RESEARCH ARTICLE

Interannual and seasonal variations in nearshore wave characteristics off Honnavar, west coast of India

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Interannual and seasonal variations in nearshore surface wave parameters over a period of three years (March 2008–March 2011) were examined based on the measured wave data at 9 m water depth off Honnavar, west coast of India. Significant wave height up to 4.3 m was observed during the summer monsoon with an average value of 1.7 m. Predominant wave spectral energy density was within 0.05–0.25 Hz and directional spreading was narrow (directional width < 20°) for high waves (significant wave height > 2 m). Average annual wave power per unit width was the same (6.2 kW m^{-1}) in different years. Yearly average wave parameters were also the same during different years. Even though the average wave parameters are the same in different years, for estimating the wave height having different return periods, data covering a large period are required.

Keywords: Mixed sea state, swell, wave spectrum, wind waves.

WAVE data are required for planning and operation of coastal facilities. Wave data covering many years are required for design of marine structures. Information on waves is obtained through measurements, wave hind casting and visual observations[1]. Data based on measurement are limited as they are costly and time-consuming. In order to validate the data obtained through wave hind casting, measured data are required. The waves along the west coast of India are influenced by the wind condition in the North Indian Ocean and largely by the summer monsoon[2]. Along the west coast of India, significant wave height (SWH) up to 6 m was reported[3] during the summer monsoon period and SWH was normally less than 1.5 m during rest of the period[4]. Waves along the southwest coast of India were studied by Baba and Kurian[4]. At present we do not know how the wave characteristics vary in different years along the west coast of India. Hence a study was carried out to find out the variations in nearshore wave parameters off Honnavar, Karnataka along the central west coast of India over a period of three years during March 2008–March 2011 based on the measured wave data at 9 m water depth.

Materials and methods

Waves at 9 m water depth off Honnavar (Figure 1) were measured using a moored datawell directional waverider buoy[5] during March 2008–March 2011. The data were recorded for 30 min duration at 1.28 Hz interval. Wave spectrum was obtained through fast Fourier transform (FFT). FFT of 6 series, each consisting of 256 measured vertical elevations of the buoy data, was added to obtain

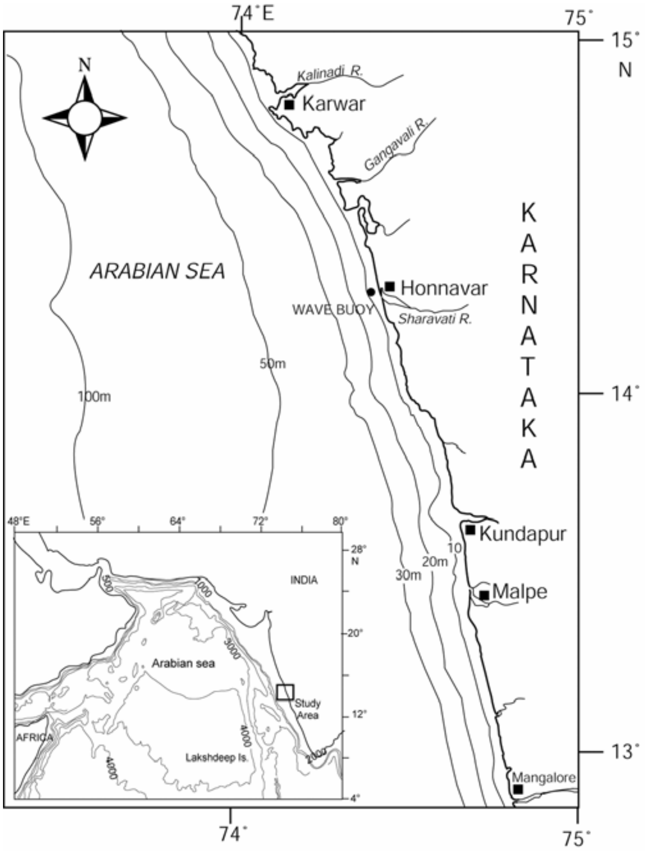

Figure 1. Map showing the wave measurement location.

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*For correspondence. (e-mail: sanil@nio.org) the spectra. The high frequency cut-off was set at 0.58 Hz and the resolution was 0.005 Hz. SWH and mean wave period (MWP) were obtained based on spectral analysis. The period corresponding to the maximum spectral energy is referred as spectral peak period (T_p) and is estimated from the wave spectrum. The sea and swell from the measured data were separated by the method described by Portilla *et al.*[6]. Mean wave direction (MWD) and circular RMS spreading (directional width) were estimated[7]. Maximum wave height (MWH) was estimated from the 30-min time series vertical elevation data of the buoy and the corresponding wave period was $T_{H\max}$. Other parameters obtained were spectral peakedness parameter (Q_p), spectral width parameter based on spectral analysis (ε) and the maximum spectral energy.

Reanalysis data of zonal and meridional components of wind speed at 6 h intervals from NCEP/NCAR[8] were obtained for the point (12.5°N; 72.5°E) close to the study area to know the influence of wind on waves. These data are provided by the NOAA–CIRES Climate Diagnostics Center, Boulder, Colorado, USA at http://www.cdc.noaa.gov/.

Results and discussion

Over an annual cycle, except during the summer monsoon period (June to September), the average SWH was less than 1 m (Figure 2). SWH up to 4.3 m was observed during the summer monsoon with an average value of 1.7 m. Variations in monthly average SWH in a particular month during different years were less than 10%, except during June. The large variation in SWH during June in different years was due to the low wave activity in 2009 resulting from the delayed monsoon compared to other years. Maximum value (4.3 m) of SWH was in July 2009 and was 15% higher than the maximum value of SWH during 2008 and 2010 (Figure 3). Even though the highest value of SWH was different, the yearly average SWH during different years was the same, i.e. around 1 m. During 10% of the time in a year SWH was more than 2 m. The maximum value of MWH of 7 m was observed in July 2009. The annual average MWH was the same (1.6 m) in different years. The high SWH during November 2009 was due to the cyclonic storm named 'Phyan'[9] which developed over the southeastern Arabian Sea.

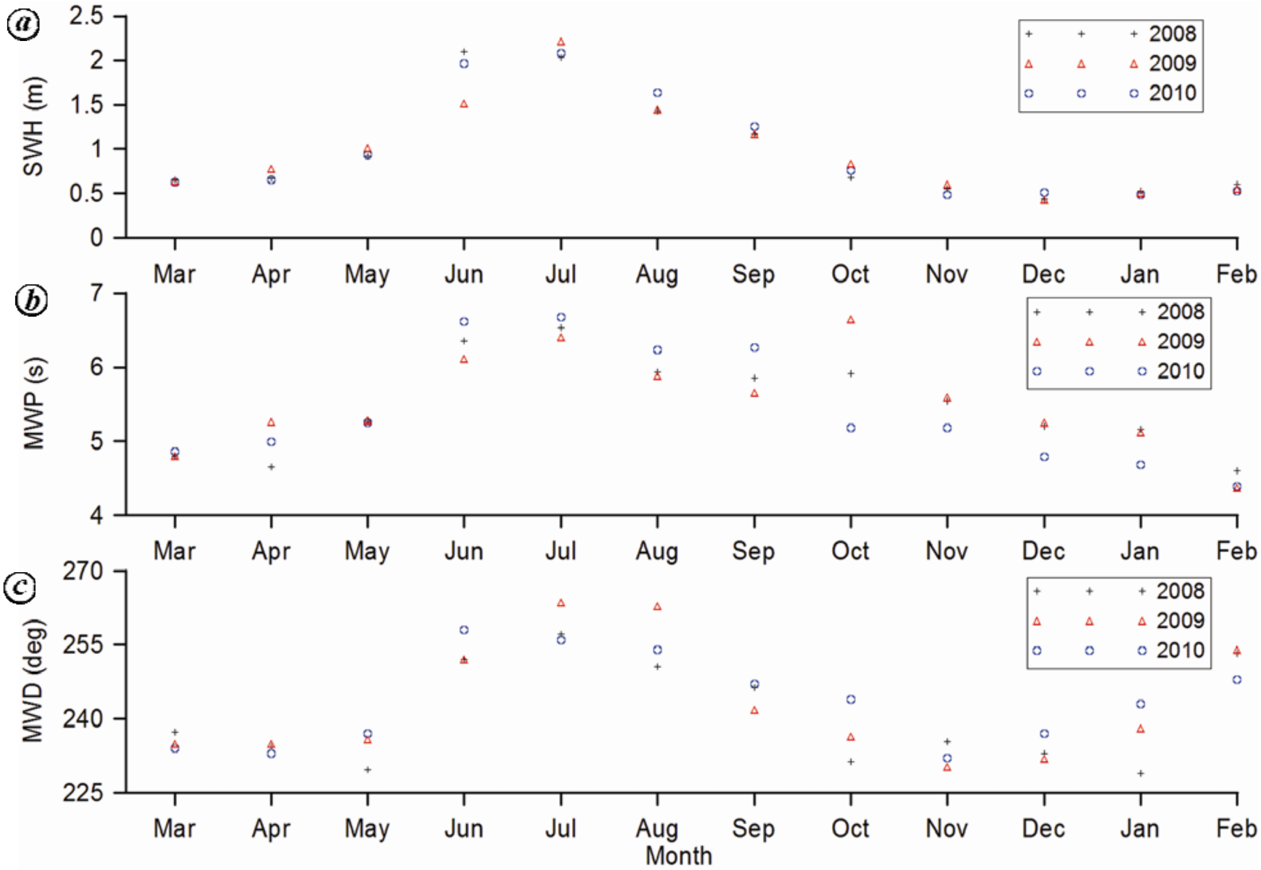

Figure 2. Average value of (***a***) significant wave height; (***b***) mean wave period and (***c***) mean wave direction in different months during 2008–2010.

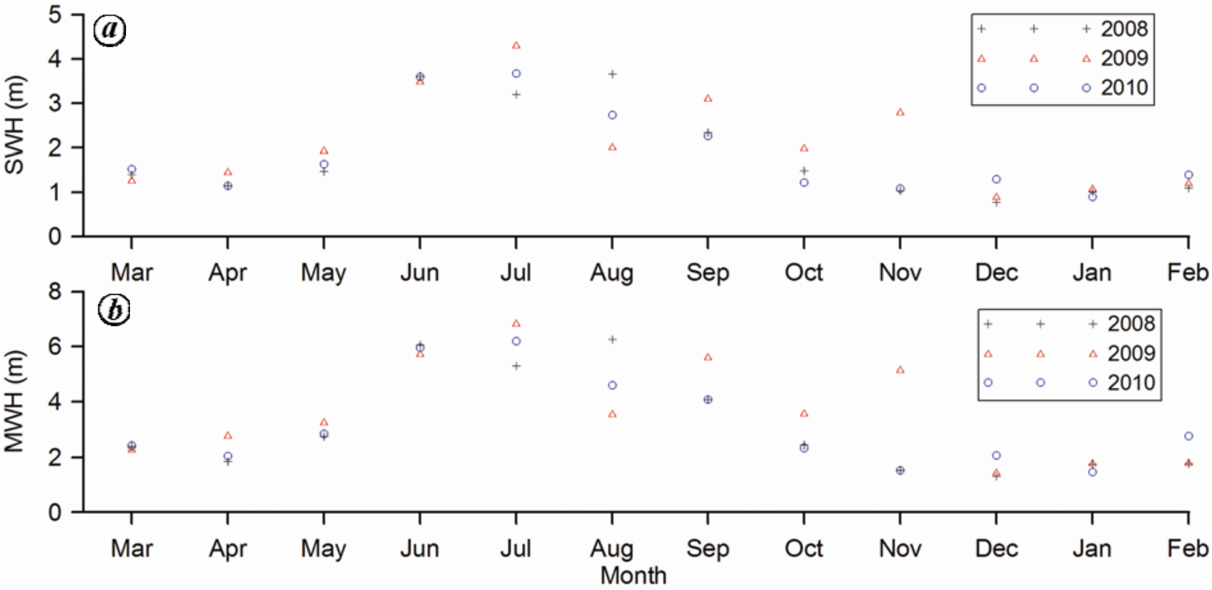

Figure 3. Maximum value of (***a***) significant wave height and (***b***) maximum wave height in different months during 2008–2010.

During this cyclone period, SWH increased from 0.5 to 2.8 m and MWP decreased from 8 to 5 s indicating the transition from swell to sea. MWP varied from 3 to 9 s with an average value of 6 s during the monsoon period. An earlier study[4] shows that the maximum breaker height observed in each year at Alleppey, south-west coast of India during 1981–1984 does not show any significant variation (2.9–3.3 m).

The coastline at Honnavar is inclined 17° to the west (Figure 1) with the depth contours aligned approximately parallel to the coastline. The depth contours of 20, 50 and 100 m occur at 9, 41 and 99 km off Honnavar. The average MWD during the monsoon was 253° and was similar during all the three years. Wave direction of 253° indicates that the wave crest was parallel to the coastline. Even though the coast is exposed to seasonally reversing monsoon winds, due to the westerly winds close to the coast during the southwest monsoon period, the waves are approaching perpendicular to the coast. The MWD during pre-monsoon is 239° and that during the post-monsoon is 235°.

Maximum spectral energy density was highest (37.2 $m^2 Hz^{-1}$) during 2009 and was 30% higher than the maximum value (28 $m^2 Hz^{-1}$) during other years (Figure 4). The annual average maximum spectral energy density was the same (≈ 2 $m^2 Hz^{-1}$) during different years. Maximum spectral energy density during monsoon was much higher (up to 37 $m^2 Hz^{-1}$) than that (< 5 $m^2 Hz^{-1}$) during the other periods. In an annual cycle, spread of spectral energy to higher frequencies (0.15–0.25 Hz) was predominant during May because the winds along the study region have a distinct signal due to sea breeze during pre-monsoon period[10] and this makes the sea during this part of the year stand out from the swell. Wave conditions in the nearshore waters will be influenced by sea/land breeze. The horizontal extent of the sea/land breeze circulation[11] over the Arabian Sea is observed up to about 80–100 km. Off Goa coast, during February–April, the seaward extent of the sea breeze[12] was about 180 km. As the measurement location was around 3 km from the coast, the sea breeze and land breeze can influence the wave parameters. The sea and land breeze effects were more during February–April and hence the percentage of sea wave was maximum (> 65%) in February. Significant influence of sea breeze on the wave parameters could not be observed during the monsoon period because during the summer monsoon (May–September), the wind field is dominated by the large-scale atmospheric circulation and the winds are westerly (inshore) along the west coast of India. Also, there is practically no land or sea breeze when the monsoon is active, but a weak land- and sea-breeze system develops during a break in the monsoon[13]. The percentage of spectral energy beyond the frequency range 0.05–0.25 Hz varied from 2 to 12 with an average value of 6 for high waves (SWH > 2 m) and beyond the frequency range of 0.04–0.35 Hz, the average percentage of spectral energy was 0 to 5 with an average value of 2. The study indicates that the predominant wave energy was within 0.05–0.25 Hz when SWH was more than 2 m. Also, the wave spectra were narrow-banded when SWH was more than 2 m. For moderate (1 < SWH < 2 m) and small (SWH < 1 m) waves, the spread of spectral energy to low and high frequency was more with 17% of the spectral energy beyond frequency range 0.05–0.25 Hz, whereas the percentage of spectral energy beyond 0.04–0.35 Hz was around 7%. In the beginning of the monsoon, the spectral peak was around 0.12–0.13 Hz and it shifted towards lower frequencies (0.07–0.09 Hz) during the peak monsoon period. The shifting of peak frequency towards the lower frequency is recognized as one of the wave growth

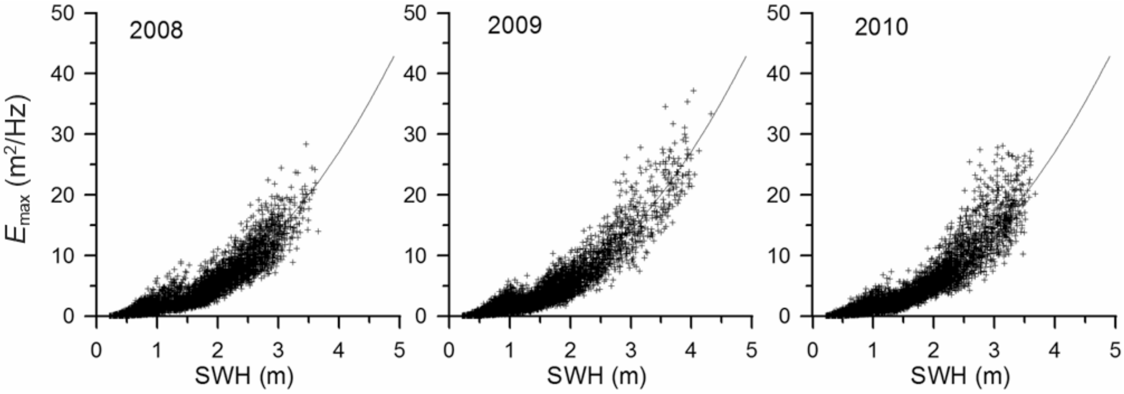

Figure 4. Variation of maximum wave spectral energy density (E_{max}) with significant wave height during different years.

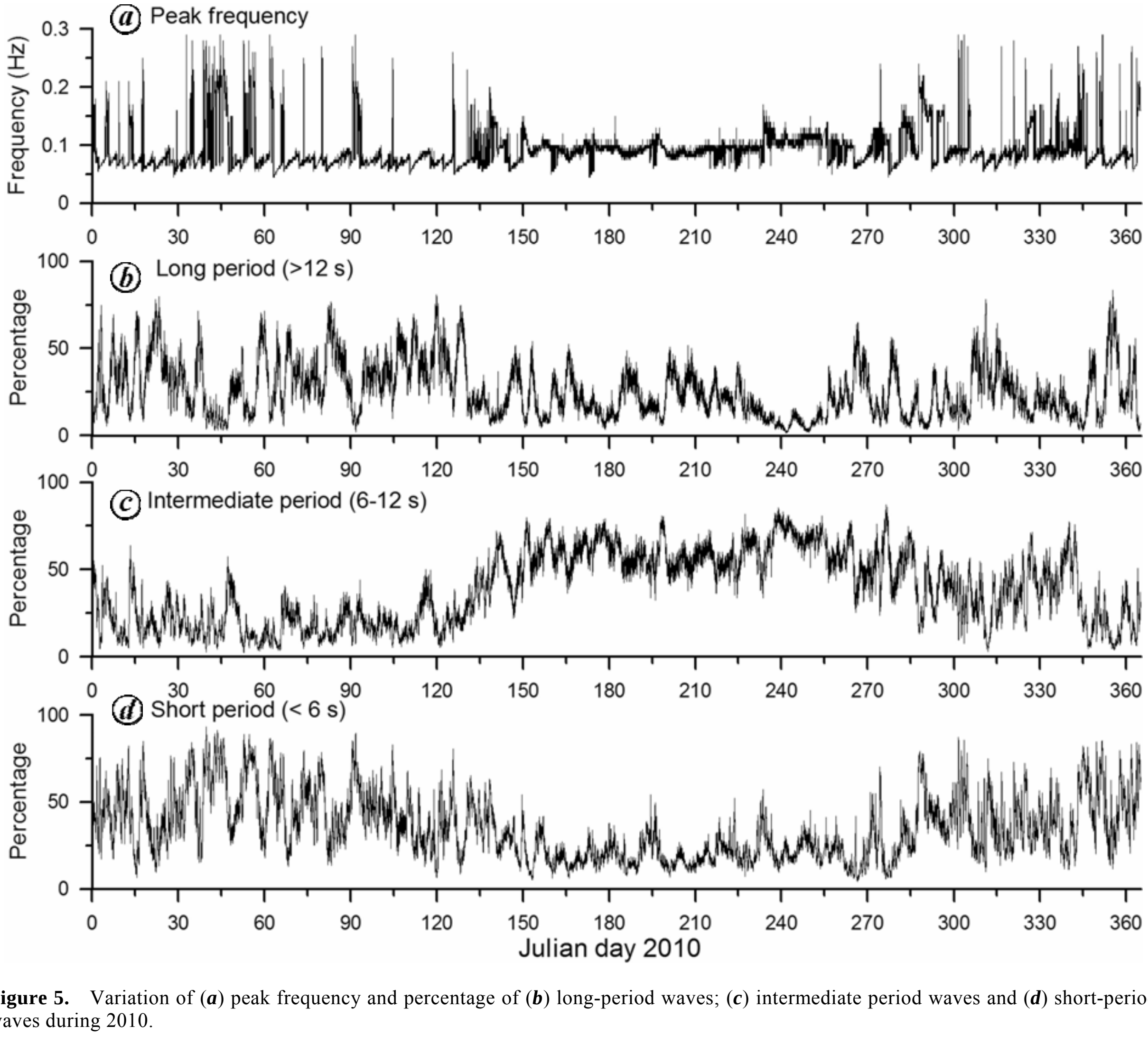

Figure 5. Variation of (***a***) peak frequency and percentage of (***b***) long-period waves; (***c***) intermediate period waves and (***d***) short-period waves during 2010.

characteristics[14]. Contribution to the wave field initially is from the region closer to the coastline, but as time progresses swells from the region farther off start contributing.

Wave spectral energy is divided into three bands[15], i.e. (i) short period (wave period, $T < 6$ s, is dominated by local seas), (ii) long period ($T > 12$ s, results primarily from swell) and (iii) intermediate period ($6 \leq T \leq 12$ s,

Table 1. Average value of wave statistical parameters in different months

Month	SWH (m)	MWH (m)	MWP (s)	T_p (s)	$T_{H\max}$ (s)	MWD (deg)	SWP	Q_p	Swell (%)	Sea (%)
Mar 08	0.7	1.0	4.8	12.4	9.6	237	0.62	1.8	44	56
Apr 08	0.7	1.0	4.7	13.8	10.3	234	0.65	1.6	46	54
May 08	0.9	1.4	5.3	13.8	10.4	230	0.66	1.5	61	39
Jun 08	2.1	3.2	6.4	11.2	9.5	252	0.55	1.9	73	27
Jul 08	2.0	3.1	6.5	10.9	9.4	257	0.52	1.9	75	25
Aug 08	1.4	2.1	5.9	11.4	9.0	251	0.55	1.7	70	30
Sep 08	1.2	1.8	5.9	11.6	9.4	246	0.58	1.8	68	32
Oct 08	0.7	1.0	5.9	12.2	10.8	231	0.66	2.1	72	28
Nov 08	0.6	0.8	5.5	12.8	10.3	235	0.64	2.2	56	44
Dec 08	0.4	0.7	5.2	12.6	9.9	233	0.67	2.1	60	40
Jan 09	0.5	0.8	5.2	12.5	10.2	229	0.65	1.8	55	45
Feb 09	0.6	0.9	4.6	9.6	7.3	253	0.51	1.8	31	69
Mar 09	0.6	1.0	4.8	12.2	8.8	235	0.59	1.5	41	59
Apr 09	0.8	1.2	5.3	12.8	10.3	235	0.65	1.8	54	46
May 09	1.0	1.5	5.3	12.1	9.3	236	0.60	1.7	56	44
Jun 09	1.5	2.3	6.1	10.9	9.0	252	0.54	1.9	70	30
Jul 09	2.2	3.4	6.4	11.6	9.7	264	0.55	1.9	74	26
Aug 09	1.5	2.2	5.9	9.8	8.6	263	0.52	2.0	71	29
Sep 09	1.2	1.8	5.7	12.8	9.7	242	0.59	1.7	62	38
Oct 09	0.8	1.3	6.6	12.7	11.3	237	0.65	2.5	73	27
Nov 09	0.6	0.9	5.6	12.0	10.0	230	0.63	2.1	61	39
Dec 09	0.4	0.6	5.3	11.9	9.3	232	0.63	1.9	53	47
Jan 10	0.5	0.8	5.1	13.6	10.2	238	0.64	1.9	48	52
Feb 10	0.6	0.8	4.4	11.4	7.3	254	0.54	1.7	30	70
Mar 10	0.6	0.9	4.9	13.6	10.2	234	0.65	1.9	49	51
Apr 10	0.7	1.0	5.0	13.4	10.6	233	0.66	1.8	52	48
May 10	0.9	1.4	5.3	13.0	9.8	237	0.62	1.6	55	45
Jun 10	2.0	3.0	6.6	11.1	9.6	258	0.54	2.0	75	25
Jul 10	2.1	3.2	6.7	11.2	9.9	256	0.54	2.0	77	23
Aug 10	1.6	2.5	6.2	10.6	9.2	254	0.53	1.8	74	26
Sep 10	1.3	1.9	6.3	10.9	9.2	247	0.54	1.8	73	27
Oct 10	0.8	1.2	5.2	10.3	8.0	244	0.54	1.8	47	53
Nov 10	0.5	0.7	5.2	11.8	9.4	232	0.61	1.8	54	46
Dec 10	0.5	0.8	4.8	11.5	8.5	237	0.59	1.8	47	53
Jan 11	0.5	0.7	4.7	11.6	8.5	243	0.58	1.7	38	62
Feb 11	0.5	0.8	4.4	10.9	7.7	248	0.55	1.7	35	65
Mar 11	0.6	0.9	4.7	12.4	9.0	239	0.61	1.6	42	58

SWH, Significant wave height; MWH, Maximum wave height; MWP, Mean wave period; T_p, Spectral peak period; T_Hmax, Wave period corresponding to MWH; MWD, Mean wave direction; SWP, Spectral width parameter; Q_p, Spectral peakedness parameter.

probably results from a mixture of local and regional wind forcing) and studied the contribution of the waves in these three categories in the annual data. Contribution of short-period waves was high (45%) during February–May than other periods indicating the influence of local wind on the wave height. Intermediate-period waves were high (60%) during the summer monsoon (Figure 5). During October–January, 73% of the time the waves were either short period or intermediate period.

To identify the swell components from the measured data, the locally generated waves and swell were separated. The percentage of swells in the data was more than 70 during June–August in all years (Figure 6). During January–April, the percentage of seas was more than 50. During the summer monsoon period, the measured waves were predominantly swells arriving from the sector between 210° and 280°. The average of the MWD during the monsoon period was 253°. During pre-monsoon period the waves were predominantly from the directional sector between southwest and northwest. An earlier study[16] indicates that during the onset of summer monsoon waves in shallow waters off the west coast of India were mainly swells arriving from the south and southwest direction.

Directional spreading indicates that the spectra were narrowest in the vicinity of the spectral peak and broader at both higher and lower frequencies consistent with previous observations[17,18]. The circular RMS spreading (directional width) parameter provides a measure of the energy spread around the mean direction of wave propagation. The directional width varied from 6° to 20° during the southwest monsoon period when SWH was more than 2 m. Directional width was 10°–65° during other periods when SWH was less than 1 m. The study indicates that directional spreading was narrow (directional width $< 20°$) for high waves (SWH > 2 m; Figure 7 *a*). Scatter plot of wave power per unit width against MWD (Figure 7 *b*) indicates that high wave power (>10 kW m^{-1}) was

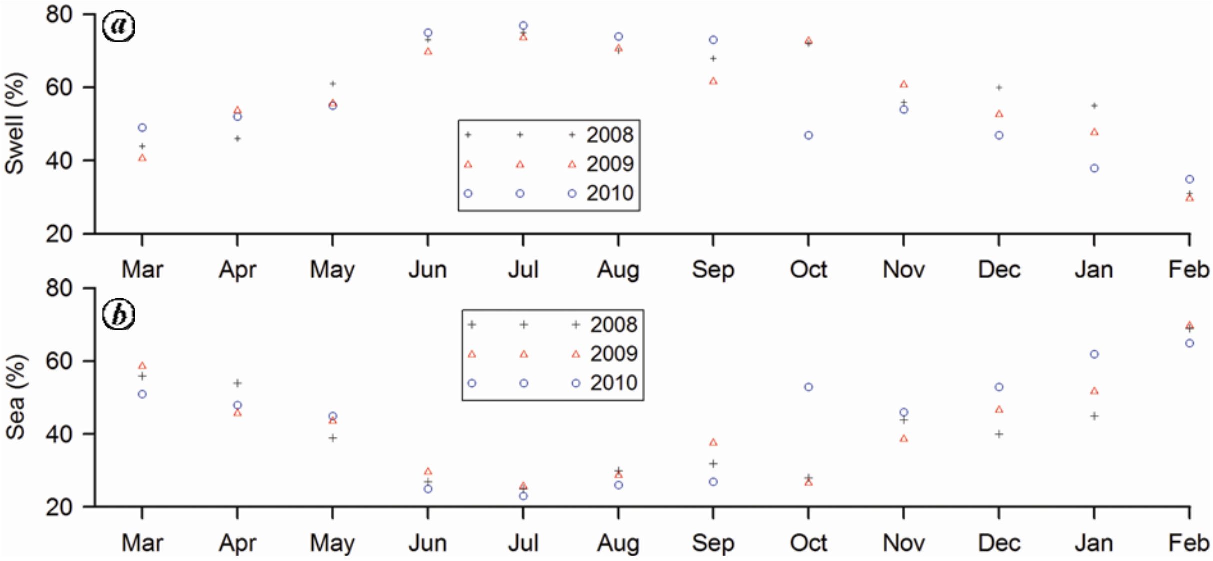

Figure 6. Average percentage of (***a***) swell and (***b***) sea during different months.

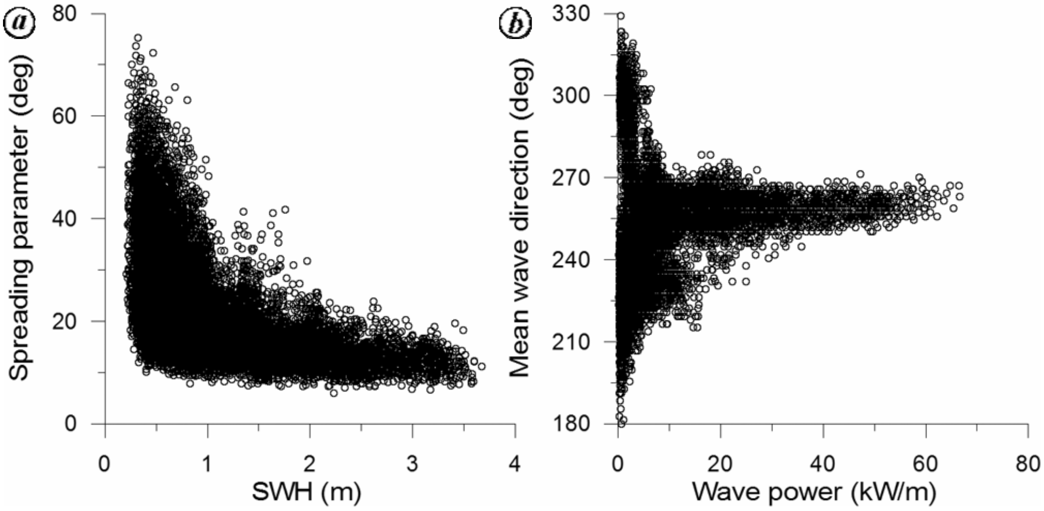

Figure 7. Scatter plot of (***a***) spreading parameter against significant wave height (SWM) and (***b***) mean wave direction against wave power during 2010.

from southwesterly waves (250°–270°) and occurred during the southwest monsoon period. During other periods, the wave power was less than 10 kW m^{-1}. Average annual wave power was 6.2 kW m^{-1} and was the same in different years.

Wave height having a specific return period, i.e. the design wave height is required while planning and designing the nearshore activities, and a number of methods are available to estimate the design wave height[19]. A study has been carried out to compare the values estimated based on monthly maximum SWH during 1-year period and that during 3-year period using Fisher Tippet-1 (Gumbel) and Weibull distributions[19]. It was found that the data correlation was good (correlation coefficient 0.95) for the Weibull distribution with shape parameter, $k = 1$ and Gumbel distribution. The wave height having 10-year return period based on 2008 data was 2–3% more than that based on 3-year period (2008–2010). The wave height having 10-year return period based on 2009 data was 11–12% more than that based on 3-year period (Table 2). The study indicates that even though the average wave parameters were the same in different years, for estimating the wave height having different return periods, data covering large period are required.

Conclusions

High SWH (up to 4.3 m) was observed during the summer monsoon with an average value of 2 m during June and July. Maximum spectral energy density during the monsoon was much higher (up to 37 m^2 Hz^{-1}) than that

Table 2. Wave height with different return periods based on data during different years

	Wave height (m) having 10-year return period		Wave height (m) having 25-year return period	
Data block	Gumbel	Weibull ($k = 1$)	Gumbel	Weibull ($k = 1$)
2008	5.4	6.0	6.2	7.1
2009	5.9	6.5	6.7	7.6
2010	5.2	5.8	5.9	6.7
2008–2010	5.3	5.8	6.0	6.7

(< 5 m^2 Hz^{-1}) during the other periods. Predominant wave energy was within 0.05–0.25 Hz when SWH was more than 2 m. Wave spectra were narrow-banded when SWH was more than 2 m. During all the three years, annual average SWH, MWH, MWD and maximum spectral energy density were the same. Contribution of short-period waves was high ($> 65\%$) during February than other periods, indicating the influence of local wind on wave height.

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ACKNOWLEDGEMENTS. We thank Integrated Coastal and Marine Area Management Project Directorate (ICMAM PD), Ministry of Earth Sciences, New Delhi for funding the measurement programme; Director, the National Institute of Oceanography, Goa and the Director, ICMAM PD, Chennai for encouragement. We also thank Mr P. Pednekar, Mr Jai Singh, Mr G. N. Naik and Mr M. Mochemadkar for help during the measurements and Mrs Kirti Kedar Dubhashi for data analysis. This is NIO contribution no. 5192.

Received 30 November 2011; revised accepted 22 June 2012