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Waves off Puducherry, Bay of Bengal, during cyclone THANE

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Abstract We studied the wave characteristics during the very severe cyclonic storm THANE which crossed the east coast of India between Puducherry and Cuddalore based on waves measured at a location in Bay of Bengal at 14 m water depth. Objective of the paper is to document the highest wave height measured in the nearshore waters of east coast of India. On 29 December 2011, cyclone passed within 77–315 km of the wave measurement location with maximum wind speed of 46.3 m/s (90 knots) and resulted in maximum wave height of 8.1 m. Maximum wave height recorded is 0.54 times the water depth, and the ratio of crest height to wave height of the highest wave recorded is 0.65. Maximum value of significant wave height estimated using the parametric wave model for deep-water conditions is 6.4 m, whereas the measured value is 6 m indicating that parametric wave model estimates the wave height reasonably well (within 8 % error) during the cyclone period.

Keywords Wave spectra · Crest height · Directional width · Parametric wave model · Wave height

1 Introduction

Tropical cyclones are among the most destructive natural disasters of the world (Singh et al. 2001). A moving tropical cyclone is an intense source of surface wind stress that causes many significant changes in the surface wave characteristics, such as significant

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wave height, directional wave spectra, and wave propagation (Chu and Cheng 2008). A number of oil and gas platforms are planned along the east coast of India. The crest height of the wave during the extreme wave condition decides the air gap of the offshore platforms. For design and safe operation of ships, it is necessary to apply wave spectra loading generated during tropical cyclones. A number of studies were carried out to understand wave generation and wave growth during hurricane (Chu and Cheng 2008; Young 2006; Xu et al. 2007; Soomere et al. 2008; Babanin et al. 2011). Significant wave height (H_{m0}) up to 7.2 m in the northern Baltic proper and 4.5 m in the Gulf of Finland was measured during windstorm Erwin/Gudrun in January 2005 (Soomere et al. 2008). H_{m0} up to 24 m was measured in 32 m water depth (Babanin et al. 2011). Knowledge on characteristics of waves in the shallow waters during the cyclone is required for validation of numerical wave models, and design of structures, and is not available for the eastern Bay of Bengal. In the northern Indian Ocean, there are 5–6 times more tropical disturbances in the Bay of Bengal than in the Arabian Sea (Dube et al. 1997). In North Indian Ocean, on average, one severe cyclone is expected to form in November every year, and November cyclones generally move westwards to west-north-westwards and strike the Andhra Pradesh or Tamil Nadu coasts of India, and they account for the highest number of natural disaster deaths in India and Bangladesh (Singh et al. 2001). A very severe cyclonic storm THANE developed over the Bay of Bengal during last week of December moved and crossed north Tamil Nadu coast between Puducherry and Cuddalore between 06:30 and 07:30 IST on 30 December 2011, and is the strongest tropical cyclone of 2011 (IMD 2011). Cyclone THANE is one of the most damaging storms along Puducherry coast, and it had wind speed of 46.3 m/s on 29 December 12:00 IST.

Objective of this paper is to document the highest H_{m0} recorded in the nearshore waters of east coast of India and study the wave characteristics during the passage of cyclone THANE. Outline of the paper is as follows. Section 2 describes methodology. Section 3 describes movement of cyclone THANE over Bay of Bengal. Section 4 describes wave characteristics including significant wave height and wave spectra and Sect. 5 gives the conclusions.

2 Materials and methods

Measured wave data available at 14 m water depth (11°55′25.9″N and 79°51′2.6″ E) off Puducherry (Fig. 1) using Datawell Directional Waverider buoy during 20–29 December 2011, for 9 days are analysed to study the wave characteristics during cyclone THANE. Technical details of the directional waverider buoy and the accuracy of the measurement are presented by Barstow and Kollstad (1991). The deployed directional waverider buoy drifted from moored location on 29 December 22:00 IST and lost; hence, data could not be obtained after 22:00 IST. Time referred in the paper is Indian Standard Time (IST) and is the local time that is 5:30 h ahead of Coordinated Universal Time (UTC). Wave data are recorded continuously at 1.28 Hz, and 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 <5 m, the buoy will not follow the wave amplitude and hence will not measure the wave. Wave spectrum is obtained through fast Fourier transform (FFT). FFT of 8 series, each consisting of 256 measured vertical elevations of the buoy data, is added to obtain the spectra. High-frequency cut-off is set at 0.58 Hz, and the resolution is 0.005 Hz. Significant wave height

(H_{m0}) which equals $4\sqrt{m_0}$ and mean wave period (T_{m02}) which equals $\sqrt{m_0/m_2}$ are obtained from the spectral moment. m_n is the nth order spectral moment and is given by $m_n = \int_0^\infty f^n S(f)\, df$, $n = 0$ and 2, $S(f)$ is spectral energy density at frequency f. Period corresponding to maximum spectral energy is referred as spectral peak period (Tp) and is estimated at the spectral peak. Zero-crossing analysis of the surface elevation time series is used to estimate maximum wave height $(Hmax)$ and $H_{1/3}$. Sea and swell from the measured data are separated through the method described by Portilla et al. (2009). Other parameters studied are spectral peakedness parameter, Qp (Goda 1970), spectral narrowness parameter, spectral width parameter based on spectral analysis, ε (Cartwright and Longuet-Higgins 1956), and maximum spectral energy density. Mean wave direction corresponding to the spectral peak (θ_m) and the directional width (σ) is estimated based on circular moments (Kuik et al. 1988). Reanalysis data of zonal and meridional components of wind speed at 6 hourly intervals from NCEP/NCAR (Kalnay et al. 1996) are obtained for a location (12.5°N; 82.5°E) close to the study area to know the influence of wind on waves. These data are provided by the NOAA-CIRES Climate Diagnostics Centre, Boulder, Colarado, at http://www.cdc.noaa.gov/. Wind data available at Joint Typhoon Warning Centre site during the cyclone period (26–29 December 2011) are used to estimate waves (Chu et al. 2012).

Maximum H_{m0} and T_p within the storm are estimated using Young's model (Young 1988) based on following expression. Input parameters to the model are radius of maximum wind for the storm (R), maximum wind speed (V_{max}), and speed of forward motion (V_{fm}).

$$\frac{g\,H_{m0}}{V_{max}^2} = 0.0016 \left(\frac{gF}{V_{max}^2}\right)^{0.5} \tag{1}$$

$$\frac{g\,T_p}{2\pi\,V_{max}} = 0.045 \left(\frac{gF}{V_{max}^2}\right)^{0.33} \tag{2}$$

where g is the acceleration of gravity and F is fetch length, which is estimated from the speed of forward motion and radius of maximum wind (Young 1988).

Deep water significant wave height (H_{m0}) and period (Tp) at the point of maximum wind are also estimated according to USACE (1984) based on following equations.

$$H_{m0} = 5.03\, e^{\frac{R\Delta P}{4700}} \left(1 + \frac{0.29\,\alpha\,V_{fm}}{\sqrt{V_{max}}}\right) \tag{3}$$

$$T_p = 8.6\, e^{\frac{R\Delta P}{9400}} \left(1 + \frac{0.145\,\alpha\,V_{fm}}{\sqrt{V_{max}}}\right) \tag{4}$$
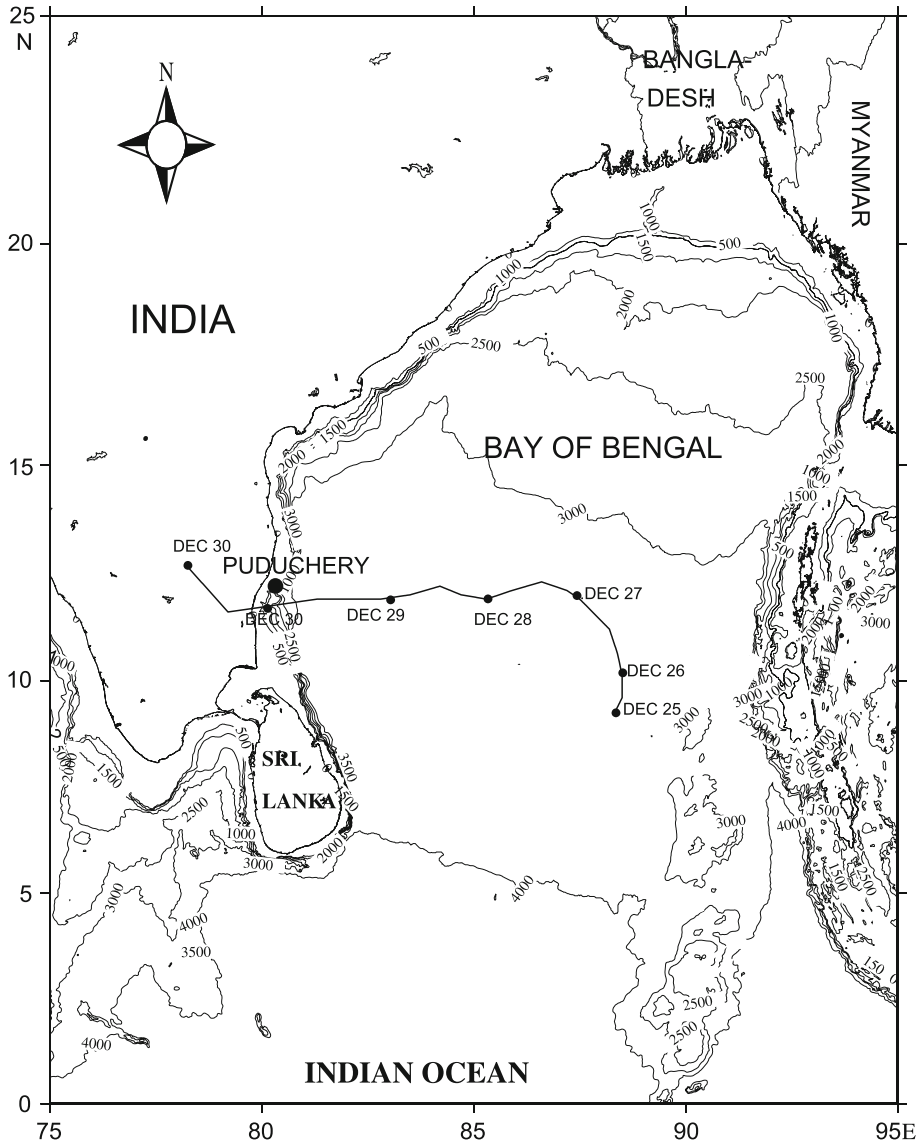
where $\Delta P = P_n - P_0$

P_n is the peripheral pressure
P_0 is the mean sea level pressure at the centre of the storm

3 Characteristics of cyclone THANE

Tropical cyclone THANE is one of the six tropical cyclones occurred in the North Indian Ocean in 2011. It is formed on 25 December 2011, as a tropical depression (TD) and

Fig. 1 Track of the cyclone THANE and the wave measurement location off Puducherry

weakened on 30 December 2011 (Chu et al. 2012). Based on the data available at Joint Typhoon Warning Centre (JTWC), the movement of cyclone THANE is presented in Fig. 1 (Chu et al. 2012). After generation as a TD at a distance of 1,000 km south east of Puducherry on 25 December, it moved eastwards with a wind speed of 15.4 m/s. Tropical depression was then developed into a tropical storm (TS) on 25 December 11:30 IST and propagated westwards towards Indian subcontinent with maximum wind speed of 25.7 m/s. TS was steadily upgraded as tropical cyclone (TC) THANE, and it moved westwards to the Indian subcontinent. On 29 December, it attained maximum wind speed of 46.3 m/s (90 knots) when it was at a distance of 239 km from the wave measurement

location (Table 1). The estimated pressure drop at the centre of the TC shows a maximum drop of 53 hPa on 29 December 11:30 IST. High wind condition was sustained for almost 2 days and TC weakened to a TS of maximum wind speed 20.6 m/s on 30 December 11:30 IST after it reaches the Indian subcontinent. The system was further weakened into a well-marked low pressure area over north Kerala and neighbourhood west coast of India on 31 December 05:30 IST. The velocity of forward motion of the cyclone varied from 1.9 to 4.1 m/s with an average speed of 3 m/s.

## 4 Results and discussions

4.1 Wave height

H_{m0} increased from 1.3 m on 26 December 02:00 IST to 6 m on 29 December 19:30 IST and is the highest H_{m0} measured in nearshore waters of the east coast of India. Within 89.5 h, significant wave height increased by 4.7 m (Fig. 2a) and T_{m02} and Tp also increased during this period (Fig. 2b, c). High waves have occurred after the peak winds have passed (Fig. 2a). Maximum wave height which can occur at 14 m water depth according to Massel (1966) is 8.4 m (0.6 times the water depth), and the measured maximum value is 8.1 m (Fig. 3). The maximum Hmax recorded is 0.57 times the water depth. When waves are propagating in water of constant depth, Nelson (1994) showed that for shallow water waves, the upper limit value for the ratio of Hmax to water depth is 0.55 and is less than that often used in engineering practice (0.78), and hence, the waves recorded during cyclone THANE are not breaking waves. Average tidal range in the study area is less (0.62 m during spring tide and 0.27 m during neap tide) and hence will not have much influence on the wave breaking criteria (Kumar et al. 2006). Maximum value of H_{m0} measured is lower than the value (9.39 m) estimated by Kumar et al. (2003) for 1 in 100-year return period at 15 m water depth for a location 120 km south of the present measurement location. Maximum measured H_{m0} for the nearby area (120 km south) is 1.8 m based on 1-year measurement during March 1995 to February 1996 (Jena et al. 2001) and is 1.7 m during March 1998 to February 1999 (Kumar et al. 2002). Hence, the H_{m0} measured during the cyclone is much higher than the earlier measured values. Along the west coast of India, H_{m0} up to 6 m and Hmax of 10 m are reported at 23 m water depth during a storm occurred in summer monsoon period in 1996 (Kumar et al. 2006) and H_{m0} of 5.65 m and Hmax of 8 m at 14 m water depth on 29 May 2006 (Kumar et al. 2010). Maximum H_{m0} measured in Bay of Bengal deep water is 8.4 m on 28 October 1999 during the passage of Orissa super cyclone (Rajesh et al. 2005). During the cyclone THANE, ratio between Hmax and H_{m0} varied from 1.4 to 1.9 with average value of 1.57 and is slightly higher than the theoretical value of 1.53 (Longuet-Higgins 1952). Water depth (d) at wave measurement location is 14 m, and hence, the measured waves will have depth influence. Wave length (L) associated with the mean wave period varied from 41 to 91 m, and d/L ratio varied from 0.13 to 0.29 indicating that the measured waves are in the transitional water. The wave length (Lp) associated with the peak wave period varied from 72 to 138 m, and d/Lp ratio varied from 0.09 to 0.17 which also indicate that the measured waves are in the transitional water. Hence, the waves measured are the transformed waves, and the wave height and the wave direction measured will be different than that will be in the deep water. For high waves, $H_{1/3} \approx 0.83 H_{m0}$ and is lower than the value ($H_{1/3} \approx 0.95 H_{m0}$) in deep water (Goda and Kudaka 2007) since the waves are measured in transitional water.

Table 1 Track record and parameters of THANE cyclone during 25–30 December 2011, along with the estimated wave height and wave period

Date	Time IST	Cyclone position		Type	Mean sea level pressure, Po (hPa)	Maximum wind speed, V_{max} (m/s)	Radius of maximum wind, R (km)	Distance of cyclone from measurement point (km)	Young		USACE	
		Latitude (°N)	Longitude (°E)						H_{m0} (m)	Tp (s)	H_{m0} (m)	Tp (s)
25	17:30	9.2	88.3	TD	1,001	15.43	74.08	965	3.5	8.7	5.8	9.2
25	23:30	9.6	88.5	TD	1,000	15.43	74.08	973	3.5	8.7	5.9	9.3
26	05:30	10.1	88.5	TD	1,000	15.43	64.82	959	3.5	8.6	5.8	9.2
26	11:30	10.6	88.4	TS	993	20.58	64.82	938	5.0	10.1	6.2	9.5
26	17:30	11.2	88.2	TS	985	25.72	64.82	907	6.8	11.4	6.7	9.9
26	23:30	11.6	87.8	TS	985	25.72	64.82	860	6.8	11.4	6.7	9.9
27	05:30	11.9	87.5	TS	985	25.72	55.56	826	6.5	11.0	6.5	9.7
27	11:30	12.1	87.2	TS	985	25.72	55.56	794	6.4	10.9	6.5	9.7
27	17:30	12.3	86.6	TS	982	28.29	55.56	729	7.5	11.8	6.6	9.9
27	23:30	12.1	85.9	TS	978	30.87	74.08	653	8.8	12.8	7.6	10.6
28	05:30	11.9	85.3	TC	974	33.44	74.08	587	9.7	13.2	8.0	10.8
28	11:30	12.0	84.7	TC	970	36.01	55.56	522	10.2	13.4	7.4	10.4
28	17:30	12.2	84.2	TC	967	38.58	37.04	468	10.3	13.2	6.6	9.9
28	23:30	12.0	83.5	TC	967	38.58	37.04	392	10.6	13.4	6.6	9.9
29	05:30	11.9	82.8	TC	959	43.73	46.30	315	12.7	14.5	7.5	10.5
29	11:30	11.9	82.1	TC	956	46.30	46.30	239	13.6	14.9	7.7	10.6
29	17:30	11.9	81.3	TC	963	41.16	46.30	152	11.9	14.2	7.3	10.4
29	23:30	11.8	80.6	TC	967	38.58	46.30	77	10.9	13.7	7.1	10.2
30	05:30	11.7	79.9	TC	974	33.44	37.04	22	8.8	12.5	6.3	9.7
30	11:30	11.6	79.2	TS	985	25.72	37.04	83	6.3	10.9	5.9	9.3
30	17:30	11.3	78.2	TS	993	20.58	74.08	205	5.1	10.2	6.4	9.7

TD Tropical depression, *TS* tropical storm, *TC* tropical cyclone
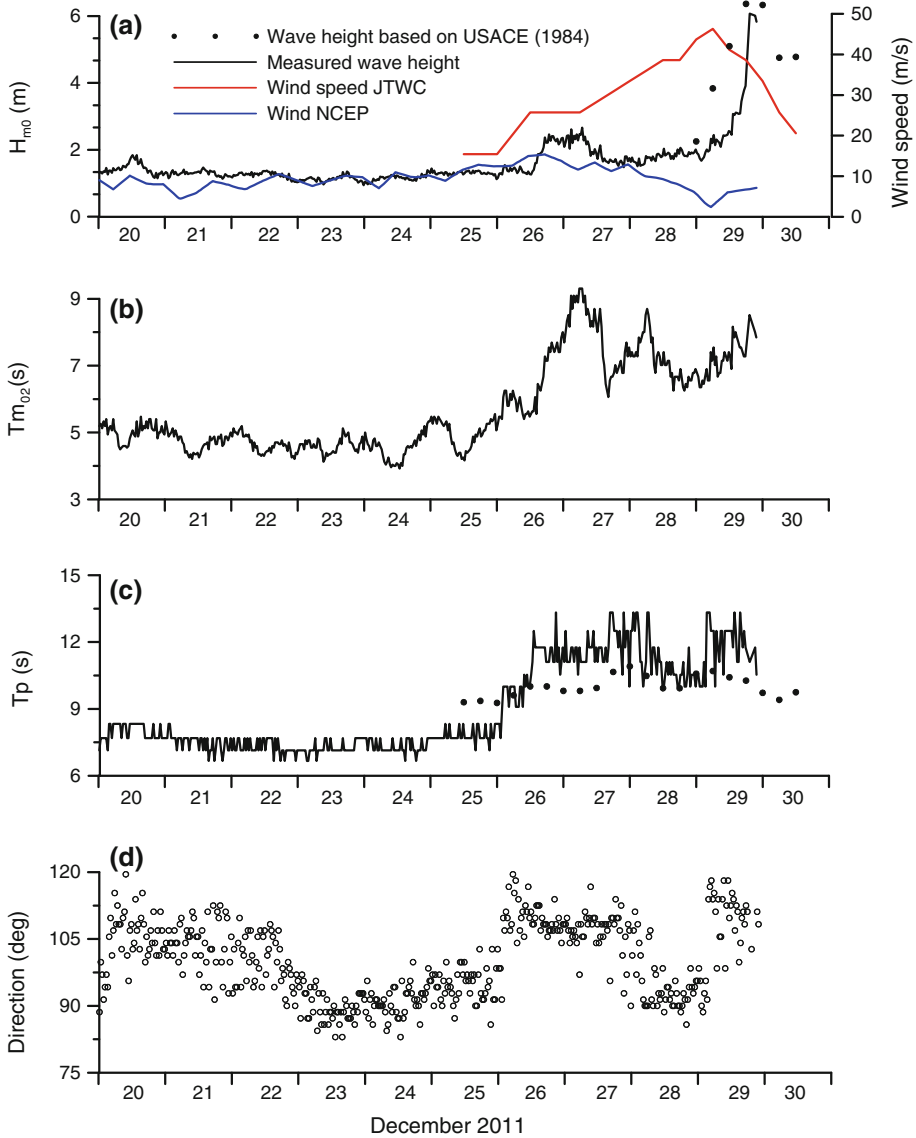
Fig. 2 *Time series plot* of measured parameters **a** significant wave height, **b** mean wave period, **c** peak wave period, and **d** mean wave direction during 20–29 December 2011, along with estimated significant wave height using USACE (1984) and wind speed based on NCEP and JTWC

Asymmetry of waves is examined through the statistics of the time series, such as skewness and kurtosis. Linear sea states will have no skewness and the positive skewness value indicating that the wave crests are bigger than troughs (Guedes Soares et al. 2004). Skewness varied from 0.04 to 0.4 with a mean value of 0.2, indicating that high waves ($H_{m0} > 2$ m) are associated with high skewness value similar to the observation of Kumar et al. (2010). Mean value of the sea surface elevation during 30-min interval varied from −0.38 to 0.21 m. For high waves, mean value is positive indicating the height of crest is
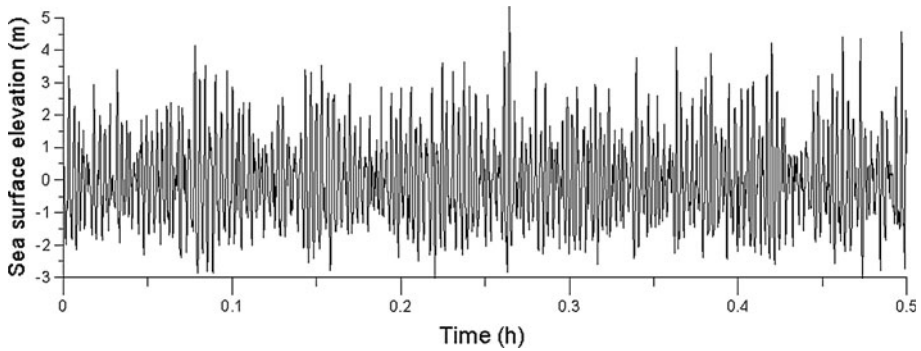
Fig. 3 Surface elevation time history of the large wave recorded on 29 December 2011, 19:30 IST

bigger than the trough. The crest height of the wave during the extreme wave condition is required to design the air gap of the offshore platforms. For the highest wave, the crest height is 5.2 m and the trough height is 2.8 m (Fig. 3), and the ratio of the crest height to wave height is 0.65 that is close to the value (0.7) recommended for 14 m water depth (DNV 2008).

4.2 Wave period

Individual wave height and associated wave period are estimated from the 30-min record during 26–29 December, and the scatter plot is presented (Fig. 4a). High waves (>6 m) are associated with wave period 8–12 s, and the measured data are not breaking waves since the wave steepness is less than the limiting value (Fig. 4a). According to DNV (2011), the mean wave period (T_{m02}) can be related to the peak period and spectral peakedness parameter (γ) by the following approximate relation.

$$Tm_{02}/Tp = 0.6673 + 0.05037\gamma - 0.00623\gamma^2 + 0.000334\gamma^3 \qquad (5)$$

The spectral period obtained from the measured data is higher than the value estimated from the above expression (Eq. 5) (Fig. 4b).

4.3 Wave spectra

Spectral energy density varied from 1 to 85 m²/Hz during 20–29 December, and hence, normalised spectral energy density is plotted in time–frequency scale to know the contribution of waves with different frequencies during the cyclone period (Fig. 5a). Wave spectra are predominantly broad banded during 20–25 December with energy spreading from 0.1 to 0.3 Hz, and during cyclone period (26–29 December), the spectra are narrowbanded with spectral energy concentrated between 0.07 and 0.14 Hz. Nature of sea state is identified based on the wave steepness. Wave steepness is expressed as the ratio between significant wave height (H_{m0}) and wave length of the peak period (L). Thompson et al. (1984) classified ocean waves based on (H_{m0}/L) as sea, young swell, mature swell, and old swell, and according to their classification, locally generated waves or sea waves have steepness values >0.025. Only during 4.9 % of the time, the steepness criteria indicate sea waves and it is on 29 December when the cyclone is close (77–239 km) to the measurement location, and during this period, the peak wave period varied from 10.5 to 12.5 s. The average swell contribution to the measured wave height during cyclone period
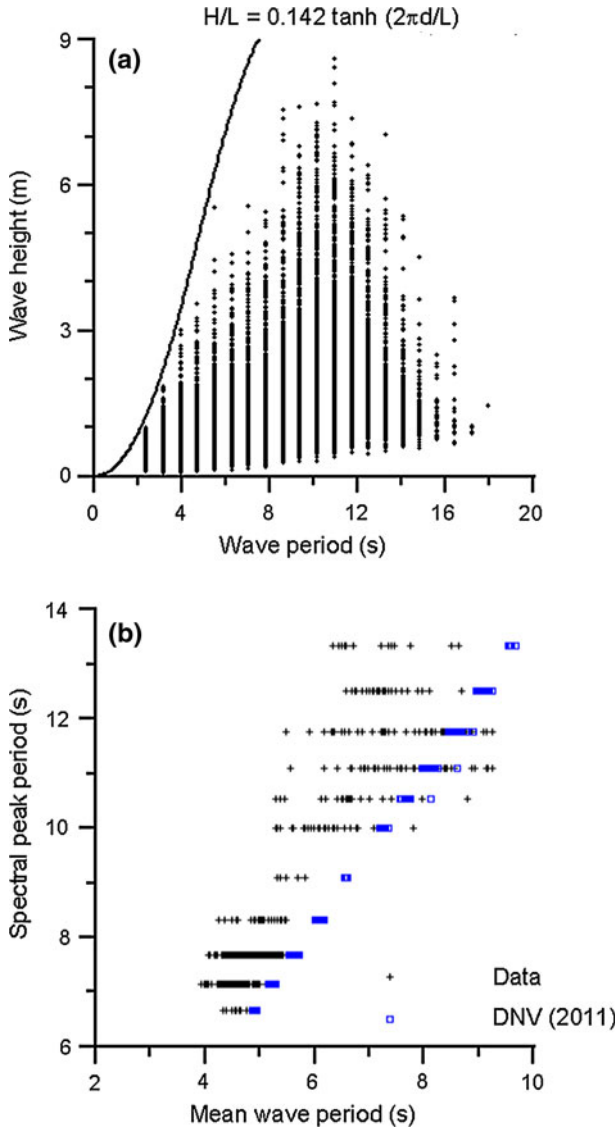
Fig. 4 *Scatter plot* of **a** wave height with wave period estimated from short-term records of 30-min duration and **b** spectral peak period with mean wave period during 26–29 December 2011, recorded at hourly interval

is 82 %. Even though, high local wind is present, when the cyclone is close to the measurement location, the measured waves are predominantly swells. In fact, previous measurements in tropical cyclones (Young 2006) indicate that this is quite normal for tropical cyclones. The reason that this occurs (i.e. swell dominating) is that swell generated in the intense wind regions of the storm typically propagates ahead of the storm and dominates the whole wave field. Hence, very little of the waves are actually locally generated wind sea. During 26–29 December, spectral narrowness parameter (v) varied from 0.4 to 0.7, and

when the wave height is high, v is relatively small with values around 0.5, indicating that the wave spectrum is relatively narrowbanded during high waves. Spectral width parameter (ε) varied from 0.8 to 0.89. Value of spectral peakedness parameter (Qp) varied from 2 to 4.3 for high waves (Fig. 6). Large values of Qp also indicate that the wave spectrum is narrowbanded for high waves. Narrowband low-frequency swell waves contained the maximum energy (85 m^2/Hz). Since the swell is a narrow spectrum, the JONSWAP spectrum (Hasselmann et al. 1973) with appropriate peak enhancement parameter (γ) can represent the swell (Goda 1983). Also, $Tp/(H_{m0})^{0.5}$ varied between 4.3 and 4.8 during the cyclone period and is within the values 3.6 and five recommended to use JONSWAP spectra (DNV 2011). Hence, Kumar and Kumar (2008) could represent the shallow water wave spectra of high waves ($H_{m0} > 2$ m) with JONSWAP spectrum with modified parameter. The study shows that single-peaked spectra of high waves ($H_{m0} > 2$ m) could be represented with JONSWAP with modified parameter α (Phillips constant) and γ (Fig. 6). During 26–29 December, average value of the JONSWAP parameters, α and γ, is 0.0018 and 1.4, and the average value for $H_{m0} > 2$ m is 0.0026 and 1.6 and is similar to the observation of Kumar and Kumar (2008), and hence, these values can be used for generation of theoretical wave spectra in design applications. Ochi and Hubble (1976) found that JONSWAP spectrum provided good approximation to the data for the unimodel spectra with JONSWAP parameters of $\alpha = 0.023$ and $\gamma = 2.2$. Scott spectrum (Scott 1965) underestimates the spectral peak for high waves (Fig. 6) similar to the earlier observation (Kumar and Kumar 2008).

4.4 Wave direction

Mean wave direction did not vary significantly due to cyclone, and it ranged from 83° to 119° (Fig. 2d). High-frequency waves (0.2–0.3 Hz) are approaching from 60° to 90° indicating the influence of NE monsoon (Fig. 5b). Circular RMS spreading (directional width) parameter provides a measure of the energy spread around the mean direction of wave propagation. The directional spreading parameter (directional width) is 20°–25° for waves with frequencies 0.1–0.2 Hz. Directional width increased rapidly at lower frequencies and gradually at higher frequencies (Fig. 5c).
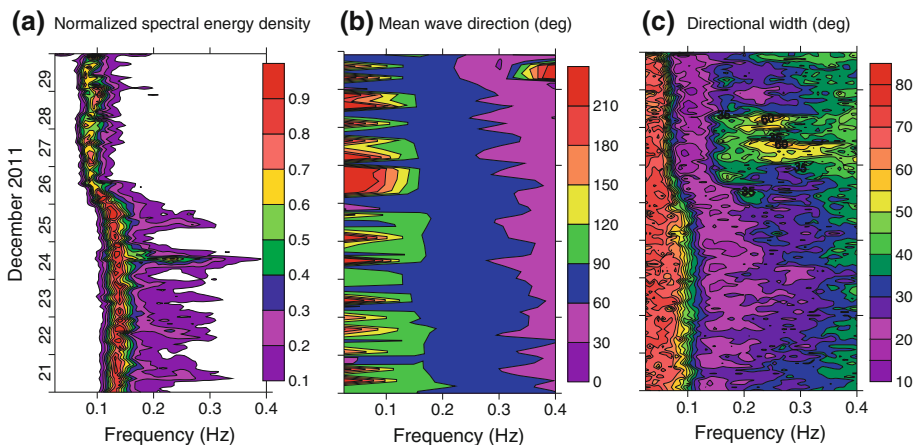
Fig. 5 *Plots of* **a** normalised spectral energy density **b** mean wave direction and **c** directional width with time and frequency
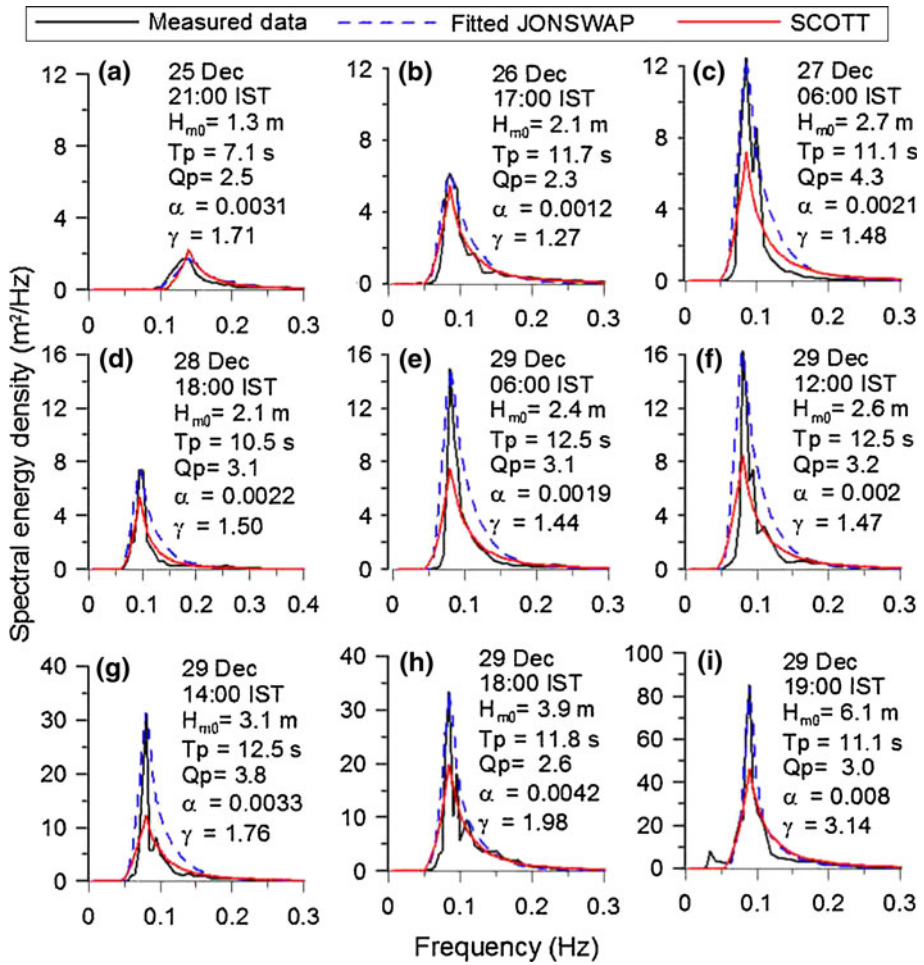
Fig. 6 Wave spectra recorded during the cyclone period along with the JONSWAP and SCOTT spectrum

4.5 Wave parameters based on parametric models

Studies in shallow water (Janssen 1991) indicate that fetch-limited wave growth in shallow water appears to follow growth laws that are quite close to deep-water wave growth for the same wind speeds, up to a point where an asymptotic depth-dependent wave height is attained (USACE 1984). It is recommended that deep-water wave growth formulae be used for all depths, with the constraint that no wave period can grow past a limiting value as per the below relationship (Vincent 1985). For 14 m water depth, the limiting wave period is 11.7 s.

$$T_p \approx 9.78 \left(\frac{d}{g}\right)^{0.5} \tag{5}$$

Wave height estimated following Eq. 1 based on Young (1988) is higher than the values estimated following Eq. 3 based on USACE (1984) (Table 1). Once H_{m0} is determined at

Table 2 Measured and estimated wave height when the cyclone is within 320 km from the buoy location on 29 December 2011

Date	Time IST	Wind speed (m/s)	Distance of cyclone from measurement point (km)	Measured H_{m0} (m)	Measured Tp (s)	H_{m0} based on Young (m)	Tp based on Young (s)	H_{m0} based on USACE (m)	Tp based on USACE (s)
29	05:30	43.73	315	2.3	12.5	3.8	14.5	2.3	10.5
29	11:30	46.30	239	2.6	12.5	6.8	14.9	3.8	10.6
29	17:30	41.16	152	4.0	11.8	8.3	14.2	5.1	10.4
29	23:30	38.58	77	6.0	11.8	9.8	13.7	6.4	10.2

radius of maximum wind speed, the approximate deep-water significant wave height for the buoy location is obtained using the isolines available in USACE (1984) considering the distance of the cyclone from the measurement location, and here, we have not used the method proposed by Young (1988).

Since the waves are measured at 14 m water depth, values of H_{m0} measured are the reduced values due to shoaling. The maximum value of H_{m0} estimated using parametric wave model (USACE 1984) for deep-water conditions is 6.4 m, whereas the measured value is 6 m (Table 2) indicating USACE (1984) estimates the wave height reasonably well (within 8 % error) during the cyclone period. The parametric wave model (USACE 1984) is simple to use but limited to slowly varying tropical cyclone paths and is meant to complement the operational ocean cyclone/hurricane wave model. An ocean spectral wave model with highly nested grids (to capture the maximum peak wind) may yield a solution with the same degree of accuracy as the parametric model at the expense of extensive computer calculations (Wu et al. 2003). Babanin et al. (2011) carried out the spectral modelling of Typhoon Krosa and found that wave height is underestimated in the vicinity of the peak values. The peak wave period estimated using Eq. 2 based on Young (1988) is 13.7–14.5 s and that using Eq. 4 based on USACE (1984) is 10.2–10.6 s. The measured Tp when the cyclone is close to the buoy location (within 77–315 km) is 11.8–12.5 s, indicating that expression based on Young (1988) overestimates the peak wave period and that based on USACE (1984) underestimates the period.

H_{m0} based on the simple formulae [$H_{m0} = 0.2 (P_n - P_o)$, where Pn is the peripheral pressure and Po is the central pressure] proposed by Hsu et al. (2000), is 7.8 m when the cyclone is close to the measurement location, and the corresponding measured value is 6 m. The H_{m0} values estimated using Hsu et al. (2000) is found to be smaller than the values estimated using the Young's model and is higher than that based on USACE (1984).

5 Conclusion

On 29 December 2011, THANE cyclone passed within 77–315 km of the wave measurement location with maximum wind speed of 46.3 m/s (90 knots) and resulted in maximum wave height of 8.1 m. Velocity of forward motion of the cyclone varied from 1.9 to 4.1 m/s with an average speed of 3 m/s. Maximum wave height recorded is 0.57 times the water depth, indicating that the measured waves are non-breaking waves. The ratio of crest height to wave height of the highest wave recorded is 0.65 and is less than the recommended value of 0.7 for 14 m water depth. Mean wave direction did not vary

significantly, and it ranged from 83 to 119°. Maximum value of H_{m0} estimated using the parametric wave model (USACE 1984) for deep-water condition is 6.4 m, whereas the measured value is 6 m indicating USACE (1984) estimates the wave height reasonably well (within 8 % error) during the cyclone period. The water depth at the measurement location is 14 m, and hence, waves measured are the transformed waves, and the wave height and the wave direction measured will be different than that will be in the deep water. The study shows that single-peaked spectra of high waves ($H_{m0} > 2$ m) could be represented with JONSWAP with modified parameter α (Phillips constant) and γ (peak enhancement parameter). Scott spectrum underestimates the spectral peak for high waves similar to the earlier observation (Kumar and Kumar 2008).

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