Waves in Gulf of Mannar and Palk Bay around Dhanushkodi, Tamil Nadu, India

R. Gowthaman[1], V. Sanil Kumar[1,*], G. S. Dwarakish[2], Soumya S. Mohan[1], Jai Singh[1] and K. Ashok Kumar[1]

[1]Ocean Engineering, CSIR-National Institute of Oceanography, Dona Paula, Goa 403 004, India
[2]Department of Applied Mechanics and Hydraulics, National Institute of Technology Karnataka, Surathkal 575 025, India

Surface wave characteristics around Dhanushkodi are studied based on the measured data in the Gulf of Mannar and in the Palk Bay. Wave spectra are mainly double-peaked in the Gulf of Mannar and single-peaked in the Palk Bay. High waves (maximum wave height up to 5.4 m) are observed in the Gulf of Mannar compared to the Palk Bay (maximum wave height is 3.6 m). Wave heights are more in the Gulf of Mannar during the southwest monsoon period and the waves are from south-southwest. In the Palk Bay, high waves are found during the northeast monsoon period. Swells dominate the Gulf of Mannar, except during the southwest monsoon period, whereas wind seas exist in the Palk Bay as distant swells cannot reach the bay due to the protection by Indian peninsula and northern extremity of Sri Lanka. Influence of cyclone *Laila* is observed during the study period in both the Gulf of Mannar and the Palk Bay.

Keywords: Spectral energy, swell, wave spectra, wind sea.

WAVES play an important role in planning the navigational routes and in the study of sediment transport and coastal processes. Wave-generated long-shore currents are the driving force for littoral drift. Along the southeast (SE) coast of India, waves during the southwest (SW) monsoon have less significance compared to those during the northeast (NE) monsoon[1]. Wave spectra are single-peaked during storm events and the percentage occurrence of double-peaked spectra is higher during low sea states[2]. The single-peaked spectra are observed during extreme events, wherein all the energies are concentrated in the low-frequency region. Wave characteristics along the east coast of India are studied by various researchers[3–6]. Kumar *et al.*[6] found that along the Indian coast about 60% of the wave spectra observed is multi-peaked due to the presence of seas and swells and they are mainly single-peaked when the significant wave height is more than 2 m. The multi-peaked spectra are mainly due to the existence of wind seas along with the swells and different methods are used for separation of wind sea and swell[7–9]. Spectral energy density at secondary peak is more than 50% of that at primary peak at 57% of the time for waves north of Tuticorin[10]. Along the east coast of India, the wave activity is significant both during SW and NE monsoons[11]. Cyclones frequently occur in the Bay of Bengal and the 1964 Rameshwaram cyclone is one of the severe storms which affected Sri Lanka and the southern Indian peninsula[12]. A shipping channel is planned connecting the Gulf of Mannar (GoM) with the Palk Bay (PB) known as the Sethusamudram channel. The characteristics of waves in this area is not known at present and hence a study was done to identify the wave characteristics in GoM and PB. Due to the strong seasonal cycle imposed by the monsoons on the climate of the region, the study was done for one-year period and the seasonal variation of wave parameters examined.

Near-shore region off Dhanushkodi in Rameshwaram, Tamil Nadu is the study area located between 9°9′–9°11′N lat. and 79°24′–79°26′E long. (Figure 1). Dhanushkodi is on the eastern side of Rameshwaram Island and this narrow strip of land is a few metres wide and surrounded on all sides by seas with GoM in the south and PB in the north. GoM is much deeper than the shallow PB, which is a sheltered area due to the Sri Lankan land mass. The cyclone of December 1964 has been the most severe storm to affect the Rameshwaram area and led to vast material and human losses. Tides in this region are semi-diurnal[13], with spring tidal range of 0.6 m and neap tidal range of 0.16 m. The wave measurement locations are one each in the GoM (9°6.75′N; 79°24.42′E) and PB (9°19.16′N; 79°26.02′E). Location in PB is 13 km and that in GoM is 6 km from the Rameshwaram Island. For location in PB, the waves are fetch-limited due to the obstruction of the Sri Lankan coast in the NE to SE and Rameshwaram Island in the south and the Indian mainland in the west and northwest. Whereas the location in the GoM is exposed to swells from south to southwest.

Directional wave data collected at 12 m water depth using Datawell directional wave rider buoys at two locations are used in the study. Wave data are recorded continuously at 1.28 Hz for a period of one year. From the recorded heave data of 30 min duration, the wave spectrum is obtained through fast Fourier transform (FFT). FFT of eight series, each consisting of 256 measured vertical elevations of the buoy heave data is added to obtain the wave spectrum. Significant wave height, H_{m0} ($= 4\sqrt{m_0}$) and the mean wave period, T_{m02} ($=\sqrt{m_0/m_2}$) are obtained from the wave spectrum. Here m_n is the nth-order spectral moment and is given by $m_n = \int_0^\infty f^n S(f)\mathrm{d}f$, $n = 0$ and 2 and $S(f)$ is the spectral energy density at frequency f. Mean wave direction (Dp) corresponding to the spectral peak is estimated based on circular moments[14]. Maximum wave height (H_{max}) is estimated from the 30-min time-series vertical elevation data of the buoy. Wind sea and swell are separated from the

*For correspondence. (e-mail: sanil@nio.org)

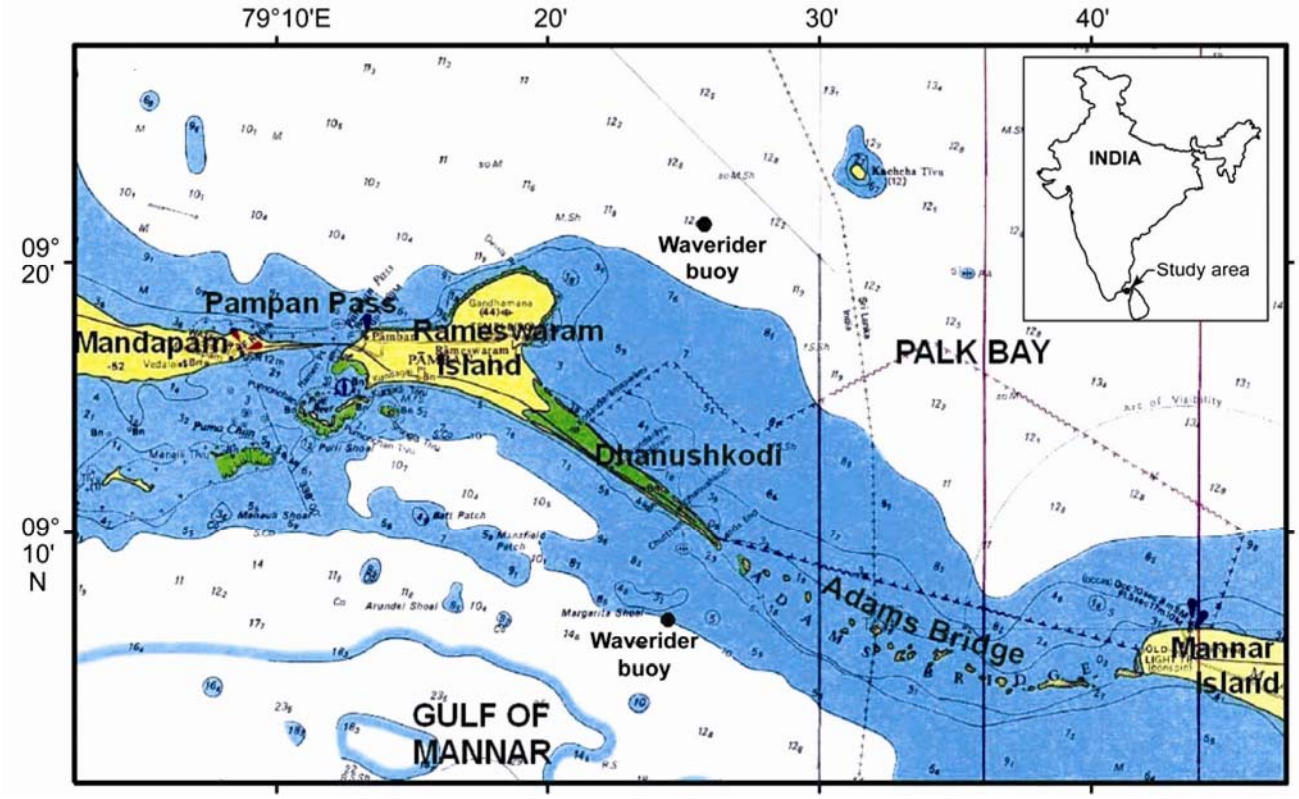

Figure 1. Study area showing the location of wave measurement.

wave spectrum and the characteristics of swell and wind sea are studied.

The wave energy spectra are either single-peaked or multi-peaked. In multi-peaked spectra, the peak in the low-frequency region is associated with swells and the peak in the high-frequency region is associated with wind seas. According to the dominance of swell or wind sea, frequency of primary and secondary peaks in the spectrum varies. Wave spectra of GoM are mainly multi-peaked, indicating the presence of two or more distinct wave systems prevailing in the region. During fair weather season (February–May), the sea states of GoM are swell-dominated with primary peak in the low-frequency region and secondary peak in the high-frequency region and during monsoon, the wind sea dominates. Distant swells from different directions also propagate to this region and form a complex sea state. The spectral peak shifts from low- to high-frequency region depending on the strength of the prevailing winds. Wave spectra of PB are mainly single-peaked, except during the SW monsoon season. Because of the dominance of wind seas, the primary peak of the wave spectrum in PB is always in the high-frequency region of the spectrum. Another feature observed during the spectral analysis is that the secondary peak occurred approximately at 1.9 times the frequency of the primary peak in the GoM and at 1.1 times the frequency in PB. The secondary peak of the multi-peaked spectra observed in GoM is similar to that (1.5–2.4 times the frequency of the main peak) reported for the open-sea locations around India[6,15]. The low value of 1.1 observed in PB is due to the absence of swells in the region and both the peaks are in the wind-sea region.

H_{m0} varied from 0.2 to 2.7 m with mean value of 0.9 m and H_{max} varied from 0.3 to 5.4 m with mean value of 1.4 m in GoM (Figure 2). Range of wave parameters in different months are presented in Table 1. H_{m0} up to 1.8 m with a mean value of 0.5 m and H_{max} up to 3.6 m is observed in PB. During NE monsoon period, wave activity is comparatively low in GoM, whereas in PB the wave activity is high. Mean value of H_{swell} is 0.7 m and that of H_{sea} is 0.5 m in GoM. H_{swell} is negligible in PB with mean value of 0.1 m. H_{m0} exceeded 1 m during 141 days in a year in GoM and 35 days in PB and will have implications on the allowable draft of the vessels using the Sethusamudram channel. According to PIANC[16] for $H_{m0} > 1$ m, the ratio of the channel depth and draft of the vessel is to be 1.3 and for $H_{m0} < 1$ m, the ratio is 1.1 m. The impact of cyclone *Laila* is observed at both locations. *Laila* cyclone developed over SE Bay of Bengal on 17 May 2010 and initially moved in the west-northwesterly direction towards south Andhra Pradesh and adjoining north Tamil Nadu coast[17]. Cyclone *Laila* produced a wind speed of 17.2 m/s in the study area with high wave heights at both locations. Highest H_{m0} of 1.9 m and H_{max}

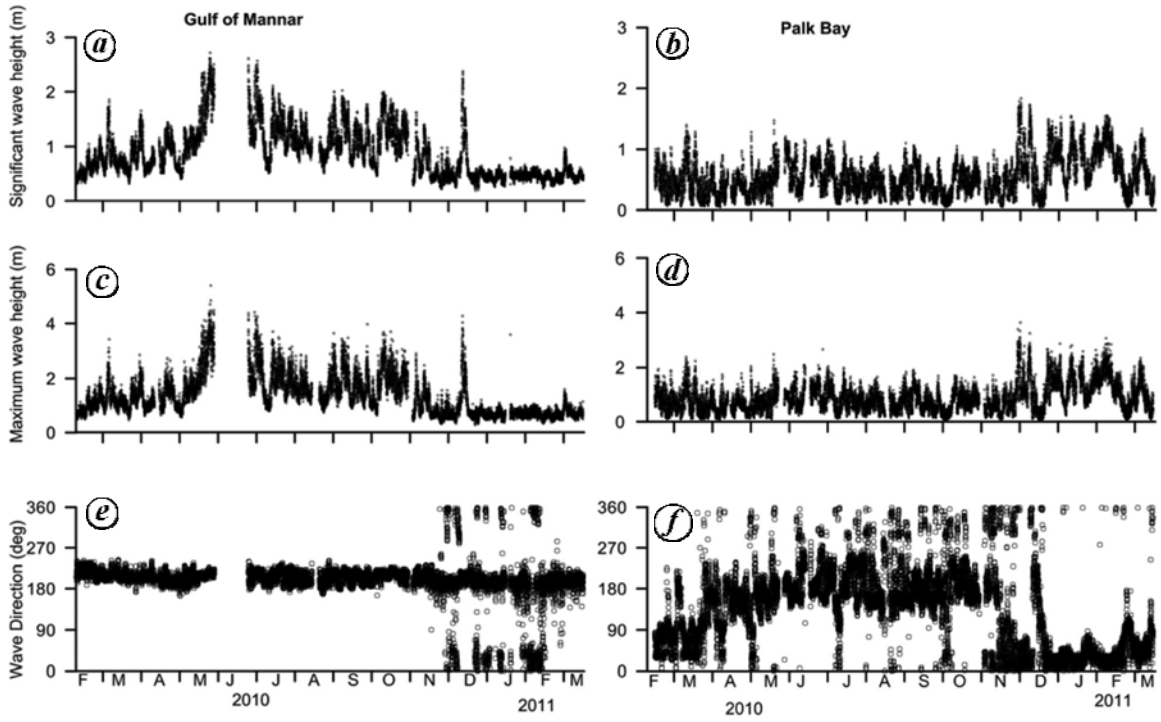

Figure 2. Variation of wave parameters: (***a***, ***b***) significant wave height; (***c***, ***d***) maximum wave height and (***e***, ***f***) mean wave direction measured at Gulf of Mannar and Palk Bay.

Table 1. Range of significant wave height (H_{m0}) and mean wave period (T_{m02}) for the swell and wind sea in different months

	Gulf of Mannar				Palk Bay			
	H_{m0} (m)		T_{m02} (s)		H_{m0} (m)		T_{m02} (s)	
Month	Swell	Sea	Swell	Sea	Swell	Sea	Swell	Sea
February 2010	0.3–1.6	0.1–0.6	10.8–16.9	1.9–3.5	0.0–0.2	0.1–0.6	9.4–21.2	1.9–3.4
March 2010	0.4–2.1	0.1–1.1	6.9–16.2	1.9–3.6	0.0–0.1	0.1–1.0	7.4–16.4	1.9–3.8
April 2010	0.4–1.4	0.1–1.1	5.9–13.2	1.9–3.6	0.0–0.1	0.0–1.4	7.5–19.3	1.8–3.3
May 2010	0.1–1.6	0.0–1.6	8.8–22.2	2.2–4.3	0.0–0.2	0.0–1.0	9.3–22.1	2.0–4.3
June 2010	0.4–1.2	0.8–1.5	11.4–17.3	3.5–5.5	0.0–0.2	0.0–1.5	6.2–20.7	2.1–4.1
July 2010	0.4–1.7	0.3–1.6	9.0–14.8	2.4–4.9	0.0–0.2	0.0–1.2	6.1–12.7	1.9–3.3
August 2010	0.0–2.7	0.0–1.6	9.0–22.3	2.4–4.3	0.0–0.1	0.0–1.2	7.7–22.1	2.0–3.7
September 2010	0.3–1.2	0.3–1.6	9.0–14.8	2.9–4.5	0.0–0.3	0.0–1.1	9.2–16.1	1.9–3.2
October 2010	0.1–1.2	0.0–1.9	9.9–22.1	2.2–6.2	0.0–0.2	0.0–1.1	7.8–21.9	1.9–4.3
November 2010	0.2–0.8	0.1–1.4	10.1–13.9	2.1–4.7	0.0–0.2	0.0–1.1	9.1–15.9	1.9–4.2
December 2010	0.2–1.1	0.1–1.5	9.1–14.4	1.9–4.9	0.0–0.2	0.0–1.7	9.1–15.1	1.9–4.2
January 2011	0.1–1.1	0.0–0.6	9.1–22.1	2.1–3.6	0.0–0.2	0.0–1.5	7.2–22.1	2.2–4.1
February 2011	0.0–0.1	0.1–0.6	9.2–14.9	2.1–4.5	0.0–0.2	0.0–1.5	6.2–11.4	1.9–3.6
March 2011	0.0–0.7	0.0–1.1	9.7–16.0	2.1–5.0	0.0–0.2	0.0–1.3	6.2–17.1	1.9–3.7

of 3 m has been reported[10] for the location at 12 m water depth situated north of Tuticorin in GoM during 1997–98, whereas during the present study, H_{max} up to 5.4 m was measured indicating the importance of site-specific data for the project. Highest H_{m0} of 2.1 m and H_{max} of 3.8 m during the NE monsoon in the area north of PB in the Bay of Bengal were observed[1] during 1995–96 and slightly lower values were observed in the present study in PB.

Good correlation (correlation coefficient of 0.94) is obtained between H_{m0} and mean wave period (T_{m02}) in PB (Figure 3 *b*) during January to March 2011 since only wind sea is present. But the correlation between H_{m0} and T_{m02} is poor in GoM (Figure 3 *a*) due to the presence of wind seas and swells. Empirical relation between H_{m0} and T_{m02} is $T_{m02} = 3.5*H_{m0}^{0.25}$ and the same expression is found valid for the data collected off Goa[18]. Good correlation is found between H_{m0} and T_{m02} with a correction coefficient

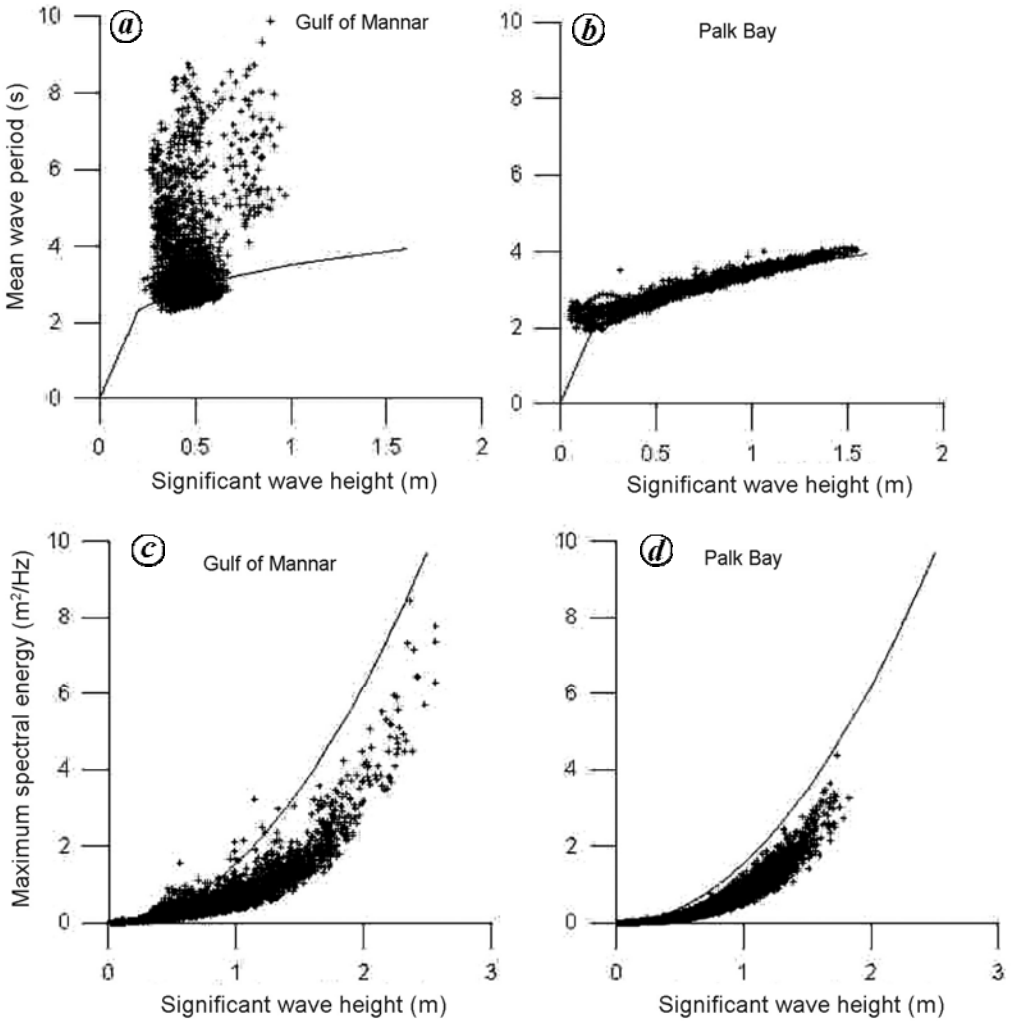

Figure 3. Variation of mean wave period, maximum spectral energy with significant wave height.

Table 2. Percentage of swell and sea

Month	Gulf of Mannar		Palk Bay	
	Swell (%)	Sea (%)	Swell (%)	Sea (%)
February 2010	98.4	1.6	0.0	100.0
March 2010	98.9	1.1	0.0	100.0
April 2010	85.8	14.2	0.1	99.9
May 2010	28.5	71.5	6.1	94.0
June 2010	3.9	96.1	2.8	97.2
July 2010	24.3	75.7	0.1	99.9
August 2010	24.2	75.8	2.1	97.9
September 2010	36.2	63.8	0.0	100.0
October 2010	6.1	93.9	1.7	98.3
November 2010	39.5	60.5	0.0	100.0
December 2010	35.6	64.4	0.0	100.0
January 2011	52.4	47.7	0.1	99.9
February 2011	58.1	41.9	0.2	99.8
March 2011	98.7	1.2	0.8	99.3

of 0.8 for the shallow water waves of the west coast of India[19]. Highest waves are not associated with longest period waves, similar to the earlier observation[20]. Maximum spectral energy density (E_{max}) is found to follow the empirical relationship proposed for normal sea states ($E_{max} = 1.55*H_{m0}^2$), with good correlation coefficient of 0.97 for PB (Figure 3 *d*) and 0.72 for the GoM (Figure 3 *c*). Similar trends are observed for Visakhapatnam coast and the expression is found valid along the Indian coast[2]. Wave periods are low (< 8 sec) during southwest monsoon and high (> 8 sec) during pre-monsoon period in GoM.

The study shows that swells are predominant in GoM during non-monsoon period (January–April) and during rest of the year wind sea dominates (Table 2). Even though wind seas are predominant during May to December, the role of swell is also significant. Dominance of swell is maximum (98%) during March and dominance of wind sea is maximum (94%) during October. Swells are insignificant in PB region as PB is a semi-enclosed region and distant swells cannot reach this region.

At GoM, the waves are from south-southwest (Figure 2) and in PB, the waves prevailed in all directions (Figure 2), with waves from north-northeast during November to March and from SE to SW during the remaining period. For the southern region of GoM, the wave direction

mostly prevailed 140–230° during SW monsoon (June to September), 85–150° during NE monsoon and 90–200° during fair weather period (Rao, B. P., 2002, unpublished thesis). The wave direction is highly variable in January and May at GoM. Wave direction mostly prevailed between 60° and 120° during the NE monsoon period, and 90° and 120° during the rest of the year north of PB[1]. Range of swell direction varied from 86° to 266° and wind sea from 14° to 324° in GoM. High-energy waves in GoM approach from directional sector between SE and SW and in PB the high-energy waves are from the north.

Wave spectra observed are mainly double-peaked in GoM and single-peaked in PB. Swells dominate in the GoM region, except during southwest monsoon period. Only wind seas exist in PB region as distant swells cannot reach because the Bay is protected by the Indian peninsula and northern extremity of Sri Lanka. Maximum wave height observed is 5.4 m at GoM and 3.6 m in PB and this is higher than the earlier reported values for GoM. Maximum wave height is observed in GoM during SW monsoon period and in PB during NE monsoon period.

1. Jena, B. K., Chandramohan, P. and Kumar, V. S., Long shore transport based on directional waves along north Tamil Nadu coast, India. *J. Coastal Res.*, 2001, **17**, 322–327.
2. Kumar, V. S., Kumar, K. A. and Raju, N. S. N., Wave characteristics off Visakhapatnam coast during a cyclone. *Curr. Sci*., 2004, **86**, 1524–1529.
3. Nayak, B. U., Chandramohan, P. and Sakhardande, R. K., Seasonal distribution of wave heights off Yanam on the east coast of India. *Indian J. Inst. Eng*., 1992, **72**, 187–193.
4. Chandramohan, P., Kumar, V. S. and Nayak, B. U., Coastal processes along shore front of Chilka Lake, east coast India. *Indian J. Mar. Sci.*, 1993, **22**, 268–272.
5. Aboobacker, V. M., Vethamony, P., Sudheesh, K. and Rupali, S. R., Spectral characteristics of the near-shore waves off Paradip, India during monsoon and extreme events. *Nat. Hazards*, 2009, **49**, 311–323.
6. Kumar, V. S., Anand, N. M., Kumar, K. A. and Mandal, S., Multipeakedness and groupiness of shallow water waves along Indian coast. *J. Coastal Res.*, 2003, **19**, 1052–1065.
7. Wang, D. W. and Hwang, P. A., An operation method for separating wind sea and swell from the ocean wave spectra. *J. Atmos. Ocean. Technol*., 2011, **18**, 2052–2062.
8. Gilhousen, D. B. and Hervey, R., Improved estimates of swell from moored buoys. In Proceeding of the Fourth International Symposium – WAVES 2001, American Society of Civil Engineering, Alexandria, 2011, pp. 387–393.
9. Portilla, J., Ocampo-Torres, F. J. and Monbaliu, J., Spectral partitioning and identification of wind sea and swell. *J. Atmos. Ocean. Technol*., 2009, **26**, 117–122.
10. Kumar, V. S., Chandramohan, P., Kumar, K. A., Gowthaman, R. and Pednekar, P., Longshore currents and sediment transport along Kannirajapuram coast, Tamil Nadu, India. *J. Coastal Res.*, 2000, **16**, 247–254.
11. Kumar, V. S., Pathak, K. C., Padnekar, P., Raju, N. S. N. and Gowthaman, R., Coastal processes along the Indian coastline. *Curr. Sci.*, 2006, **91**, 530–536.
12. Rao, N. S. B. and Mazumdar, S., A technique for forecasting storm waves. *Indian J. Meteorol. Geophys*., 1996, **17**, 333–346.
13. Anon., Indian tide tables 2011, Indian and selected foreign ports. Survey of India, Government of India, 2011, p. 238.
14. Kuik, A. J., Vledder, G. and Holthuijsen, L. H., A method for the routine analysis of pitch and roll buoy wave data. *J. Phys. Oceanogr.*, 1988, **18**, 1020–1034.
15. Baba, M. and Dattatri, J., Ocean wave spectra off Cochin, west coast of India. *Indian J. Mar. Sci*., 1989, **18**, 106–112.
16. PIANC, Approach channels: A guide for design. Final Report of the Joint PIANC-IAPH Working Group II-30 in cooperation with IMPA and IALA, Supplement to Bulletin No. 95, June 1997.
17. www.imd.gov.in/section/nhac/dynamic/Annual2010.pdf
18. Kumar, V. S., Sajiv Philip, C. and Nair, T. N. B., Wave in shallow water off west coast of India during the onset of summer monsoon. *Ann. Geophys*., 2010, **28**, 817–824.
19. Swain, J., Ananth, P. N. and Rao, C. V. K. P., Shallow water wave characteristics off Cochin during monsoon 1986. *Indian J. Mar. Sci*., 1993, **22**, 256–262.
20. Dattatri, J., Waves off Mangalore harbor – west coast of India. *J. Waterw., Harbors Coastal Eng. Div., ASCE*, 1997, **9**, 39–58.

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