

Characteristics of long-period swells measured in the near shore regions of eastern Arabian Sea

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Abstract

Measured wave data covering two years simultaneously at 3 locations along the eastern Arabian Sea reveals the presence of long-period (peak wave period > 18 s) low-amplitude waves (significant wave height < 1 m) and the characteristics of these waves are described in this article. In a year, 1.4–3.6% of the time, the low-amplitude long-period swells were observed, and these waves were mainly during the non-monsoon period. The wave spectra during these long-period swells were multi-peaked with peak wave period around 18.2 s, the secondary peak period around 13.3 s and the wind-sea peak period at 5 s. The ratio of the spectral energy of the wind-sea peak and the primary peak (swell) was slightly higher at the northern location (0.2) than that at the southern location (0.15) due to the higher wind speed present at the northern location.

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Keywords: Surface waves; Swells; Significant wave height; Wave period; Wave spectrum; West coast of India

1. Introduction

Swells observed at the ocean surface can propagate thousands of kilometers (Munk et al., 1963). Identification of low-frequency swells propagating large distances from the generation region is vital in wave hindcast studies (Ardhuin et al., 2008). Due to near resonance conditions, the long-period swells can cause large heave motions of drilling rigs and hinder with other offshore operations (Gjevik et al., 1988). Many ports exposed to open ocean experienced a reduction in efficiency of cargo handling operations and mooring line breakages and structural damages to facilities and the factors identified for the cause were vessel and mooring characteristics, long-period swells and its orientation with moored vessel (McComb et al., 2009). The long-period waves and low-

amplitude swells observed from wave buoys deployed in the western North Atlantic Ocean are examined by Hamilton (1992). Sanil Kumar et al. (2011) reported long-period swells with peak wave period (T_p) more than 18 s in the northern Arabian Sea during 2009. Glejin et al. (2013) observed long-period waves with the period over 18 s at Ratnagiri, which were propagated from the Southern Ocean. Southwest (SW) waves with T_p values greater than 18 s were observed by Sanil Kumar et al. (2014a) off the central west coast of India. Waves in the eastern Arabian Sea also show a large response to seasonal variability [monsoon (JJAS), pre-monsoon (FMAM) and post-monsoon (ONDJ)] due to the reversal of the large-scale wind field over the north Indian Ocean between the boreal summer and winter (Sanil Kumar et al., 2014a). Characteristics of the long-period swell simultaneously at different locations in the eastern Arabian Sea are not studied. Hence, we examined the wave data collected during two years period simultaneously at 3 locations to know whether the long-period swells occur at different locations simultaneously in the eastern Arabian Sea. The objective of

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the study is to document the observation of low-amplitude long-period swells in the eastern Arabian Sea and to study their characteristics.

The study region covers 350 km along the west coast of India and lies between Honnavar (southern location) and Ratnagiri (northern location). The measurement locations were i) off Honnavar at 9 m water depth (geographic position 14.3042° N; 74.3907° E), ii) off Karwar at 15 m water depth (geographic position 14.8217°, 74.0524°) and iii) off Ratnagiri at 13 m water depth (geographic position 16.9801° N; 73.2584° E) (Fig. 1). The distance of the locations from the west coast of Indian mainland is 2.5 km at Honnavar, 5 km at Karwar, 2 km at Ratnagiri. The distance between Honnavar and Karwar is 80 km, and that between Karwar and Ratnagiri is around 270 km. These locations were selected since they are open to the swells of the Indian Ocean, and the buoy measured wave data are available at these locations. The wave spectral characteristics of Ratnagiri and Honnavar are presented in Sanil Kumar et al. (2014a). The average significant wave height of the study area varies from 1.8 to 2 m during the

monsoon period and from 0.6 to 0.8 m during the remaining period (Sanil Kumar et al., 2014a). Tides in the region are mixed and are predominantly semi-diurnal (Sanil Kumar et al., 2014a). The average spring tidal range at Ratnagiri is about 1.8 m, and the neap tidal range is 0.9 m (Glejin et al., 2012). The average tidal range at Karwar, location 70 km north of Honnavar is 1.58 m during spring tide and 0.72 m during neap tide (Sanil Kumar et al., 2014a).

2. Data and methodology

Wave data measured simultaneously at all the 3 locations from 1 January 2011 to 31 December 2012 using a 0.9-m diameter Datawell Directional Waverider buoy (Datawell, 2009) equipped with a three-component Hippy accelerometer, compass, and tilt sensors were used in the study. The vertical and horizontal (eastward and northward) displacements of the buoy were obtained by double integration of the respective acceleration signal without applying a filter. The time referred in the paper is in UTC. The displacement data

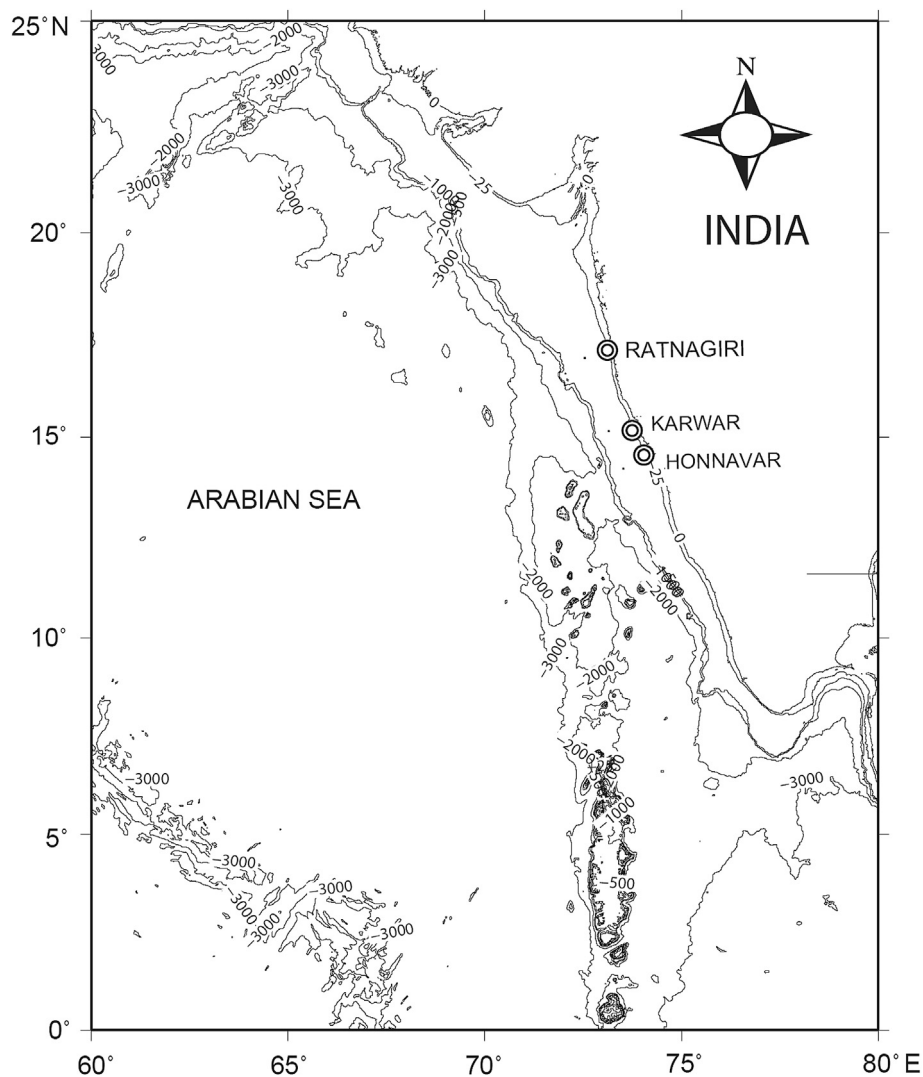


Fig. 1. Study area showing the measurement locations.

recorded continuously at 1.28 Hz and the data for every 30 min were processed as one record. The details of the data analysis are presented in Sanil Kumar et al. (2014b). Fast Fourier Transform (FFT) analyzed data from Datawell buoy processor were used (Datawell, 2009). Significant wave height (H_s) and mean wave period (T_z) was obtained from the spectral moment. Wave spectrum was obtained through FFT with the high-frequency cutoff at 0.58 Hz and a resolution of 0.005 Hz for frequency up to 0.1 Hz and 0.01 Hz for frequency from 0.1 to 0.58 Hz. The period corresponding to maximum spectral energy, i.e., spectral peak period (T_p) was estimated at the spectral peak. From the measured wave data, the wind-seas and swells were separated through the proposed 1-D separation algorithm (Portilla et al., 2009), on the basis of the assumption that, the swell system energy at the peak frequency cannot be higher than the value of a PM spectrum with the same peak frequency (Portilla et al., 2009). It calculates the ratio (γ^*) between the peak energy of a wave system and the energy of a PM spectrum at the same frequency. If γ^* is less than the threshold value of 1, the system is considered to represent swell, else it is taken as wind-sea (Sanil Kumar et al., 2014a). Swell H_s is obtained by integrating the spectral energy density over the swell bandwidth. Mean wave direction was estimated according to Kuik et al. (1988). The analysis procedures are best described by Glejin et al. (2013). The wind data at the hourly interval at a spatial resolution of $0.5^\circ \times 0.5^\circ$ from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) (Saha et al., 2010) were used for studying the wind at the locations.

3. Results and discussion

The data measured during 2011 and 2012 at the study locations indicate that in a year around 50% of the waves were with H_s between 0.5 and 1 m and is similar to the observation of Glejin et al. (2015). The average H_s during the monsoon (JJAS) was 2 m and is around three times that in the non-monsoon period (~ 0.7 m) and around two times of the annual average H_s (~ 1.1 m). The average significant wave height at the locations studied in 2012 during the post-monsoon is ~ 0.6 m and is less than that during the pre-monsoon ~ 0.8 m. From the wave data collected for two years period, swells of period more than 18 s and significant wave height less than 1 m were separated at the three locations along the west coast of India (Fig. 1) and used to study the characteristics of low-amplitude long-period swells. Along the

study region, the long-period swells were observed maximum at Honnavar (3.6%) during 2011 and minimum (1.4%) off Ratnagiri and Karwar during 2012. The difference in the number of total data sets analyzed in Table 1 was because of the removal of error data from the measured wave data by the wave buoy through standard error checks for spikes, steepness, and constant signals of time series (Haver, 1980). During 2011, 2012, at the southern location occurrence of long-period swells were 1051, whereas it was 666 at the northern location. The presence of long-period swells were relatively high at the southern location and showed slight decrease towards the northern Arabian Sea (Table 1). These long-period waves were also subjected to attenuation due to energy transfer between the wave and local wind field, bottom and boundary friction and turbulence (Ardhuin and Jenkins, 2005; Ardhuin et al., 2008) and hence can vary from locations to locations. Decrease in long-period waves towards the northern Arabian Sea was caused by the dissipation of swells due to the interaction between wind-sea and swell (Ardhuin and Jenkins, 2005). The decay of swell from south to north stations spaced at 350 km was also due to the bottom friction, and due to the enhancement of wind-sea from south to north due to the presence of higher wind speed in the northern location. Fig. 2 shows the variation in zonal and meridional components of wind speed at Ratnagiri and Honnavar, and it shows higher zonal components of the wind at Ratnagiri than at Honnavar. Sea breeze generated wind-sea was dominated from the northwest (NW) and long-period swells propagate from SW direction. The dominant swells were from the SW direction, and the corresponding wind-seas were from the NW direction except during the SW monsoon period (Glejin et al., 2013). The relative direction of wind to the swell propagation also influence the swell dissipation (Ardhuin and Jenkins, 2005).

Low-amplitude ($H_s < 1$ m) long-period swells were mainly during the pre and post-monsoon seasons (Figs. 3 and 4). Due to the calm condition (low wind-seas) of the eastern Arabian Sea during the pre-monsoon period, the propagation of swells from the southern hemisphere is more visible, whereas these swells are less during the monsoon season due to turbulence in the north Indian Ocean created by strong winds (Glejin et al., 2013). Hence, long-period swells were negligible during the monsoon period compared to other seasons. During the SW monsoon period, swells were observed in the intermediate period waves (Glejin et al., 2013) with wave period between 8 and 13 s with a mean wave period of 11 s. So in this study we have considered only the low-amplitude long-period waves

Table 1
Measurement locations and the percentage of long-period swells observed in different years.

Year	Location	Latitude Longitude	Water depth (m)	Total data analyzed	Occurrence of long-period swells (%)
2011	Ratnagiri	16.9801° N; 73.2584° E	13	17517	2.4
2012				17463	1.4
2011	Karwar	14.8217° N; 74.0524° E	15	17517	2.8
2012				17323	1.4
2011	Honnavar	14.3042° N; 74.3907° E	9	17420	3.6
2012				17524	2.4

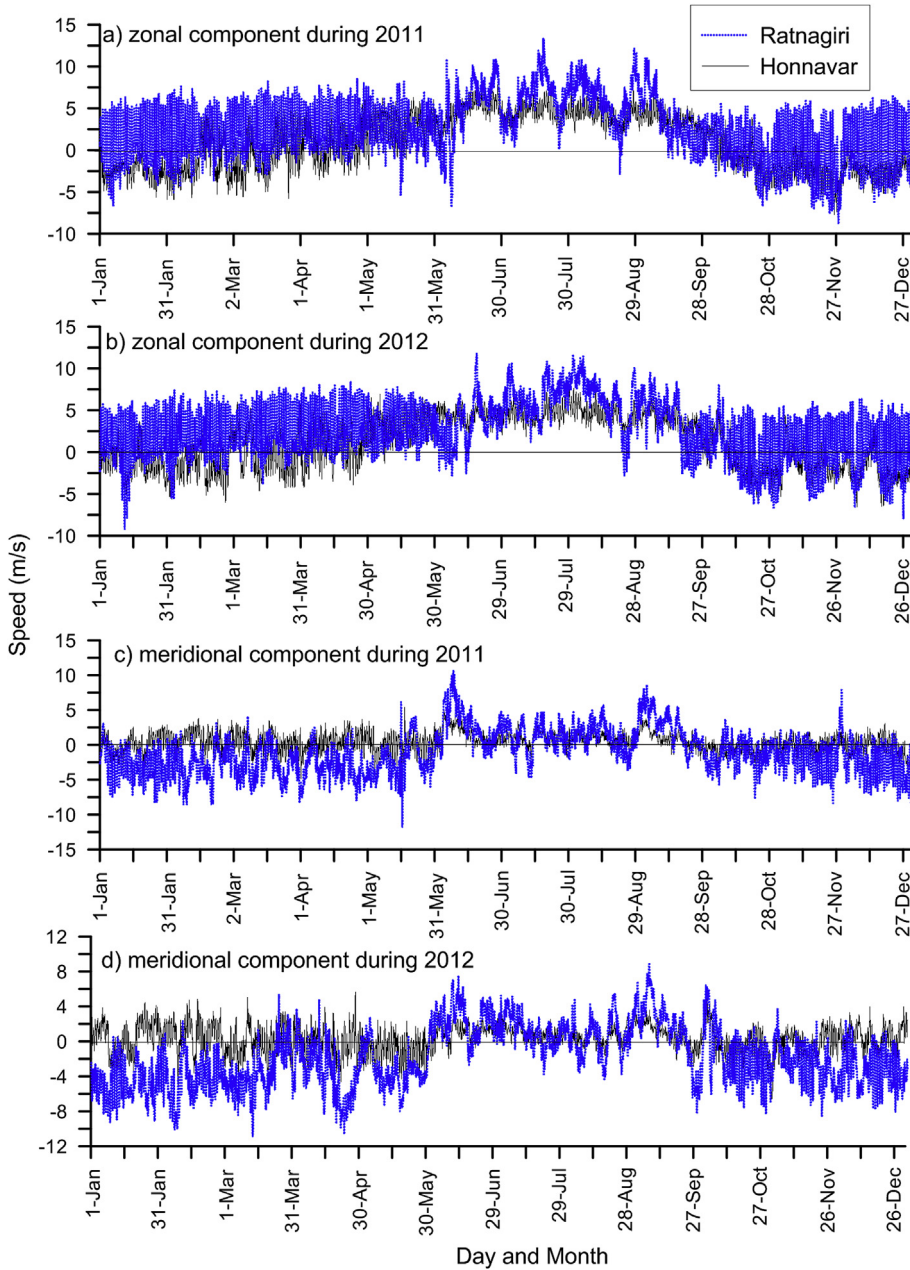


Fig. 2. Time series plot of a) and b) zonal component of wind during 2011 and 2012 and c) and d) meridional component during 2011 and 2012 at Ratnagiri and Honnavar.

observed with wave period of more than 18 s and a significant wave height less than 1 m. The occurrence of swells was mostly during the same period along the 350 km distance in both years (Figs. 3 and 4) since they were propagated from the Southern Ocean (Glejin et al., 2013). The average H_s of the long-period swells varied from 0.64 to 0.77 m and the mean wave period (T_z) varied from 4.6 to 5.9 s (Table 2).

Even during the dominance of swell energy, the spectra at all locations were characterized by a spread of energy across both lower (swell) and higher (wind-sea) frequencies. During the occurrence of the long-period swells, the average wave spectra of the waves were multi-peaked with two peaks in the swell (primary swell peak in the range of 15–30 s and

secondary swell peak in 8–15 s region) band and a single peak in the wind-sea band (0–8 s). These multi-peak spectra represent independent wave systems propagates towards the measurement location off the west coast of India corresponding to long-period swells generated by remote storms, swells generated by nearby storms and locally generated wind waves (Fig. 5). The average wave spectra were observed with a narrow swell and a broader wind-sea. The peak wave period was at 18.2 s, the secondary peak was at ~13.3 s, and the wind-sea peak was at ~5 s (Fig. 5). The maximum spectral energy density varied from 0.42 to 0.72 m^2/Hz at Ratnagiri, 0.66–0.88 m^2/Hz at Karwar and 0.54–0.84 m^2/Hz at Honnavar. The maximum spectral energy density was slightly

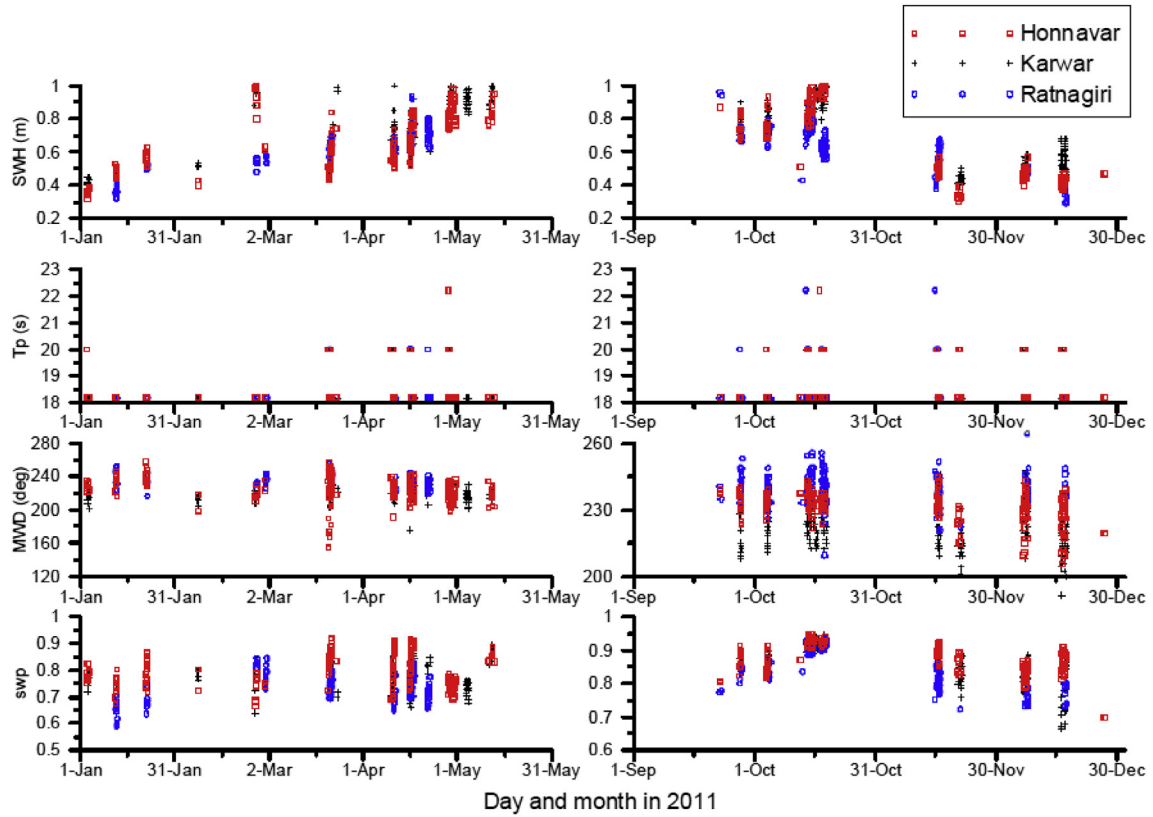


Fig. 3. Wave characteristics (significant wave height-Hs, peak wave period-Tp, mean wave direction-MWD and spectral width parameter-swp) during low-amplitude long-period swells during 2011.

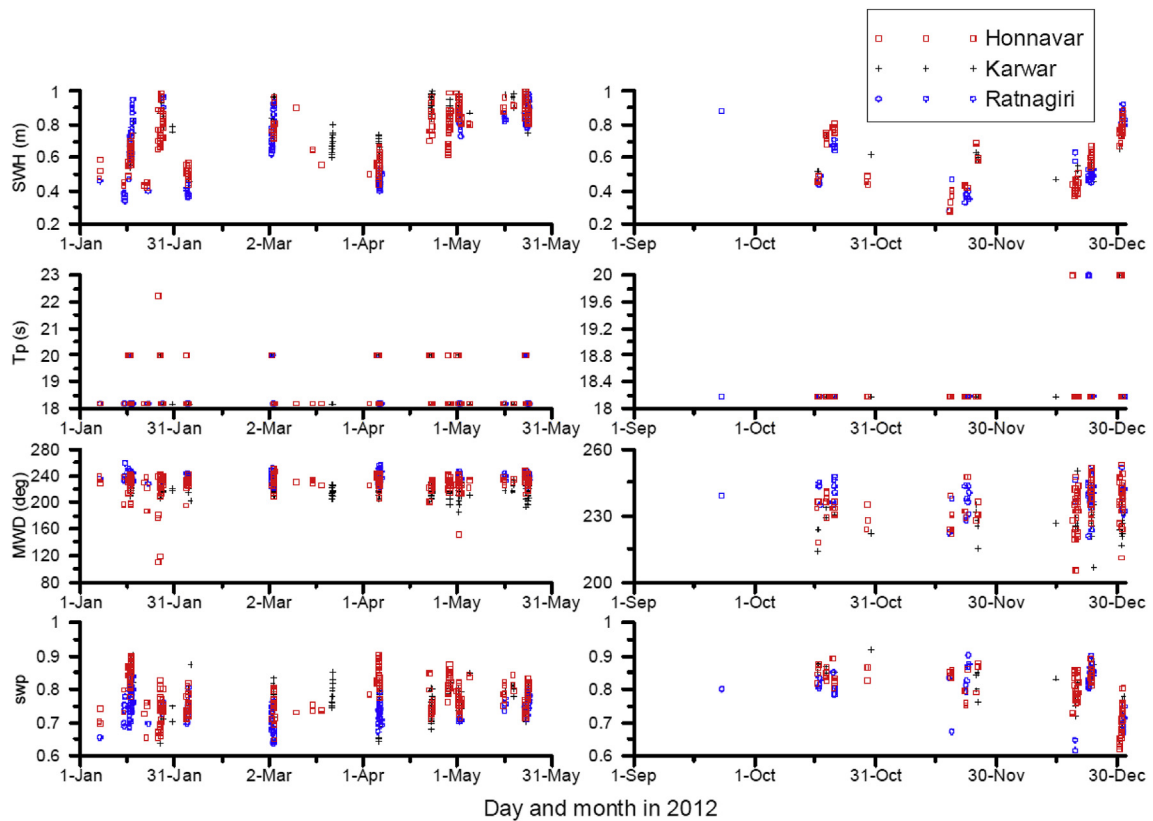


Fig. 4. Wave characteristics (significant wave height-Hs, peak wave period-Tp, mean wave direction-MWD and spectral width parameter-swp) during low-amplitude long-period swells during 2012.

Table 2
Average value of wave characteristics during the long-period swells at the locations studied.

Location	Year	Hs (m)	Hmax (m)	Tz (s)	Swell (%)	Qp	Dp (deg)
Ratnagiri	2011	0.64	0.95	5.6	46	1.7	237
	2012	0.66	0.97	4.6	61	1.5	239
Karwar	2011	0.69	1.05	5.4	40	1.6	221
	2012	0.77	1.14	4.8	56	1.5	220
Honnavar	2011	0.65	0.98	5.9	64	1.7	227
	2012	0.70	1.04	5.1	52	1.5	230

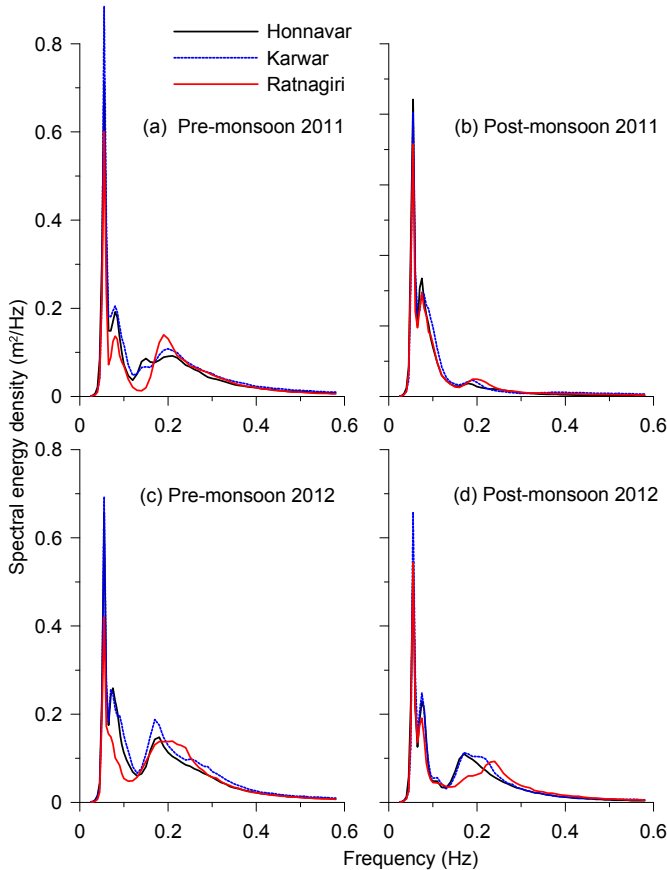


Fig. 5. Average wave spectrum of low-amplitude long-period waves during (a) pre-monsoon 2011 (b) post-monsoon 2011 (c) pre-monsoon 2012 and (d) post-monsoon 2012.

higher at Karwar and can be due to the higher water depth of the measurement location. At Ratnagiri, the ratio of the maximum spectral energy at wind-sea peak and primary peak varied from 0.19 to 0.21 during the pre and post-monsoon seasons (Table 3), and it was 0.16 at Karwar and 0.15 at Honnavar. The wind-sea peak period at Ratnagiri reduces during 2012, while those at other locations increase during 2012 when compared to 2011. The spectral energy at higher frequency was more at Ratnagiri than at other locations due to the influence of local winds. Fig. 2 shows that the local winds were higher at the northern location (Ratnagiri) than at the southern location (Honnavar). A typical directional wave spectrum for all the 3 locations on 21 March 2011 and 30 April 2012 representing the pre-monsoon period is presented in Fig. 6. At all the 3 locations, distinct swells and wind-sea from different directions were observed and the spectral energy density at high-frequency part is higher at Ratnagiri (Fig. 6). The directional spreading of spectral energy density was higher for the wind-sea than that for the swell. Also spectral energy was observed at lower frequency from east, which was due to the reflection of long-period waves from the coast. Anoop et al. (2014) observed that along the west coast of India, less than five percentage of the incident spectral energy was reflected back during the SW monsoon season and a gradual increase was observed during the post (5–15%) and pre-monsoon seasons (10–15%).

The percentage of swells in the measured data varied from 40 to 64%. The average swell Hs was 0.34 m at Ratnagiri, 0.38 m at Karwar and 0.39 m at Honnavar during 2011. Percentage of wind-sea was more during the pre-monsoon than that during the post-monsoon season due to the relatively strong sea breeze system during the pre-monsoon season (Glejin et al., 2013). The wind-sea Hs was 0.65, 0.63 and 0.59 m during the pre-monsoon season at 3 locations and was 0.50, 0.48 and 0.47 m during the post-monsoon season due to stronger local wind system in the northern part of the study area compared to the southern part (Sanil Kumar et al., 2014a). The predominant direction of the swells was from SW to W–SW, indicating that they were from the south Indian Ocean. Since the northern and western part of the Arabian Sea is restricted by the Arabian peninsula and African continent,

Table 3
Characteristics of average wave spectrum during the occurrence of low-amplitude long-period swells.

Location	Year	Season	Primary peak wave period (s)	Secondary peak wave period (s)	Wind-sea peak period (s)	Emax at primary peak (m²/Hz)	Emax at secondary peak (m²/Hz)	Emax at wind-sea peak (m²/Hz)
Ratnagiri	2011	Pre-mon	18.2	12.8	5.2	0.60	0.13	0.14
		Post-mon	18.2	13.3	5.2	0.72	0.29	0.05
	2012	Pre-mon	18.2	–	4.8	0.42	–	0.14
		Post-mon	18.2	13.3	4.2	0.54	0.19	0.09
Karwar	2011	Pre-mon	18.2	12.3	5.0	0.88	0.20	0.11
		Post-mon	18.2	13.3	5.3	0.81	0.29	0.05
	2012	Pre-mon	18.2	14.3	5.9	0.69	0.25	0.19
		Post-mon	18.2	13.3	5.9	0.66	0.25	0.11
Honnavar	2011	Pre-mon	18.2	12.5	4.9	0.71	0.19	0.09
		Post-mon	18.2	13.5	5.5	0.84	0.33	0.04
	2012	Pre-mon	18.2	13.3	5.6	0.66	0.26	0.15
		Post-mon	18.2	13.3	5.9	0.54	0.23	0.11

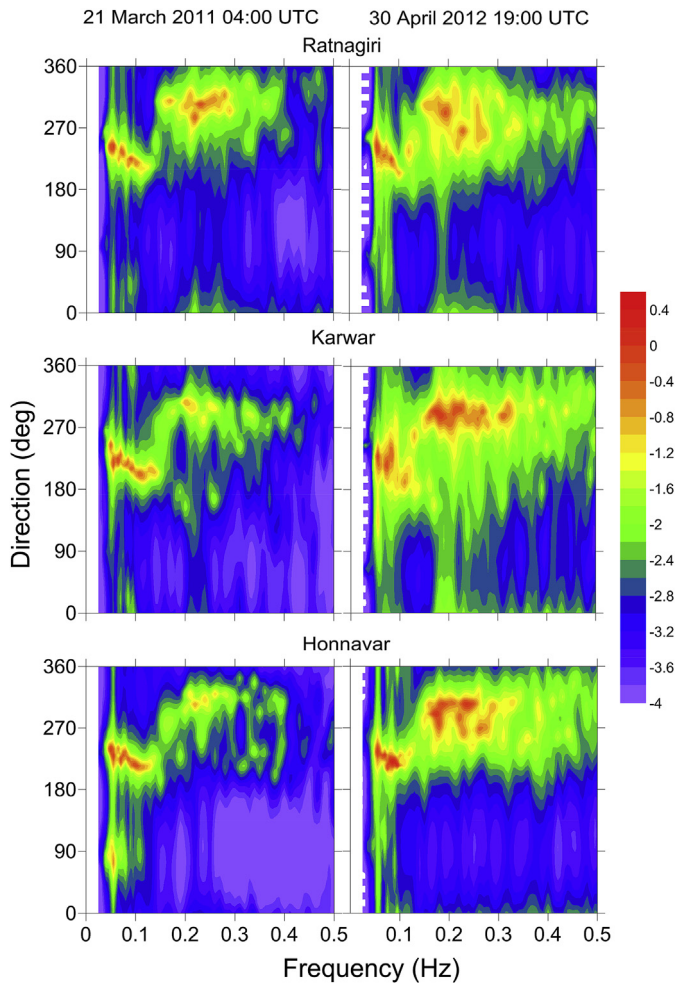


Fig. 6. Typical directional spectrum during the low-amplitude long-period waves at 3 locations studied on 21 March 2011 04:00 UTC and 30 April 2012 19:00 UTC. The spectral energy ($\text{m}^2/\text{Deg}/\text{Hz}$) is shown in logarithmic scale base to 10.

the domination of long-period swells were from the SW direction. Spectral width parameter was slightly higher at the southern location compared to other locations (Figs. 3 and 4) indicating relatively narrow spectra at this location. The sea surface elevation was positively skewed during the occurrence of long-period swells.

4. Conclusions

Using the wave data measured simultaneously at three locations for two years using directional wave rider buoy, ocean swells with period more than 18 s and significant wave height less than 1 m were studied to describe the long-period swell characteristics along the eastern Arabian Sea. The presence of long-period swells were relatively high at the southern location (Honnavar) and showed slight decrease towards the northern Arabian Sea. During 1.9, 2.1 and 3.0% of the time, small amplitude long-period swells were observed off Ratnagiri, Karwar, and Honnavar respectively during the study

period extending from January 2011 to December 2012. Average values of main wave parameter such as significant wave height, mean wave period and wave direction were between 0.64 and 0.77 m, 4.6–5.9 s and $220\text{--}237^\circ$ respectively. The average significant wave height during the monsoon (~ 2 m) was around three times that in the non-monsoon period (~ 0.7 m) and around two times of the annual average value (~ 1.1 m). The average wave height during the post-monsoon (~ 0.6 m) is less than that during the pre-monsoon (~ 0.8 m). The multi-peak spectra during the long-period swell dominated period represent independent wave systems propagates towards the measurement location corresponding to long-period swells generated by remote storms, swells generated by nearby storms and locally generated wind waves. The wave spectra observed were with the peak wave period at 18.2 s, the secondary peak at ~ 13.3 s and the wind-sea peak at ~ 5 s.

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