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Spectral characteristics of high shallow water waves

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Abstract

The spectral characteristics of shallow water waves with significant wave height more than 2 m based on the data collected along the Indian coast is examined. It was found that the value of JONSWAP parameters (α and γ) increases with significant wave height and mean wave period and decreases with spectral peak period. The estimated average value (0.0027 and 1.63) of the JONSWAP parameters, α and γ were less than the generally recommended values of 0.0081 and 3.3 respectively. By carrying out a multi regression analysis, an empirical equation is arrived relating the JONSWAP parameters with significant wave height, peak wave period and mean wave period. It was found that the Scott spectra underestimate the maximum spectral energy of high waves. The study shows that the measured wave spectra can be represented by JONSWAP spectra with the JONSWAP parameters estimated based on the equation proposed in this paper.

Keywords: JONSWAP spectra, Scott spectra, Indian coast, significant wave height, spectral energy

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1. Introduction

The Indian coastal waters are being used by the oil and gas industries besides the ports and harbour. Wave spectra at a given location are necessary for almost every engineering activity. Considerable research has been done in modeling unidirectional spectra. It is generally believed that a unique spectral model, which is applicable to all storm situations in all parts of the world, is difficult to develop. For different locations and climatic conditions a number of semi-empirical spectral models were proposed (Chakrabarti, 2005). For a fully arisen sea condition, Pierson-Moskowitz spectrum (Pierson and Moskowitz, 1964) can be used to describe the spectral characteristics. For a growing sea state JONSWAP spectrum (Hasselman et al., 1973) can be used. Scott spectrum (Scott, 1965) is recommended for the west coast of India by Dattatri et al. (1977), Narasimhan and Deo (1979), Baba et al. (1989) and Kumar et al. (1994), by analysing the data collected off Mangalore, Bombay High, Cochin and Karwar respectively. Harish and Baba (1986) proposed PMK spectral model combining the Pierson-Moskowitz and Kitaigordskii et al., (1975) for the south-west coast of India. Ochi and Hubble (1976) found that JONSWAP spectrum provided good approximation to the data for the unimodel spectra with mean JONSWAP parameters of γ (peak enhancement parameter) = 2.2 and α (Phillips constant) = 0.023. Donelan et al. (1985) have proposed a spectrum with high frequency face proportional to f^{-4} instead of f^{-5}.

Young (1992) reviewed the wave spectral representation and highlighted many limitations. Young made an attempt to define a consistent representation of the spectral parameters in terms of significant wave height and peak period. Ochi (1993) and Young (1998) have shown that the spectra recorded during storm conditions were uni-model and appeared similar to typical fetch limited data and were represented by JONSWAP form. Young (1998) examined 229 spectra from 16 hurricanes and found that JONSWAP and Donelan et al. (1985) spectra approximate the data well and concluded that the spectra actually consists of a combination of locally generated high frequency waves, together with remotely generated low frequency swell. For engineering design purposes, Young (1998) and Young (2003) concluded that the spectral form proposed by Donelan et al. (1985) together with the relationships for the parameters α and γ obtained from fetch limited data is a reasonable approximation to the hurricane wave spectra. Babanin and Soloviev (1998) related the JONSWAP parameters with wave age.

Kumar et al. (2003) found that along the Indian coast, about 60% of the wave spectra observed had two predominant peaks but they were mainly single peaked when the significant wave height was higher. The double peaked spectra observed were mainly swell dominated with average value of the ratio of the two spectral peaks around 0.6 and the average value of the difference between peak frequencies around 0.09 Hz. Even though the spectra were having two peaks, Kumar et al. (2003) found that Scott and Scott-Wiegel spectra estimate the maximum spectral energy reasonably well except during the high wave at all the locations studied.

In view of the above, a study was done to identify suitable theoretical spectra for waves having significant wave height (Hs) more than 2 m based on the measured wave data at different locations along the Indian coast.

2. Materials and Methods

2.1 Data

The data available at National Institute of Oceanography, Goa, India, collected using Datawell directional waverider buoy (Barstow and Kollstad, 1991) at 6 locations (Figure 1) having different water depths (Table 1) along the Indian coast in the past were used for the analysis. At all locations, the buoy was moored with standard Datawell rubber shock cord with the configuration suggested by the manufacture. The data were recorded for 20 minutes duration at a frequency of 1.28 Hz. The collected time series was subjected to standard error checks for spikes, steepness and constant signals (Haver, 1980). The data used in the present study are all collected in the open ocean (Figure 1). The measured spectrum referred in the paper is the wave spectra obtained through Fast Fourier transform (FFT). FFT of 8 series, each consisting of 256 measured vertical elevations of the buoy data, were added to obtain the spectra. The high frequency cut off is set at 0.58 Hz with a resolution of 0.005 Hz and the low frequency cut off is 0.03 Hz. The heave is measured in the range of -20 to 20 m with a resolution of 1 cm and an accuracy of 3%. When the moored buoy follows the waves, the force of the mooring line may change resulting in a maximum error of 1.5% in the

measurement of surface elevation. Also, if the wavelength is less than 5 m, the buoy will not follow the wave amplitude. The presence of noise causes limitations in the buoy frequency range. One obvious source of noise in the buoy data, which measures the translational motion, is from the current induced mooring line forces. A useful parameter in the error analysis is the 'check ratio' (R), which is a measure of the ratio of the vertical and horizontal responses of the buoy (Tucker, 1989). For a perfectly surface-following buoy R will be 1. This check ratio is modified due to the change in dispersion relationship of a moored buoy due to Doppler effects when the currents change the apparent phase velocity of the waves. Hence, one often sees values of R significantly different from unity due to currents and mooring restraints. Kumar and Anand (2004a) found that the average value of R is around 1 for frequencies from 0.07 to 0.25 Hz ($\pm$0.5 times the peak frequency) and the check ratio deviates from 1 at lower and higher frequencies and can give error in the estimation of wave direction at lower and higher frequencies. The average percentage of spectral energy beyond the frequency range of 0.05 to 0.25 Hz at different locations varied from 2.3 to 4.1 (Table 1). Beyond the frequency range of 0.04 to 0.35 Hz, the average percentage of spectral energy was 0.7 to 1.4. Since in the present study, the predominant wave energy is within 0.05 to 0.25 Hz, the error due to currents and mooring restraints on the spectral parameters is negligible.

The significant wave height (Hs) and the mean wave period (T_{02}) were obtained from the spectral analysis. The period corresponding to the maximum spectral energy is referred as spectral peak period (Tp). The significant wave steepness is estimated as the ratio of the significant wave

height to the wave length corresponding to the mean wave period. In the present study waves with significant wave height more than 2 m only is considered in the analysis. Table 1 presents the percentage of data used in the analysis. The long-term distribution of all the data collected at location 4 is presented in Kumar and Deo (2004) and hence not discussed in the present paper. At location 4, TMA spectrum (Bouws et al., 1985) matched the observed sea spectra very well when the sea breeze was active (Neetu et al., 2006). During this period the significant wave height was less than 2 m. For high waves, it was found that TMA model, without modifying the model parameters, over predict the maximum spectral energy, similar to the JONSWAP model.

Various theoretical spectra used for comparison with the measured spectra are given below.

2.2 JONSWAP Spectrum

Observations made during the Joint North Sea Wave Project (JONSWAP), found that the Pierson-Moskowitz spectra (1964) underestimate the spectral peak which could be due to the assumptions of fully developed sea condition. Hasselmann et al. (1973) showed that the spectrum in the young sea state is described by,

$$S(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right] . \gamma^{\exp\left[-\frac{(f-f_p)^2}{2\sigma^2 f_p^2}\right]} \qquad (1)$$

Where, S(f) = spectral energy
α = Phillips constant =0.0081
g = acceleration due to gravity

f = wave frequency

$$\sigma = \begin{cases} 0.07 & f < f_p \\ 0.09 & f \geq f_p \end{cases} \quad (2)$$

f_p = frequency corresponding to the peak value of energy spectrum

For the mean JONSWAP spectrum, γ = 3.3. JONSWAP spectrum is widely used for North Sea (Chakrabarti, 2005). Ochi (1993) fitted the JONSWAP spectral form to the hurricane data and represented JONSWAP parameters as below:

$$\alpha = 4.5\ Hs^2\ f_p^4 \quad (3)$$

$$\gamma = 9.5\ Hs^{0.34}\ f_p \quad (4)$$

Young (1988) showed that

$$\alpha = 0.008\ (U_{10}/Cp)^{0.73} \quad (5)$$

$$\gamma = 1.9 \quad (6)$$

Where, U_{10} = wind speed at 10 m above mean sea level

Cp = wave celerity corresponding to peak period

2.3 Donelan et al. (1985) spectrum

In the JONSWAP spectra the high frequency tail of the spectrum decays in a form proportional to f^{-5}. A number of observations found that high frequency decay can be better approximated by a form proportional to f^{-4}. Using this assumption and extensive laboratory and field data, Donelan et al. (1985) proposed the fetch limited spectral form as given below.

$$S(f) = \frac{\alpha g^2}{(2\pi)^4 f^4 f_p} \exp\left[-\left(\frac{f}{f_p}\right)^{-4}\right] . \gamma^{\exp\left[-\frac{(f-f_p)^2}{2\sigma^2 f_p^2}\right]} \quad (7)$$

Donelan et al. (1985) related the JONSWAP parameters with wave age as given below:

$\alpha = 0.006\ (U_{10}/Cp)^{0.55}$ (8)

$\gamma = 1.7$ for $0.83 < U_{10}/Cp < 1$ (9)

$= 1.7 + 6 \log_{10} (U_{10}/Cp)$ for $1 \leq U_{10}/Cp < 5$

2 .4 Scott Spectrum

This is modified form of Darbyshire spectrum (Darbyshire, 1959) and is based on a different data analysis (Scott, 1965). Scott spectrum is expressed in terms of Hs as given below;

$$s(\omega) = 0.214\ H_s^2 \exp\{-[\frac{(\omega - \omega_p)^2}{0.065(\omega - \omega_p + 0.26)}]^{1/2}\}$$

$-0.26 < (\omega - \omega_p) < 1.65$ (10)

$= 0$ otherwise

Where, $s(\omega)$ is the spectral energy at angular wave frequency 'ω' and ω_p is the peak angular wave frequency.

Scott spectrum is used for the Indian coast (Dattatri, 1977; Narasimhan and Deo, 1979; Kumar et al., 1994). The probable reason might be the fact that the original validation of Scott spectrum was carried out using considerable swell dominated data. Similar situation usually prevails at many sites along the Indian coast.

The Scott-Wiegel spectrum (Wiegel, 1980) is also used for comparing with the measured spectra.

3. Results and discussions

3.1 Wave parameters

Sea state is generally defined using few parameters derived from the wave spectrum. Significant wave height (Hs) and peak period (Tp) are the most commonly used parameters. Range and average value of wave parameters of the data considered in the study along with water depth at the location of measurement is presented in Table 2. Mean wave period associated with high wave is usually obtained by assuming a significant wave steepness. In the present study, it was found that T_{02} varied between 3.2 $Hs^{0.5}$ and 5.5 $Hs^{0.5}$ (Figure 2). For deep water waves, the significant wave steepness is 1/18 and will result in T_{02} = 3.4 $Hs^{0.5}$. In case of fetch limited waves, wave steepness of 1/14 is applicable. The significant steepness of the waves considered in the study varied from 1/16 to 1/47. ISSC (1979) recommends T_{02} in a range of 2.6 $Hs^{0.5}$ to 3.9 $Hs^{0.5}$. The present study shows that T_{02} varied beyond this range. Labeyrie (1990) found $T_{02} = (8\ Hs + 21)^{0.5}$ for the data from Frigg field and this equation provides an average value of T_{02} for a given Hs value (Figure 2).

Tp was found to be between 3.9 $Hs^{0.5}$ and 8.85 $Hs^{0.5}$ (Figure 3). Using JONSWAP spectrum with γ as 1, period corresponding to spectral peak is 1.41*T_{02}. Tp was found to be varying between the values estimated using the equations (Figure 4) given below.

$$Tp = 7.44\ T_{02} - 28.2 \quad (11)$$

$$Tp = 13.9 - 3.6\ T_{02} + 0.39\ T_{02}^2 \quad (12)$$

3.2 JONSWAP spectral parameters

The range and mean value of α and γ obtained by matching the JONSWAP spectra with the measured spectra for different data set collected at various depths are shown in Table 3. The study shows that γ value varied from 1.1 to 3.3 with an average value of 1.63 and the α value varied from 0.0005 to 0.0095 with an average value of 0.0027. Average value (0.0027 and 1.63) of the JONSWAP parameters, α and γ were less than the generally recommended values (0.0081 and 3.3). The difference may be due to the large fetch available at the measurement locations along the Indian coast. JONSWAP measurements were limited to a maximum fetch of 160 km. Young (1998) found that the mean value of γ is 1.9 for the hurricane data set.

It was found that the value of JONSWAP parameters (α and γ) increases with significant wave height (Figure 5) and mean wave period and decreases with spectral peak period (Figure 6). A multi regression analysis is carried out relating the JONSWAP parameters with Hs, Tp and T_{02} and the following empirical equation is obtained.

$$\alpha = 0.18\, H_s^{1.52}\, T_p^{-3.53}\, T_{02}^{1.34} \qquad (13)$$

$$\gamma = 8.38\, H_s^{0.57}\, T_p^{-1.26}\, T_{02}^{0.41} \qquad (14)$$

In the above equations, the unit of H_s is m and that of T_p and T_{02} are s. Even though the above equations are dimensionally in-correct, it was found that JONSWAP parameters estimated using these equations were close to the values obtained from the measured spectra. In the present study, the range of significant wave height considered is from 2 to 5.7 m and the water depth at the data collection locations varied from 12 to 70 m. The validity of the above

equations for conditions beyond the range of significant wave height and water depth considered in the present study needs to be investigated. Since in the present study simultaneous wind data was not available at all locations, the study results were not compared with the earlier studies relating JONSWAP parameters with wave age.

3.3 Wave spectra

The comparison of wave spectra estimated based on various theoretical formulations with the measured spectra for relatively high waves (Hs varied from 2 to 5.7 m) shows that the JONSWAP spectra with the JONSWAP parameters estimated based on equations (13) and (14) closely represent the measured spectra (Figures 7 and 8). For higher wave heights the spectral peak estimated by the Scott and Scott-Wiegel spectra was lower than the measured peak value. It was found that the Donelan et al. spectra overestimated the spectral peak. In the present study, the wave with Hs more than 2 m is only considered and found that most of the spectra were with predominant single peak. The average value of the spectral peakedness parameter was around 2 showing the spectrum was narrow band spectra. Root mean square value between maximum spectral energy obtained from measured and estimated using JONSWAP with modified JONSWAP parameter is less compared to that estimated based on other spectral models (Table 4) at all locations considered. The spectral shape of the JOSWAP spectra generally depends on the peak frequency. In the present study, the peak frequency from the measured data is used instead of the fetch. In areas

where measured data is not available, the equations proposed in the present study can not be used.

The measured spectral shape in the high frequency region lies between the curves proportional to f^{-5} and f^{-3} (where f is the frequency) and is close to f^{-5}. Hence the high frequency part is estimated reasonably well using the JONSWAP spectra with modified parameter (Figure 9). Young and Verhagen (1996) found that the exponent is approximately -5 in deep water and around -3 in finite depth. In the present study such reduction could not be observed.

The maximum (or peak) wave spectral energy density estimated based on various theoretical spectra with the measured spectra is presented in Figure 10. The maximum spectral energy estimated using JONSWAP spectra with the JONSWAP parameters estimated based on Ochi (1993) was found to be lower than that estimated using Scott and Scott-Wiegel spectra. The least square error between the measured and estimated maximum spectral energy was 3.18, 5.08, 5.85 and 5.85 for that estimated using JONSWAP spectra with modified parameters, Scott-Wiegel, Scott and Donelan et al. spectra respectively. The maximum spectral energy was estimated reasonably well (regression coefficient = 0.95 and the least square error was minimum) with the help of JONSWAP spectra using the modified JONSWAP parameters.

All spectral models predicted the low energy part well. In order to have a comparison between the measured and theoretical spectra, the spectral moments m_o (zeroth), m_1 (first order) and m_2 (second order) estimated from the theoretical spectra are compared with that estimated from the measured

data (Figure 11). Scott and Scott-Wiegel spectrum estimated the zeroth moments better than other spectra.

4. Conclusions

In the present study, waves with Hs varying from 2 to 5.7 m are considered and found that most of the wave spectra were with predominant single peak. The average value of the JONSWAP parameters, α and γ was 0.0027 and 1.63 and was less than the generally recommended values of 0.0081 and 3.3. The JONSWAP parameters can be estimated using the following expression.

$$\alpha = 0.18\, H_s^{1.52}\, T_p^{-3.53}\, T_{02}^{1.34}$$

$$\gamma = 8.38\, H_s^{0.57}\, T_p^{-1.26}\, T_{02}^{0.41}$$

The maximum spectral energy was estimated reasonably well (least square error was minimum = 3.18) with the help of JONSWAP spectra using the modified JONSWAP parameters.

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Table 1. Measurement duration, percentage of data with significant wave height more than 2 m considered in the present study, water depth and the percentage of spectral energy beyond frequency range of 0.05 to 0.25 Hz and 0.04 to 0.35 Hz at the location of measurements

Location number	Water depth at location of measurement (m)	Measurement duration	Percentage of data with Hs > 2 m considered in the present study	Percentage of spectral energy (average value) beyond frequency range of 0.05 to 0.25 Hz	Percentage of spectral energy (average value) beyond frequency range of 0.04 to 0.35 Hz
1	12	12 months	1.6	2.8	1.0
2	14	15 days	53	2.3	0.7
3	18	3 months	6.2	4.1	1.3
4	23	12 months	13.7	2.4	0.8
5	50	1 month	30.1	3.6	1.1
6	70	10 months	3.7	3.8	1.4

Table 2. The range and average value of wave parameters of the data considered in the study along with water depth at the location of measurement. Values inside the bracket indicates average value

Wave Parameter	Water depth at location of measurement (m)					
	12	14	18	23	50	70
Hs (m)	2-3.7 (2.3)	2-5.7 (3.1)	2-3.6 (2.5)	2-5.7 (3.2)	2-3.3 (2.8)	2-2.8 (2.4)
T_{02} (s)	5.4-7.6 (6.9)	6.1-8.7 (7.3)	4.5-8.1 (6.3)	5.5-8.9 (7.3)	5.1-7.3 (6.4)	5.3-8.2 (6.4)
Tp (s)	7.1-14.3 (10.2)	8.3-14.3 (11.8)	5.9-13.3 (10.7)	8.3-13.3 (12.0)	5.9-14.3 (9.9)	7.7-13.3 (9.3)
Maximum spectral energy (m^2/Hz)	2.2-33.9 (8.1)	4.1-63.3 (17.9)	1.9-27.3 (8.2)	4.1-88.0 (20.9)	2.7-20.0 (10.4)	3.0-16.9 (7.3)
Peakedness parameter (Qp)	1.49-3.75 (2.23)	1.59-3.59 (2.28)	1.27-2.99 (1.79)	1.51 – 3.41 (2.19)	1.37-2.86 (2.04)	1.42-4.25 (2.22)

Table 3. JONSWAP parameters estimated from the measured wave spectra for different locations

Location number	α		γ	
	Range	Mean	Range	Mean
1	0.0005 – 0.0071	0.0028	1.095 - 2.676	1.6495
2	0.0007 – 0.0087	0.0026	1.152 - 3.075	1.6096
3	0.0005 – 0.0095	0.0023	1.095 – 3.267	1.5190
4	0.0007 – 0.0070	0.0026	1.148 – 2.649	1.5955
5	0.0006 – 0.0078	0.0036	1.119 – 2.844	1.8318
6	0.0005 – 0.0055	0.0033	1.098 – 2.286	1.7705

Table 4. Root mean square value between maximum spectral energy obtained from measured and various theoretical spectra at different locations

Location number	Root mean square value between maximum spectral energy obtained from				
	Measured and JONSWAP with modified parameter	Measured and Scott spectra	Measured and Scott-Wiegel spectra	Measured and Donelan et al spectra	Measured and JONSWAP with Ochi parameter
1	3.35	3.93	3.68	3.22	4.73
2	3.68	6.37	5.69	6.79	7.78
3	1.95	2.89	2.74	2.92	3.41
4	4.54	10.15	8.37	9.37	10.93
5	2.29	2.70	2.64	3.33	3.36
6	1.69	1.92	1.86	2.27	2.48

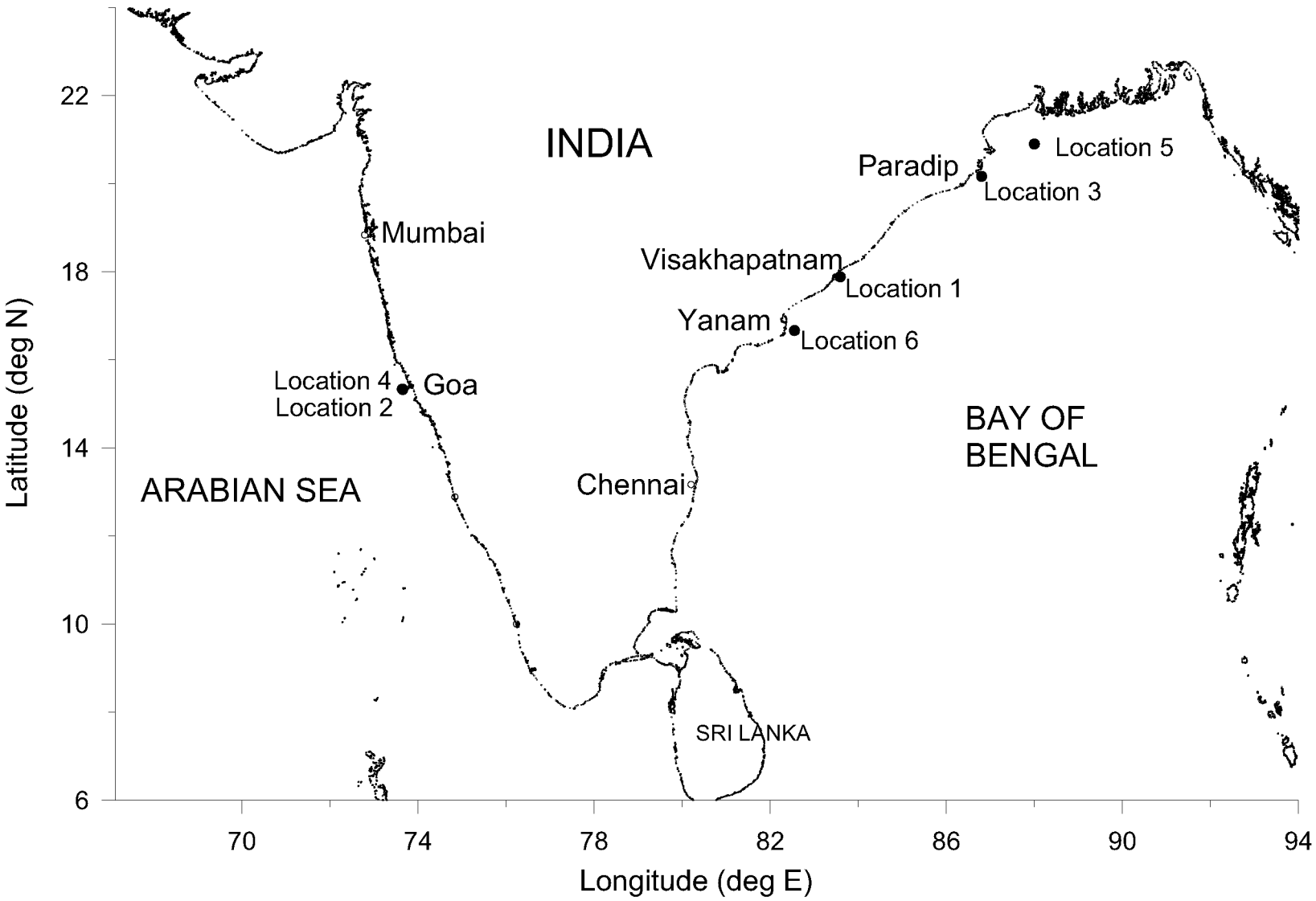

Figure 1. Locations showing the measured wave data used in the study

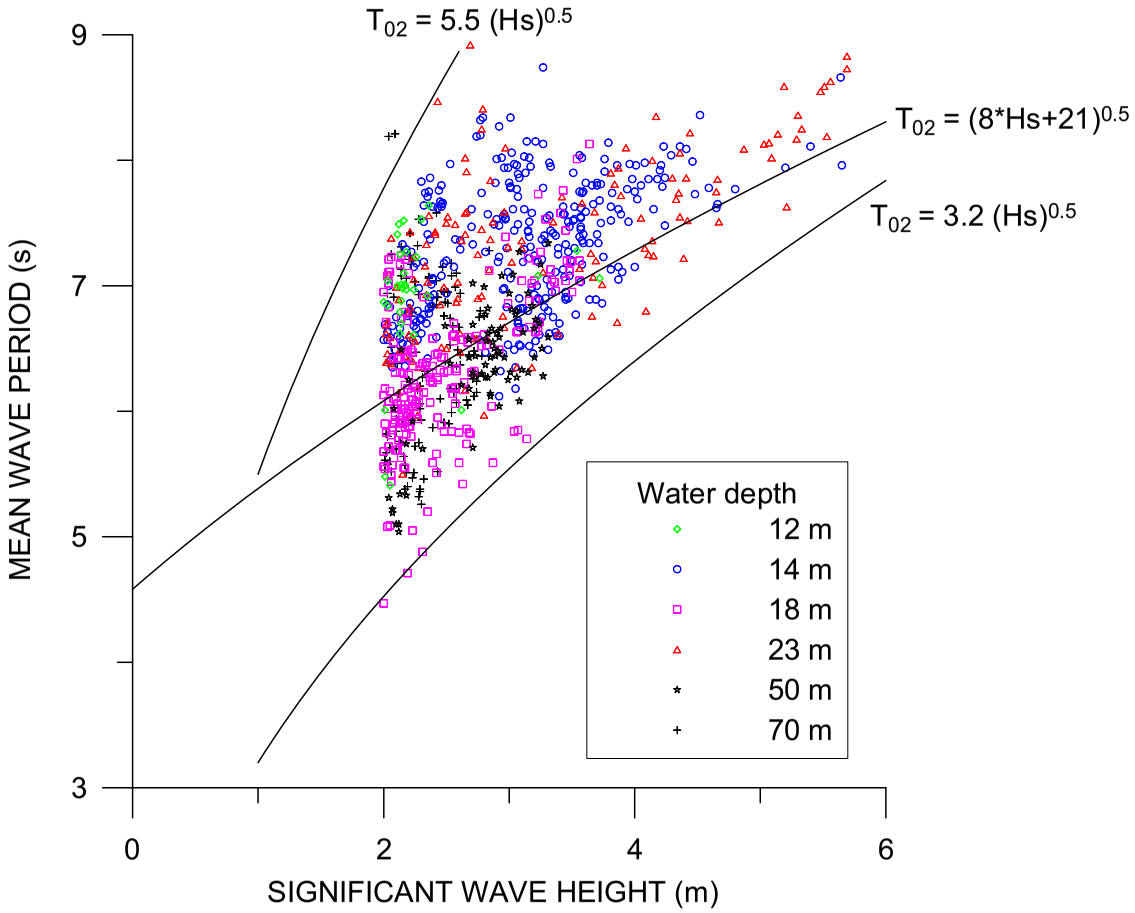

Figure 2. Variation of mean wave period with significant wave height

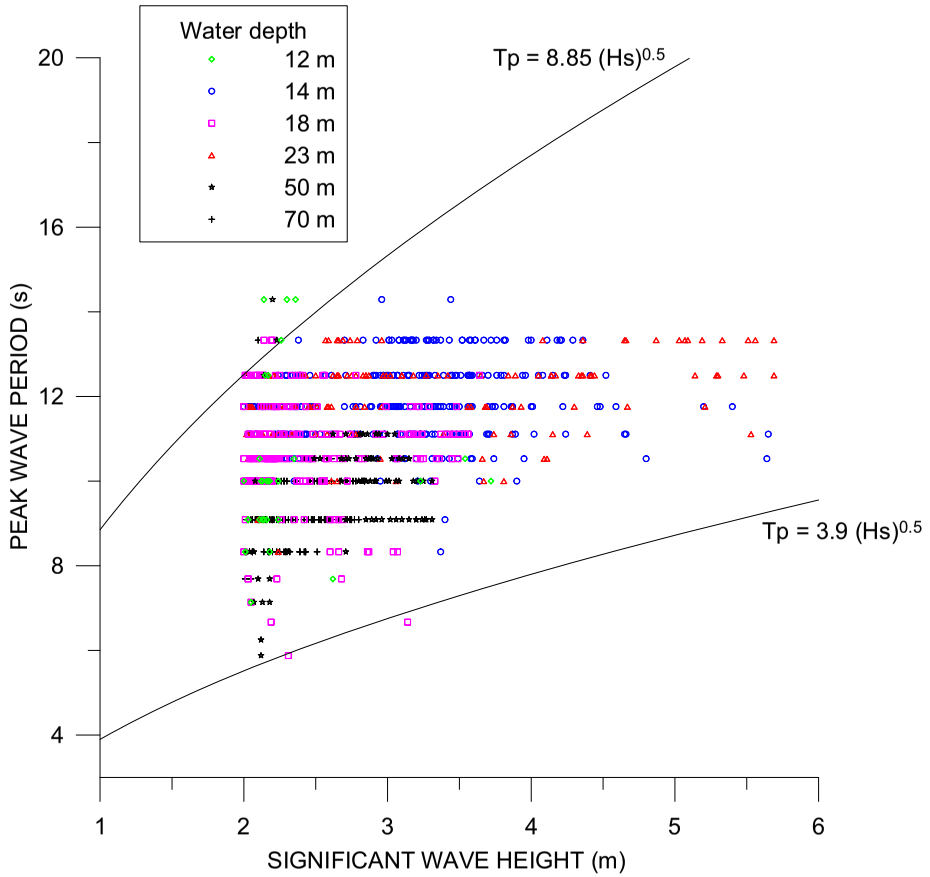

Figure 3. Variation of peak wave period with significant wave height

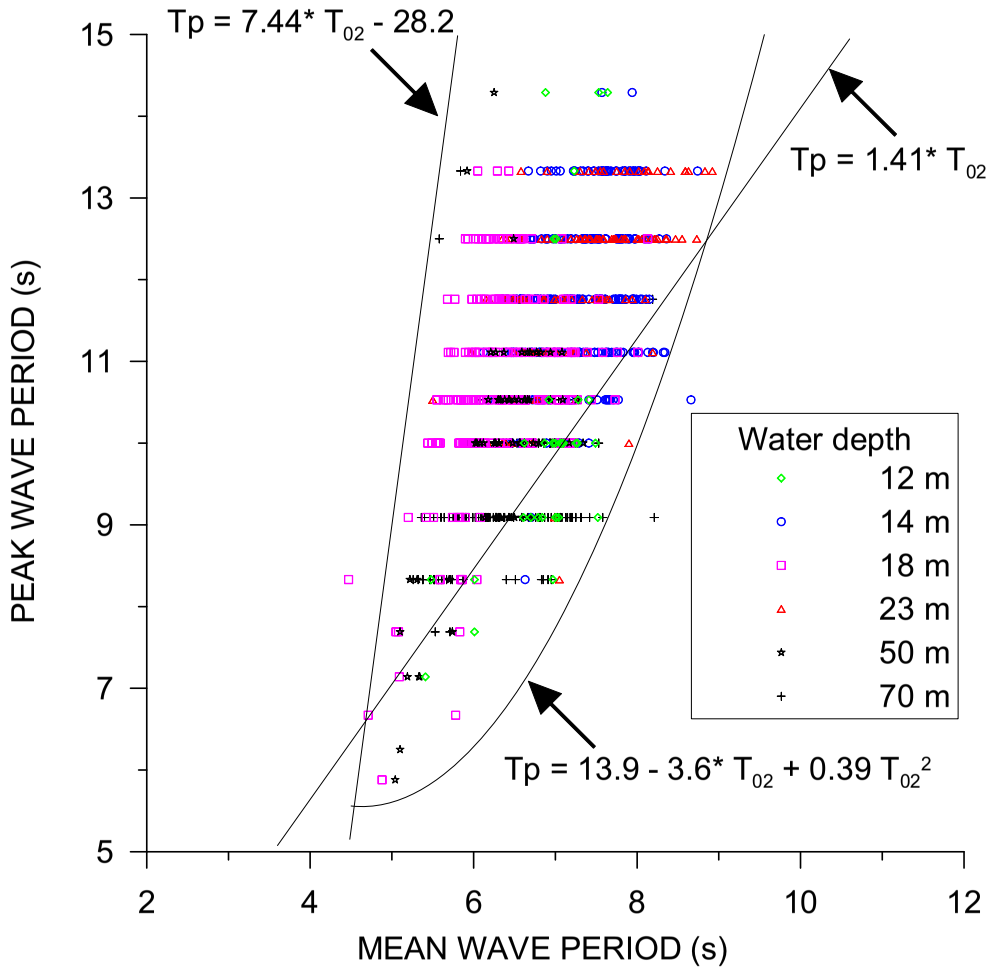

Figure 4. Variation of peak wave period with mean wave period

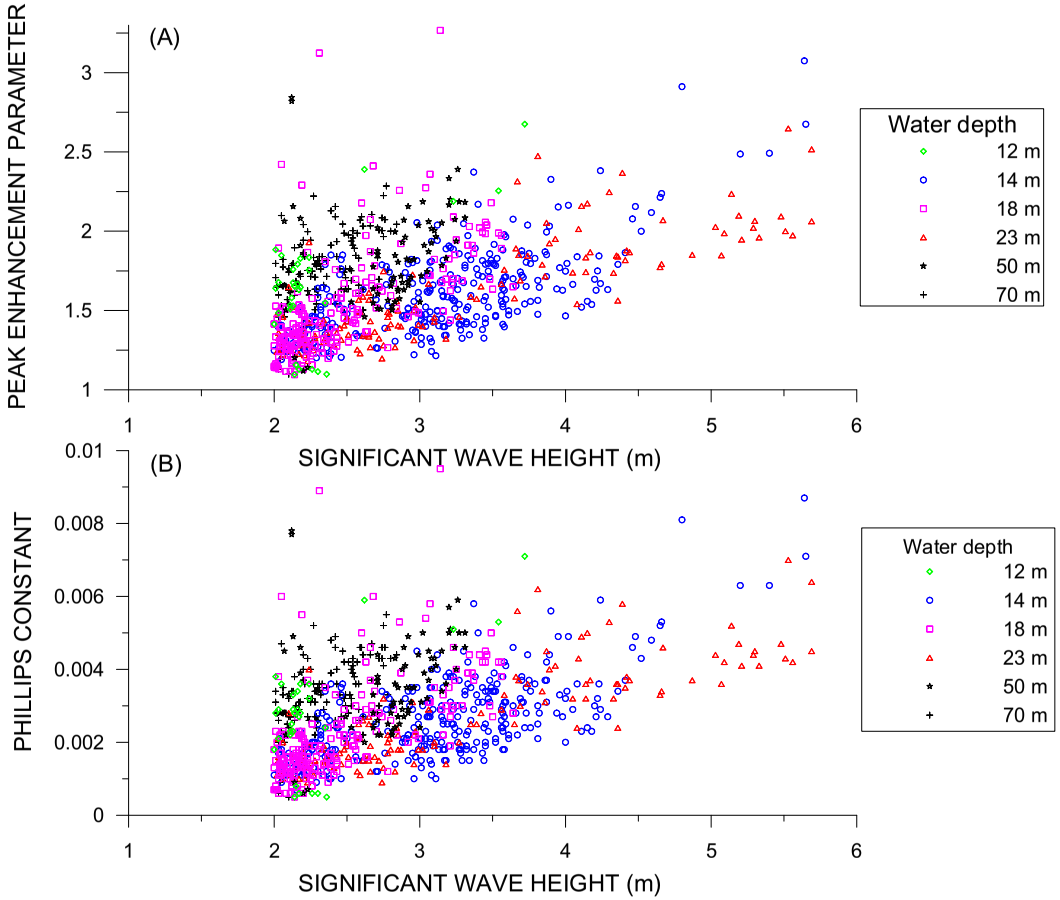

Figure 5. Scatter plots of (A) peak enhancement parameter with significant wave height and (B) Phillips constant with significant wave height

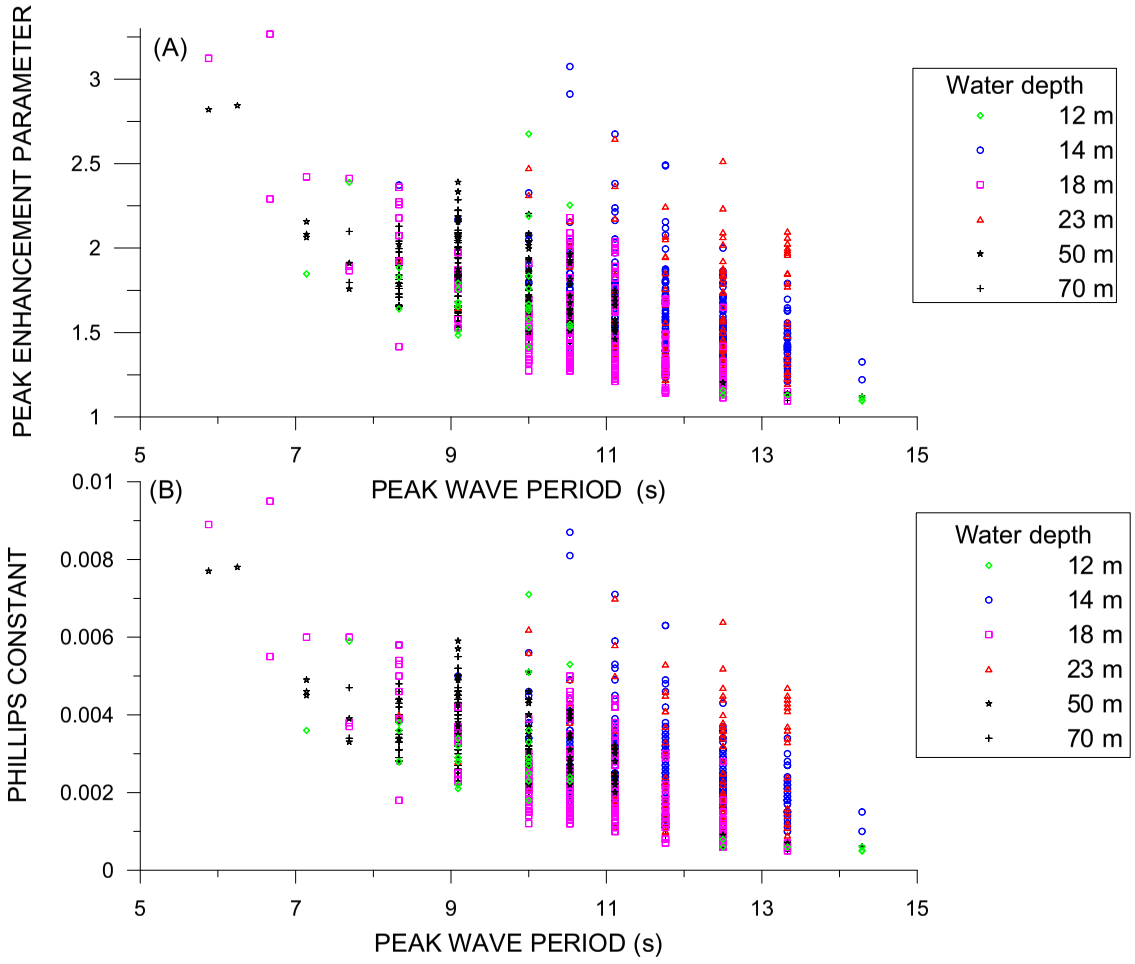

Figure 6. Scatter plots of (A) peak enhancement parameter with peak wave period and (B) Phillips constant with peak wave period

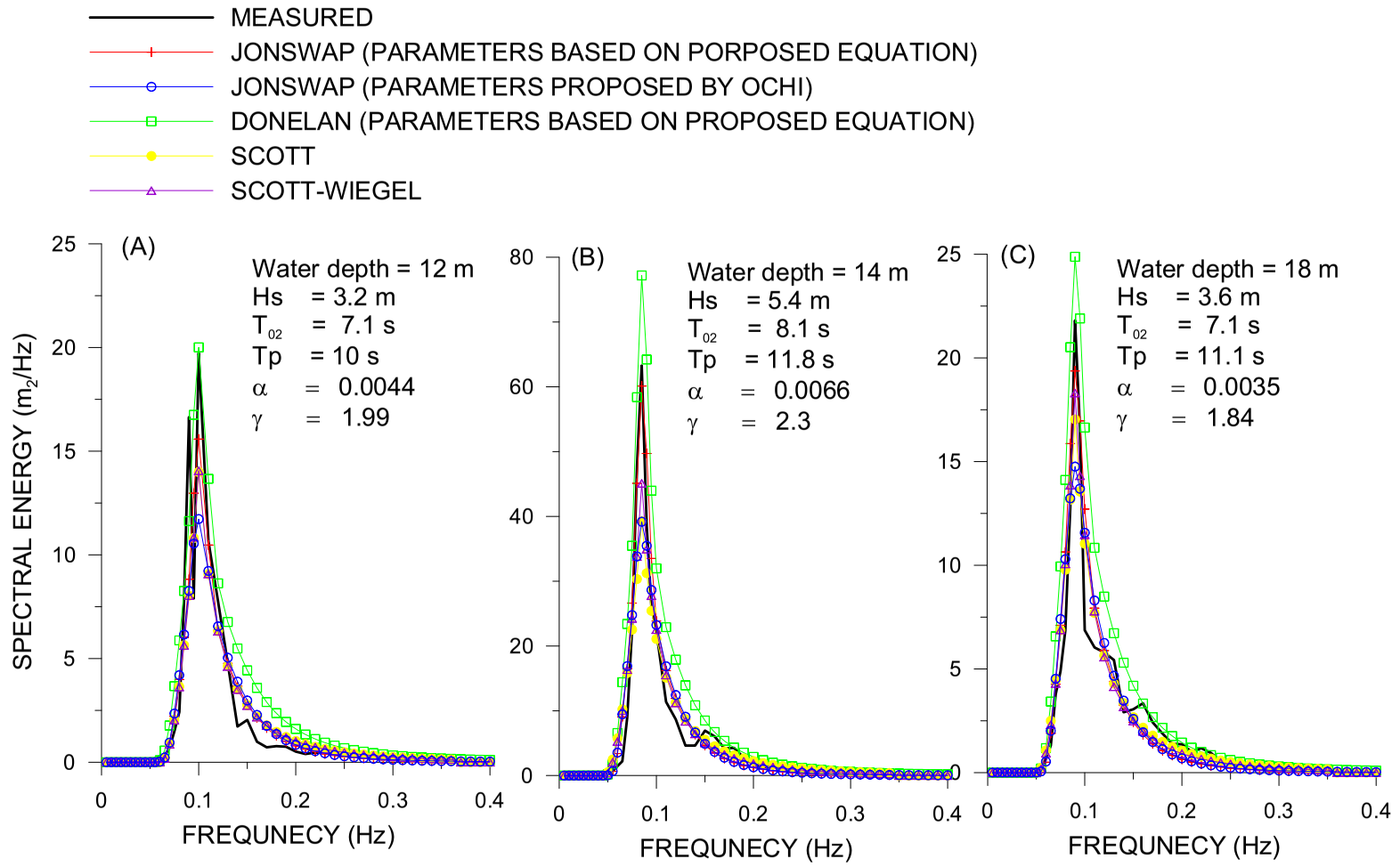

Figure 7. Measured spectra with theoretical spectra at (A) 12 m water depth (B) 14 m water depth and (C) 18 m water depth

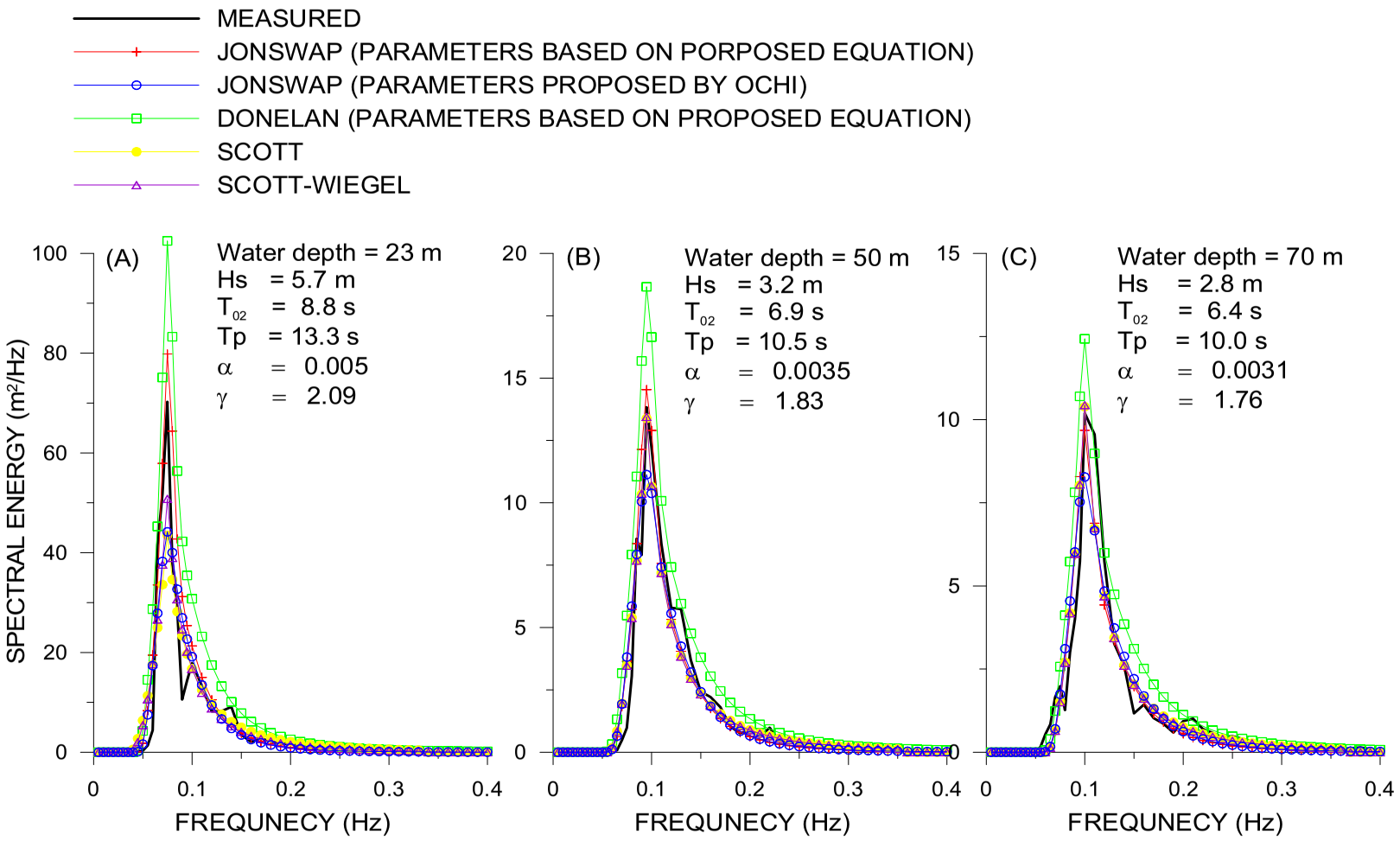

Figure 8. Measured spectra with theoretical spectra at (A) 23 m water depth (B) 50 m water depth and (C) 70 m water depth

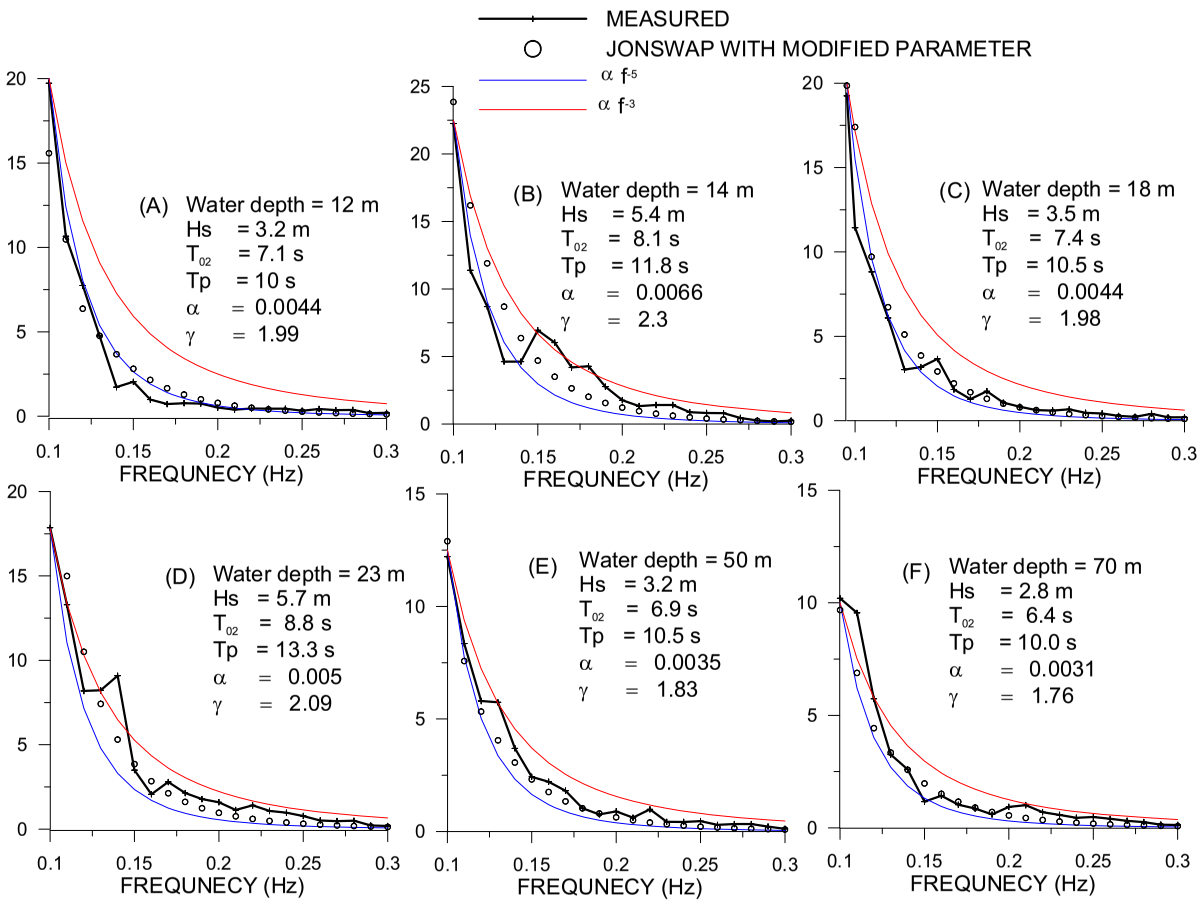

Figure 9. Variation of high frequency part of the measured spectra and that estimated using JONSWAP with modified parameter. The high frequency face proportional to f^{-5} and f^{-3} is also shown in the figure.

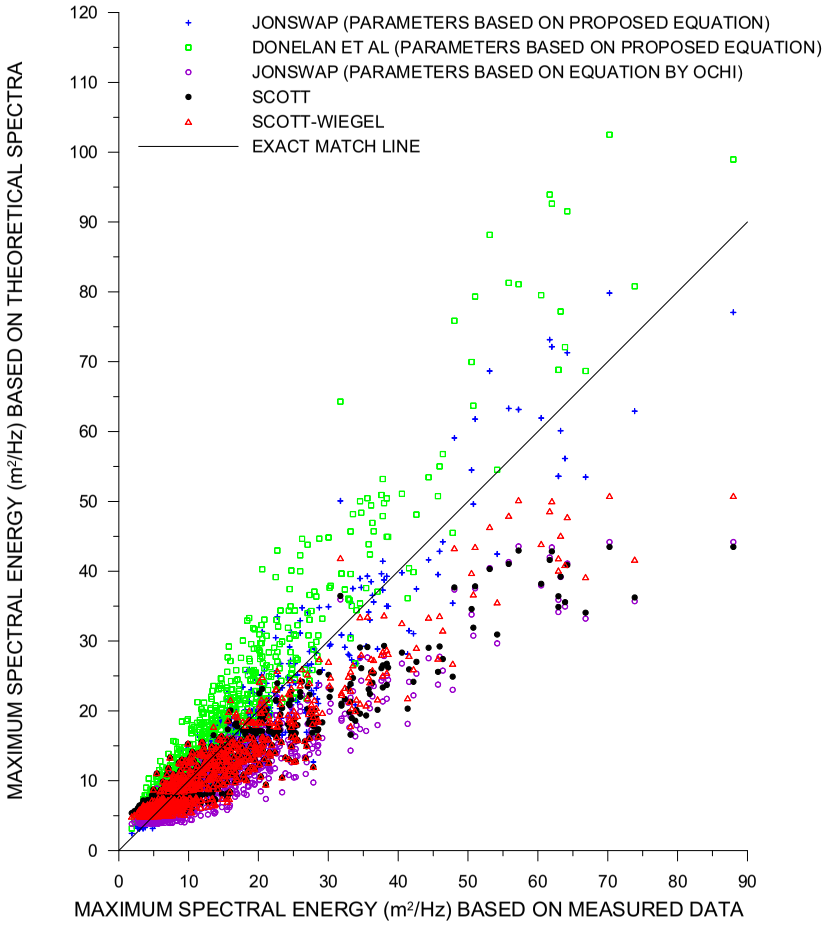

Figure 10. Scatter plots of maximum spectral energy based on measured spectra and that obtained from various theoretical spectra.

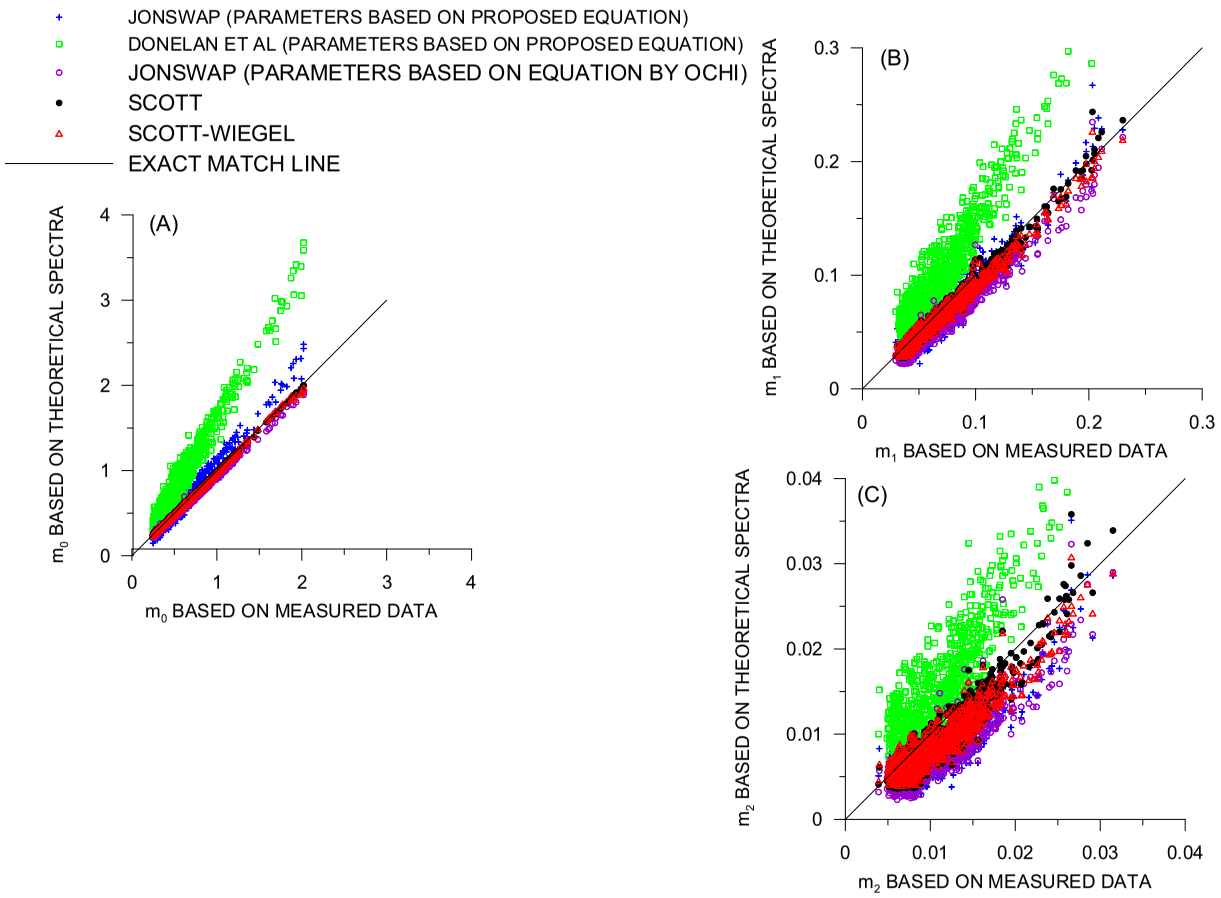

Figure 11. Variation of spectral moments estimated based on measured and theoretical spectra (A) m_0, (B) m_1 and (C) m_2