estimate, $H_s = 4 \sqrt{m_0}$ for each record. Solid line is the least squares best fit of the data.

Figure 6. Typical wave spectra measured during the study period along with significant wave height (H_s), spectral width parameter (ϵ), spectral peakedness parameter (Q_p) and ratio of the $H_{1/3}$ and H_s .

Figure 7. Comparison of observed and theoretical individual wave height distribution based on Rayleigh probability of occurrence in different month

Figure 8. Joint distribution of normalized wave height and normalized wave period during January, April, July and October and that based on bivariate log-normal distribution

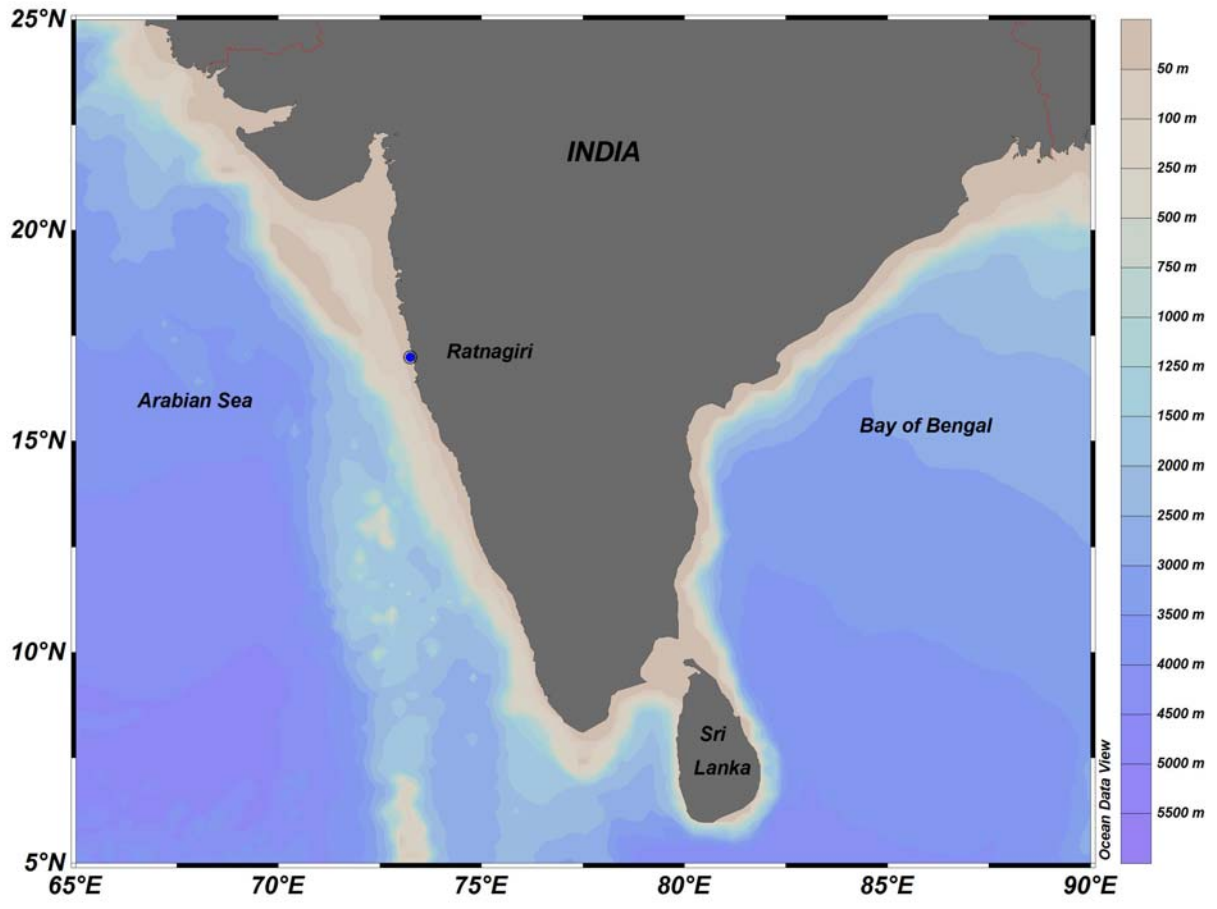


Figure 1. Map showing the study location in North Indian Ocean. The contours are the depth in m. Map is plotted using ocean data viewer.

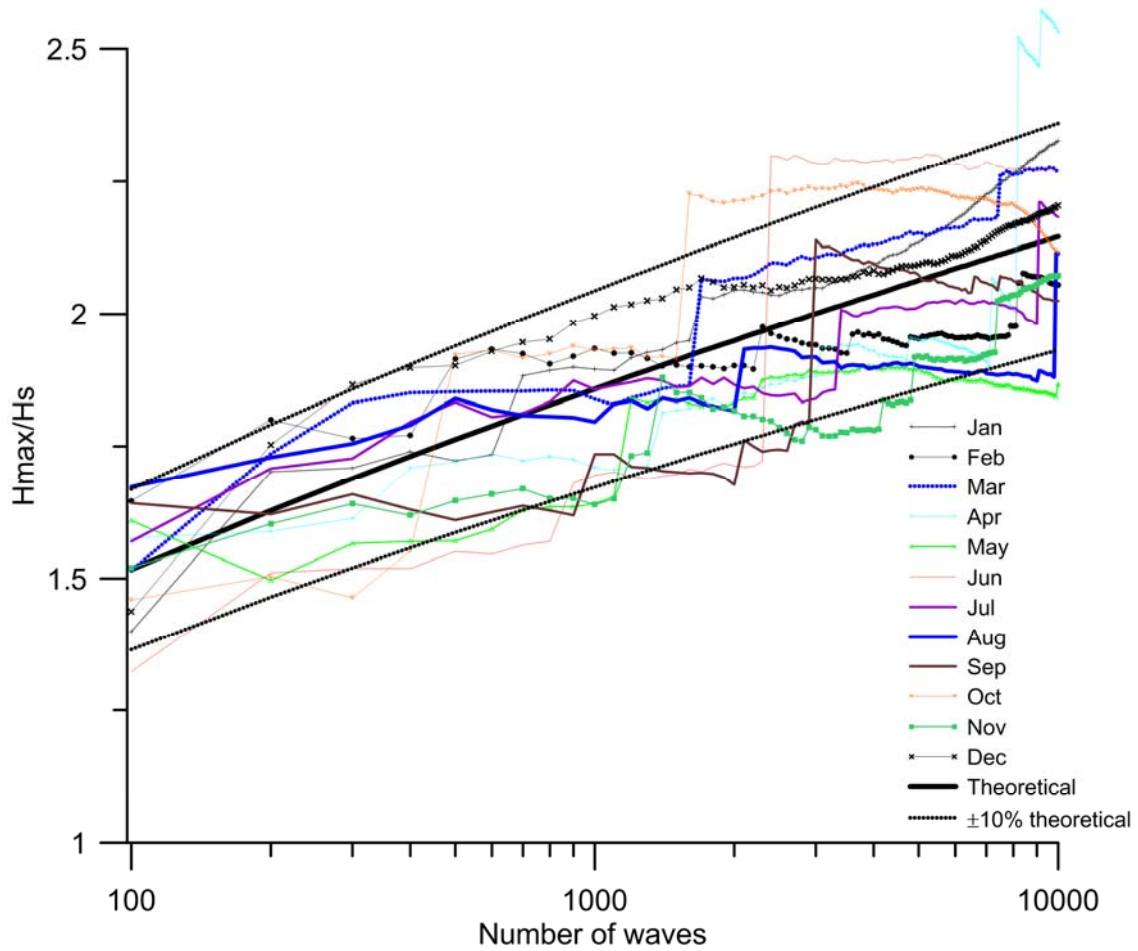


Figure 2. Ratio of Hmax and Hs for record with number of waves 100 to 10000 in different months. The ratio of Hmax and Hs based on Rayleigh distribution is also shown in black thick line along with 10% variation (dotted black line).

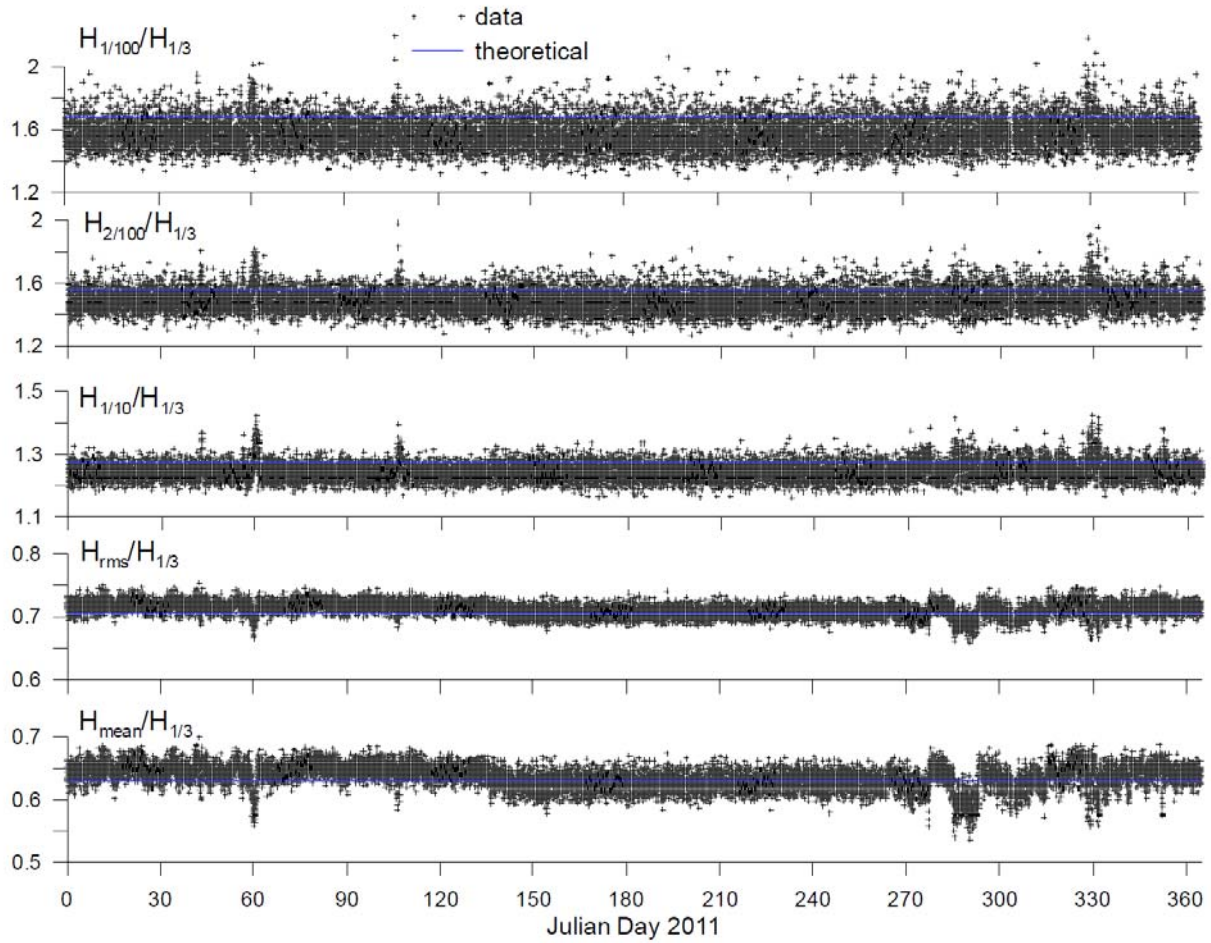


Figure 3. Time series plot of the ratio between a) $H_{1/100}$ and $H_{1/3}$, b) $H_{2/100}$ and $H_{1/3}$, c) $H_{1/10}$ and $H_{1/3}$, d) H_{rms} and $H_{1/3}$ and H_{mean} and $H_{1/3}$ for the 30 minutes record for one year period

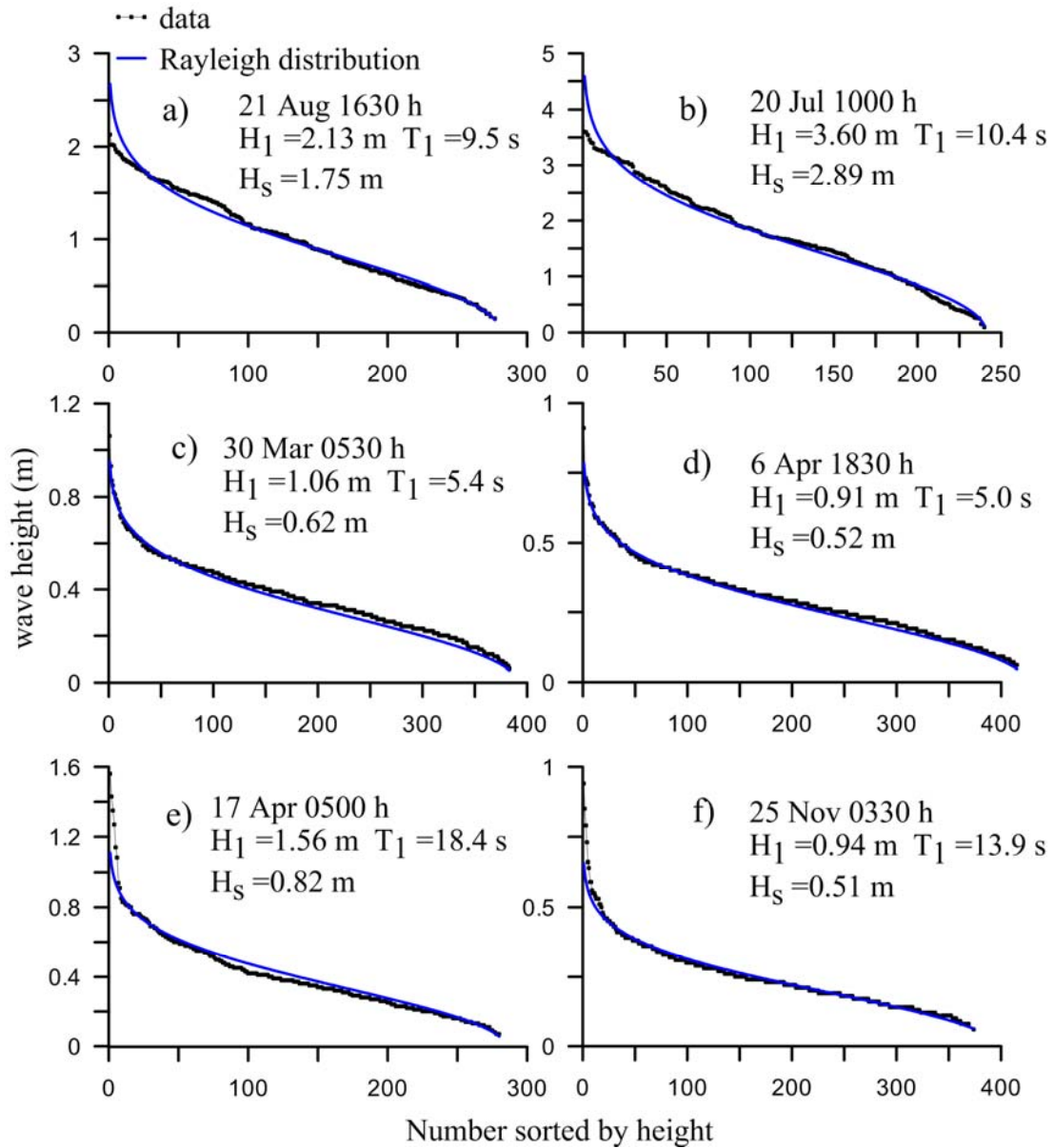


Figure 4. Plot of wave height measured and estimated using Rayleigh distribution during 30 minutes for selected time. The ratio between highest 1% wave and $H_{1/3}$ is low for a) and b), is equal to Rayleigh distribution value for c) and d) and is high for e) and f).

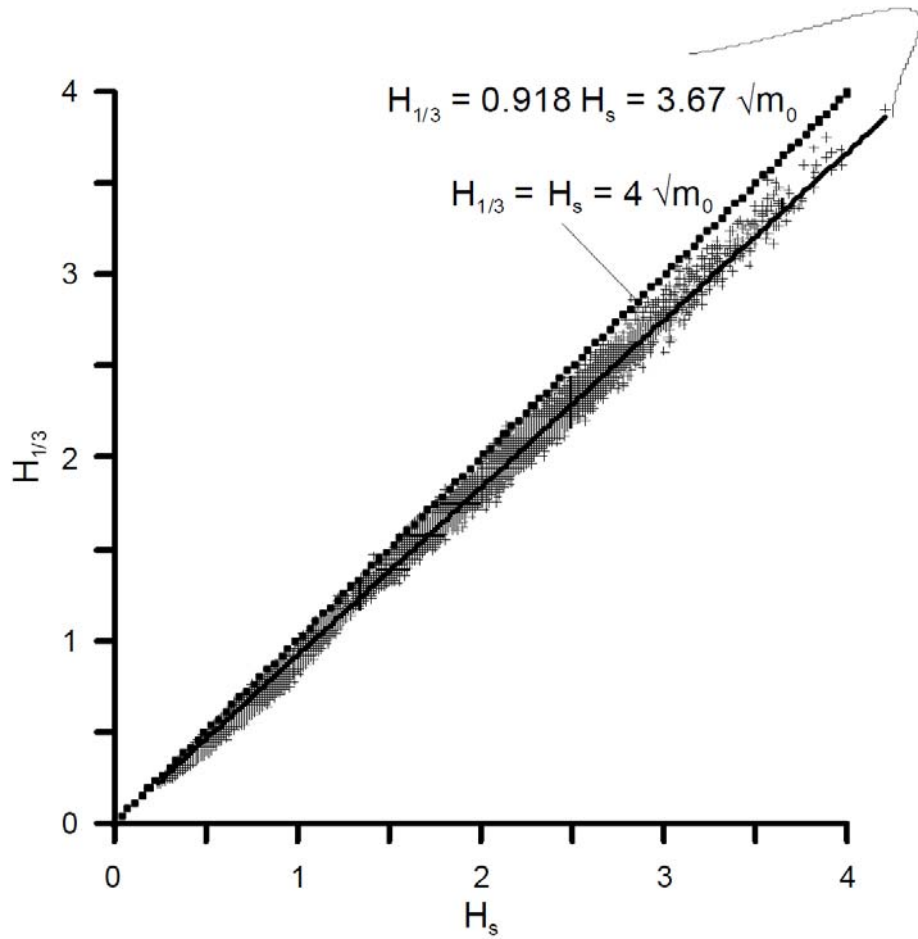


Figure 5. The significant wave height $H_{1/3}$ estimated from the time records of the waves, compared with the theoretical estimate $H_s = 4 \sqrt{m_0}$ for each record. Solid line is the least squares best fit of the data

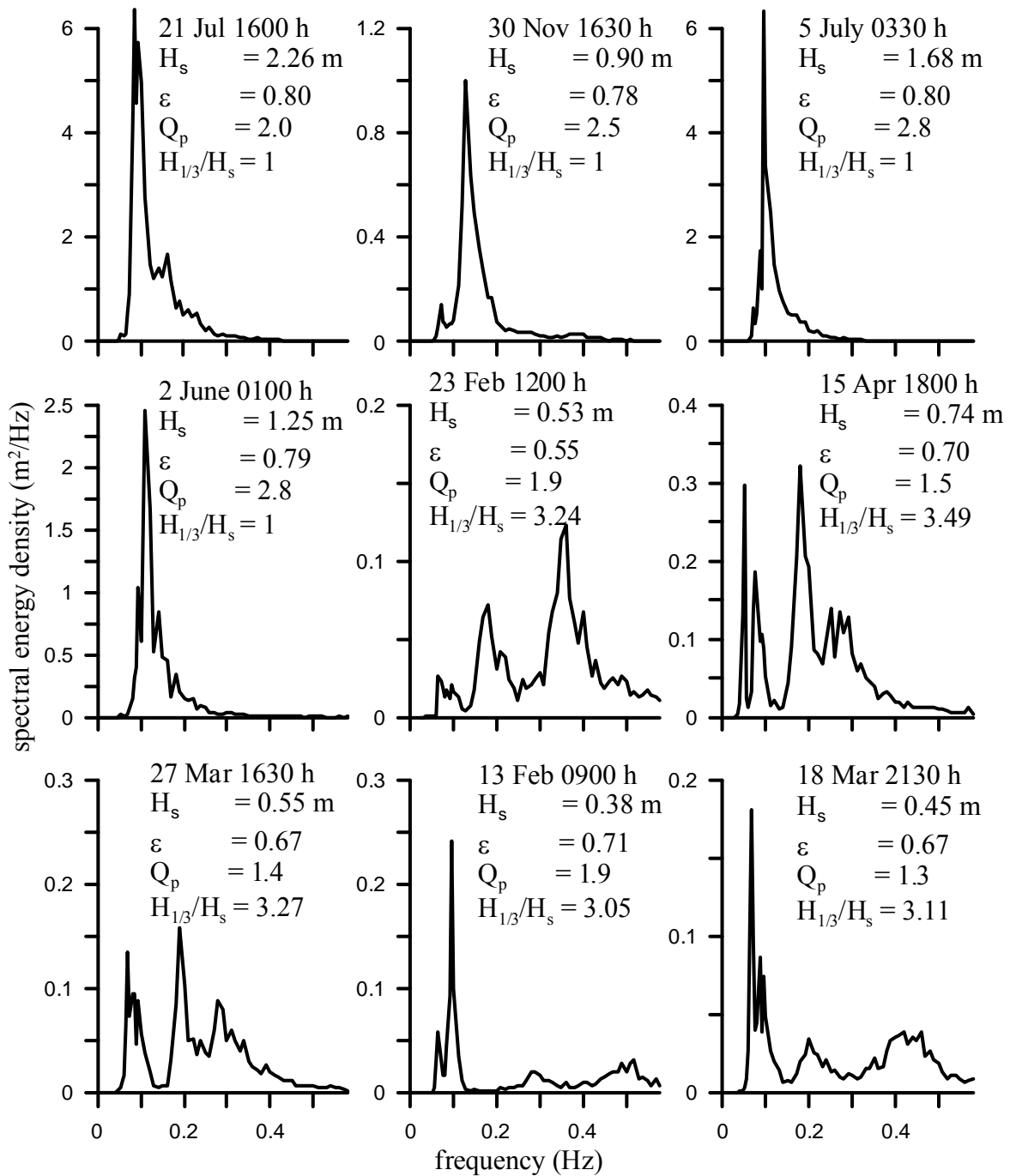


Figure 6. Typical wave spectra measured during the study period along with significant wave height (H_s), spectral width parameter (ϵ), spectral peakedness parameter (Q_p) and ratio of the $H_{1/3}$ and H_s .

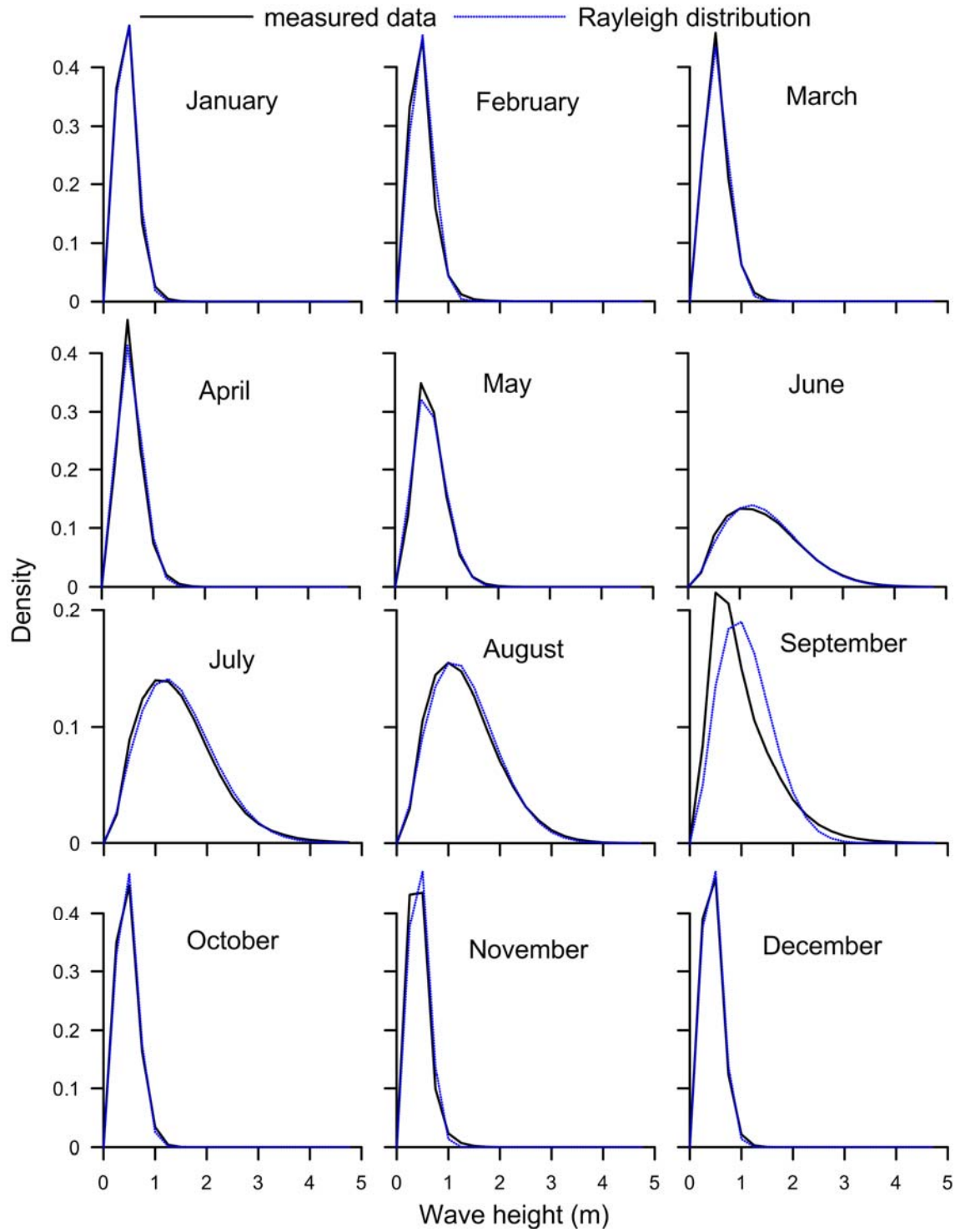


Figure 7. Comparison of observed and theoretical individual wave height distribution based on Rayleigh probability of occurrence in different month

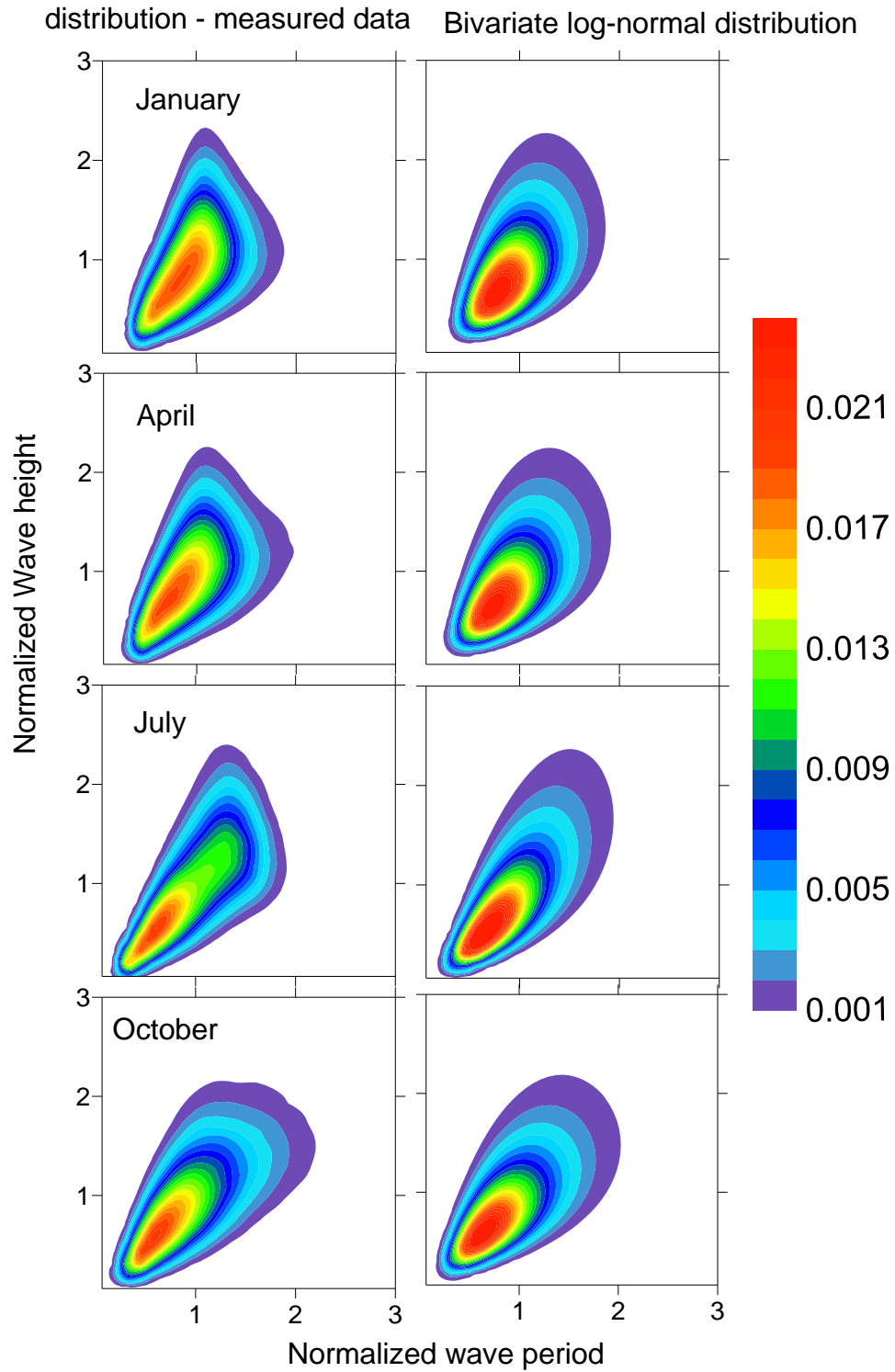


Figure 8. Joint distribution of normalized wave height and normalized wave period during January, April, July and October and that based on bivariate log-normal distribution

Table 1. Number of waves measured in each month and its height and period

Month	Number of waves	Number of waves used in analysis	Average wave height (m)	Root mean square wave height (m)	Maximum wave height (m)	Significant wave height of monthly data (m)	Mean significant wave height of each record (m)	Average wave period (s)	Maximum wave period (s)
Jan	626120	596365	0.33	0.38	1.99	0.53	0.56	4.3	18.7
Feb	572464	545974	0.37	0.43	2.98	0.60	0.63	4.2	21.7
Mar	612482	587833	0.41	0.46	2.34	0.65	0.70	4.4	19.6
Apr	574692	552041	0.44	0.50	2.37	0.69	0.76	4.5	19.8
May	523545	505961	0.56	0.63	2.99	0.88	0.97	5.1	18.7
Jun	380474	374172	1.35	1.53	6.92	2.18	2.29	6.8	17.6
Jul	394750	388543	1.32	1.51	6.97	2.15	2.26	6.8	19.0
Aug	413534	406533	1.20	1.37	5.51	1.94	2.04	6.5	22.1
Sep	404577	394951	0.90	1.11	6.52	1.61	1.57	6.4	21.1
Oct	472210	448938	0.35	0.40	1.67	0.56	0.61	5.7	24.9
Nov	526884	495823	0.31	0.36	2.38	0.50	0.54	4.9	20.9
Dec	610337	575365	0.32	0.36	1.63	0.51	0.52	4.4	18.4

Table 2. Mean value of wave statistical parameters for 30 minutes record in different seasons

Parameter	Pre-monsoon (February-May)	Monsoon (June-September)	Post-monsoon (October- January)
Number of waves	396	272	379
Mean H (m)	0.43	1.18	0.32
Mean T (s)	4.60	6.64	4.95
$H_{1/3}$ (m)	0.68	1.89	0.50
$T_{1/3}$ (s)	5.89	8.65	6.57
H_{rms} (m)	0.48	1.34	0.35
H_{max} (m)	1.17	3.15	0.86
T_{Hmax} (s)	6.56	8.95	7.55
$H_{1\%}$ (m)	1.06	2.94	0.79
$H_{2\%}$ (m)	1.01	2.79	0.75
$H_{1/10}$ (m)	0.84	2.34	0.62
Ratio of H_{max} to $H_{1/3}$	1.72	1.67	1.73
Ratio of $H_{1\%}$ to $H_{1/3}$	1.57	1.56	1.58
Ratio of $H_{2\%}$ to $H_{1/3}$	1.49	1.48	1.50
Ratio of $H_{1/10}$ to $H_{1/3}$	1.24	1.24	1.25
Ratio of H_{rms} to $H_{1/3}$	0.72	0.71	0.71
Ratio of H_{mean} to $H_{1/3}$	0.64	0.63	0.64
Short period waves (%)	79	43	75
Intermediate period waves (%)	14	24	14
Long period waves (%)	7	33	11

Table 3. Distribution of waves in different wave height class in different months. The number indicates the number of waves in that particular group.

Wave height (m)	January	February	March	April	May	June	July	August	September	October	November	December	Total
0.00-0.25	233160	194622	160334	123826	67199	10105	10554	13180	36127	167286	228068	240095	1484556
0.25-0.50	271619	236978	264981	250020	177482	33318	35525	43855	85576	196075	206107	255345	2056881
0.50-0.75	74195	82287	117429	124739	148709	45227	48524	58998	80539	69425	46010	66579	962661
0.75-1.00	14362	22888	34956	39199	74154	49904	54331	62936	58389	14358	11047	11645	448169
1.00-1.25	2532	6159	8266	10898	26479	49200	53760	59685	41327	1664	3380	1537	264887
1.25-1.50	423	1889	1534	2705	8352	45882	48931	50925	30566	123	948	155	192433
1.50-1.75	65	694	290	581	2568	40097	40961	39350	21858	7	220	9	146700
1.75-2.00	9	297	36	57	750	31989	31459	28384	14545	0	37	0	107563
2.00-2.25	0	103	6	14	202	24285	22499	19610	9588	0	5	0	76312
2.25-2.50	0	46	1	2	52	16752	15115	12533	6106	0	1	0	50608
2.50-2.75	0	6	0	0	12	11111	9736	7805	3964	0	0	0	32634
2.75-3.00	0	5	0	0	2	7107	6245	4416	2433	0	0	0	20208
3.00-3.25	0	0	0	0	0	4201	4037	2442	1508	0	0	0	12188
3.25-3.50	0	0	0	0	0	2369	2640	1236	920	0	0	0	7165
3.50-3.75	0	0	0	0	0	1273	1608	672	603	0	0	0	4156
3.75-4.00	0	0	0	0	0	666	990	269	369	0	0	0	2294
4.00-4.25	0	0	0	0	0	378	671	140	223	0	0	0	1412
4.25-4.50	0	0	0	0	0	159	415	54	133	0	0	0	761
4.50-4.75	0	0	0	0	0	80	232	29	78	0	0	0	419
4.75-5.00	0	0	0	0	0	35	145	9	37	0	0	0	226
5.00-5.25	0	0	0	0	0	26	82	2	20	0	0	0	130
5.25-5.50	0	0	0	0	0	4	38	2	21	0	0	0	65
5.50-5.75	0	0	0	0	0	3	23	1	9	0	0	0	36
5.75-6.00	0	0	0	0	0	0	14	0	7	0	0	0	21
6.00-6.25	0	0	0	0	0	0	3	0	2	0	0	0	5
6.25-6.50	0	0	0	0	0	0	2	0	2	0	0	0	4
6.50-6.75	0	0	0	0	0	0	2	0	1	0	0	0	3
6.75-7.00	0	0	0	0	0	1	1	0	0	0	0	0	2
Total	596365	545974	587833	552041	505961	374172	388543	406533	394951	448938	495823	575365	5872499

Table 4. Joint distribution of wave height and period during one year period. The number indicates the number of waves in that particular group

Wave height (m)	Wave period (s)												Total
	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	
0.0-0.5	150615	1636834	1154215	361034	111775	44181	17917	5302	1249	292	66	11	3483491
0.5-1.0	665	247031	668301	324840	123249	50659	25123	11488	3426	680	114	12	1455588
1.0-1.5	0	18067	136786	149030	105539	42744	9662	1762	267	14	3	0	463874
1.5-2.0	0	1069	32782	79862	91206	43847	7753	639	52	7	1	0	257218
2.0-2.5	0	35	6739	34272	54443	28706	4363	304	33	9	1	1	128906
2.5-3.0	0	1	1143	11956	25057	13804	1861	104	25	6	1	0	53958
3.0-3.5	0	0	161	3473	9674	5639	719	53	7	0	0	0	19726
3.5-4.0	0	0	18	925	3378	2022	208	20	2	2	0	0	6575
4.0-4.5	0	0	1	206	1162	775	80	5	0	0	0	0	2229
4.5-5.0	0	0	0	43	344	250	21	0	0	0	0	0	658
5.0-5.5	0	0	0	8	117	77	2	0	0	0	0	0	204
5.5-6.0	0	0	0	2	34	19	3	0	0	0	0	0	58
6.0-6.5	0	0	0	0	6	3	0	0	0	0	0	0	9
6.5-7.0	0	0	0	0	3	2	0	0	0	0	0	0	5
Total	151280	1903037	2000146	965651	525987	232728	67712	19677	5061	1010	186	24	5872499