

## Waves in the nearshore waters of northern Arabian Sea during the summer monsoon

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### **Abstract**

Waves at 15 m water depth in the northern Arabian Sea are measured during the summer monsoon for a period of 45 days and the characteristics are described. The significant wave height varied from 1.1 to 4.5 m with an average value of 2.5 m. 75% of the wave height at the measurement location is due to the swells arriving from the south-west and the remaining is due to the seas from south-west to north-west. Wave age of the measured data indicates that the waves in the nearshore waters of northern Arabian Sea during the summer monsoon are swells with young sea.

**Key Words:** Sea, Swell, wind waves, Arabian Sea, summer monsoon, mixed sea state, wave spectrum

## 1. Introduction

The waves in the northern Arabian Sea largely depend on the winds blowing over the Indian Ocean and Arabian Sea. Waves along the west coast of India are high during the summer monsoon with significant wave height ( $H_{m0}$ ) up to 6 m (Kumar et al., 2006) and the  $H_{m0}$  are normally less than 1.5 m during rest of the period. The wave energy spectrum generally have more than one peak depending on the generation source and also the waves at any point in the ocean are generally sum of local wind sea and swell components propagating from distant storms (Hanson and Phillips, 1999). Kumar et al. (2003) found that along the Indian coast, about 60% of the wave spectra observed are multi-peaked and they are mainly single peaked when the  $H_{m0}$  is more than 2 m. The double peaked spectra observed are 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 are having two peaks, Kumar et al. (2003) found that Scott and Scott-Wiegel spectra estimate the maximum spectral energy density reasonably well except during the high wave along the Indian coast. Off Goa, TMA spectrum (Bouws et al., 1985) matched the observed sea spectrum well when the sea breeze is active (Neetu et al., 2006) and during this period,  $H_{m0}$  is less than 2 m. For high waves, it is found that TMA model, without modifying the model parameters; over predict the maximum spectral energy, similar to the JONSWAP model (Hasselmann et al., 1973). Kumar and Kumar (2008) found that at different water depth (12 to 70 m) around the Indian coast, the JONSWAP spectrum with the modified spectral parameters represented the measured spectrum well for  $H_{m0}$  more than 2 m. Kumar et al. (2010) found that the waves in shallow water location off the west coast of India during the onset of summer monsoon are mainly swells arriving from south and south-west direction. A number of studies describe the wave characteristics during wave growth (Phillips, 1957; Miles, 1957; Donelan and Hui, 1990). Young (1997) studied the effect of fetch length on the growth rate in a finite depth and found that for longer fetches, the growth rate decreases in finite depth compared to deep water. Wind sea growth and dissipation in a swell-dominated open ocean environment is investigated by Hanson and Phillips (1999). Hanson and Phillips (1999) and Violante-Carvalho et al. (2004) have found no obvious influence of swell on the wind sea growth rates.

Apart from the wave height and wave period, wave direction near the coast is important for coastal engineers working on beach nourishment, port development and navigational studies. Based on the analysis of directional wave data, Goda et al. (1981), Kuik et al. (1988), Benoit (1992) and Besnard et al. (1994) concluded that the mean wave direction ( $\theta_p$ ) is the most representative index to describe the wave direction. When the wave spectrum is bimodal, it is important to know the direction of both sea and the swell.

The knowledge on characteristics of waves in the shallow waters during the summer monsoon is required for prediction of waves using wave models and design of coastal structures. Hence a study is carried out to know the wave parameters during the summer monsoon period by deploying a directional waverider buoy at 15 m water depth in the northern Arabian Sea off the coast of Gujarat, India.

## **2. Materials and methods**

The waves at 15 m water depth off Muldwarka, Gujarat, India (location  $20^{\circ} 44.42'N$ ;  $70^{\circ} 39.50' E$ ) measured using the Datawell directional waverider buoy (Barstow and Kollstad, 1991) during 5 June to 24 July 2009 are used in the study. The wave data are recorded continuously at 1.28 Hz. From the recorded heave data covering 30 minutes duration, the wave spectrum is obtained through Fast Fourier Transform (FFT). FFT of 6 series, each consisting of 256 measured vertical elevations of the buoy heave data, are added to obtain the spectrum. The high frequency cut off is set at 0.58 Hz and the resolution is 0.005 Hz. 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. The significant wave height ( $H_{m0}$ ) and the mean wave period ( $T_{m02}$ ) are obtained from the spectral analysis. Definition of wave parameters used in the study is presented in Annexure. The period corresponding to the maximum spectral energy density is referred as spectral peak period ( $T_p$ ) and is estimated from the wave spectrum. The sea and swell from the measured data is separated through the method described by Portilla et al. (2009). Other parameters obtained are spectral peakedness parameter ( $Q_p$ ) (Goda 1970), spectral width parameter ( $\varepsilon$ ) based on spectral analysis (Cartwright and Longuet-Higgins, 1956), spectral narrowness parameter ( $\nu$ ) and the maximum spectral energy density. Traditionally wave height is estimated by visual observations of a trained mariner and is found to be

most nearly equal to the average height of the 1/3 largest waves in a record ( $H_{1/3}$ ). Zero-crossing analysis of the surface elevation time series is used to estimate  $H_{1/3}$ ,  $H_{1/10}$ , maximum wave height ( $H_{max}$ ).  $T_{H_{max}}$  and  $T_{1/3}$  are also estimated from the 30 minutes record.

Reanalysis data of zonal and meridional components of wind speed at 10 m height at 6 hourly intervals from NCEP / NCAR (Kalnay et.al., 1996) is obtained for the point (20° N; 70° E) close to the study area to know the influence of wind on waves. These data are provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado at <http://www.cdc.noaa.gov/>.

### **3. Results**

#### **3.1 Wave height**

To identify the swell components from the measured data, the locally generated waves and the swell are separated.  $H_{m0}$  upto 4.5 m (Figure 2A) is recorded at 15 m water depth. The average maximum wave height is 3.8 m with a maximum value of 8 m. Mean  $T_{m02}$  is 6.8 s and the mean period of swell is 10 s (Figure 2B). The measured waves are predominantly swells arriving from south (Figure 2C). Seas are from south-west corresponding to the direction of wind (Figure 2D). 75% of the wave height is due to the swells and the remaining is the seas (Table 1). Good positive correlation (correlation coefficient of 0.97) is observed between  $H_{m0}$  and  $H_{max}$ . The ratios of significant wave parameters are expected to be constant and the theoretical value proposed for  $H_{max}/H_{1/3}$  is 1.53 (Longuet-Higgins, 1952). Our analyses show that the ratio between  $H_{max}$  and  $H_{m0}$  is 1.65 (Figure 3A) and is similar to the earlier reported results (Dattatri et al., 1979; Kumar et al., 2003; Kumar et al., 2010). For the present data, significant wave height based on zero crossing analysis ( $H_{1/3}$ ) is found to be  $3.72 \sqrt{m_0}$  (Figure 3B). In practice,  $H_{m0}$  is operationally defined as  $4 \sqrt{m_0}$ . For deep-water narrow band spectrum,  $H_{1/3}$  and  $H_{m0}$  are equivalent estimates of significant wave height (Sarpkaya and Isaacson, 1981). When a narrow frequency spectrum is assumed, all characteristic wave heights are theoretically proportional to the standard deviation of the water surface. Many field measurements have established the relationship of  $H_{1/3} \cong 0.95 H_{m0}$  in deep water because of the spectral bandwidth effect (Goda and Kudaka, 2007). However, the key assumptions are not always valid, especially in shallow water (Vandever

et al., 2008). Goda (1979) analysed field data and found that for wind-driven waves in deep water, the ratio is approximately 3.8 instead of the narrow-band value of 4 which gives a reduction of 5%. The reduction in present case is 7% and the reduction is due to the presence of sea and swells in the measured data which makes the wave spectrum relatively broad banded. For wind-driven sea waves, the assumption of a narrow-banded frequency spectrum is no longer valid. In deep water, the Rayleigh distribution still holds to a very good approximation for the zero-crossing wave heights (Longuet-Higgins, 1980), but the ratios of wave height to standard deviation have to be reduced to account for the finite frequency bandwidth. We have found  $H_{1/10}/H_{1/3}$  to be 1.25 and are slightly lower than the Rayleigh value of 1.275 due to the shallow water effects (Figure 3C).

Guedes Soares et al. (2004) showed that in addition to individual wave parameters, the asymmetry of waves can be described by the statistics of the time series, such as the skewness and kurtosis. Skewness reflects quantitatively the increased frequency of occurrence of high wave crests, as compared to the linear theory predictions, while kurtosis reflects the frequency of encountering large crest-to-trough excursions. Linear sea states will have no skewness and the positive skewness value indicate that the wave crests are bigger than the troughs. Present study showed that the skewness varied from -0.07 to 0.49 with a mean value of 0.16 which indicates that the wave crests are slightly bigger than the troughs at shallow water location. The correlation between  $H_{m0}$  and skewness is 0.72, which shows that there is a significant relation between these parameters. High waves ( $H_{m0} > 4\text{m}$ ) are associated with high (0.3-0.4) skewness value (Figure 3D). The kurtosis varied from -0.45 to 0.97. The correlation between the abnormality index (ratio of  $H_{max}$  to  $H_{m0}$ ) and the kurtosis of the sea surface elevation is 0.6. The dependence of the abnormality index on the kurtosis agrees with the results of Guedes Soares et al. (2004).

Forristall (2000) used mean wave steepness ( $S$ ) and the Ursell number ( $Ur$ ) for the parameterization of the model. The mean steepness measures the geometrical nonlinearity of the wave field, due to nonlinear wave-wave interactions and the Ursell number measures the dynamical nonlinearity, due to the finite water depth effects.  $Ur$  is high for waves with high skewness which indicates increasing of the non-linear effect lead to increasing the asymmetry in the wave field (Figure 3E). The mean steepness is high (0.04-0.05) for high waves ( $H_{m0} > 4\text{m}$ ) (Figure 3F).

### 3.2 Wave period

Significant wave period,  $T_{1/3}$  (average of the wave period associated with the largest 1/3<sup>rd</sup> of wave heights) is found to be 1.4 times the mean wave period ( $T_{m02}$ ) (Figure 4A). Long period swells with peak period more than 18 s are present during 2.2% of the time (Figure 4B). High waves ( $H_{m0} = 4$  to 5 m) have lower peak frequency (0.08 to 0.1 Hz). The values of  $T_{1/3}$  is close to the values of  $T_{m01}$  (Figure 4C). The correlation between  $T_{m02}$  and  $H_{m0}$  is 0.72, which shows that there is a significant relation between these parameters (Figure 4D). The variation of  $T_{m02}$  with  $H_{m0}$  is not following the relation proposed in SPM (1984). The relationship between these parameters can be represented by the regression:

$$T_{m02} = a H_{m0}^b \quad (1)$$

Where  $a = 5.03$  and  $b = 0.345$

Kamphuis (2001) presented the value of  $a$  and  $b$  for different locations as given below.

$a = 3.54$ ;  $b = 0.6$  for Lake Huron

$a = 4.45$ ;  $b = 0.45$  for Lake Ontario

$a = 3.94$ ;  $b = 0.38$  for North Sea

$a = 4.04$ ;  $b = 0.47$  for Dubai

$a = 6.96$ ;  $b = 0.28$  for Israel

Kumar et al. (2010) found that off Goa coast at 14 m water depth,  $a = 5.4$  and  $b = 0.25$ . The high waves ( $H_{m0} = 4$  to 5 m) are associated with mean wave period of 6.5 to 7.5 s and the high wave period (9 to 11 s) is associated with  $H_{m0}$  varying from 2.5 to 3.5 m (Figure 4D) due to the fact that the swells that are originating from a distant storm are decayed with time causing a low wave height whereas the wave period remains high.

The water depth at the wave measurement location is 15 m and hence the measured waves can be influenced by water depth. Wave length associated with the mean wave period varied from 33 to 114 m and the  $d/L$  ratio varied from 0.13 to 0.46 indicating that the measured waves are in the transitional water (SPM, 1984). 77% of the sea waves satisfy the deep water condition. The ratio of depth and wave length associated with the swell

wave period (varied from 0.06 to 0.22) satisfies the transitional water condition. Hence the waves measured are the transformed waves and the wave height and the wave direction measured can be different than that in the deep water.

### **3.3 Wave spectral characteristics**

During the measurements, the spectral narrowness parameter ( $\nu$ ) has a mean value of around 0.53 and is slightly large (around 0.6 to 0.7) when bimodal nature of the spectrum consisting of swell from north Indian Ocean and a high frequency local component is present. When the wave height is high,  $\nu$  varied from 0.4 to 0.45 indicating that the wave spectrum is relatively narrow banded during high waves. The spectral width parameter ( $\varepsilon$ ) varied from 0.64 to 0.9. During the high waves, the value of  $\varepsilon$  varied from 0.75 to 0.8. The value of the spectral peakedness parameter ( $Q_p$ ) varied from 2 to 3 for high waves. Large values of  $Q_p$  also indicate the wave spectrum is narrow banded for high waves.

The average value of JONSWAP parameters,  $\alpha$  and  $\gamma$  obtained by matching the JONSWAP spectrum with the measured spectrum is 0.002 and 1.45 and is less than the generally recommended value (0.0081 and 3.3). The difference may be due to the large fetch available at the measurement location. JONSWAP measurements are limited to a maximum fetch of 160 km. Young (1998) found that the mean value of  $\gamma$  is 1.9 for the hurricane data set.

The nature of sea state is identified based on the wave steepness ( $H_{m0}/L$ ) and the wave age ( $C/U_{10}$ ), where  $C$  is the phase speed. Thompson et al. (1984) classified ocean waves based on  $H_{m0}/L$  as sea, young swell, mature swell and old swell. According to their classification, locally generated waves or sea waves have steepness values greater than 0.025. In the present case, correlation between wave age and wave steepness is low and 8% of the time wave steepness was less than 0.025. Young sea is defined when wave age  $< 10$  and an old sea is defined as wave age  $> 25$ . Wave age of the measured data is less than 25 with most values (99%) less than 10. Hence the waves are young sea with presence of swells. Donelan et al. (1993) proposed that  $U_{10}/C_p = 0.83$  corresponds to the value of the spectrum at full development, where the spectral components below this value are classified as swell and above as wind sea. In the present case, 21% of the time the

inverse wave age is more than 0.83 (Figure 5). The non-dimensional energy [ $E = H_{m0}^2 g^2 / (16 U_{10}^4)$ ] is slightly higher than the value proposed by Donelan et al., (1992).

The maximum (or peak) wave spectral energy density estimated based on various theoretical spectra with the measured spectra is presented in Figure 6. The maximum spectral energy estimated using JONSWAP spectrum with the JONSWAP parameters estimated based on Ochi (1993) is found to be lower than that estimated using Scott and Scott-Wiegel spectra. The maximum spectral energy is estimated reasonably well (regression coefficient = 0.9) with the help of JONSWAP spectrum using the modified JONSWAP parameters.

#### 4. Conclusions

The following conclusions are based on 45 day measurement which is typical of a part of summer monsoon in India.

- Skewness of the surface elevation varied from -0.07 to 0.49 with a mean value of 0.16 which indicates that the wave crests are slightly bigger than the troughs at shallow water location.
- 75% of the wave height at the measurement location is due to the swells arriving from the south-west and the remaining is due to the seas from south-west to north-west.
- Long period swells with peak period more than 18 s are present during 2.2% of the time.
- The high waves ( $H_{m0} = 4$  to 5 m) are associated with mean wave period of 6.5 to 7.5 s and the high wave period (9 to 11 s) is associated with  $H_{m0}$  varying from 2.5 to 3.5 m.
- Wave age of the measured data is less than 25 with most values (99%) less than 10 indicating that the waves in the nearshore waters of northern Arabian Sea during the summer monsoon are swells with young sea.
- Spectral narrowness parameter varied from 0.4 to 0.45 when the wave height is high and slightly large (0.6 to 0.7) when bimodal nature of the spectrum consisting of low-



energy swell from north Indian Ocean and a high frequency local component is present.

- The water depth at the measurement location is 15 m and hence waves measured are the transformed waves and the wave height and the wave direction measured are different than that will be in the deep water.

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### Annexure: Definition of wave parameters used in the study

$$\text{Significant wave height } (H_{m0}) = 4 \sqrt{m_0} \quad (1)$$

$$\text{Mean wave period } (T_{m02}) = \sqrt{\frac{m_0}{m_2}} \quad (2)$$

$$\text{Spectral width parameter } (\varepsilon) = \sqrt{1 - \frac{m_2^2}{m_0 m_4}} \quad (3)$$

$$\text{Spectral narrowness parameter } (\nu) = \sqrt{\frac{m_0 m_4}{m_2^2} - 1} \quad (4)$$

$$\text{Spectral peakedness parameter } (Q_p) = \frac{2}{m_2^2} \int_0^\infty f S^2(f) df \quad (5)$$

$$\text{Mean wave steepness } (S) = \frac{2\pi}{g} \frac{H_{m0}}{T_{m02}^2} \quad (6)$$

$$\text{Ursell number } (Ur) = \frac{H_{m0}}{d^3 k_{01}^3} \quad (7)$$

Where  $m_n$  is the nth order spectral moment and is given by,

$$m_n = \int_0^\infty f^n S(f) df \quad n=0, 1, 2 \text{ and } 4$$

$S(f)$  is the spectral energy density at frequency  $f$ .

$k_{01}$  is the deep water wave number, corresponding to  $T_{m01}$  and  $d$  is the local water depth and  $T_{m01} = m_0/m_1$ .

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Table 1. Range and average value of wave parameters

Wave parameter	Range	Average	Standard deviation
Significant wave height, $H_s$ (m)	1.1-4.5	2.5	0.8
Significant wave height of sea, $H_{ss}$ (m)	0.4-3.4	1.2	0.4
Significant wave height of swell, $H_{sw}$ (m)	0.4-4.2	2.2	0.8
Maximum wave height, $H_{max}$ (m)	1.5-8.0	3.8	1.3
Mean wave period, $T_{m02}$ (s)	4.6-10.4	6.8	1.1
Mean wave period of sea, $T_{m02s}$ (s)	2.9-6.4	4.1	0.3
Mean wave period of swell, $T_{m02sw}$ (s)	7.1-20.5	9.9	1.6
Wave period corresponding to $H_{max}$ (s)	3.9-18.0	9.8	1.8
Peak wave period, $T_p$ (s)	6.3-20.0	11.5	2.1
Spectral peakedness parameter, $Q_p$	1.3-4.7	2.2	0.5
Spectral width parameter, $\varepsilon$	0.64-0.90	0.83	0.03
Spectral narrowness parameter, $\nu$	0.37-0.68	0.53	0.05
Peak wave direction, $\theta_p$ (deg)	157-257	225	11
Mean wave direction of sea, $\theta_{se}$ (deg)	142-318	233	13
Mean wave direction of swell, $\theta_{sw}$ (deg)	116-253	224	12
Percentage of sea	3-95	25	16
Percentage of swell	5-97	75	16
Wave length (m)	33-114	65	15
Maximum spectral energy ( $m^2 Hz^{-1}$ )	1-55	13	9.6
Wind speed ( $m s^{-1}$ )	0.3-14.9	7.1	2.7
Inverse wave age ( $U_{10}/c_p$ )	0.03-1.38	0.64	0.24
Separation Frequency (Hz)	0.06-0.2	0.15	0.03

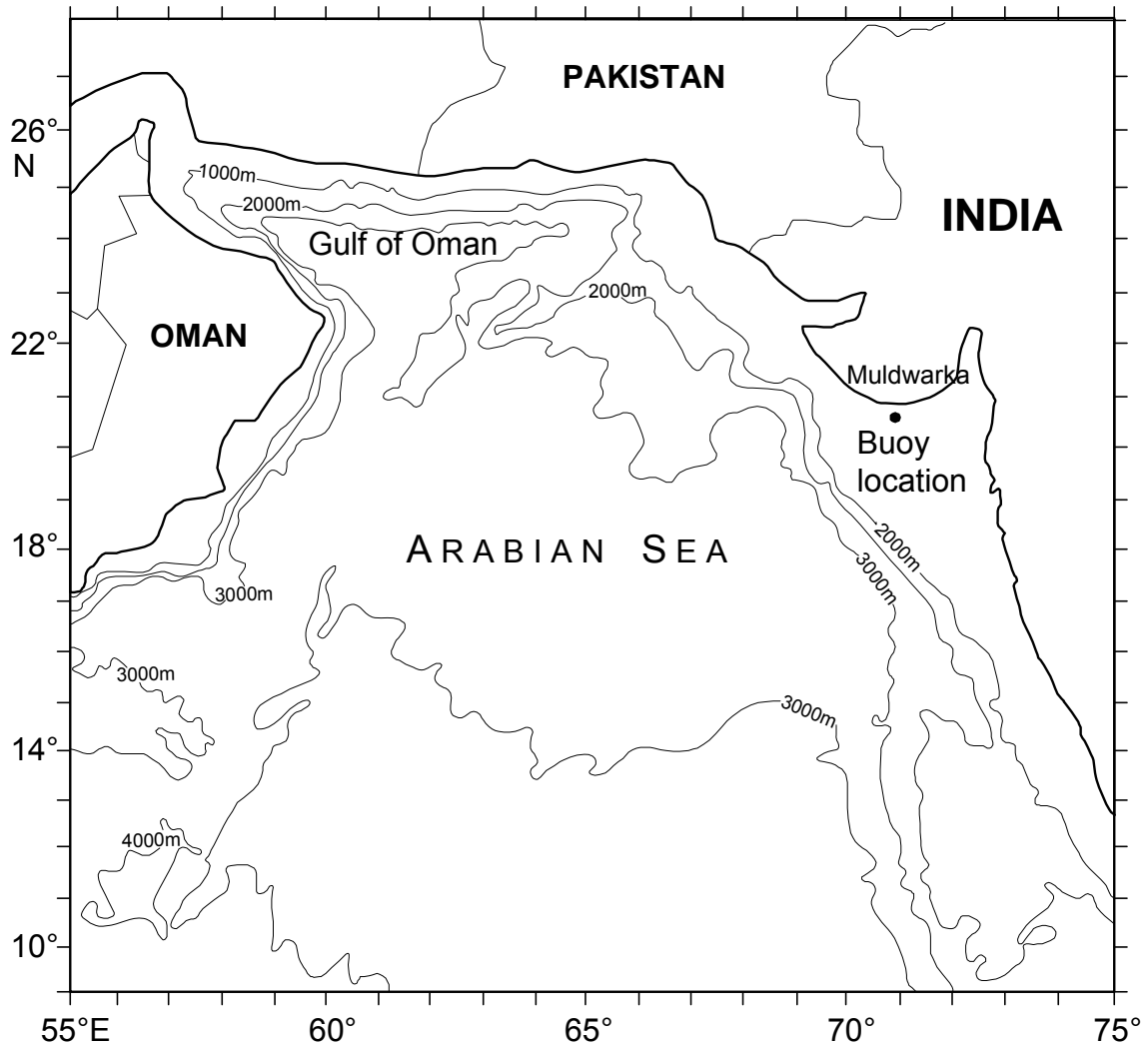


Figure 1. Location of the wave data collected during the summer monsoon period. The water depth at the measurement location is 15 m.

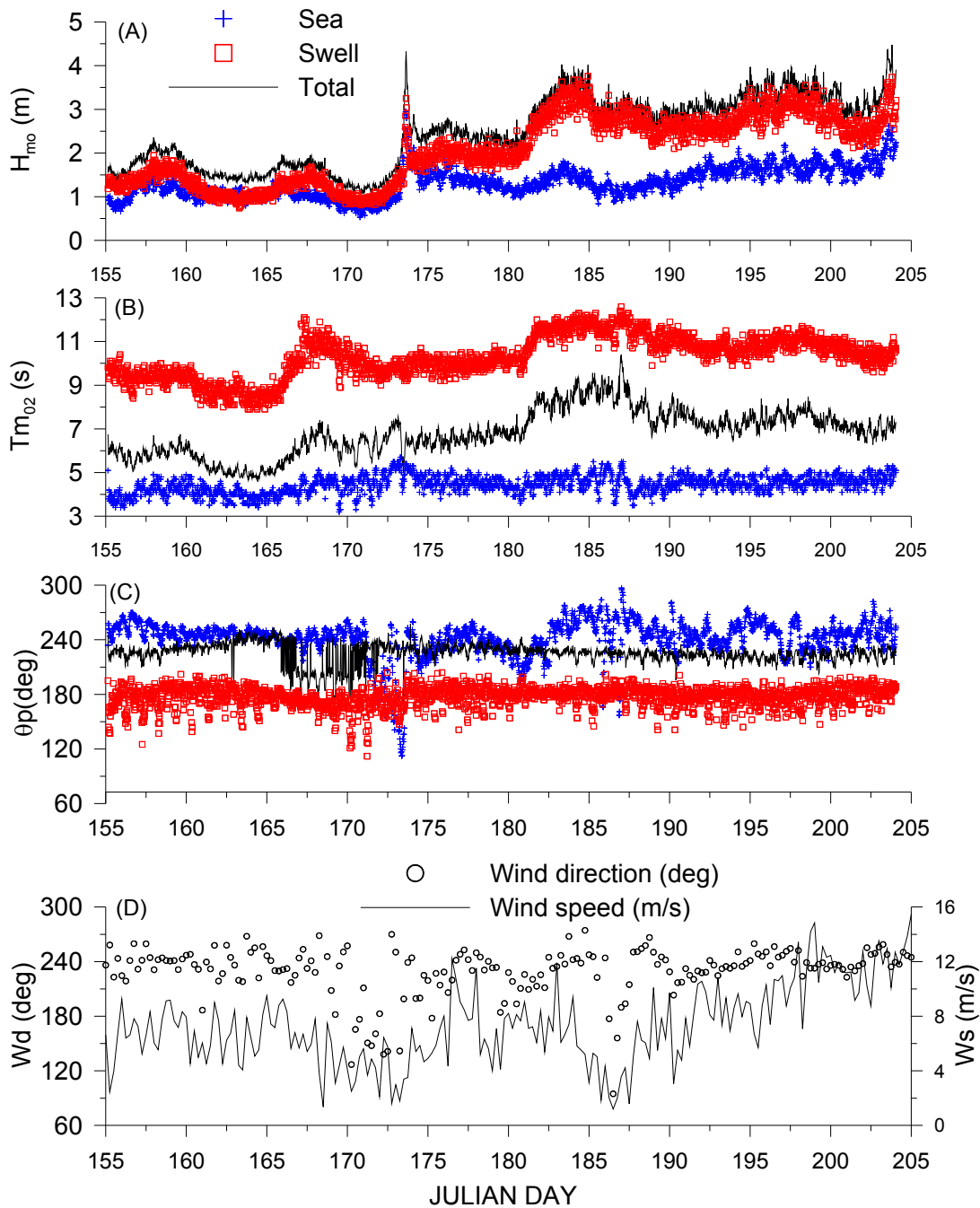


Figure 2. Variation of (A) significant wave height (-), sea (+) and swell (B) height, (B) mean wave period (-), mean wave period of sea (+), mean wave period of swell (B) (C) Mean wave direction of swell (B), mean wave direction of sea (+) and peak wave direction (D) Wind speed (-) and direction (o)



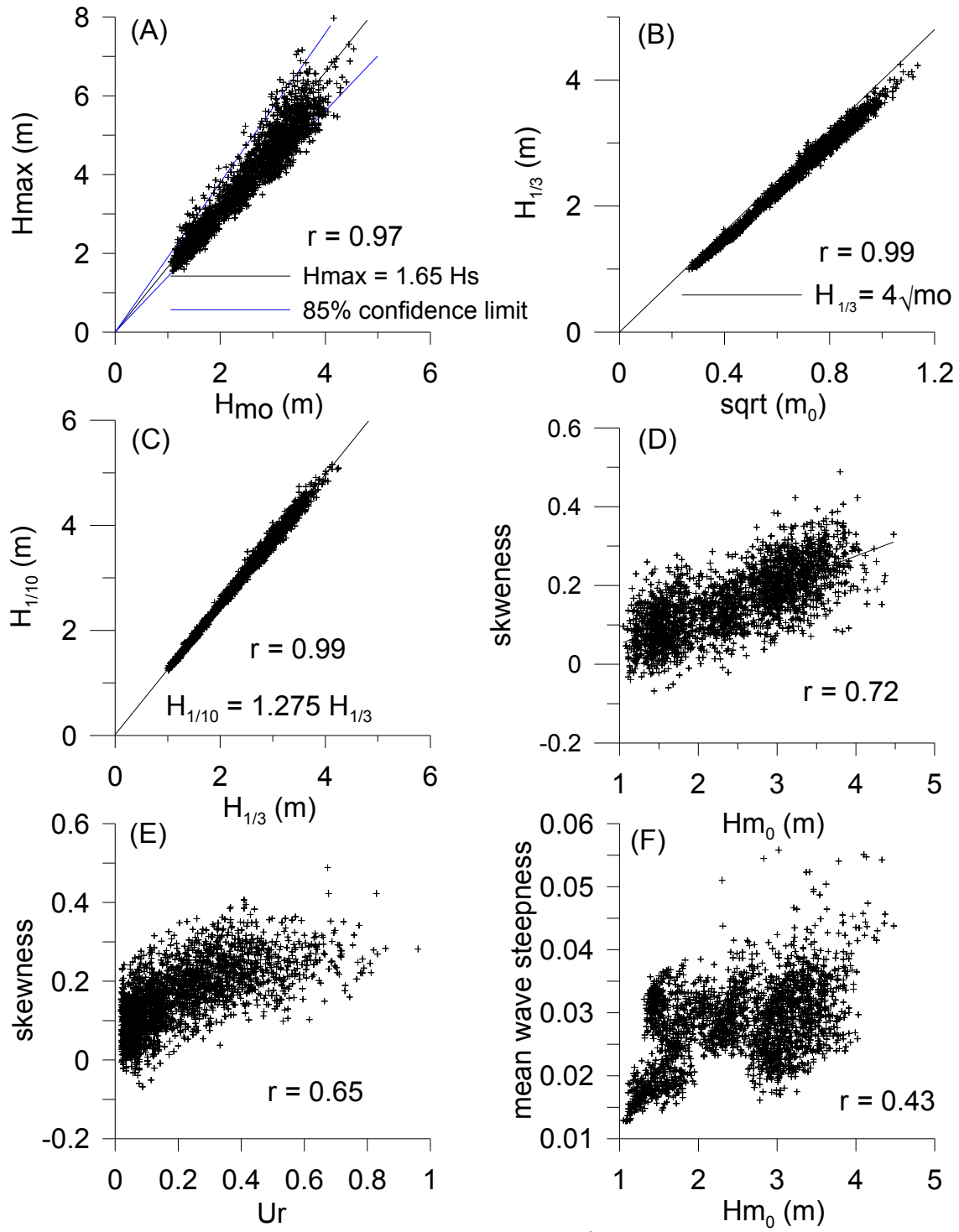


Figure 3. Variation of (A)  $H_{max}$  with  $H_{m0}$ , (B)  $H_{1/3}$  with  $\sqrt{m_0}$ , (C)  $H_{1/10}$  with  $H_{1/3}$ , (D) skewness with  $H_{m0}$ , (E) skewness with Ursel number ( $Ur$ ) and (F) mean wave steepness with  $H_{m0}$

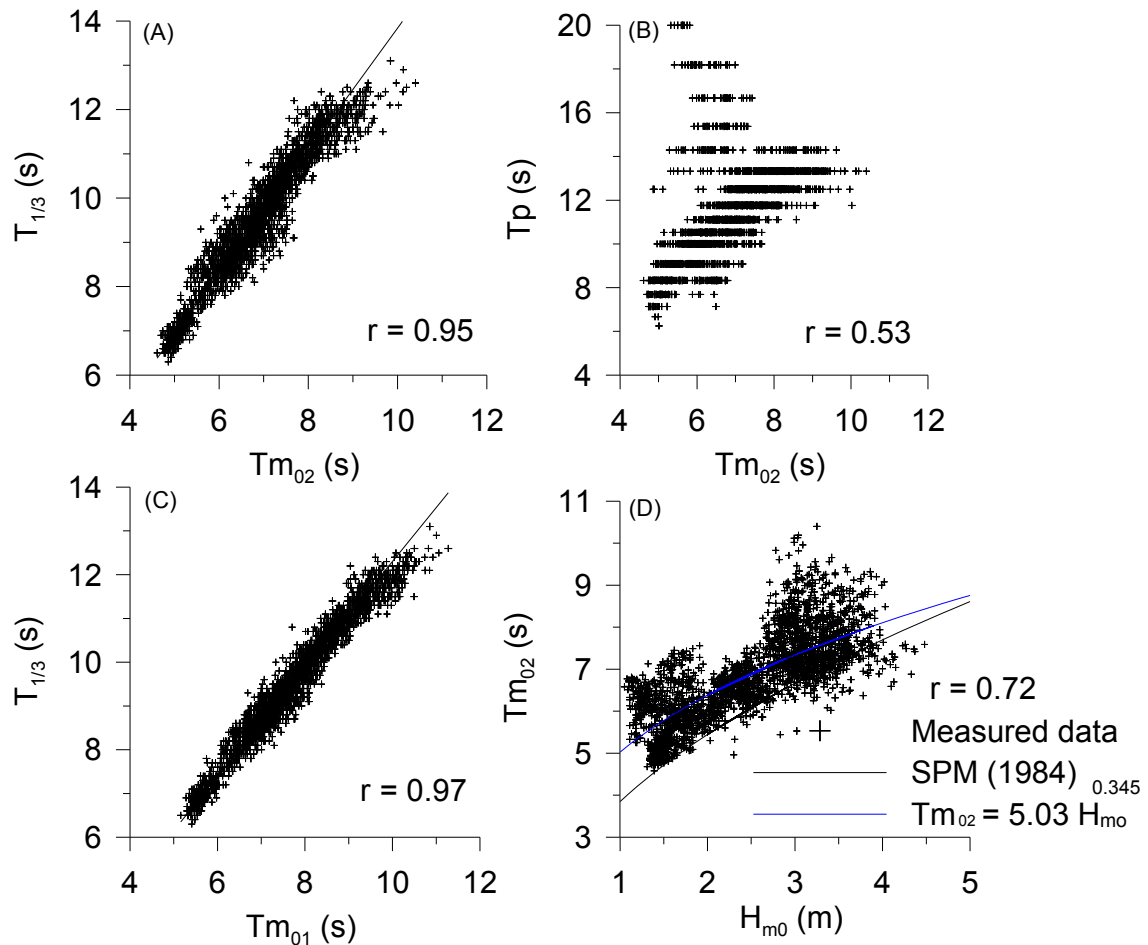


Figure 4. Variation of (A)  $T_{1/3}$  with  $Tm_{02}$ , (B)  $Tp$  with  $Tm_{02}$ , (C)  $T_{1/3}$  with  $Tm_{01}$  and (D)  $Tm_{02}$  with  $H_{m0}$

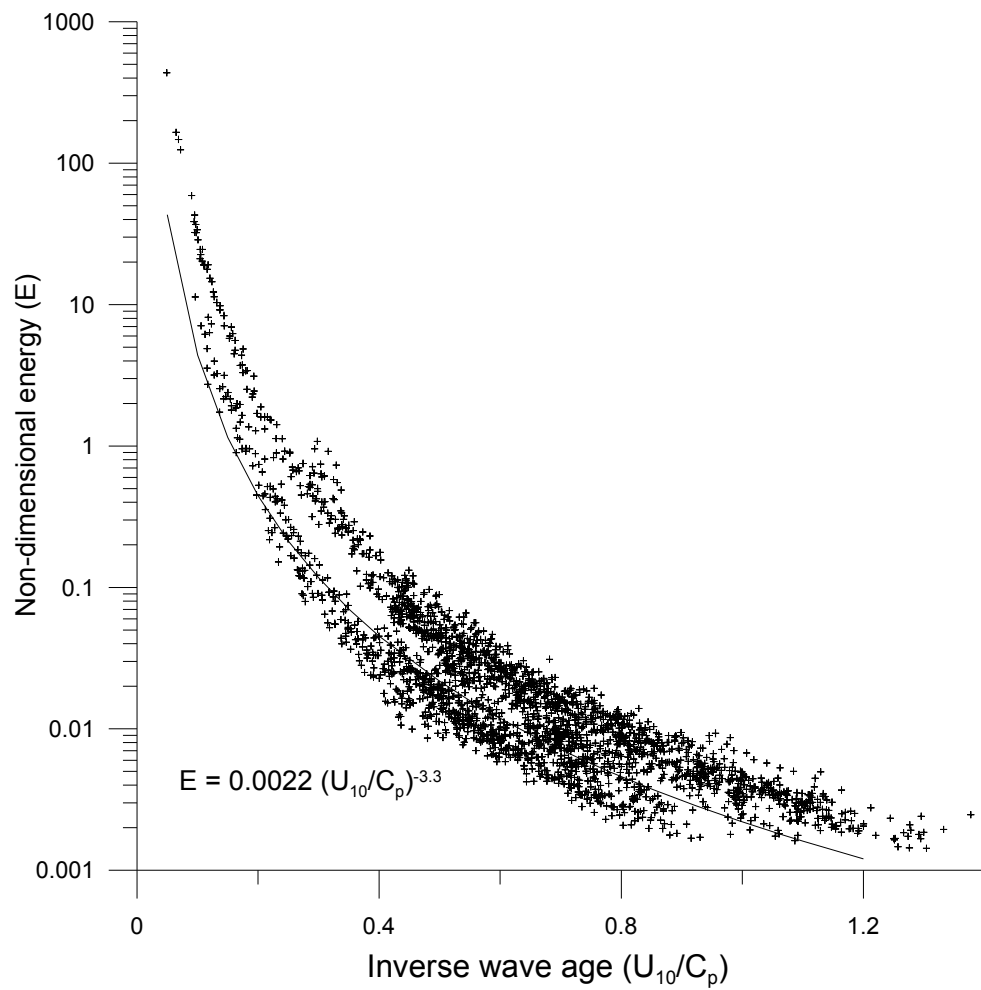


Figure 5. Variation of non-dimensional energy with inverse wave age

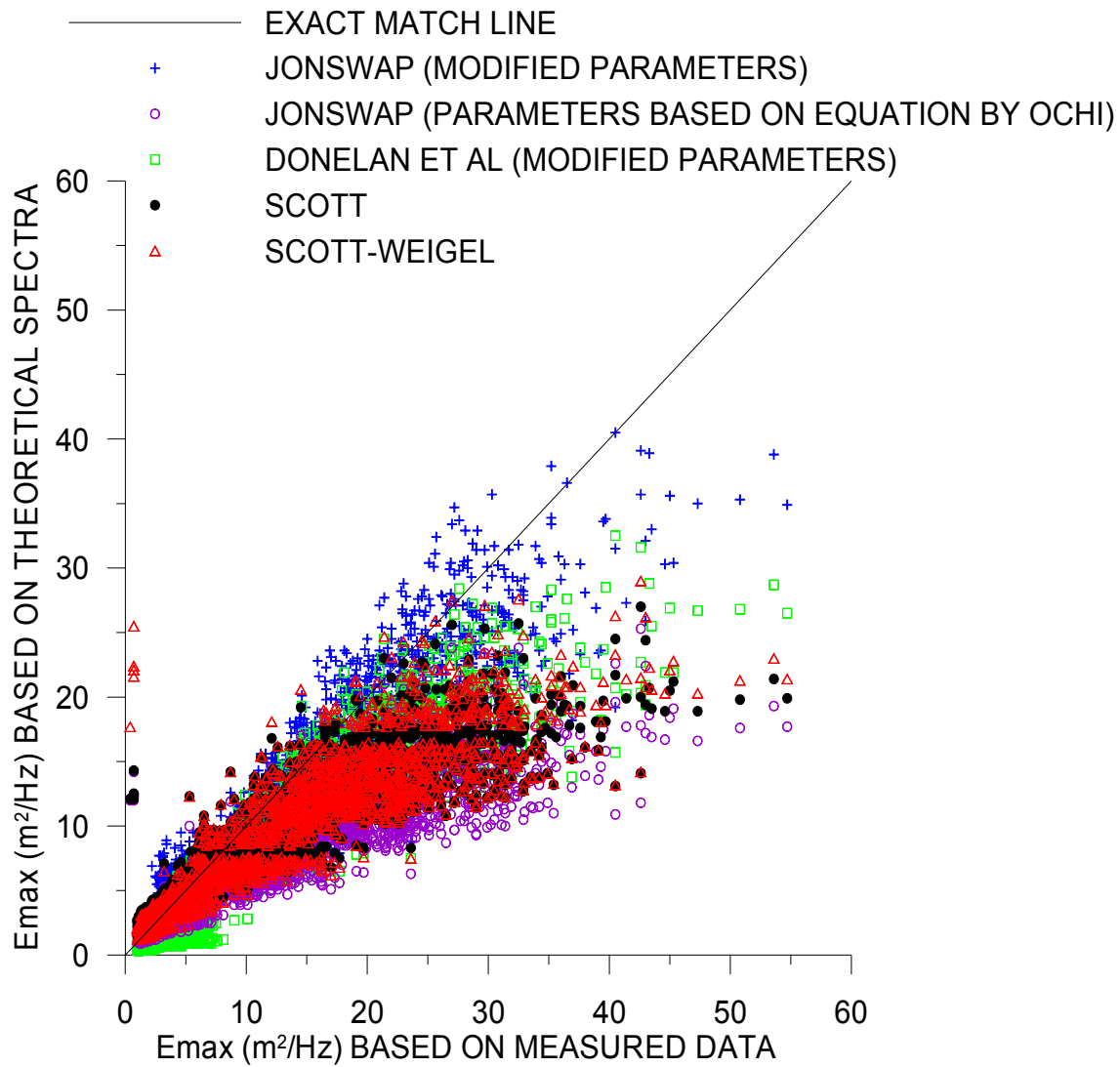


Figure 6. Variation of maximum spectral energy density ( $E_{max}$ ) estimated based on different theoretical formulations and the one estimated from the measured time series of sea surface elevation