

Wave crest height distribution during the tropical cyclone period

V. Sanil Kumar*, S. Harikrishnan, Sourav Mandal

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 email:sanil@nio.org

Abstract

The wave crest height plays a vital role in designing both the fixed and floating marine structures. The present study examines the measured wave crest data at 18 m water depth off Visakhapatnam in the northwestern Bay of Bengal during the tropical cyclone (TC) Hudhud. The maximum significant wave height (H_s) measured during the TC is 7.59 m on 12 October 2014 at 1030 UTC; the maximum wave height is 10.75 m and the crest height is 6.81 m. The average ratio of the crest height of the wave to the wave height is 0.4 to 0.7 during the TC. For waves with H_s more than 6 m, the most extreme wave height is 1.46 to 1.83 times the H_s and the crest height of the wave is 0.81 to 1.47 times the H_s of the same 30-minutes record. The study shows that during the high wave events, the Weibull distribution agrees with the crest height distribution of observed data better than the Rayleigh distribution.

Keywords: Wind wave, Tropical Cyclone, Wave crest height, Rayleigh distribution, Weibull distribution, Extreme waves

1. Introduction

Extreme waves are responsible for the most extreme loadings on ocean vessels and offshore structures (Cuilin et al., 2010). The waves grow from absorbing the energy and momentum of the forcing wind. When the wave crest is higher than the deck elevation, the structure is more likely to get damaged. One of the causes of failure of platforms is wave-in-deck loads and unexpectedly high crest heights (McConnell et al., 2004). Thus, if extreme crest height is generated at the location of marine structures, this can be a significant issue in the design of these structures. It is therefore important that statistical models describing the crest height distribution are required during the design process of structures. The crest height distribution is a function of wave steepness and the water depth. When ocean waves are studied as random processes, wave location at a fixed point is assumed to be Gaussian-based on linear wave theory. In the case of a Gaussian sea, where there is zero up-crossing, the wave height distribution follows Rayleigh distribution (Longuet-Higgins, 1952). A real wave shows a small but distinct departure from a Gaussian surface. In such a case, the wave asymmetry can be described by adding a quadratic correction term to the linear model (Forristall, 1978). The resulting process is non-Gaussian and referred to as a second-order Weibull model.

According to Prevosto et al. (2000), Weibull parameterisations should take both the wave steepness and the dimensionless depth into account. The common expectation is that the Rayleigh distribution over-predicts the probability occurrence of large waves when compared with field data and, the crest height distributions based on second-order wave theory agree with most high-quality measurements (Forristall, 1978; Tayfun, 1990; Massel, 1996; Mori et al., 2002; Krogstad and Barstow, 2004; Stansell, 2005; Muralidharan et al., 2007; Lian and Haver, 2015). Forristall (2000) established a second-order crest distribution, based on a large number of simulations and is now commonly being used to describe the short-time second-order crest distribution. As the wave propagates, the profile becomes asymmetric with higher crests together with shallower and flatter troughs due to the interaction between individual sine waves. Butler et al. (2009) show that the linear wave model is often simplistic and leads to errors in the predicted crest height of about 10-20%. The theoretical derivation of the distribution of crest height is a tricky problem, especially when non-linearities have to be considered. In a given length of time, the maximum crest height over an area will be larger than the maximum crest at a single point (Forristall, 2006). Lian and Haver (2015) compared the second-order distribution by Forristall (2000) to the measurements at 190 m water depth in the North Sea and reported that the second-order distribution follows very well the measured data. Weibull distribution is also more effective for the simulation of maximum wave height distributions and estimating various wave height parameters (Muralidharan et al., 2007).

Amrutha and Kumar (2017) observed that for the high waves in the eastern Arabian Sea, the most extreme wave height is 1.50 to 1.62 times of the significant wave height, whereas the most extreme crest height is 1.23 to 1.35 times the significant wave height of the same 30-minutes record.

The high waves are generated due to the tropical cyclones, also described as typhoons or hurricanes depending on global origin. In the north Indian Ocean, especially in the Bay of Bengal, the occurrence of tropical cyclones (TC) is high. In the Bay of Bengal, significant wave height up to 7.3 m is measured during the TC Phailin (Amrutha et al., 2014) and 8.4 m during the passage of Orissa super cyclone (Rajesh et al., 2005). Young (2006) reported the influence of the TC on wave parameters. Numerical modeling of the wave heights during the tropical cyclone Hudhud indicates that the numerical model overestimates (~5 to 17%) the wave heights during most of the TC period, except the peak value, which was underestimated by ~15% (Samiksha et al., 2017).

Although the influence of TC on the wave parameters has been an area of active research, the distribution of crest height during the TC is not described in the literature. Hence, it is important to know the crest height distribution of waves during the TC and is the aim of the present study. The data used in this study and the methods are described in section 2. Results and discussion in section 3 and the conclusions are summarised in section 4.

2. Data and methodology

The domain of the present study is the coastal waters of Visakhapatnam. The annual distribution of the wave characteristics of the study area is presented by Anjali Nair et al. (2019). The wave data measured from 10 to 14 October 2014 at an interval of 30 minutes at 18 m water depth covering the period of TC Hudhud with the Datawell directional waverider buoy is used in the study. The wave data of 2 October 2014 is used to compare the crest height distribution during the low wave conditions. Buoy use accelerometers to measure waves with wave heights up to 40 m and wave periods of 1.6–30 s with a vertical resolution of 0.01 m. The displacement of the buoy is sampled at a rate of 3.84 Hz and the data are transmitted and logged with a sampling frequency of 1.28 Hz. In the present study, the memory card data of the buoy is used to avoid transmission losses. An apparent wave is defined as the profile of the sea surface between two consecutive up-crossings of the still-water level. The wave crest height (H_c), i.e., the height of the crest level above still-water level and the wave trough height (H_t), i.e., the depth of trough below the mean water level for each individual wave are calculated from the heave time series data of 30-minutes duration. The wave height (H) of the individual wave is the sum of the crest height and trough height. The height of the maximum wave in a 30-minutes duration is H_{max} . The cyclonic storm Hudhud originated from a

low-pressure system in the Andaman Sea on 6 October 2014 intensified into a severe cyclonic storm on 9 October 2014 (IMD, 2014). Severe cyclonic storm Hudhud crossed the waverider buoy location within 10 km distance and made landfall about 30 km west-northwest of Visakhapatnam on 12 October 2014, noon local time (Fig. 1) with maximum sustained wind speeds of ~50 m/s (IMD, 2014). The track of the cyclone is shown as the red line in Figure 1. ERA5 wind data (Hersbach and Dee, 2016), the atmospheric reanalyses of the global climate produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) nearest location (18.50° N; 84.50° E) is used to assess the wind during the cyclone.

The wave crest height, η is the maximum of the apparent wave. Second-order Weibull distribution satisfying various environmental conditions and water depths is suggested as the short-term model for crest heights (Cuilin et al., 2010). The sea surface elevation is generally described by the second-order process and this distribution is commonly used in the estimation of extreme crests (Lian and Haver, 2015).

$$P(\eta) = \exp \left[- \left(\frac{\eta}{\alpha H_s} \right)^\beta \right] \quad (1)$$

Where H_s is the significant wave height and η is the crest height. The parameters α and β are expressed in terms of two parameters, a measure of steepness S_1 and Ursell number U_r is a measure of the impact of water depth on nonlinearity of waves.

$$S_1 = \frac{2\pi H_s}{gT^2} \quad U_r = \frac{H_s}{k^2 d^3}$$

Where k is the wave number related to the wave period (T), d is the water depth. For long-crested sea, α and β can be expressed as,

$$\alpha = 0.3536 + 0.2568 S_1 + 0.0800 U_r$$

$$\beta = 2 - 1.7912 S_1 - .5302 U_r + 0.2824 U_r^2$$

The crest height follows the same Rayleigh distribution because of the symmetry of a Gaussian sea state. According to Mori et al. (2002), the Rayleigh distribution over-predicts the probability of occurrence of large waves when compared with models of field data. The wave crest height distribution can be obtained as,

$$F = \exp \left[- \frac{H^2}{8\sigma^2} \left(1 + \frac{\lambda}{4\sigma^2} H^2 \right)^2 \right] \quad (2)$$

Where σ is wave surface standard deviation. The variance σ^2 is an important parameter in wave probability forecast.

$$\lambda = \frac{\delta^2}{8} \quad \text{where } \delta \text{ is the wave steepness defined as } \delta = \frac{2\pi\bar{H}}{gT^2}$$

Where, the characteristic mean period \bar{T} and mean height \bar{H} are obtained from the zero up-crossing definition.

Stansberg (1991) gives an approximation for crest height in deep water, where the expected maximum crest elevation, η_{\max} for a given wave extreme wave height H_{\max} can be obtained by:

$$\eta_{\max} = \frac{H_{\max}}{2} \left[\frac{2\pi}{\lambda} \cdot \frac{H_{\max}}{2} \right] \quad (3)$$

Where λ is the wavelength, derived with linear wave theory, using mean wave period and H_{\max} is the maximum wave height.

The wave elevation time series can be expressed as (see Branlard, 2010);

$$\eta(t) = \sum_n A_n \cos(\omega_n t - k_n x + \epsilon_n) \quad (4)$$

where $A_n = \sqrt{2S(f_n)\Delta f}$, $\epsilon_n = \text{rand}(0, 2\pi)$, $S(f_n)$ being the given spectrum and k_n being the wave number, satisfies the dispersion relation $\omega_n^2 = gk_n \tanh k_n h$, where ω_n , g and h are being the angular frequency, gravitational constant and water depth respectively. The dispersion relation has a real root (k_n) and multiple numbers of imaginary root. To find the roots of dispersion relation, Newton-Raphson method is applied with $\omega_n = 2\pi f_n$, Thereafter substituting k_n , ω_n and ϵ_n in the expression of $\eta(t)$ for non-zero x , the simulated time series obtained.

The theoretical distribution (A_i) is compared with observed distribution (B_i) using BIAS and root-mean-square error (RMSE).

$$\text{BIAS} = \frac{1}{N} \sum_{i=1}^N (A_i - B_i) \quad (5)$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (A_i - B_i)^2} \quad (6)$$

Where N is the number of data points, and the overbar represents the mean value.

3. Results and discussion

During 9 to 13 October 2014, the significant wave height (H_s) estimated from the wave spectrum varies from 1.17 to 7.59 m, with an average value of 2.74 m (Fig. 2). $H_{1/3}$ from the zero up-crossing method varied from 1.07 to 7.34 m, with an average value of 2.58 m. As reported in earlier studies, the

$H_{1/3}$ from the time series is smaller than the H_s from the wave spectrum. The H_s is high mainly on 12 October 2014 with a daily mean value of 4.03 m, whereas on 11 and 13 October, daily mean H_s is 2.92 and 2.18 m, respectively (Table 1).

The maximum sustained wind speed during the cyclone is around 50 m/s (IMD, 2014) and the maximum wave height measured is 10.75 m. Whereas, the wind speed from ERA5 for nearest location (18.50° N; 84.50° E) indicate that wind speed varied from 6 to 26.1 m/s. The wind speed during TC is largely underestimated in reanalysis data due to the still too low model resolution and dependence on parameterized processes used in the reanalyses (Hodges, 2017). Hence, the wind speed reported in Fig. 2 is to be used with caution. The relative change in the wave height (1.2 to 7.6 m) is higher when compared to the relative change in the wind speed (6 to 26.1 m/s) (Fig. 2).

The time series plots of four records containing the high waves on 12 October 2014 are presented in Figure 3. The height of the waves before and after the maximum wave height measured is 55 to 84% of the maximum value in different records. The height of the top 20 waves in a 30-minutes record containing the highest H_s on 12 October 2014 at different times indicates that the second-highest wave height is ~5 to 14% less than the highest wave height (Fig. 4a). The maximum wave height measured is 10.75 m and the second-highest wave in the same 30 minutes record is 10.2 m (Fig. 4a). H_s for the 30 minutes record containing the highest waves is 7.59 and the ratio of H_{max} to H_s is ~ 1.4 and is lower than the theoretical value of 1.62 to 1.64 for 190 to 220 waves (Longuet-Higgins, 1952). During the TC, the ratio between H_{max} and H_s for the 30 minutes record varied from 1.4 to 2.3, with an average value of 1.66 and the average value measured is close to the theoretical value. Since the wave data during the cyclone has a peak period between 9.1 and 12.5 s with an average value of 10.8 s, the available sea states are in a regime of intermediate and shallow water depth. The period of a wave can have a major effect on the dynamic response of marine structures. The wave period corresponding to the highest wave height is 13.7 s (Fig. 4d). The wave period varied from 9 to 15 s for the highest 20 waves on 12 October 2014.

In a 30-minutes record, the crest height is 0.81 to 1.47 times the H_s of the same 30-minutes data (Table 1). For the highest waves recorded elsewhere, such as Andrea and New Year waves, the crest height is 1.63 and 1.55 times the H_s (Bitner-Gregersen et al., 2014). The highest value observed in the present study is less than that reported elsewhere. The waves are often referred to as “rogue” or “freak” waves when the crest height exceeds 1.25 H_s or the crest-to-trough height is above twice the H_s (Haver, 2000). Sanil Kumar et al. (2013) and Amrutha et al. (2014) observed that during the TCs, the average ratio of crest height to the corresponding wave height in 30 minutes record varied from 0.6 to 0.7. In the present study, the average ratio of crest height to the corresponding wave height ranged from 0.4 to

0.7 with an average value of 0.58 (Fig. 4b). The ratio of the crest height to the trough height of the top 20 waves in 30-minutes record varied from 0.7 to 2.4 with an average value of 1.46 (Fig. 4c). The surface profile containing the extreme wave crests and extreme wave troughs on 12 October 2014 is presented in Figure 5. The maximum crest height is 6.81 m and the maximum trough height is 5 m.

Scatter plot of crest and trough heights from the 30-minutes record for waves with significant wave height more than 3 m from 10 to 13 October 2014 for all the data and for maximum wave height data in a 30-minutes record is presented in Figure 6. Wave crest height is greater than the trough height for the maximum wave height data. During the growth process, waves also become steeper and hence high waves have larger crest heights than the trough height. The maximum crest height in a 30 minutes record is for the highest wave for height more than 8 m, whereas for waves with height less than 8 m, the maximum crest height is either for the highest wave or for waves with height less than the highest wave (Fig. 7a). In each 30-minutes records, the height of the wave having a maximum trough height is mainly less than the maximum wave height (Fig. 7b).

During the study period, the maximum crest height varied from 1.66 to 6.81 m. Figure 8 compares the two theoretical distributions with the field data at different times on 12 October 2014. The Weibull distribution agrees well with the observed distribution, but the Rayleigh distribution shows a deviation from the other two distributions for high waves (Fig. 8a to 8e). The maximum crest height measured is ~ 8% lower than that obtained following the conventional Rayleigh distribution based on data recorded. The earlier studies have shown that Rayleigh distribution over-predicts the probability of occurrence of large waves compared with the observed data (Massel, 1996). From the figure 8a to 8e, it is clearly shown that the Rayleigh distribution estimates are higher than the observed value for high waves. As the wave height increases, the period also increases to a certain extent (Fig. 9a). Due to the increase in the wave period, the wavelength increases and the wave feel the bottom and hence, the height can change. When the significant wave height is more than 3 m, the wave satisfies the intermediate wave regime (depth/wavelength between 0.05 and 0.5). In intermediate water, the highest wave disagrees with theoretical values. Most of the probability models of wave crest heights considered the effects of non-linearities. It is seen from Fig. 8 that for this location, the Forristall second-order model (i.e., the Weibull model) nearly coincides with observed data for high waves (Fig. 8a to 8e). These models yield a significant larger extreme crest height than the Rayleigh model. The Rayleigh distribution appears to be somewhat conservative as compared to the second-order model of Forristall. It should, however, be stressed that regarding the most extreme waves, the higher-order effect may have a certain impact and, therefore, the Forristall model can be considered as a lower bound model regarding extreme crest heights.

The Root Mean Square Error (RMSE) and BIAS between the various distribution functions and field data for all the 30-minutes records on 12 October 2014 are determined and presented in Figure 9a to 9c along with the wave height and wave period. For high waves ($H_{1/3} > 3$ m), the RMSE and BIAS are less for Weibull distribution compared to Rayleigh distribution. On 12 October 2014, the RMSE of the Rayleigh distribution varies from -0.02 to 3.32 m with a mean value of 1.82 m, whereas that of Weibull distribution is from -0.7 to 0.98 m with a mean value of 0.57 m. The Rayleigh distribution is biased 0.08 m higher than the observed distribution and the Weibull distribution is biased 0.04 m lower than the observed data (Fig. 9b and 9c).

The Weibull and Rayleigh distributions are also fitted to the data during the low wave conditions ($H_{1/3} < 1$ m) (Fig. 10). During the low wave conditions, both distributions perform well, but still, the Weibull distribution outperforms the Rayleigh distribution as evident from the low RMSE and BIAS values (Fig. 9e and 9f). The analysis shows that the Weibull distribution has better agreement with the observed data than the Rayleigh distribution, both during the high and low wave conditions.

In order to know how the time series generated from the wave spectrum differs from the original measured time series, the stochastic wave time series is generated from the given spectrum. Figure 11 shows the measured time series and simulated time series along with the wave spectrum. It is important to note that in the process of making spectrum from a wave signal, the phase information of the signal is lost; hence, it is not possible to simulate the original wave time-series signal. Since ϵ_n in equation (4) is a random number between 0 and 2π , simulated time series is not unique. The H_{\max} based on zero up-crossing method from the simulated time series is 11.7 m, whereas that of the measured time series is 10.75 m. From the measured time series, zero down-crossing method resulted in H_{\max} of 11.8 m. The maximum crest and trough height from the simulated time series is 6.88 m and 6.45 m, whereas it is 6.81 m and 5 m from the measured time series. However, the spectrum generated from the simulated time series has nearly similar statistical properties of the given spectrum. The agreement between the two spectra reveals that the procedure for the generation of time series is valid. Hence, the simulated time series nearly satisfy the expected statistics of the original time series.

4. Concluding remarks

The examination of the time series data on sea surface elevation recorded during the TC Hudhud indicates that the highest wave height measured is 10.75 m with a wave period of 13.7 s and the significant wave height of the 30-minute record is 7.59 m. The second-highest wave height in a 30-minutes record is ~5 to 14% less than the highest wave height. The crest height of the wave is 0.81 to 1.47 times the significant wave height of the same 30-minutes data and the most extreme wave

height is 1.46 to 1.83 times the significant wave height. The crest height distribution agrees with the Weibull distribution.

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Reference

- Amrutha, M.M. Sanil Kumar, V., Anoop, T.R., Balakrishnan Nair, T.M., Arun Nherakkol, Jeyakumar, C., 2014. Waves off Gopalpur, northern Bay of Bengal during the Cyclone Phailin, *Annales Geophysicae*, 32, 1073-1083 doi:10.5194/angeo-32-1073-2014.
- Amrutha, M.M., Sanil Kumar, V., 2017. Characteristics of high monsoon wind-waves observed at multiple stations in the eastern Arabian Sea. *Ocean Science Discussions*, 1–30. <https://doi.org/10.5194/os-2017-84>.
- Anjali Nair, M., Sanil Kumar, V., Amrutha, M.M., Murty, V.S.N., 2019. Features of locally and remotely generated surface gravity waves in the inner-shelf region of northwestern Bay of Bengal. *Int J Climatol*. 39:1644-1664, doi: 10.1002/joc.5907
- Bitner-Gregersen, E. M., Fernandez, L., Lefèvre, J. M., Monbaliu, J. And Toffoli, A., 2014. The North Sea Andrea storm and numerical simulations, *Nat. Hazards Earth Syst. Sci.*, 14, 1407–1415.
- Branlard, E., 2010. Generation of time series from a spectrum: Generation of wind time series from the Kaimal spectrum, Generation of wave time series from the JONSWAP spectrum, Technical report, Technical university of Denmark, 1-19.
- Butler, R.W., Machado, U. B., Rychlik, I., 2009. Distribution of wave crests in a non-Gaussian sea, *Applied Ocean Research*, 31, 57-64.
- Cuilin, L.I., Dingyong, Y.U., Gao Yangyang, Yang Junxian., 2010. Crest-Height Distribution of Nonlinear Random Waves. *J. Ocean Univ. China (Oceanic and Coastal Sea Research)*. 31-36.
- Forristall, G.Z., 1978. On the statistical distribution of wave heights in a storm. *J. Geophys. Res.:* Oceans 83 (C5), 2353–2358.
- Forristall, G.Z., 2000. Wave crests distributions: Observations and second order theory, *J. Phys. Oceanography*. 30, 1931- 1943.

- Forristall, G.Z., 2006. Maximum wave heights over an area and the air gap problem, Proc. OMAE 2006: 25th International Conference on Offshore Mechanics and Arctic Engineering, OMAE2006-92022, Hamburg.
- Haver, S., 2000. Evidences of the existence of freak waves. In *Rogues Waves 2000*. Proceedings of a Workshop Organized by Ifremer and held in Brest, France, 29-30.
- Hersbach, H., Dee, D., 2016. ERA5 reanalysis is in production. ECMWF Newsletter 147.7.
- Hodges, K., Cobb, A., Vidale, P.L., 2017. How Well Are Tropical Cyclones Represented in Reanalysis Datasets?. *J. Climate*, 30, 5243–5264.
- IMD, 2014. Very Severe Cyclonic Storm, HUDHUD over the Bay of Bengal (07-14 October 2014): A Report, Cyclone Warning Division India Meteorological Department, New Delhi, India. <http://www.rsmcnewdelhi.imd.gov.in/images/pdf/publications/preliminary-report/hud.pdf> (accessed 1 September 2019).
- Krogstad, H., Barstow, S.F., 2004. Analysis and Applications of Second-Order Models for Maximum Crest Height. *Journal of Offshore Mechanics and Arctic Engineering*. 126, 66-71.
- Lian, G., Haver, S.K., 2015. Measured crest height distribution compared to second order distribution. In: *Proceedings of the 14th International Workshop on Wave Hindcasting and Forecasting*, Key West, Florida, USA November 8-13, 2015.
- Longuet-Higgins, M. S., 1952. On the statistical distribution of sea waves. *J. Mar. Res.*, XI(3), 245–265.
- Massel, S. R., 1996. *Ocean surface waves: Their physics and prediction*, World Scientific, Singapore.
- McConnell, K., Allsop, W., Cruickshank, I., 2004. Piers, jetties and related structures exposed to waves: Guidelines for hydraulic loadings. *Proceedings of the Institution of Civil Engineers - Maritime Engineering*, Volume 158, 138–148.
- Mori, N., Liu, P.C., Yasuda, T., 2002. Analysis of freak waves measurements in the sea of Japan. *Ocean Engineering* 29, 1399–1414.
- Muralidharan, G., Rao, A.D., Mourani, S., 2007. Extreme wave height prediction and validation for a cyclonic condition during southwest monsoon. *3rd International Conference on Solar Radiation and Day Lighting*, New Delhi, India, vol. 1, 180–188.
- Prevosto, M., Krogstad, H., Agnes Robin, 2000. Probability distributions for maximum wave and crest heights. *Coastal Engineering*. 40, 329–360.
- Rajesh, G., Joseph, K.J., Harikrishnan, M., Premkumar, K., 2005. Observations on extreme meteorological and oceanographic parameters in Indian seas, *Curr. Sci.*, 88, 1279–1282.
- Samiksha, V., Vethamony, P., Antony, C., Bhaskaran, P., Nair, B., 2017. Wave-current interaction during Hudhud cyclone in the Bay of Bengal. *Natural Hazards and Earth System Sciences*, 17, 2059-2074.

Sanil Kumar, V., Johnson Glejin , Dubhashi, K.K, Balakrishnan Nair, T.M., 2013, Waves off Puducherry, Bay of Bengal during cyclone THANE, *Natural Hazards*, 69 (1), 509-522, doi 10.1007/s11069-013-0713-z.

Stansberg, C.T. 1991. Extreme wave asymmetry in full scale and model scale experimental wave trains, Proc. 10th OMAE conference, Stavanger, Norway.

Stansell, P., 2005. Distributions of extreme wave crest and trough heights measured in the North Sea. *Ocean Engineering*, 32, 1015-1036.

Tayfun, M.A., 1990. Distribution of large wave heights. *J. Waterw. Port, Coast. Ocean Eng.* 116 (6), 686–707.

Young, I.R., 2006. Directional spectra of hurricane wind-waves, *J Geophys Res* 111, C08020, doi:10.1029/2006JC003540.

Table 1. Range and mean value of various wave height parameters along with the crest and trough height ratios for records with maximum wave height equal or above 3 m during 10 to 13 October 2014

	10 October 2014		11 October 2014		12 October 2014		13 October 2014	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
H_s (m)	1.80-2.18	1.97	1.94-4.51	2.92	1.92-7.34	4.03	1.80-2.51	2.18
H_c (m)	1.63-2.22	1.94	1.92-4.39	2.86	1.85-6.81	4.09	1.80-2.38	2.11
H_t (m)	1.45-1.98	1.61	1.62-3.61	2.35	1.53-5.00	2.95	1.62-2.29	1.91
H_{avg} (m)	1.08-1.36	1.22	1.18-2.76	1.79	1.14-4.67	2.51	1.14-1.63	1.36
H_{max} (m)	3.01-3.70	3.25	3.19-7.05	4.84	3.23-10.75	6.59	3.10-4.49	3.70
H_c/H_s	0.89-1.11	0.99	0.81-1.32	0.98	0.84-1.47	1.02	0.84-1.24	0.97
H_t/H_s	0.74-0.95	0.82	0.69-0.95	0.81	0.59-1.04	0.76	0.73-1.08	0.88
H_{max}/H_s	1.48-1.83	1.65	1.38-2.15	1.67	1.39-2.34	1.66	1.51-1.95	1.70
H_c/H_{max}	0.52-0.69	0.60	0.52-0.65	0.59	0.53-0.72	0.61	0.49-0.65	0.57
H_t/H_{max}	0.44-0.56	0.50	0.39-0.56	0.49	0.37-0.62	0.46	0.44-0.59	0.52

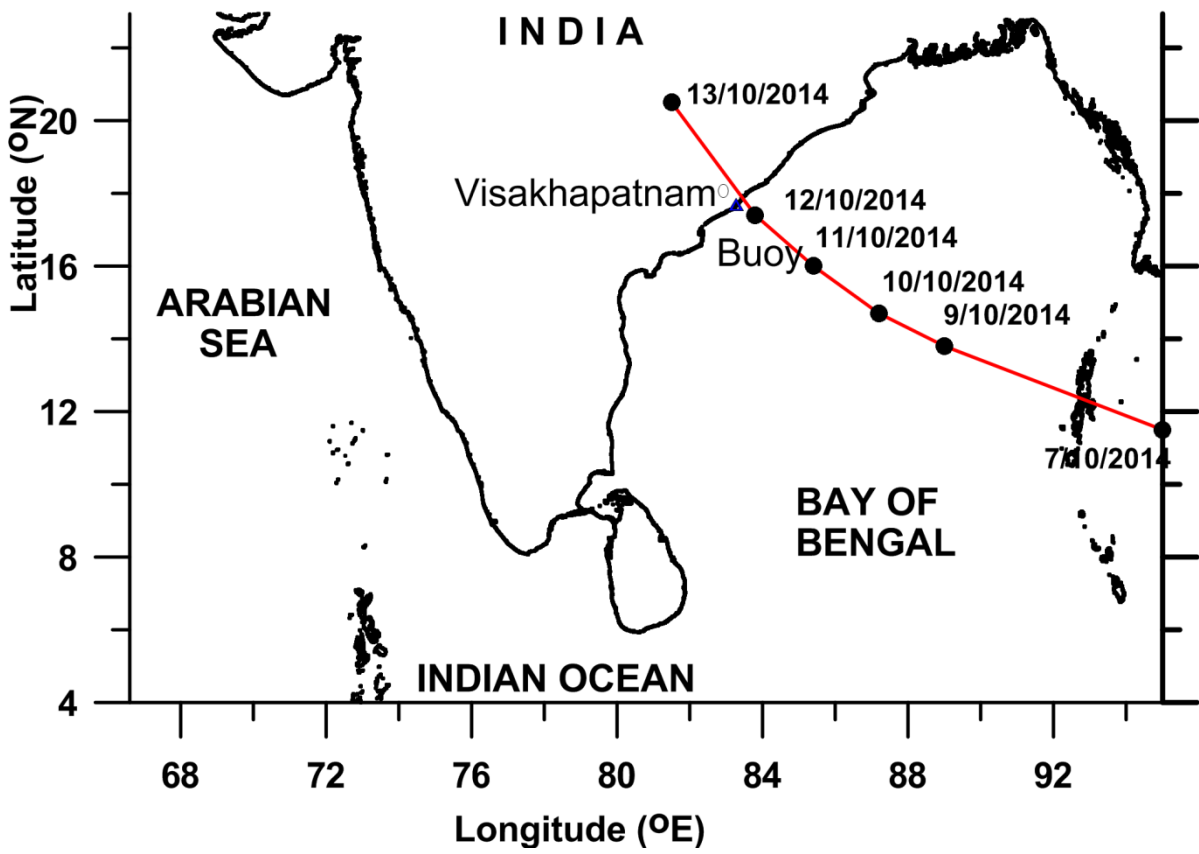


Figure 1. Track of the tropical cyclone Hudhud and the waverider buoy location

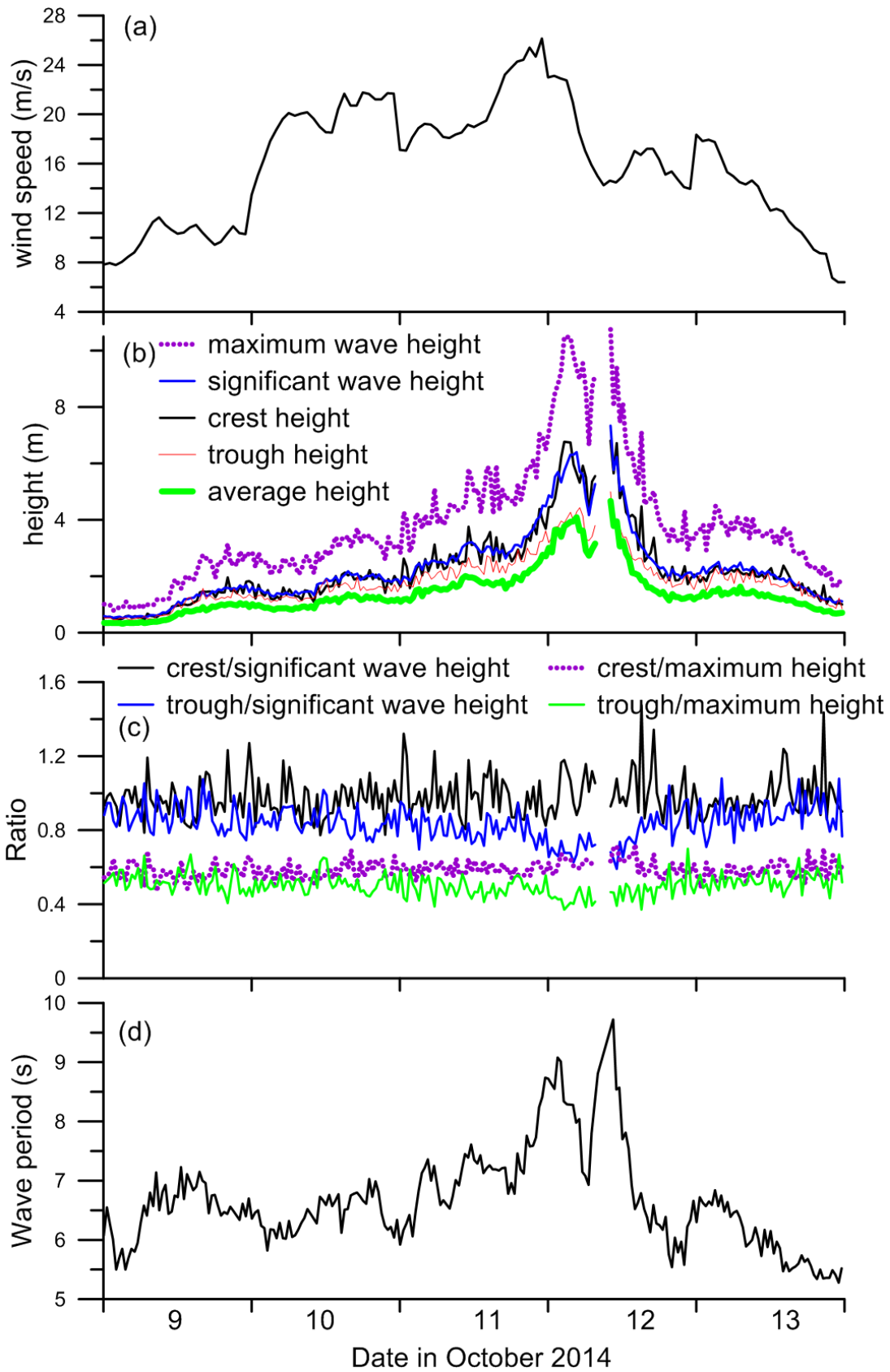


Figure 2. Time series plot of a) wind speed, b) maximum wave height, significant wave height, crest height, trough height and average wave height, c) ratio of crest to significant wave height, trough to significant wave height, crest to maximum wave height and trough to maximum wave height during 9 to 13 October 2014

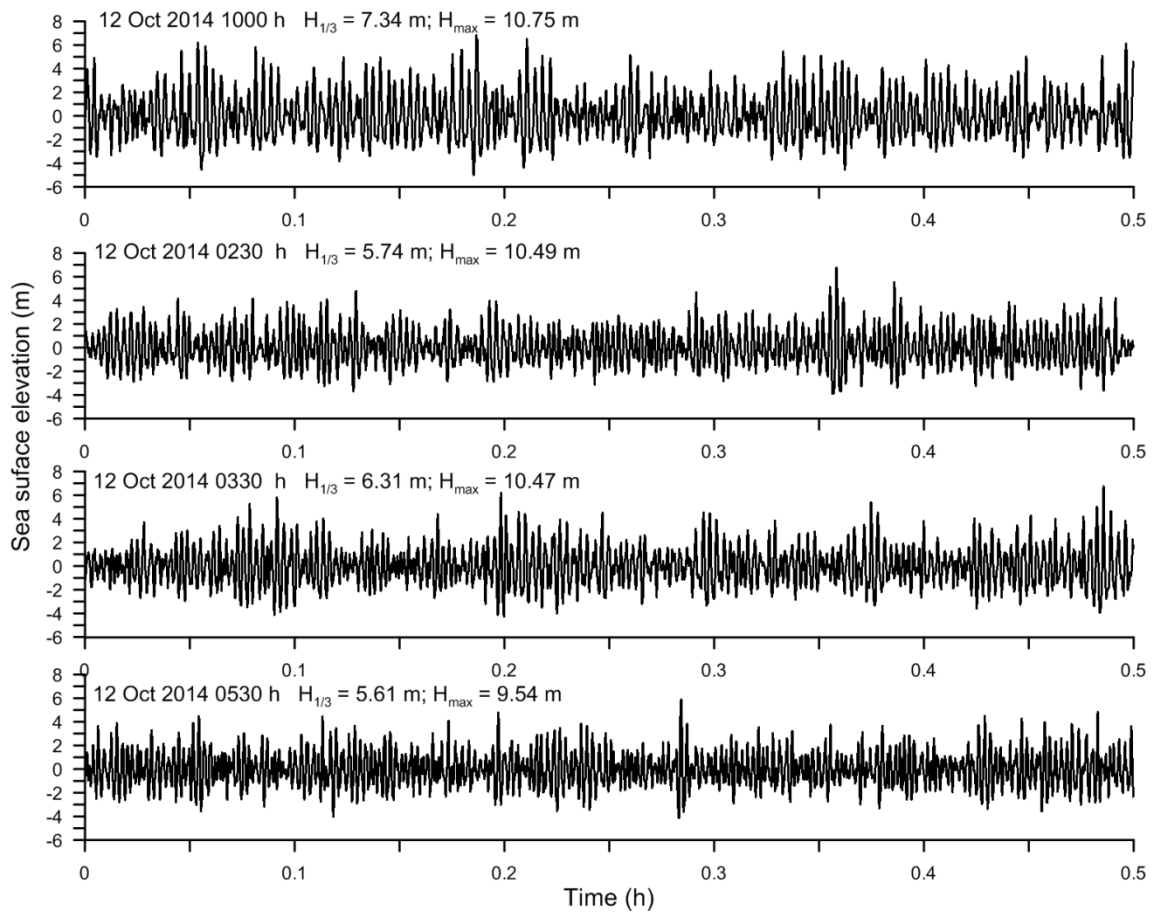


Figure 3. Surface elevation time series record of 30-minutes duration on 12 October 2014 containing the highest wave. The 30-minutes records with top 4 values of H_{max} (10.75, 10.49, 10.47 and 9.54 m) at 1000, 0230, 0330 and 0530 h are presented.

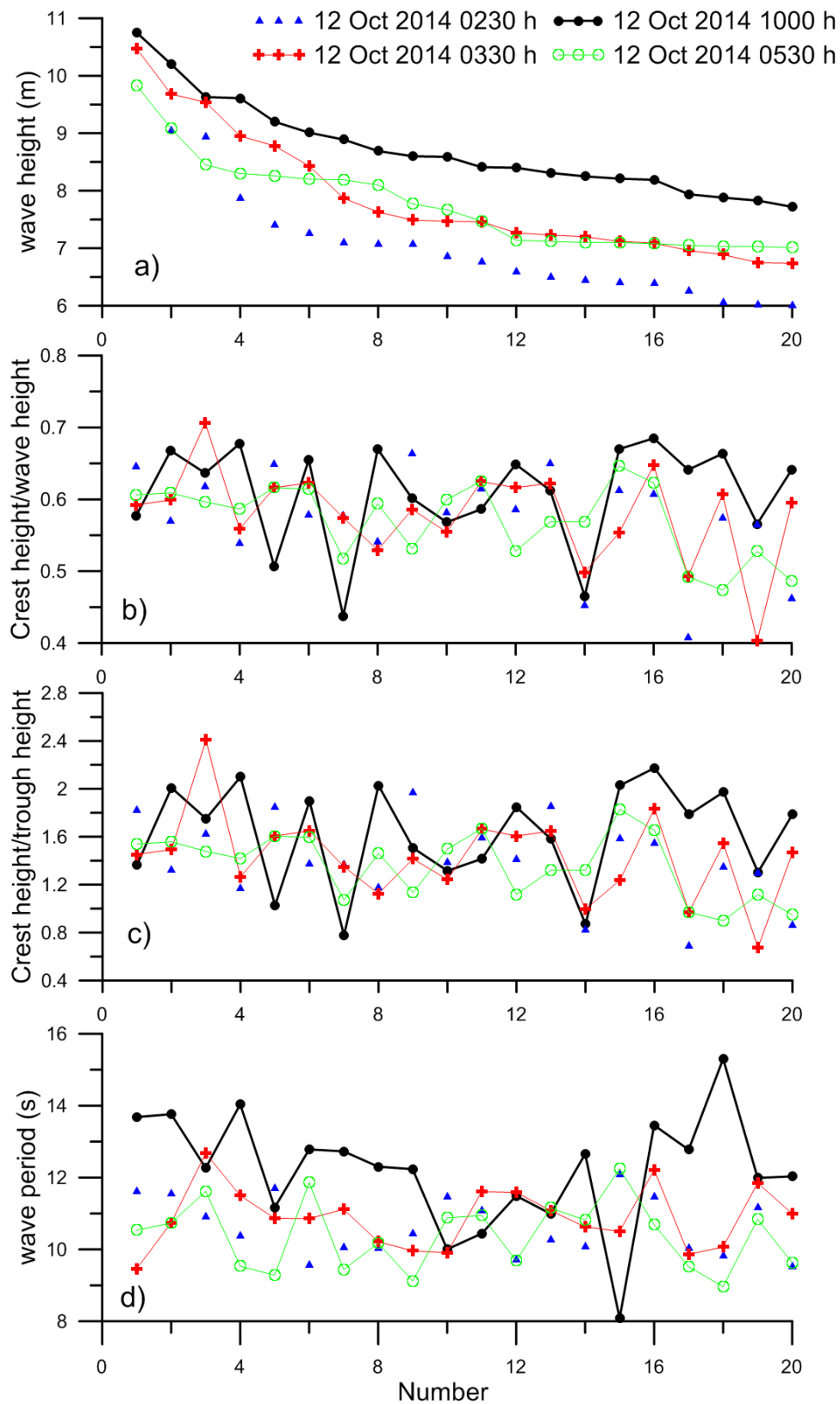


Figure 4. a) Height of the top 20 waves in the 30-minutes record containing the highest maximum wave height, b) ratio of the crest height and wave height, c) ratio of crest height and trough height and d) wave period. The 30-minutes records with top 4 values of H_{max} (10.75, 10.49, 10.47 and 9.54 m) at 1000, 0230, 0330 and 0530 h are presented.

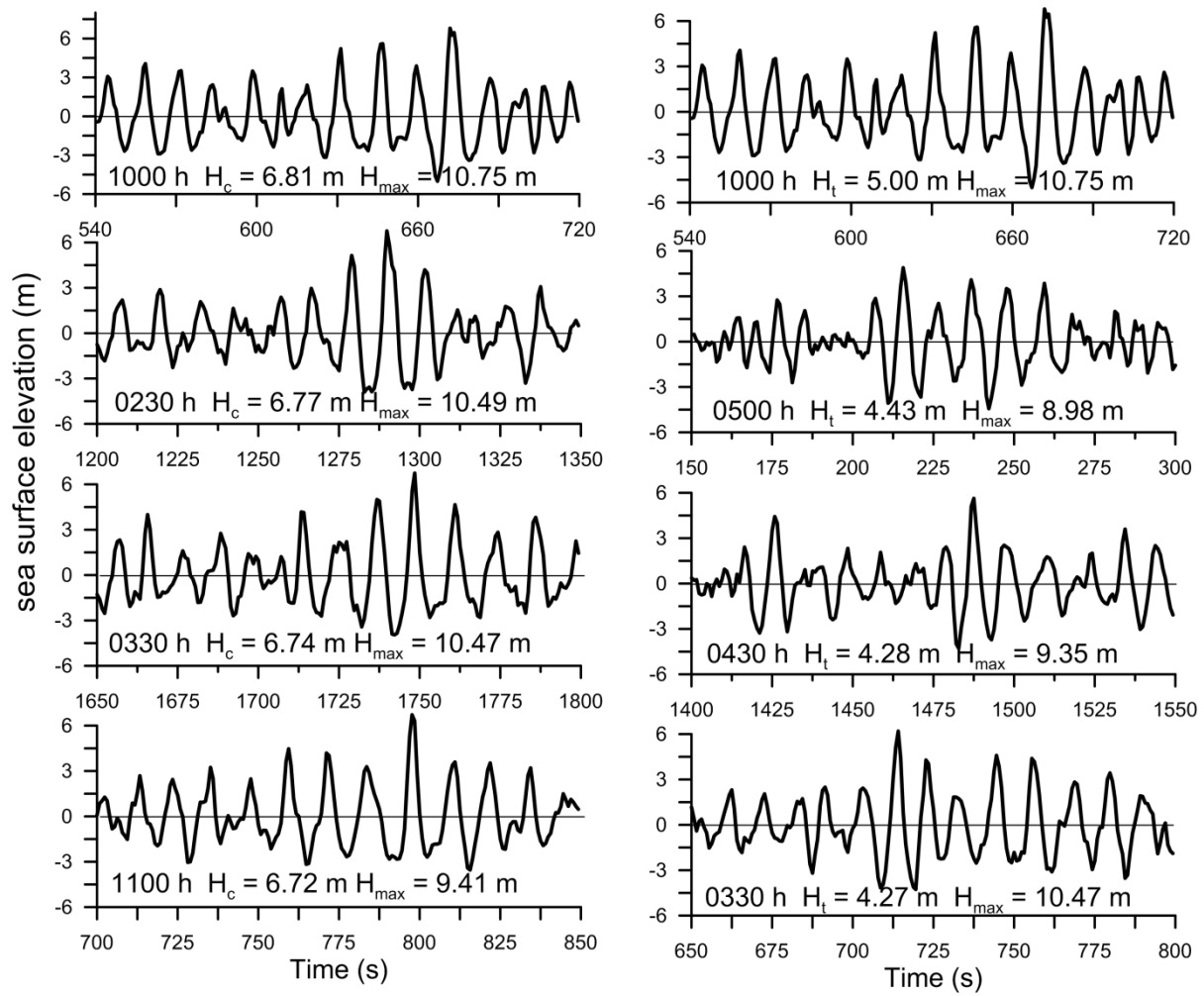


Figure 5. Surface elevation time series record containing extreme wave crest and trough measured on 12 October 2014. Top 4 records having highest crest heights (6.81, 6.77, 6.74 and 6.72 m) are presented in left panel and those with highest trough heights (5.00, 4.43, 4.28 and 4.27 m) are in right panel.

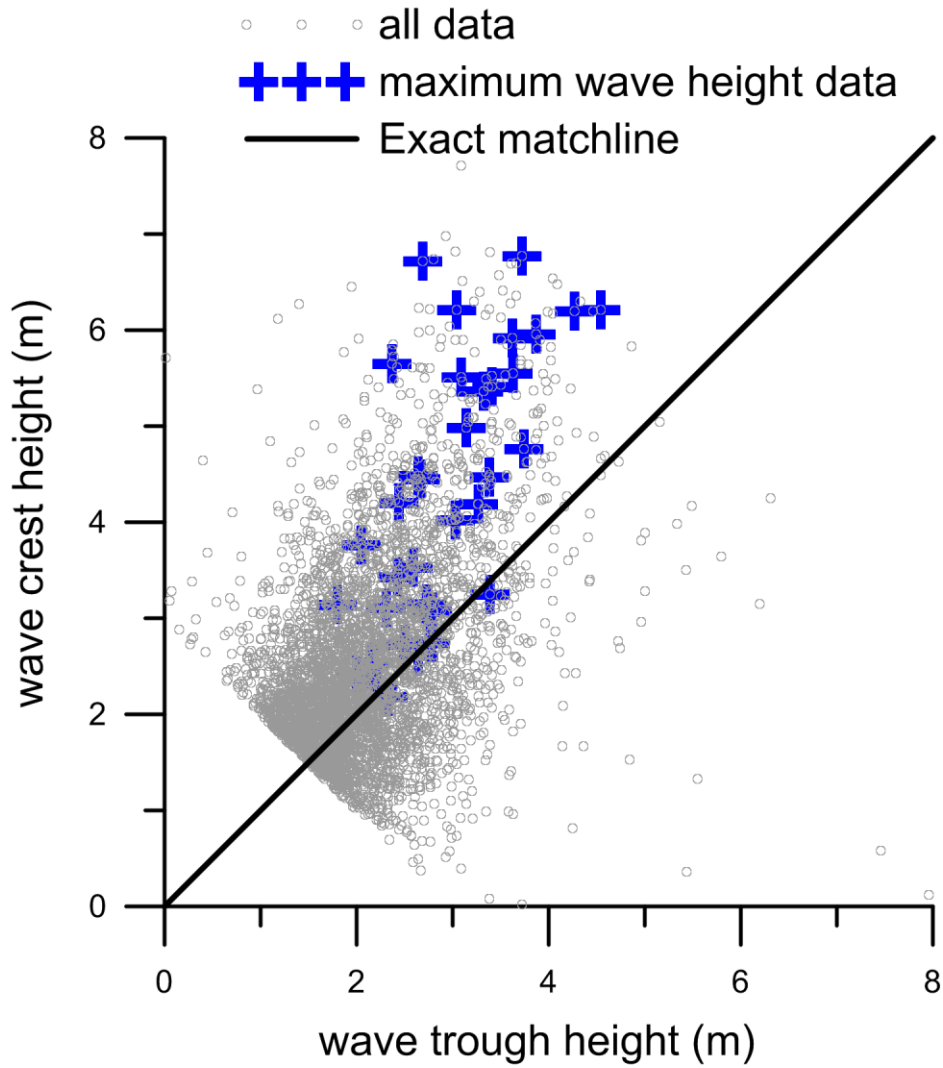


Figure 6. Scatter plot of crest and trough heights from 30-minutes record for waves with significant wave height more than 3 m, showing departures from the 1:1 slope. The grey dots indicate all the data and the blue cross is for maximum wave height data in the 30-minutes record

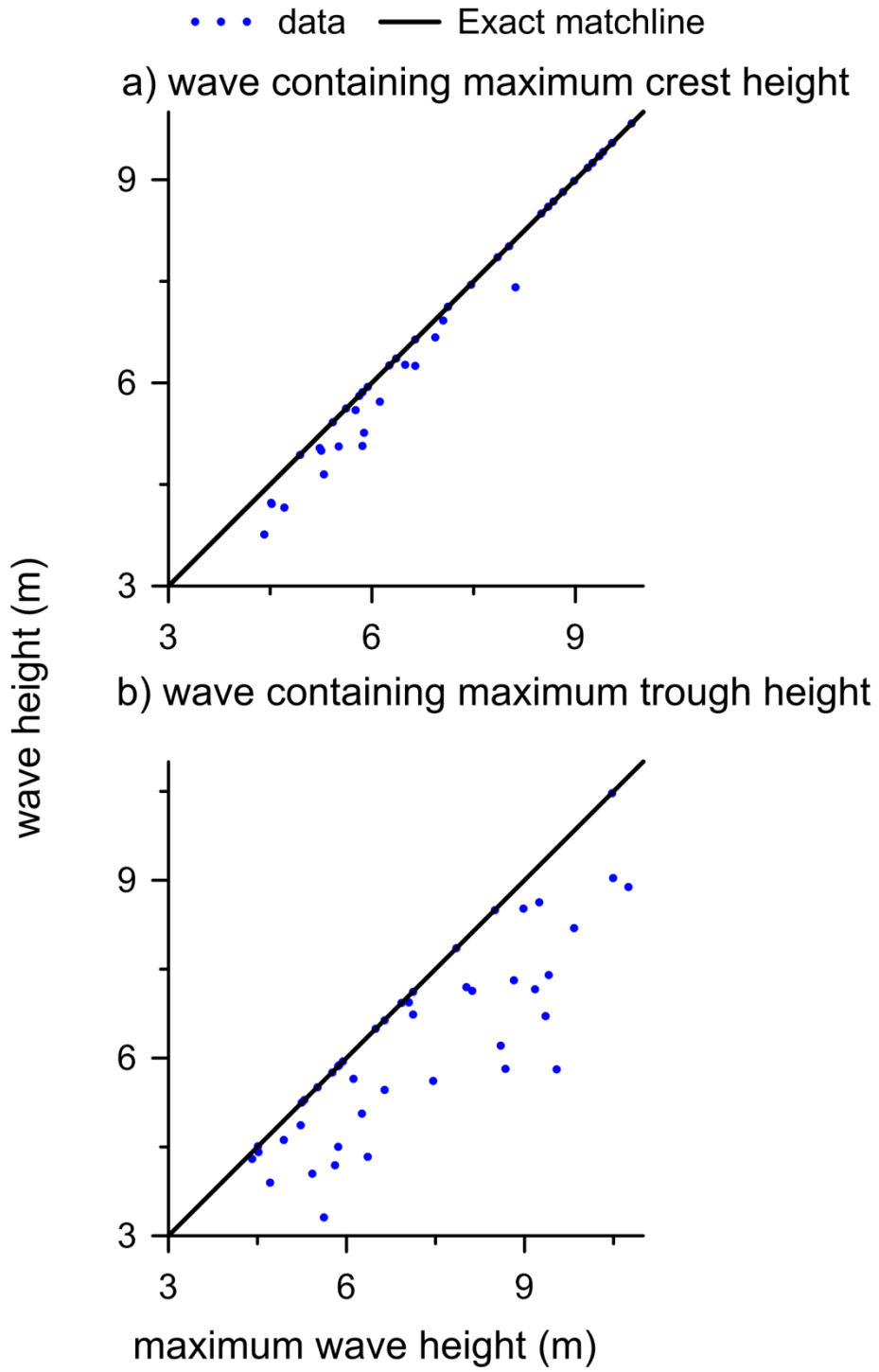


Figure 7. Scatter plot of a) wave height containing maximum crest height with maximum wave height in 30-minutes record and b) wave height containing deepest trough height and maximum wave height in 30-minutes record

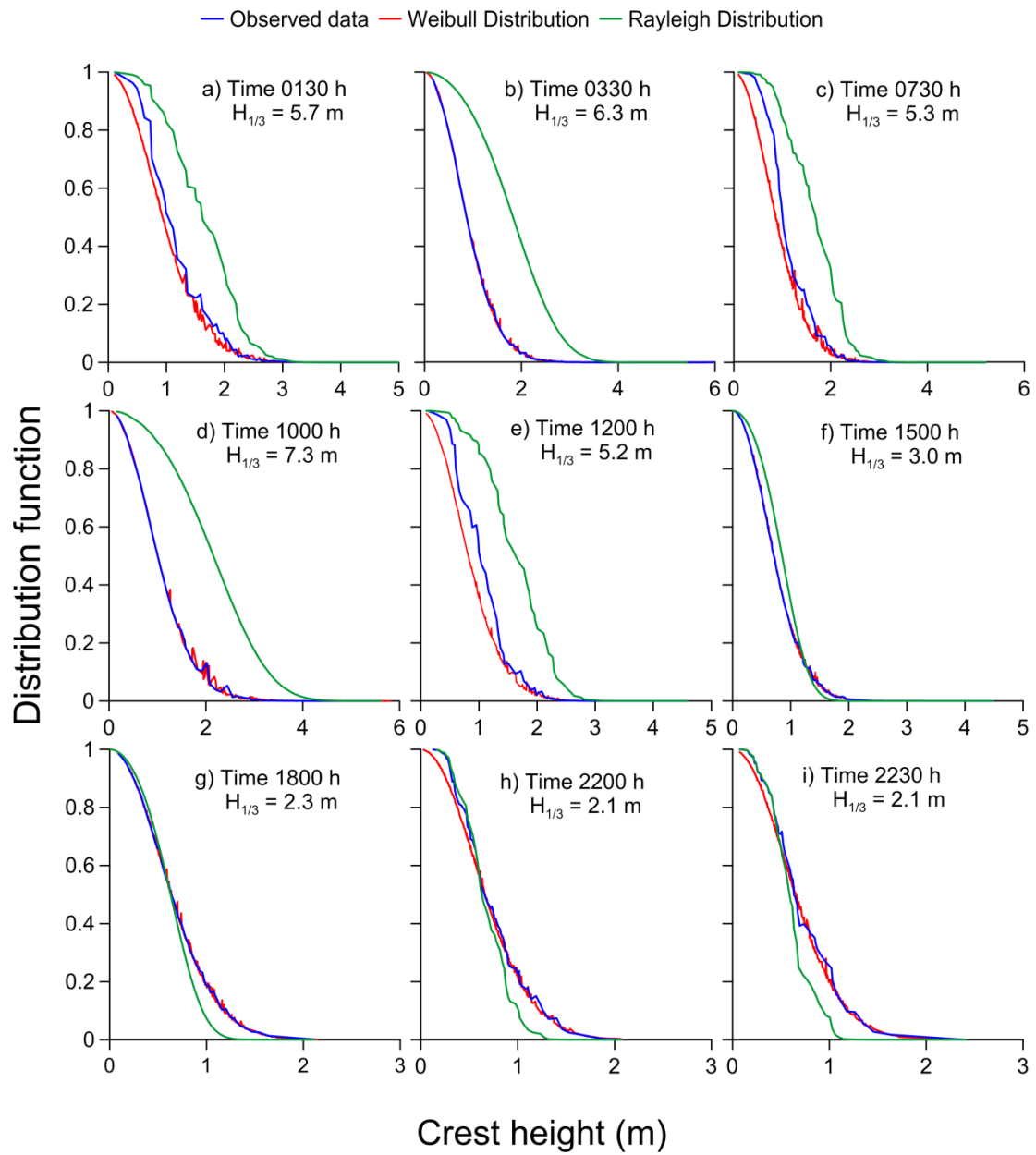


Figure 8. Crest height distribution on 12 October 2014 at different time for select records. a) to e) are for high waves with $H_{1/3} > 3\text{ m}$ and f) to i) are for waves with $H_{1/3} \leq 3\text{ m}$

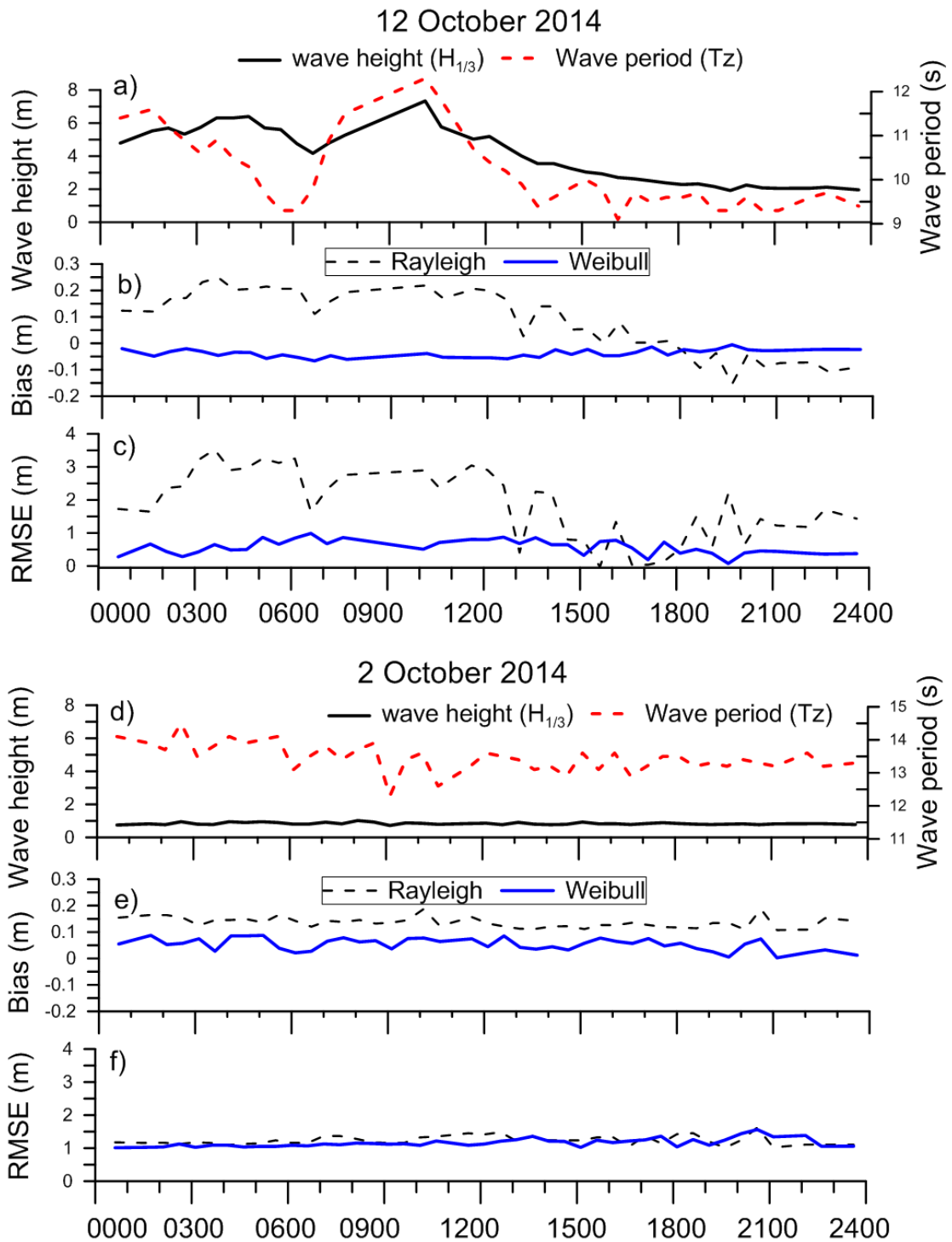


Figure 9. a and d) Significant wave height and mean wave period, b and e) Bias of theoretical distributions (Rayleigh and Weibull) with observed distribution and the corresponding RMSE is presented in c and f). a,b and c are for 12 October 2014 during high wave condition (tropical cyclone) and d,e and f are for 2 October 2014 during low wave conditions

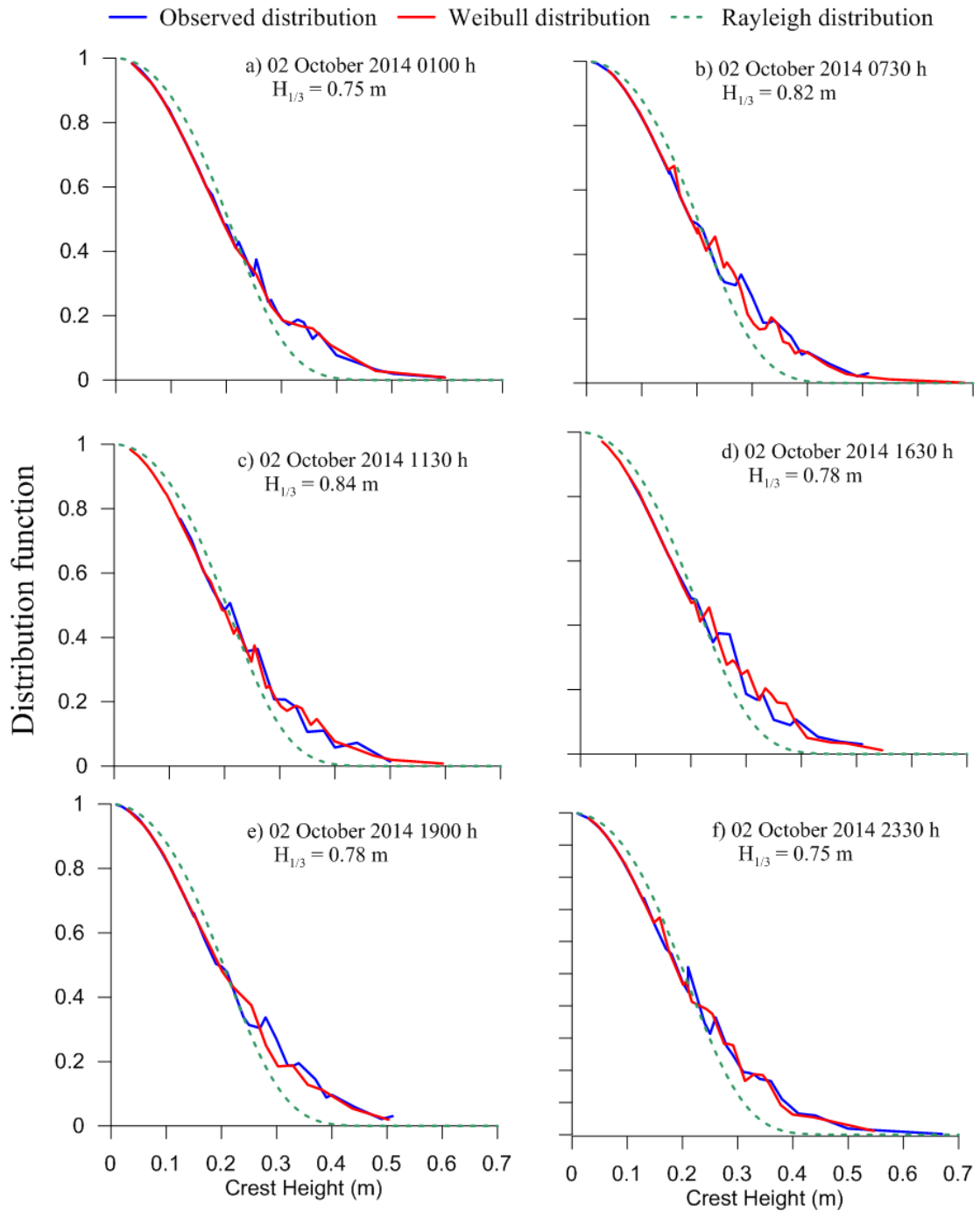


Figure 10. Crest height distribution on 2 October 2014 at different time for select records. All the data presented are with $H_{1/3}$ less than 1 m

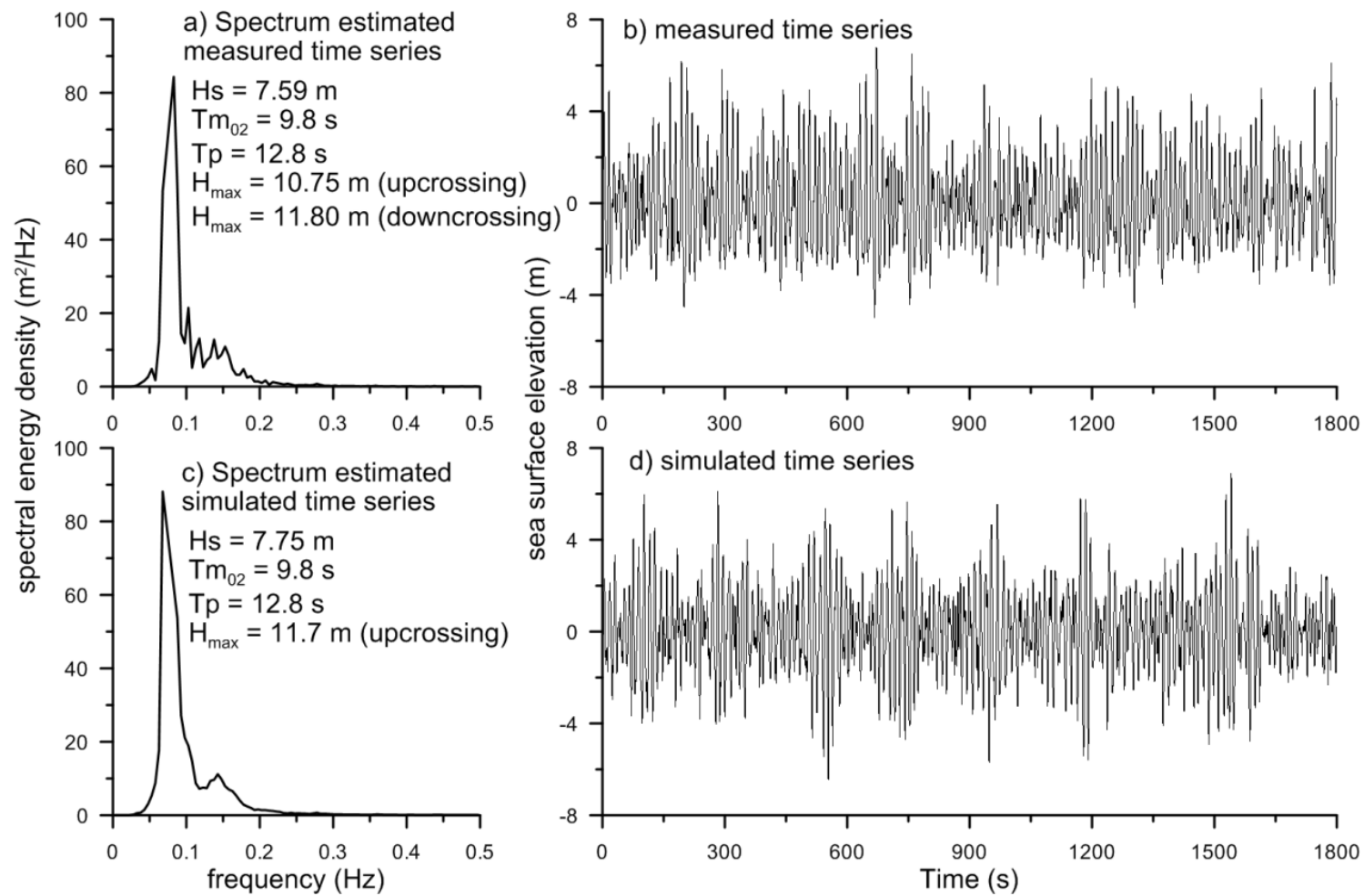


Figure 11. a) wave spectrum estimated from the measured time series shown in b, c) wave spectrum estimated from simulated time series shown in d. The wave record is for 12 October 2014 at 1030 UTC