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Influence of winds on temporally varying short and long period gravity waves in the near shore regions of Eastern Arabian Sea

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Abstract

Wave data collected off Ratnagiri, west coast of India during 1 May 2010 to 30 April 2012 is used in the study. Seasonal and annual variation in wave data controlled by the local wind system such as sea breeze and land breeze, and remote wind generated long period waves observed along the west coast of India, is studied. Sea breeze plays an important role in determining the sea state during pre and post monsoon seasons and the maximum wave height is observed during peak hours of sea breeze at 15:00 UTC. Long period waves (peak period over 13 s) are observed mainly during the pre and the post monsoon season. Maximum peak period observed during the study is 22 s and is in the month of October. Long period waves observed during the south west monsoon period of 2011 are identified as swell propagated from the Southern Ocean with an estimated travelling time of 5–6 days. The swells reaching the Arabian Sea from the South Indian Ocean and Southern Ocean, due to storms during the pre and post monsoon periods will modify the near surface winds, due to the dominant wave induced wind regime. Energy spectrum of observed waves indicates onset and decline of strong south west monsoon winds. Convergence of energy-containing frequency bands corresponding to short period waves ($T_p < 8$ s) and long period waves ($T_p > 13$ s) to intermediate period waves ($8 < T_p < 13$ s) are observed at the end of the pre monsoon season; divergence is observed during the start of the post monsoon period from intermediate period waves to short period waves and long period waves. South west monsoon period is characterized by the energy corresponding to the frequency band of intermediate period waves along the west coast of India.

1 Introduction

Waves are the dominant factor influencing the near shore processes. The dominant portion of the wave spectrum in terms of energy is associated with the surface waves ranging from 1 to 30 s (gravity waves). Two types of gravity waves in the ocean are (i) wind-sea due to local wind and (ii) swells generated elsewhere due to remote wind systems and propagating over large distances. In coastal regions, gulfs and bays, although mixed-seas are frequently observed, there is a predominance of wind-seas (Hwang et al., 2011). In open and large oceanic regions, usually there is a predominance of swell fields, generated by remote storms. A proper estimation of the wind-sea is needed for improving our theoretical understanding of wave growth and for validating wave models (Ardhuin et al., 2009; Donelan et al., 1985). The gravity waves along the west coast of India mainly depends on the wind conditions prevailing over the three different seasons; viz. south west (SW) monsoon or summer monsoon (June–September), north east (NE) monsoon or post monsoon (October–January) and pre-monsoon or fair weather period (February–May) (Glejin et al., 2012).

Wave climate of the Arabian Sea and that along the west coast of India is influenced by the monsoonal winds during the SW monsoon resulting in high wave activity. Relatively calm condition prevails during the rest of the year. Direction of wave approach is from the west and WSW during SW monsoon, west and WNW during the NE monsoon and SW during fair weather period (Kumar et al., 2006). Neetu et al. (2006) studied the impact of sea breeze on the diurnal cycle of the sea state off Goa region along the west coast of India during pre-monsoon season. A general wave condition in the Arabian Sea during pre-monsoon period also depend on the swells coming from far North-West Arabian Sea because of the north westerly blowing Shamal winds (Aboobacker et al., 2011). Average wind speed during the SW monsoon is $9.7\,\mathrm{m\,s^{-1}}$ and reaches up to a maximum of $12.5–15.3\,\mathrm{m\,s^{-1}}$. During the post and pre monsoon seasons, the mean wind speed decreases to $5.6\,\mathrm{m\,s^{-1}}$ (Kumar et al., 2006). In pre monsoon season, wind sea plays a major role in near shore wave climate (Rao and Baba, 1996). Kumar et al. (2010) studied the characteristics of swells and wave growth during the onset of summer monsoon. Dominance of swell along west coast of India is observed during the SW monsoon (Glejin et al., 2012; Kumar et al., 2000, 2012).

When winds are blowing over the sea surface they transfer momentum from the atmosphere to the sea waves, forming wind generated waves. When long waves travel

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faster than the surface wind, momentum can be transferred from ocean wave to near surface air. This is known as the wave generated wind. Hanley et al. (2010) studied the coupling between wind and wave using inverse wave age. Hanley et al. (2010) also used the inverse wave age calculation method to identify the presence of swells in the tropics generated by the Southern Ocean storms. Hamilton (1992) studied the measured long period waves and low amplitude swells observed from wave buoys deployed in the Western North Atlantic Ocean. Swell waves of long period are also identified and studied in the Pacific Ocean (Munk et al., 1963; Snodgrass et al., 1966) and Atlantic Ocean (Barber and Ursell, 1948).

Present study examines the seasonal variations of wind-sea and swell characteristics of gravity waves, and the effect of local wind systems and of waves from distant storms reaching the inshore regions of the west coast of India at Ratnagiri, using the measured wave data during 2010 and 2011 obtained from moored directional wave rider buoy.

2 Data and methodology

Wave data measured off Ratnagiri, Eastern Arabian Sea (Fig. 1) during the years 2010 and 2011 using directional wave rider buoy (Barstow and Kollstad, 1991) is used in the study. The measurement location is off the west coast of India at a water depth of 13 m (16°58′48.324″ N and 73°15′30.312″ E). The data recorded continuously at 1.28 Hz and the data for every 30 min are processed as one record. Wave spectrum is obtained through Fast Fourier transform (FFT). FFT of 8 series, each consisting of 256 measured vertical elevations of the buoy data, are added to obtain the spectra. The high frequency cutoff is at 0.58 Hz and the resolution is 0.005 Hz. Significant wave height (H_{m_0}) which equals $4\sqrt{m_0}$ and mean wave period ($T_{m_{02}}$) which equals $\sqrt{m_0/m_2}$ are obtained from the spectral moments. 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, $S(f)$ is the spectral energy density at frequency f. Period corresponding to the maximum spectral energy, i.e. spectral peak

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period (T_p) is estimated from the wave spectrum. Peak wave direction (D_p) corresponding to the spectral peak is estimated based on circular moments (Kuik et al., 1988). Measurements are made in Coordinated Universal Time (UTC) and the time referred in the paper is in UTC. The local time is 05:30 h ahead of UTC. Measured wave data for the period 1 May 2010 to 30 April 2011 is termed as data for 2010 and that during 1 May 2011 to 30 April 2012 is termed as data for 2011.

Wind seas and swells from the measured data are separated through the method described by Portilla et al. (2009). Portilla et al. (2009) proposed a 1-D separation algorithm on the basis of the assumption that the energy at peak frequency of a swell system cannot be higher than the value of a PM spectrum (Pierson and Moskowitz, 1964) with the same peak frequency. The algorithm 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 above a threshold value of 1, the system is considered to represent wind sea, else it is taken to be swell and a cut off frequency f_c is estimated. Swell parameters are computed by integrating frequency ranging from 0.025 Hz to f_c and wind sea parameters are computed by integrating frequency ranging from f_c to 0.58 Hz.

Reanalysis data of zonal and meridional components of wind speed at 10 m height at 6 hourly intervals from NCEP/NCAR (Kalnay et al., 1996) is used to identify the propagation of the Southern Ocean storm and the seasonal wind pattern over the Western Indian Ocean. These data were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado at http://www.cdc.noaa.gov/. To determine the sea breeze–land breeze system at Ratnagiri during the study period, simultaneous wind measurements were carried out using Autonomous Weather Station (AWS) at every 10 min interval. The AWS measure the wind speed in the range 0–60 $\mathrm{m\,s^{-1}}$ with an accuracy of 0.2 $\mathrm{m\,s^{-1}}$ and direction from 0 to 360° with an accuracy of 3°.

Inverse wave age is the ratio of sea surface wind speed to the speed of the waves at the peak of the spectrum and is equal to $U_{10}\cos\theta/C_p$. Here U_{10} is 10 m wind speed, θ is relative angle between the wind and the wave and C_p is peak phase speed ($C_p = gT_p/2\pi$). Inverse wave age is calculated using the measured wave data and the NCEP wind data. Three type of wind-wave interaction regime as in Hanley et al. (2010) are (i) wind induced wave regime when inverse wave age > 0.83 (strong winds transfer momentum to waves) (ii) wave induced wind regime when 0 < inverse wave age < 0.15 (fast moving swells transfer momentum towards near surface winds) and (iii) mixed wind wave regime when 0.15 < inverse wave age < 0.83 (both wind induced wave and wave induced wind will be present).

3 Results and discussion

3.1 Sea breeze and land breeze

Analysis of wind and wave data collected at Ratnagiri shows that sea breeze and land breeze play an important role in the near shore sea state during the pre monsoon and post monsoon. Two important parameters that characterize the waves are mean wave period and significant wave height. We used these two parameters to study the variation in wave characteristics (Figs. 2 and 3) at the study location along with wind direction and wind speed (Fig. 4) measured using Autonomous Weather Station (AWS). Neetu et al. (2006) reported the presence of sea breeze system and its impact on the measured wave height during the pre monsoon season. Their study using 3-h wave data shows the maximum wave height at 12:30 UTC and also observed the presence of land breeze during the early hours of a day.

Present study shows the presence of sea breeze-land breeze system with reversal of wind direction and simultaneous changes in wind speed over the diurnal cycle (Fig. 4) during pre and post monsoon seasons. Observed sea breeze shows a maximum during the pre monsoon. Maximum wind speed on the daily basis occurs at 09:30 UTC during pre monsoon and at 12:30 UTC during post monsoon season. The observed direction of the sea breeze is from the NW and that of the land breeze is NE. Analysis shows that during the pre and post monsoon period, wave height reaches a maximum value at around 15:00 UTC similar to the observations of Pattiaratchi et al. (1997) and

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Pokheral and Lee (2011) because of the sea breeze persisting over the coastal region of India and resulting wind sea. Minimum wave height is observed during the early hours of the day (03:00–06:00 UTC) due to the land breeze system. Maximum mean wave period is found between 06:00–09:00 UTC (Fig. 3) due to the strong land breeze over the region. Hourly average of mean wave period indicates the co-occurrence of maximum sea breeze at 09:30 UTC and 12:30 UTC (Figs. 3 and 4) during the pre and post monsoon seasons. The estimated time lag between the maximum wind speed and resultant maximum wave energy spectra is around 3–4 h at Ratnagiri. The time lag is due to the time taken by the waves to reach its maximum wave growth (Neetu et al., 2006). Mean wave period and significant wave height of measured waves depends on the combination of both swell and wind sea over the measurement location. The observed swells show a small variation in wave height and wave period throughout the day, independent of sea breeze system. Near shore wave climate during the sea breeze system is purely dependent on the short period waves (wind sea). Increase in mean wave height from January to May is caused by wind sea generated due to sea breeze (Fig. 2) and decreasing trend from October to December due to the corresponding variations in intensity of swells.

During the summer monsoon (June–September), the land and sea breezes are weak and the swells dominates along the west coast of India. The mean wave period and mean wave height are different from the rest of the year and both are dependent on each other. During this period the increase in wave height and variation in mean wave period is depending on the swells associated with the SW monsoon winds.

Calculation of distance travelled by the waves to reach the observation area from the generation area, using the time difference between the minimum and maximum wave period and the mean wave period, gives around 40–50 km from the measurement location. The estimated distance of wave generation area is closer than that estimated by Vethamony et al. (2011) for Goa region.

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3.2 Inverse wave age and distant swells

Figure 6 depicts the seasonal and annual distribution of inverse wave age at Ratnagiri during 2010 and 2011 and is used to identify the occurrences of wind driven wave and wave driven wind regime in the Arabian Sea. The distribution of inverse wave age is almost identical in 2010 and 2011 during the seasonal and annual scales. Due to the strong SW monsoon winds (Fig. 5) in the Arabian Sea, the dominance of swells and wind seas (Fig. 6b) are observed with inverse wave age in the mixed sea state range (0.3–0.5). Usually positive wave age is associated with SW monsoonal waves with mixed wind wave regime. The analysis of the inverse wave age in three seasons indicates that during 2010 and 2011 the inverse wave age is positive from the start of the SW monsoon season in June. It continues positive till the end of the SW monsoon season in to the last of September 2010 and 2011. inverse wave age shows the end of SW monsoon. Small peak in the negative region of inverse wave age distribution indicates the early withdrawal of summer monsoon winds reaching the west coast of India in 2010 compared to 2011. Inverse wave age distribution in the post monsoon period of 2010 indicates typical example for the wind system in the Arabian Sea without the occurrence of any storms and cyclonic activities in Northern Indian Ocean.

Negative values of inverse wave age during the pre monsoon season of 2010 and post monsoon season of 2011 indicates the presence of storms and cyclonic activities over the Arabian Sea in the Northern Indian Ocean. Negative values of inverse wave age indicates the wave induce wind regime. During the pre and post monsoon period the wind direction is NE (Fig. 5). This will make a relative wind wave angle of more than 90° at the measurement location between the NE wind and swells from NW and SW direction. This will happen when the swells produced by the storms and cyclones move into the measurement location from the SW and NW direction. This will induce a higher distribution of inverse wave age in the range of −0.2 to 0 compared to the distribution of 0.15 (Fig. 6) during the typical pre and post monsoon season over the Arabian Sea without cyclones. It is observed that the higher distribution of inverse wave

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age of more than 0.15 during the pre and post monsoon season of 2010 and 2011 are characterized by the presence of cyclonic activity over the Arabian Sea.

During the pre monsoon (Fig. 6a) and post monsoon (Fig. 6c) period, the near shore region of Ratnagiri is dominated by inverse wave age values less than 0.2 with peak in the region of negative values. That indicates the dominance of swells in the Arabian Sea propagating against the seasonal winds, not a locally generated wind-sea. Figure 6a, c shows a shift from mixed wind wave regime (0.15 < inverse wave age < 0.83) during SW monsoon to wave generated wind regime (inverse wave age < 0.15) during pre and post monsoon seasons respectively. In an annual period (Fig. 6d) the region along the west coast of India is influenced by the presence of swells and wind-sea. The time period of observing purely wind induced waves are relatively less compared to the period of pure wave induced wind regime. The distribution of wave age indicates that the region along the west coast of India mainly experiences the wave induced wind regime and the mixed (both wave induced wind and wind induced wave) regime and not the wind induced wave regime.

3.2.1 Southern Ocean swells

The propagation of a swell originated due to a Southern Ocean storm is identified in the Northern Indian Ocean at Ratnagiri. These swells are identified by the increase in peak wave period and corresponding change in the swell period and swell height. The normal wave condition at Ratnagiri is with a peak swell period in the range of 8–12 s and these waves are result of strong SW summer monsoon winds of 15 m s^{-1} (Kumar et al., 2006). During 7–8 August 2011 (period of summer monsoon of 2011), waves having peak period of 17–20 s are observed at Ratnagiri. To produce a wave with peak period of about 20 s ($C_p \sim 31$ m s^{-1}), the maximum wind speed of 25 m s^{-1} ($U = 0.83\ C_p$) is required and mostly these high wind speeds are result of the Southern Ocean storms (Fig. 7). Figure 7 shows the movements of a Southern Ocean storm from west to east with SW wind direction blowing towards the Indian Ocean during 1–2 August 2011. The swell generated at the Southern ocean propagates with a group

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speed of 14 $m s^{-1}$ towards the Indian Ocean according to the winds over the region. The propagation time of 5–6 days is estimated for the swell to reach Ratnagiri across the Indian Ocean. The direction of propagation of these long period swell are from the SW direction of 240° with mean significant swell height of 2.5 m.

3.3 Classification of waves along the west coast of India

For the proper understanding of seasonal and annual wave climate in the Arabian Sea off Ratnagiri, waves are classified into three categories based on the spectral peak period (T_p); (1) short period waves, (2) intermediate waves and (3) long period waves.

3.3.1 Short period waves

Waves with short periods ($T_p < 8$ s) are observed during the pre and post monsoon season. This is due to the domination of wind sea produced by the local wind system of sea breeze (Pattiaratchi et al., 1997) and the Shamal swells (Aboobacker et al., 2011) produced by the Shamal winds from the NW direction over the waves from the SW direction. These short period waves are mainly from the NW direction in pre and post monsoon season. During the SW monsoon season the waves are coming from the WSW direction due to strong SW monsoon winds (Fig. 8a–c).

3.3.2 Intermediate period waves

Intermediate period waves (8–13 s) are mainly observed during the SW monsoon period. These waves are mainly from the west south-west direction (Fig. 8d–f) and their origination and propagation are influenced by the SW monsoonal winds (Fig. 5b) in the Southern Arabian Sea. The significant wave height associated with these waves reaches up to 4.2 m. During SW monsoon period, waves generated by the SW monsoonal winds over the Arabian Sea will dominate the energy spectrum and shifts the peak period (T_p) toward the intermediate range of 8–13 s. Intermediate period waves

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are observed with relatively low percentage of occurrence during the pre and post monsoon seasons because of minimum wind speed over the Arabian Sea during these season (Fig. 6).

3.3.3 Long period waves

The presence of long period waves ($T_p > 13$ s) is persistent throughout the wind cycle in the Arabian Sea (Fig. 8g–i).The long period waves are a minimum during the southwest monsoon season due to the dominance of SW swells in the energy spectrum during the strong SW monsoon. The direction of propagation of long period waves is mainly restricted to the SW region indicating the presence of waves from the South Indian Ocean and Southern Ocean. The long period waves with period over 18 s from the Southern Ocean are observed during all three seasons.

3.4 Frequency-time diagram

Main parameters influencing the near shore wave climate are the spectral energy and direction associated with the wave propagation through the ocean. Figure 9 depicts the seasonal variation of normalized wave spectral energy density and wave direction within a frequency–time diagram during different seasons. During pre-monsoon period, relatively calm wind condition is prevailing over the Southern Arabian Sea compared with the Northern Arabian Sea because of the NW Shamal winds (Aboobacker et al., 2011) and the dominant sea breeze system results in the concentration of wave energy near 0.2 and 0.1 Hz (Fig. 9a, b). The wave energy is shifting towards the lower frequency region due to the strengthening of SW monsoon winds over the Southern Arabian Sea and the Indian Ocean. The presence of SW swells generated in the Southern Ocean with peak period more than 17 s dominates during 15–17 May and indicates two separate bands of energy in the Arabian Sea.

SW monsoon season is dominated by the swells and wind seas produced by the monsoonal winds and reaching the near shore area from the SW direction. The NW

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swells and wind sea due to summer Shamal winds are also observed during the SW monsoon season of 2010 and 2011. The energy spectra during the SW monsoon season are concentrated to a single band with period ranging from 8–13 s (Fig. 9c, d).

During the post monsoon period, the wave energy is mainly concentrated in the frequency range of 0.1 and 0.3 Hz due to the NW swells and wind seas observed along the west coast of India. During this period, the wave energy spectrum is characterized by the shifting of wave energy towards the higher frequency region (Fig. 9e, f). Weakening of SW monsoon generated swells, and generation of short period waves as part of the sea breeze–land breeze system prevailing over the region, results in a shift of energy towards higher frequency. The waves having period between 10 and 22 s are only due to the SW swells.

3.5 Wind sea and swell domination

Analysis of wind sea and swell parameter is a useful way to assess the influence of wind on near shore wave characteristics. Wave data of 2010 and 2011 collected off Ratnagiri are used to analyze the dominating type of wave (Table 1). The domination of wind sea and swell during the pre and SW monsoon season is almost identical during 2010 and 2011. The domination of swell is observed during SW monsoon season (74 and 72 % during 2010 and 2011) and wind sea is observed during the pre monsoon season (72 and 73 % during 2010 and 2011, respectively). During the post monsoon period, the wind sea is 67 % in 2010 and 60 % in 2011. The presence of higher cyclonic activity during the year 2011 compared to 2010 (IMD, 2011, 2012) influenced the presence of swells and wind sea along the west coast of India. This caused the arrival of more swells at the wave measurement area with an increase of 7 % of swells during the post monsoon period in 2011 compared with 2010.

Mean period of wind-sea is 4 s and shows similar characteristics in wind-sea direction during pre and post monsoon periods. The dominant swells reaching the west coast of India are from the SW direction and the corresponding wind sea is from the NW direction except during the SW monsoon period. Wind-sea direction during the SW

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monsoon is 260° because of strong SW monsoonal wind pattern. This produces the wind seas from the WSW direction. The maximum swell period and minimum swell height is observed during the pre and post monsoon seasons. And during the SW monsoon period, the swell wave height is a maximum and swell period is a minimum due to strong SW monsoon winds in the annual cycle.

3.6 Sea state and wave characteristics along west coast of India

Wave data collected off Ratnagiri during 2011 is used to analyze monthly, seasonal and annual wave characteristics of near shore waves along the west coast of India. Significant wave height varied between a minimum of 0.2 and a maximum of 4.2 m during the year 2011 (Table 2). During pre monsoon and post monsoon season the sea state is in smooth to moderate range. Sea state is in its extreme condition (maximum wave height up to 7 m) from June to September (SW monsoon) due to high winds of the SW monsoon. Significant wave heights are maximum during the SW monsoon season and minimum during the post monsoon season; values in the pre monsoon season are intermediate. The increase in wave height in pre monsoon season is due to the presence of sea breeze system during the period. Peak wave direction varied from 197° to 335° with an average value of 262° and the variation between lower and upper limit of wave direction is maximum in the pre and post monsoon season and minimum during the SW summer monsoon.

4 Conclusions

Wave data collected at Ratnagiri for the years 2010 and 2011 are used to analyze the effect of wind system on the waves observed along the west coast of India. The presence of NW waves is due to the wind sea produced by the sea breeze and short period swells by the Shamal events. During the pre monsoon and post monsoon period the near shore wave characteristics are induced by the sea breeze blowing over the region

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and wave height reach maximum values at around 15:00 UTC. Storm produced swells from Southern Ocean is identified with a travelling time of 5–6 days to reach the west coast of India during the SW monsoon period with a unique direction of 240°. Long period waves are also observed with low wave height mainly during the pre and post monsoon season and the waves are always restricted to the SW direction. The presence of (i) sea breeze induced wind seas and (ii) swells from the South Indian Ocean are responsible for the multi peaked wave energy spectra. The Arabian Sea is characterized by a mixed sea state for 52 % of time in an annual cycle, by wave-generated wind regimes for 47 % of the time and by wind-generated wave regime for a period 1 % of the time. The wind sea and swell domination is observed respectively during the calm pre monsoon season and during rough SW monsoon season conditions. The variation in the presence of swells and wind sea during the post monsoon season along the west coast of India depends upon the cyclonic activity occurring in the Arabian Sea.

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Table 1. Seasonal percentages of wind sea and swell conditions in 2010 and 2011 off Ratnagiri, west coast of India.

Season	Period	Swell				Wind sea			
		Percentage	Height (m)	Period (s)	Direction (°)	Percentage	Height (m)	Period (s)	Direction (°)
Pre M	2010	28	0.4	11	238	72	0.7	4	299
SW		74	1.7	9	256	26	0.9	4	260
Post M		33	0.3	11	236	67	0.5	4	296
Pre M	2011	27	0.4	11	242	73	0.7	4	299
SW		72	1.7	9	258	28	1.0	4	260
Post M		40	0.4	11	237	60	0.5	4	299

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Table 2. Monthly variation of sea state variables in 2011 off Ratnagiri, west coast of India.

Month	Wave parameters											
	Wave direction (°)			Sig. wave height (m)			Mean wave period (s)			Maximum wave height (m)		
	min	max	avg	min	max	avg	min	max	avg	min	max	avg
Jan 2011	208	333	292	0.3	1.1	0.6	2.9	5.5	4.1	0.4	2.0	0.9
Feb 2011	204	331	279	0.3	1.8	0.6	2.8	6.1	4.1	0.4	3.0	1.0
Mar 2011	197	325	278	0.4	1.2	0.7	3.0	7.9	4.2	0.5	2.3	1.1
Apr 2011	200	319	266	0.4	1.3	0.8	3.1	6.6	4.3	0.5	2.4	1.1
May 2011	204	314	260	0.7	1.7	1.0	3.6	6.7	4.9	0.9	3.0	1.5
Jun 2011	245	287	261	1.1	3.2	2.3	5.2	8.2	6.6	1.6	6.9	3.5
Jul 2011	232	274	259	1.4	4.0	2.3	4.9	8.0	6.5	2.0	7.0	3.5
Aug 2011	233	276	260	1.3	3.1	2.0	5.0	7.7	6.2	1.7	5.5	3.2
Sep 2011	218	276	252	0.6	4.2	1.6	4.0	7.9	6.2	0.8	6.5	2.4
Oct 2011	204	322	241	0.3	1.0	0.6	2.9	10.2	5.6	0.4	1.7	0.9
Nov 2011	203	335	241	0.2	1.3	0.5	2.9	7.8	4.8	0.4	2.4	0.8
Dec 2011	217	322	258	0.4	0.9	0.5	3.4	6.2	4.5	0.5	1.6	0.8

min – Minimum
max – Maximum
avg – Average

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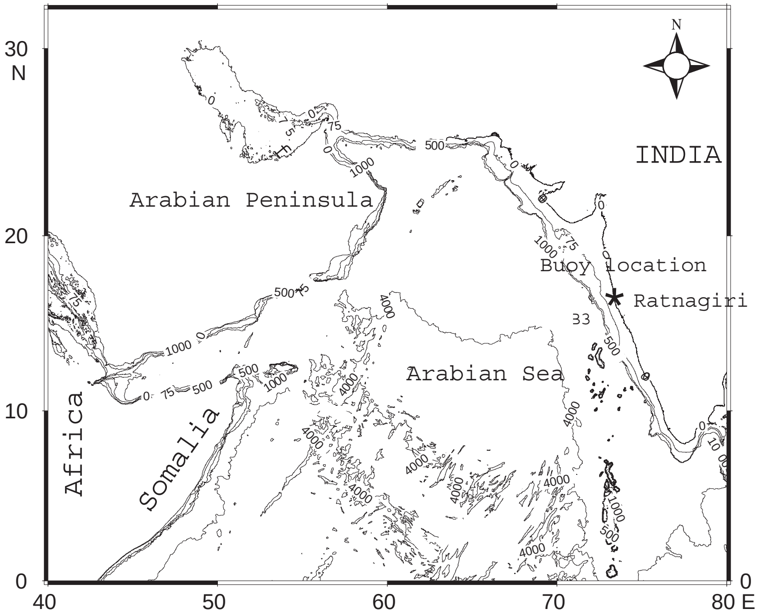

Fig. 1. Study area showing the wave measurement location. The depth contours are in meters.

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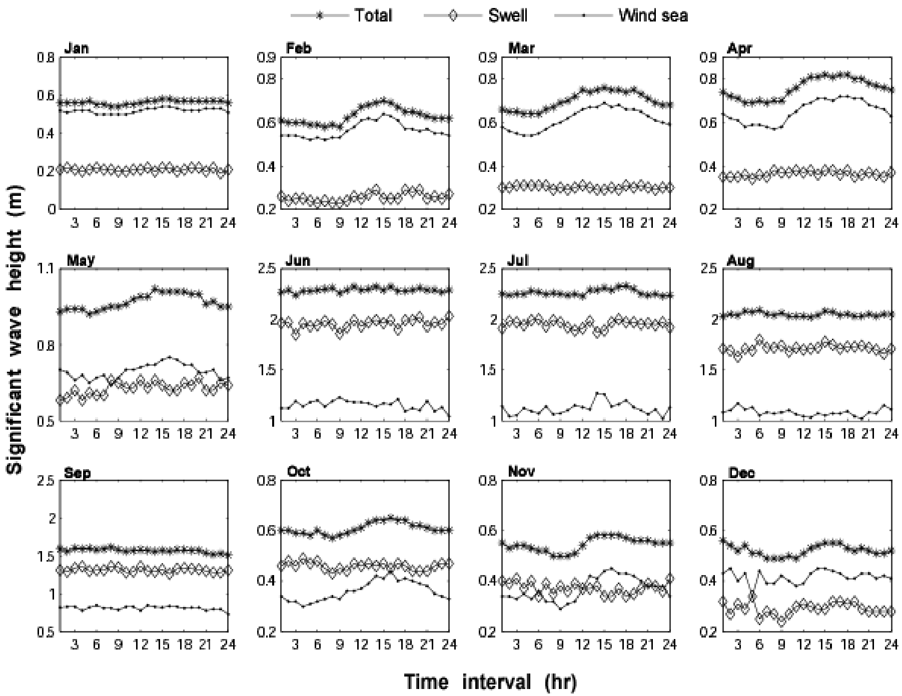

Fig. 2. Hourly variation of monthly average significant wave height at Ratnagiri during 2011 in UTC.

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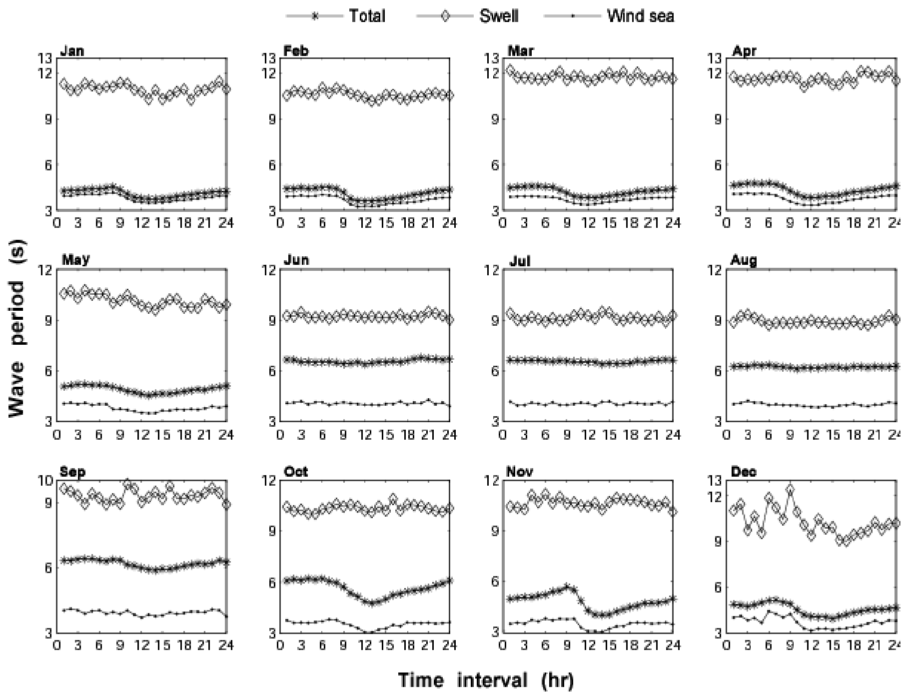

Fig. 3. Hourly variation of monthly average mean wave period at Ratnagiri during 2011 in UTC.

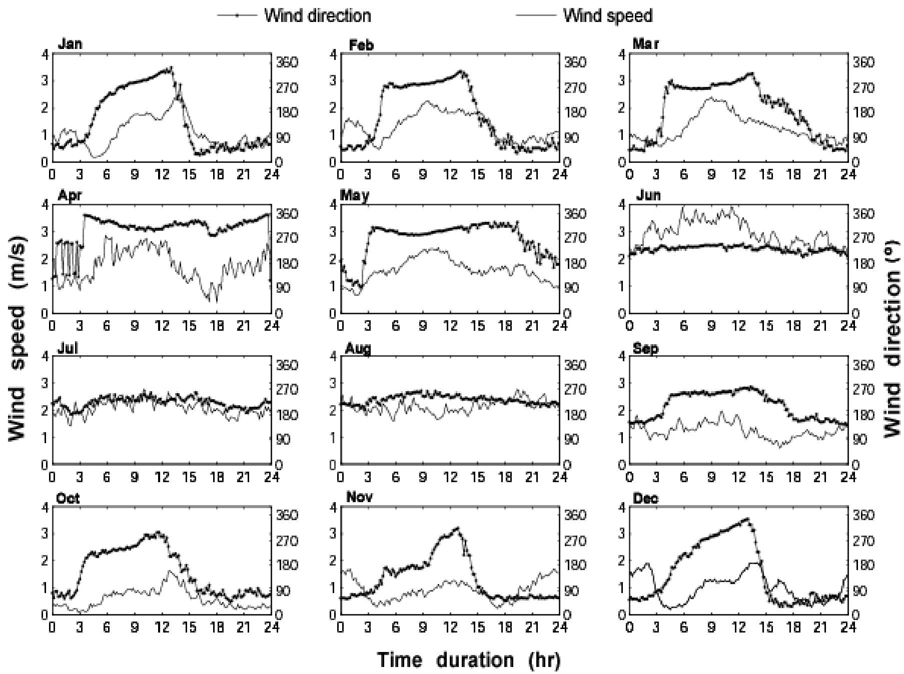

Fig. 4. Hourly variation of wind speed and wind direction at Ratnagiri during 2011 in UTC.

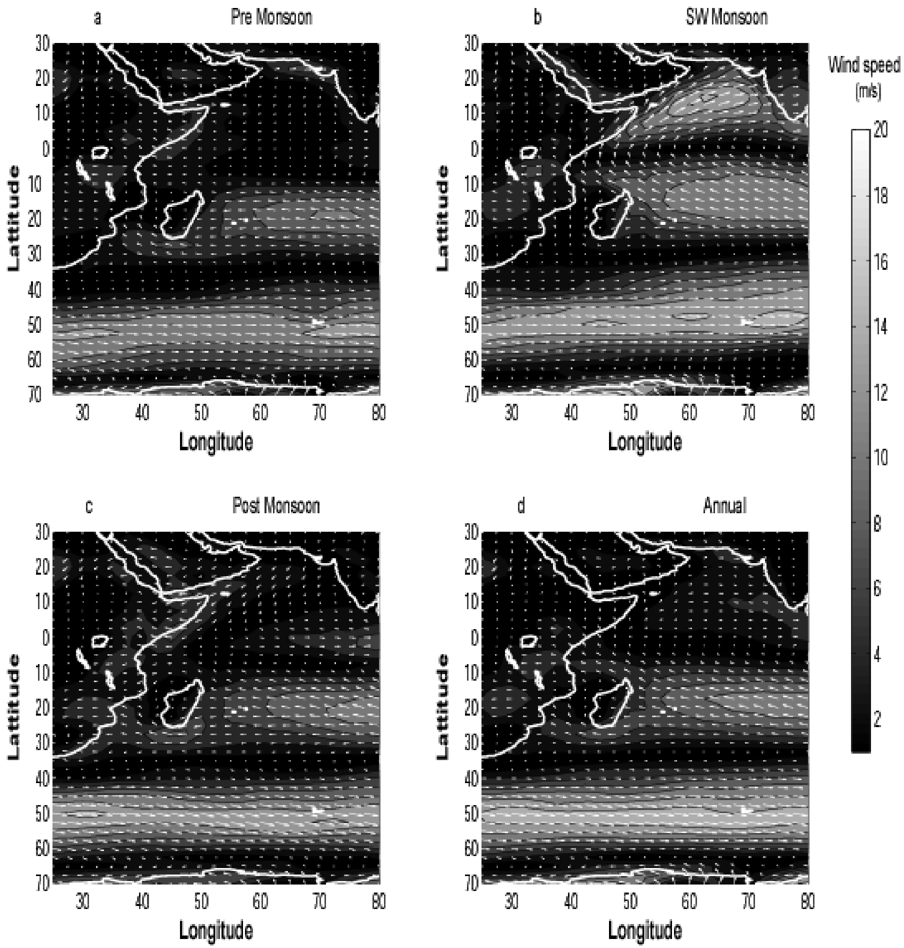

Fig. 5. Seasonal and annual composite image of NCEP wind over Western Indian Ocean.

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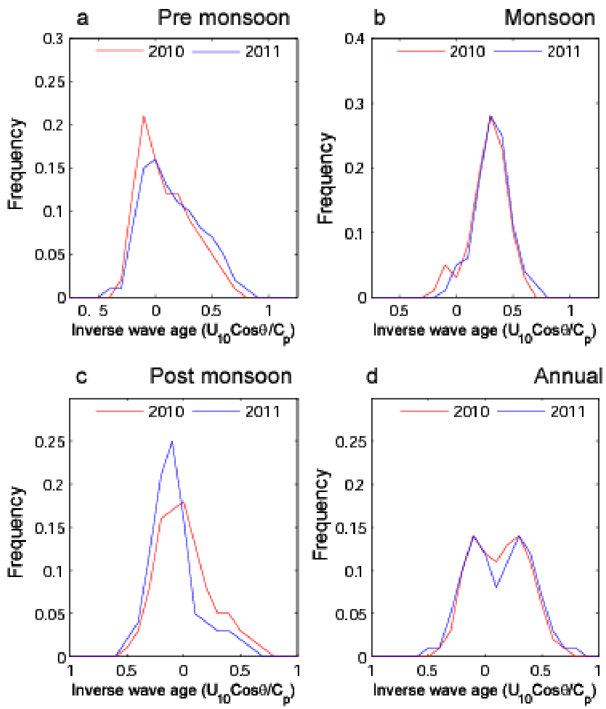

Fig. 6. Histogram of inverse wave age calculated based on observed wave direction and NCEP wind data at Ratnagiri during **(a)** pre monsoon, **(b)** monsoon, **(c)** post monsoon and, **(d)** annual 2010–2012.

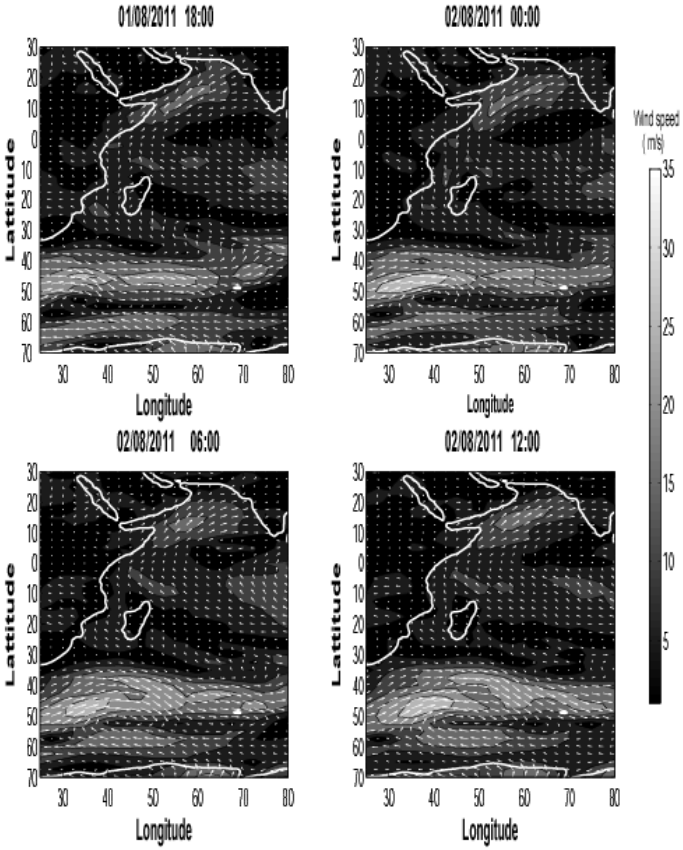

Fig. 7. Southern Ocean and Indian Ocean wind system during 1 and 2 August showing the propagation of storm from west to east.

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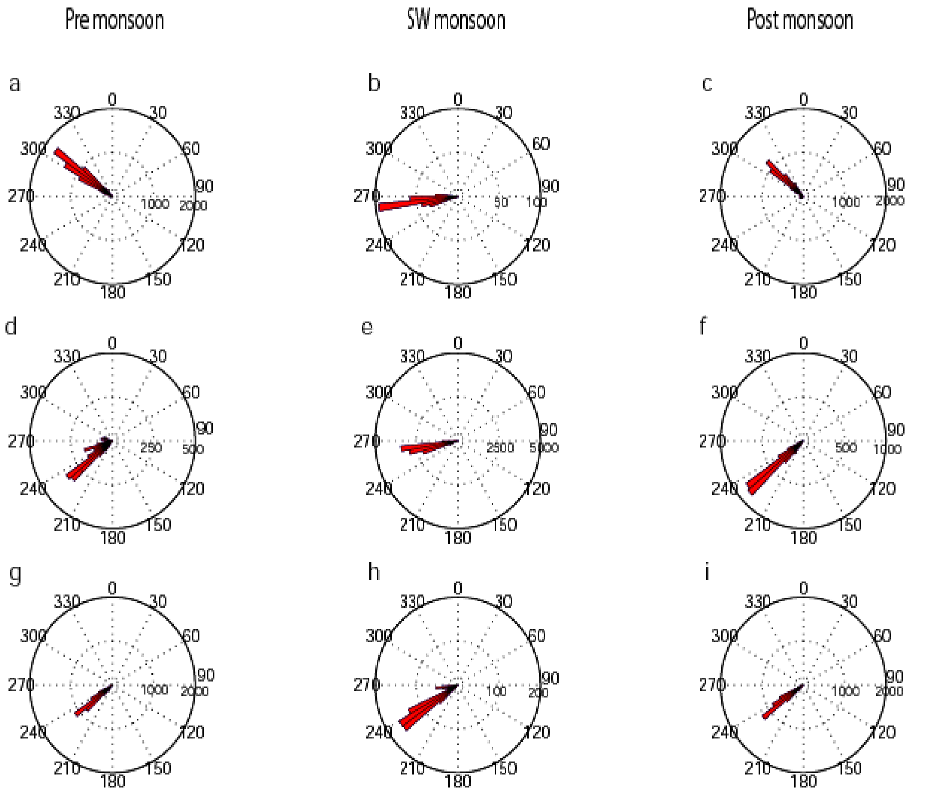

Fig. 8. Seasonal variations in wave direction of short period waves during **(a)** pre-monsoon, **(b)** SW monsoon and **(c)** post monsoon, intermediate period waves during **(d)** pre-monsoon **(e)** SW monsoon and **(f)** post monsoon, long period waves during **(g)** pre-monsoon **(h)** SW monsoon and **(i)** post monsoon along the west coast of India. X-axis to right or left from the center indicates the number of values in each band.

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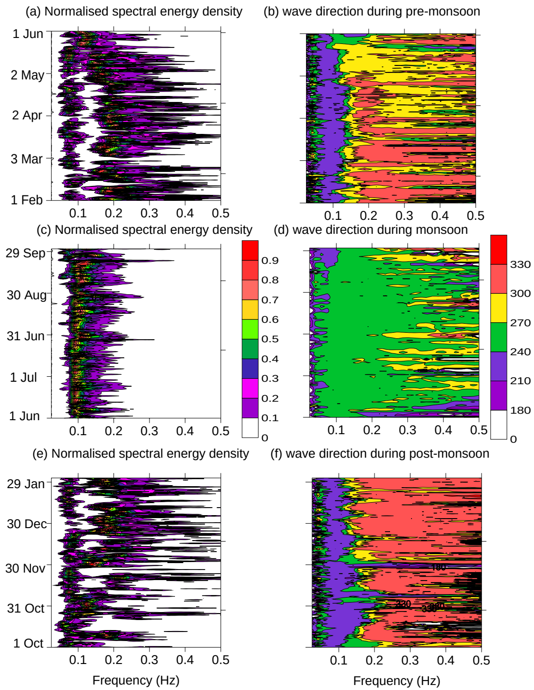

Fig. 9. Normalised spectral energy density and mean wave direction during pre-monsoon **(a,b)**, monsoon **(c,d)** and post-monsoon **(e,f)** period.

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