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Co-existence of wind seas and swells along the west coast of India during non-monsoon season

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Abstract

Wave data collected along the west coast of India (off Goa, Ratnagiri and Dwarka) during non-monsoon season have been analysed to study the co-existence of wind seas and swells. Diurnal variation in wind and wave parameters is noticeable along the central west coast of India (off Goa and Ratnagiri), and this is not present along the northwest coast of India (off Dwarka). Swells are predominantly mature (91 %) and old (88 %) during late pre-monsoon and post-monsoon seasons, respectively. Sea Swell Energy Ratio quantifies wind sea, swell and mixed seas prevailing in the regions during non-monsoon season. Intermodal Distance (ID) between the energy peaks is moderately separated during non-monsoon season, whereas, during the shamal events, energy peaks are very close to each other (ID ~ 0). However, pure wind seas (ID ~ 1) are found to co-exist with the swells during non-monsoon season. Wind seas are growing, when wind and wind seas are opposite to swell direction. Wind seas have minimum angular spreads in multimodal state. Under low winds, the interaction between wind sea and swell dominates and thereby the multimodal state reduces to unimodal state. The fetch available for the evolution of the wind sea spectrum has been estimated, and it is found to be less than 150 km. For the fetch limited condition, a non-dimensional empirical relation has been derived relating the significant wind sea height in terms of wind speed and peak wind sea period, and this relation fits for the west coast of India.

1 Introduction

Ocean wave spectra consist of wind seas generated by local winds and swells of distant storms. The characteristics of these waves are different in different seasons. An attempt has been made to understand the co-existence of wind seas and swells at different coastal regions in the Indian side of the Arabian Sea during non-monsoon season. Wave spectra along the west coast of India are generally multi-peaked (Harish and Baba, 1986; Kumar et al., 2003; Sanil Kumar et al., 2007), and multi-peakedness is mainly due to the co-existence of locally generated wind seas and distant swells (Vethamony and Sastry, 1986). It has been observed that winds along the west coast of India are primarily dominated by sea breeze – land breeze systems during pre-monsoon season (Aparna et al., 2005). Sea breeze has impact on the diurnal cycle of sea state off Goa (Neetu et al., 2006), and the diurnal variations are due to the superimposition of local wind seas with pre-existing swells (Vethamony et al., 2011). The development of pure wind-driven waves is controlled by three basic processes: energy input from wind to surface waves, nonlinear wave-wave energy transfer and energy dissipation due to wave breaking. The interaction of individual wave systems in the directional and frequency spaces is an important factor in how the co-existence of swells modify the growth of wind driven waves.

Identification and separation of wave components into wind seas and swells provide a more realistic description of the sea state, and this has importance to both scientific and engineering applications. Gerling (1992) identified and grouped wave systems from spatially and temporally distributed observations of directional wave spectra. Hanson and Phillips (2001) developed automated swell tracking and storm source identification capabilities to facilitate investigations of surface wave processes in the open ocean. Based on wave steepness, Gilhousen and Hervey (2001) and Wang and Hwang (2001) estimated separation frequency to distinguish wind sea and swell. The partitioning methods (e.g. Gerling, 1992; Wang and Hwang, 2001; Portilla et al., 2009) primarily involve separating the wave spectra into two frequency bands, low-frequency band representing swells and a high-frequency band representing wind seas. Portilla et al. (2009) found that the use of partitioning gives more consistent identification results for both 1-D and 2-D spectra. They improved the results of wind sea and swell classification from 1-D spectra by proposing an algorithm for peak enhancement factor (γ^*).

As sea state develops, due to nonlinear interactions peak energy shifts towards lower frequencies. Distinct double peaks in the spectra indicate that wind sea and swell energies are well separated. Relatively close double peaks (looks as if single-peaked) indicate combination of two wave systems coming from the same/different directions (Guedes Soares, 1991). Guedes Soares (1984) proposed the ratio of peak frequencies of two components to describe the relation between two wave systems. Rodriguez and Guedes Soares (1999) proposed two related parameters, the Sea Swell Energy Ratio (SSER) and the Intermodal Distance (ID) for the classification of sea states and to identify spectral distribution in each sea state. In the present study, the asymmetric and bimodal nature of spectral distribution is examined for these two parameters.

Swells are classified into young, mature and old swells based on significant wave steepness – a measure of relative wave age to see the types of swells prevailing during the non-monsoon seasons. Swell steepness diminishes as it propagates into distant areas. Swells having steepness value less than 0.004 are considered as old swell, between 0.010 and 0.004 as mature swells and between 0.025 and 0.010 as young swells (Thompson et al., 1984). Aboobacker et al. (2011b) have identified potential swell generation areas during different seasons in the Arabian Sea (from SW direction during SW monsoon and from SW/SSW and NW directions during both pre-monsoon and post-monsoon seasons).

Fetch geometry plays a significant role in wave development (Donelan, 1985). Holthuijsen (1983) found that shape of the directional energy distribution in an ideal fetch limited wave generation situation agrees well with $\cos^{2s}(\theta/2)$ model, whereas during non-ideal situations it strongly influences the geometry of the fetch. Ardhuin et al. (2007) considered two situations: an ideal fetch-limited wave generation and a non-ideal situation which includes slanted fetch. For moderate angles between the wind and shore-normal direction (i.e. slanting fetch) and for unstable atmospheric condition, Ardhuin et al. (2007) observed that evolution of E^* (non-dimensional energy) and f_p^* (non-dimensional peak frequency) with X^* (non-dimensional fetch) agrees well with growth curves obtained by Kahma (1981). Kahma (1981) studied development of wave spectrum with fetch in a steady wind using wave buoy data in the Bothnian Sea and found a relation between dimensionless peak frequency and dimensionless

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fetch. As the situation is similar for the west coast of India, we have used the equation obtained by Kahma (1981) for the estimation of fetch for wind sea generation.

In the present study, we have separated the wave directional spectrum into wind seas and swells to examine how the wind sea growth modifies in the presence of pre-existing swells during non-monsoon season. Further, fetch estimation for wind sea generation has been done. A non-dimensional empirical relationship has been derived for the wind seas generated along the west coast of India during pre-monsoon and post-monsoon seasons.

2 Area of study

The study area and measurement locations are shown in Fig. 1. Goa and Ratnagiri are located on the central west coast of India, separated by a distance of 185 km. The topographic features are nearly the same and the bathymetry contours are almost parallel to the coast. The shorelines of Goa and Ratnagiri are oriented at 337.5° and 348.75°, respectively with respect to the north. Dwarka is situated along the northwest coast of India, and the shoreline is oriented at 315° (NW) with respect to the north. The northern part of Dwarka is open to the Gulf of Kachchh, a semi-enclosed basin. Off Dwarka, the bathymetry is irregular and very complex (Fig. 1).

The west coast of India, in general, experiences three types of seasons: pre-monsoon (February–May), southwest monsoon (June–September) and post-monsoon (October–January). Waves are usually very high during SW monsoon season and the predominant swells are from SW/WSW. During non-monsoon season (post- and pre-monsoons), along with predominant swells from SW/SSW, shamal swells (Aboobacker et al., 2011a) generated in the NW Arabian Sea are also present.

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3 Data and methodology

Wave data have been collected at 6 locations (Fig. 1) off Goa, Ratnagiri and Dwarka using Datawell Directional Waverider Buoys (Datawell, B.V., 2006). Table 1 provides details of geographical location, water depth and wave measurement duration. Data have been recorded for 20 min duration at 30 min interval. Simultaneous wind measurements at 10 min sampling intervals were carried out using Autonomous Weather Stations (AWS) installed near to the buoy locations (accuracy of AWS: $\pm 0.3\,\mathrm{m\,s^{-1}}$ for wind speed and $\pm 3^{\circ}$ for wind direction). AWS data were reduced to 10 m height, using Prandtl 1/7 law approximation (Peterson and Hennessey, 1978). Further, we have also used CERSAT/IFREMER Blended winds (Bentamy et al., 2007) available in $0.25^{\circ} \times 0.25^{\circ}$ grids at 6 h intervals in the form of U (zonal) and V (meridional) components.

Wind sea and swell parameters have been separated from the wave spectra using the methodology proposed by Gilhousen and Hervey (2001). The separation is based on the wave steepness algorithm, which partitions the wave spectrum into wind sea and swell components. The steepness parameter (ratio between wave height and wavelength) of each frequency is calculated to estimate the separation frequency. The wave steepness parameter, ξ at all frequencies f, can be written as

$$\xi(f) = \frac{H_s(f)}{\lambda(f)} \tag{1}$$

Where H_s is the significant wave height and λ is the wave length associated with mean wave period (T_z).

$$\lambda(f) = \frac{gT_z^2(f)}{2\pi} \tag{2}$$

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Substituting for $\lambda(f)$ and spectral moments (m_0, m_2), Eq. (1) can be modified as

$$\xi(f) = \frac{8\pi \int_{f_l}^{f_u} f^2 E(f)\mathrm{d}f}{g\sqrt{\int_{f_l}^{f_u} E(f)\mathrm{d}f}} \tag{3}$$

Where f_u = upper frequency limit (0.58), f_l = lower frequency limit and it varies as f_l = 0.025, 0.03, 0.035,...,0.58. $E(f)$ = variance density and g = acceleration due to gravity. $\xi(f)$ for all frequencies has been calculated from the measured data. The peak frequency f_x of the steepness parameter $\xi(f)$ has been identified, and then used to calculate the separation frequency f_s as follows.

$$f_s = Cf_x \tag{4}$$

Where C = 0.75 is an empirically determined constant (Gilhousen and Hervey, 2001). Wind sea and swell part of the spectra have been separated using f_s, and accordingly, significant wave height, mean wave period and mean wave direction of wind seas and swells were calculated from the moments.

The swell part of the spectrum is classified as young, mature and old swells based on significant wave steepness (Thompson et al., 1984), which is defined as the ratio between significant wave height and wavelength $\left(\frac{H_s}{\lambda}\right)$. The sea states along the west coast of India are classified according to the dimensionless parameters, SSER and ID (Rodriguez and Guedes Soares, 1999).

SSER is the ratio of energies associated with each wave system as given below:

$$\mathrm{SSER} = \left(\frac{m_{0ws}}{m_{0sw}}\right) \tag{5}$$

Where m_{0ws} is the zero order moment of wind sea and m_{0sw} the zero order moment of swell part of the spectrum. These are calculated based on spectral moment m_0,

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defined as:

$$m_0 = \int_0^\infty S(f)\mathrm{d}f \tag{6}$$

The sea states are classified as follows: (i) swell dominated sea state (SSER ≤ 0.8): the major part of the wave energy is associated with low frequency spectral peak, but significantly influenced by wind sea, (ii) mixed sea state with comparable energy of wind sea and swell (0.8 < SSER < 1.2): the wave energy is distributed over the low and high frequency ranges and (iii) wind sea dominated sea state (SSER ≥ 1.2): the maximum energy is confined to high frequency part of the spectrum.

Intermodal Distance (ID) is the frequency separation between the spectral frequency peaks, f_p, corresponding to swell and wind sea, which is defined as:

$$\mathrm{ID} = \left(\frac{f_{pws} - f_{psw}}{f_{pws} + f_{psw}}\right) \tag{7}$$

Where, f_{pws} is the peak frequency of wind sea and f_{psw} is the peak frequency of swell part of spectra.

The dominant sea states are classified based on ID as follows: (i) ID value close to zero, that is, when swell and wind sea spectral peaks are very close to each other, (ii) wave fields with double-peaked sea states whose modal spectral frequencies are moderately separated and (iii) ID close to 1.0, which represents sea state with swell and wind sea spectral peaks well separated. We have selected the range for each class of ID as follows: (i) ID-I (ID ≤ 0.3), (ii) ID-II (0.3 < ID < 0.7), and (iii) ID-III (ID ≥ 0.7). Depending on swell or wind sea absence, ID may vary from 0 (pure swell) to 1 (pure wind sea).

A non-dimensional empirical relationship has been derived based on wind (blended winds) and wind sea parameters. Estimation of the non-dimensional significant wind

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sea height H^*_{sws} and non-dimensional peak wind sea period T^*_{pws} as follows:

$$H^*_{sws} = \frac{gH_{ws}}{U^2} \quad \text{and} \quad T^*_{pws} = \frac{gT_{pws}}{U} \qquad (8)$$

Where g = acceleration due to gravity, U = wind speed ($\mathrm{m\,s^{-1}}$) at 10 m height, H_{sws} = significant wind sea height (m), T_{pws} = peak wind sea period (s).

4 Results and discussion

The wind sea and swell and coastal wind pattern off Goa, Ratnagiri and Dwarka are presented in Fig. 2. Local winds play a major role in shaping the wave characteristics along the west coast of India. For example, it has been observed earlier that winds and waves along the west coast of India exhibit systematic diurnal variations during pre-monsoon season (Vethamony et al., 2011) and predominant winds are either from NW (sea breeze) or NE (land breeze). Winds from NE are generally weak, and it extends only a few kilometers from the coast, whereas the NW winds are strong, especially in the afternoon hours. The wind seas generated under fetch-limited conditions interact with the swells arriving from SW. The mean periods of these swells are between 6 and 11 s and the wind seas are between 2 and 4 s. Diurnal variations are present during early pre-monsoon and post-monsoon seasons as well, but not as significant as pre-monsoon season. During early pre-monsoon, the predominant winds are from NW and NE. Swells (SW/SSW) are relatively weaker during non-monsoon season; however, the shamal winds generate high NW swells in the Arabian Sea during early pre-monsoon season (Aboobacker et al., 2011a). During post-monsoon season, the predominant winds are from N, NE and NW directions. Systematic diurnal variations are more predominant in pre-monsoon season than the post-monsoon season. The coastal winds off Dwarka show diurnal variations in wind speed and direction, but diurnal pattern of wave is not as distinct as off Goa during pre-monsoon season. It is

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found that wind seas increase towards sea as available fetch increases in NE direction, whereas swells increase towards the coast due to nonlinear wave-wave interaction and the prevailing wind direction during the study period, and this presents two well defined opposing wave systems (Fig. 2).

Generally waves are classified into wind sea and swell, when information on mixed sea state is not available. SSER provides detailed analysis of wave systems, classifying into swell, mixed and wind sea. During late pre-monsoon season, swells are dominant (54 % and 71 % at 25 m and 15 m water depths off Goa, respectively) (Table 2 and Fig. 3). During early pre-monsoon season, waves are primarily dominated by wind seas (44 % and 48 % at 35 m and 15 m depths, respectively off Ratnagiri) followed by swells (39 % at both the depths). However, during post-monsoon season, wind seas are dominated (45 %) at 30 m depth (away from the coast) while swells are dominated (61 %) at 15 m depth (closer to the coast) off Dwarka. This is attributed to generation of NE wind seas, and their growth is towards offshore. Sufficient fetch is available at 30 m depth for NE wind seas to grow compared to 15 m depth, and hence, wind sea energy is relatively higher at this location. Considerable amount of mixed seas was observed during late pre-monsoon season, whereas, during early pre-monsoon and post monsoon seasons it was the least. When swells dominate, mixed sea is less, and this happens at the fully developed stage. However, when wind seas dominate, mixed seas also increase as the waves are still in the developing condition.

In addition to SSER, ID also provides differentiation of the spectral peaks for non-monsoon season. During late pre-monsoon season, maximum waves are under the category ID-II (85 % and 95 % at 25 m and 15 m depths off Goa, respectively, Table 3). This indicates that spectral peaks of wind sea and swell are moderately separated. During early pre-monsoon season, majority of waves fall under the category ID-I (57 % and 56 % at 35 m and 15 m depths off Ratnagiri, respectively), indicating that the spectral peaks are very closer to each other (spectra appear to be unimodal). One example is, spectral peaks during shamal events (purely swell, ID $\sim$ 0). During post-monsoon season, all the waves fall under the category ID-II (60 % and 75 % at 30 m and 15 m

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water depths off Dwarka, respectively), indicating that spectral peaks are moderately separated. Even though wind seas play a dominant role during non-monsoon season, spectrum with pure wind seas (ID ~ 1) was weakly present. The wind sea spectrum was always co-existent with swell, which are prevailing almost all the time.

The directionality of the wind sea and swell systems is found to influence the development of wind-waves. The directional spread distribution of mixed seas exhibits features different from those of pure wind seas. Such mixed seas of swell and wind seas result in a multimodal wave field, and the development of this multi-system is to be explored.

The minimal directional spread is located at the peak frequency of the spectra. Off Goa, during late pre-monsoon season, we find that wind seas grow when the wind and the wind sea are in the same direction (i.e. both are from NW). During the growth of wind seas, the directional spread ranges between 30° and 50°. As the wind direction changes from NW to NE and wind speed reduces (say, $0.5\,\mathrm{m\,s^{-1}}$), swells dominate from SW and accelerate the decay of NW wind seas (Fig. 4). That is, swell and wind sea are nearly normal to each other, whereas, wind is opposite to swell and normal to wind sea direction. At this stage, the bimodal sea state turns into unimodal state (Fig. 4). The angular spread increases in the higher frequency range above 0.2 Hz due to the decay of wind seas. As a result of sea breeze at noon hours, wind direction changes from NE to NW, and the speed reaches to a maximum of $5\,\mathrm{m\,s^{-1}}$. Wind sea starts developing and reaches its peak during evening hours with the co-existence of swells from SW direction, leading to a bimodal sea state. As the wind sea matures, the minimal spread of wave energy decreases and shifts towards lower frequency (Fig. 4).

Off Ratnagiri, during early pre-monsoon season, we can see four peaks in the spectrum from different directions (Fig. 5). These peaks are: swell from SW and wind sea from SW, NW and NE directions. The contributions of SW and NE wind seas are minimum in the multimodal spectra (Fig. 5). The angular spread is minimum for wind seas than for swells, with energies distributed over the frequency range 0.2 to 0.4 Hz. The interaction between wind seas and the swells occurs in transforming the young wind seas to mature wind seas. As the wind sea matures, directional spread shifts towards lower frequencies. Multimodalism is reduced to bimodalism in the wave spectrum. When the shamal event occurs, the wind and wave directions shift to NW and wind speed reaches to a maxmimum of 7 $\mathrm{m\,s^{-1}}$. The spectral energy is narrowed down in the swell part of the spectrum in the NW direction. Light swell energy from SW direction is also observed in the wave spectrum with large directional spread. Prevailing swell dominates, and ultimately absorbs the wind sea energy. This leads to broadening of energy density of swell peak and disappearance of bimodal state.

Off Dwarka, the directional spectrum and spread are totally different for the post monsoon season (Fig. 6) compared to the pre-monsoon season at the other two locations. We can observe two distinct swell peaks from S/SSW direction and two wind sea peaks from NW/NE directions in the wave spectrum. When the winds are from NW and they are weak, NE wind seas decay with gradual increase in angular spread. However, when the winds shift to NE direction and the speed increases to 3 $\mathrm{m\,s^{-1}}$, NE wind seas grow with minimal spread. As the NE wind sea reaches the maximum, it interacts with the wave systems: NW wind sea and S swell. The absorption from NE wind sea and S swell energy produces an overshoot in the energy density of NW wind sea with minimum spread. The interaction between the two systems results in the integration of most of the swell and NE wind sea energy into the old wind sea (Fig. 6). Later, wind shifts to NE direction and the peak NW wind sea starts dissipating and imparting its energy to swells and NE wind seas. At later stages, NE wind seas are disappeared and multi directional spectrum reduces to bimodal spectrum. Swells are dominating with minimal angular spread and wind seas are dissipating with high angular spread. Further, the wind sea energy is absorbed by the prevailing swells with the transformation of bimodal to unimodal wave spectrum.

An investigation has been carried out to identify the various types of swells prevailing in the Arabian Sea during non-monsoon season. The analysis of swells present along the west coast of India indicates that mature swells are predominant (92 % and 91 % at 25 m and 15 m depths off Goa, respectively) due to the onset of monsoon during

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late pre-monsoon season (Table 4). Young, mature and old swells are nearly the same, varying between 30 % and 40 % during early pre-monsoon season (January–February 2008). Most of the swells in the Arabian Sea is from SW, whereas, due to the shamal event occurs in the Persian Gulf produces swells in the NW direction. However, old swells (53 % and 88 % at 30 m and 15 m depths off Dwarka, respectively) and mature swells (39 % and 13 % at 30 m and 15 m depths off Dwarka, respectively) are predominant during post-monsoon season (December 2007–January 2008). It is also observed that the SW/SSW swells generated in the Southern Ocean during pre-monsoon and post-monsoon season are old swells, SW swells generated in the South Arabian Sea during SW monsoon (or late pre-monsoon season) are mature swells and NW swells generated (during early pre-monsoon season) in the North Arabian Sea are young and mature swells.

As fetch also plays a significant role in wave growth, we used the Kahama equation (1981) for the estimation of fetch for wind sea generation. AWS was not able to capture offshore winds, as it is installed away from the buoy (on the land). Hence, we have used IFREMER Blended wind data (0.250 × 0.250), available at every 6 h, to calculate the offshore extent of the wind sea fetch along the west coast of India. Fetch was obtained using Kahma equation (1981) for Goa, Ratnagiri and Dwarka coastal regions. Figure 7 shows the minimum fetch available for the wind sea generation along the west coast of India. Aparna et al. (2005) observed that the maximum offshore extension of the sea breeze along the southwest coast of India can reach upto 180 km. The fetch available for the development of wind seas is minimum during early post-monsoon season, and therefore, shows the presence of swell dominance. Observations also support the growth of wind seas during early pre-monsoon season. The fetch increases when winds are NW, however decreases when winds are NE (as the wave measurement location is very near to coast and no fetch is available in this direction). Off Goa, fetch observed for wind sea evolution was about 80 km. It increases and reaches the maximum at every 4 h; off Ratnagiri, fetch is about 120 km; it increases and reaches the maximum during shamal event, off Dwarka, when the predominant winds are NE, fetch

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is minimum, as there is no fetch available in this direction. Fetch increases, as the wind direction changes to NW.

During non-monsoon season, the waves generated by the local winds are fetch limited. The relation has been obtained for non-dimensional formulas relating the significant wave height, dominant wave period and wind speed parameters. To derive a non-dimensional empirical relation, logarithmic values of the non-dimensional significant wind sea height H_s^* and peak wind sea period T_p^* have been calculated (Fig. 8). The best fit between $\log(H_{sws}^*)$ and $\log(T_{pws}^*)$ has been estimated and resolved as follows:

$$\frac{gH_{sws}}{U^2} = 0.0085 \cdot \left(\frac{gT_{pws}}{U}\right)^{1.515} \quad (9)$$

The above equation is found to be satisfied in all the locations (Goa, Ratnagiri and Dwarka) and can be used for fetch-limited condition along the west coast of India. Equation (9) is very close to the empirical relation derived by Wen et al. (1989).

5 Conclusions

Measured waves along the west coast of India show distinct variations in the wave parameters due to the co-existence of wind seas with pre-existing swells during non-monsoon season (pre-monsoon and post-monsoon seasons). The diurnal patterns observed in wind speed, wave height and wave period are very typical for the west coast of India during pre-monsoon season. SSER classifications bring out salient features of different wave systems present along the central west coast and northwest coast of India during non-monsoon season. Swells are predominant (61 %) along the northwest coast of India (off Dwarka) during post-monsoon season, and wind seas are predominant (48 %) during late post-monsoon and early pre-monsoon seasons. During late pre-monsoon season, swells (71 %) are predominant along the central west coast of India (off Ratnagiri and Goa, respectively). During most part of the non-monsoon

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season, the energy peaks of swell and wind sea in the spectra are moderately separated and their Intermodal Distance are between 0.3 and 0.7, and those during shamal events are less than 0.3 as the energy peaks are very close to each other (unimodal).

The diurnal variations are not as significant in the post and early pre-monsoon seasons as in the late pre-monsoon season. Wind seas in multimodal spectrum have minimum spreads than pure wind seas. The short wind seas are more influenced by interaction with swells than by wind forcing. Under low winds, the wind sea development was dominated by interactions with swell. Situations of mixed seas showed that coupling between wave systems had a stabilizing effect of reducing a multimodal energy spectrum to a unimodal wave spectrum.

The contribution of high NW swells generated in the North Arabian Sea during late post-monsoon and early pre-monsoon (shamal events) seasons is very significant along the west coast of India, but otherwise Arabian Sea is relatively calm. According to swell classification, mature swells (91 %) and old swells (88 %) are predominant during late pre-monsoon (May) and post-monsoon (December) seasons, respectively. Young (29 %), mature (33 %) and old (38 %) swells are almost equally distributed during late post-monsoon (January) and early pre-monsoon (February) seasons along the west coast of India.

The fetch available for the evolution of wind sea spectrum off Goa and Dwarka are about 80 km during late pre-monsoon and post-monsoon periods. However, fetch increases (off Ratnagiri) and reaches about 120 km during pre-monsoon period.

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References

Aboobacker, V. M., Vethamony, P., and Rashmi, R.: "Shamal" swells in the Arabian Sea and their influence along the west coast of India, Geophys. Res. Lett., 38, L03608, doi:10.1029/2010GL045736, 2011a.

Aboobacker, V. M., Rashmi, R., Vethamony, P., and Menon, H. B.: On the dominance of pre-existing swells over wind seas along the west coast of India, Cont. Shelf Res., 31, 1701–1712, 2011b.

Aparna, M., Shetye, S. R., Shankar, D., Shenoi, S. S. C., Mehra, P., and Desai, R. G. P.: Estimating the seaward extent of sea breeze from QuikSCAT scatterometry, Geophys. Res. Lett., 32, L13601, doi,10.1029/2005GL023107, 2005.

Ardhuin, F., Herbers, T. H. C., Watts, K. P., Van Vledder, G. P., Jensen, R., and Graber, H.: Swell and slanting fetch effects on wind wave growth, J. Phys. Oceanogr., 37, 908–931, 2007.

Bentamy, A., Ayina, H.-L., Queffeulou, P., Croize-Fillon, D., and Kerbaol, V.: Improved near real time surface wind resolution over the Mediterranean Sea, Ocean Sci., 3, 259–271, doi:10.5194/os-3-259-2007, 2007.

Datawell, B. V.: Datawell wave rider reference manual, Datawell BB, Zumerlustraat 4, 2012 LM Haarlem, The Netherlands, 2006.

Donelan, M. A., Hamilton, J., and Hui, W. H.: Directional spectra of wind-generated waves, Philos. Trans. Roy. Soc. London A., 315, 509–562, 1985.

Gerling, T. W.: Partitioning sequences and arrays of directional ocean wave spectra into component wave systems, J. Atmos. Ocean. Technol., 9, 444–458, 1992.

Gilhousen, D. B. and Hervey, R.: Improved estimates of swell from moored buoys, in: Proceedings of the Fourth International Symposium WAVES 2001, ASCE: Alexandria, VA, 387–393, September 2-6, 2001, 2001.

Guedes Soares, C.: Representation of double-peaked sea wave spectra, Ocean Eng., 11, 185–207, 1984.

Guedes Soares, C.: On the occurrence of double peaked wave spectra, Ocean Eng., 18, 167–171, 1991.

Hanson, J. L. and Phillips, O. M.: Automated analysis of ocean surface directional wave spectra, J. Atmos. Ocean. Technol., 18, 277–293, 2001.

Harish, C. M. and Baba, M.: On spectral and statistical characteristics of shallow water waves, Ocean Eng., 13, 239–248, 1986.

Kahma, K. K.: A study of the growth of the wave spectrum with fetch, J. Phys. Oceanogr., 11, 1503–1515, 1981.
Kumar, V. S., Anand, N. M., Kumar, K. A., and Mandal, S.: Multipeakedness and groupiness of shallow water waves along Indian coast, J. Coast. Res., 19, 1052–1065, 2003.
Holthuijsen, L. H.: Observations of the directional distribution of ocean wave energy, J. Phys. Oceanogr., 13, 191–207, 1983.
Neetu, S., Shetye, S. R., and Chandramohan, P.: Impact of sea-breeze on wind seas off Goa, west coast of India, J. Earth Syst. Sci., 115, 229–234, 2006.
Peterson, E. W. and Hennessey Jr, J. P.: On the use of power laws for estimates of wind power potential, J. Appl. Meteorol., 17, 390–394, 1978.
Portilla, J., Francisco, J. O., and Monbaliu, J.: Spectral partitioning and identification of wind sea and swell, J. Atmos. Ocean. Technol., 26, 107–122, 2009.
Rodriguez, G. R. and Guedes Soares, C.: The Bivariate distribution of wave heights and periods in mixed sea states, J. Offshore Mech. Arct. Eng., 121, 102–108, 1999.
Sanil Kumar, V., Ashok Kumar, K., Pednekar, P., and Gowthaman, R.: Sea and swell along west coast of India: study based on measured data, in: Fourth Indian National Conference on Harbour and Ocean Engineering, 12–14 December 2007, NITK, Surathkal, 736–745, 2007.
Thompson, W. C., Nelson, A. R., and Sedivy, D. G.: Wave group anatomy, in: Proceedings of 19th Conference on Coastal Engineering, Vol. I, American Society of Civil Engineers, 661–677, Houston, Texas, September 3-7, 1984.
Vethamony, P. and Sastry, J. S.: On the characteristics of multipeaked spectra of ocean surface wave, J. Inst. Eng. India, 66, 129–132, 1986.
Vethamony, P., Aboobacker, V. M., Sudheesh, K., Babu, M. T., and Ashok Kumar, K.: Demarcation of inland vessels limit off Mormugao port region, India: a pilot study for the safety of inland vessels using wave modeling, Nat. Hazards, 49, 411–420, 2009.
Vethamony, P., Aboobacker, V. M., Menon, H. B., Ashok Kumar, K., and Cavaleri, L.: Superimposition of wind seas on pre-existing swells off Goa coast, J. Mar. Syst., 87, 47–54, 2011.
Wang, D. W. and Hwang, P. A.: An operational method for separating wind sea and swell from ocean wave spectra, J. Atmos. Ocean. Technol., 18, 2052–2062, 2001.
Wen, S. C., Zhang, D. C., Guo, P. Z., and Chen, B. H.: Parameters in wind-wave frequency spectra and their bearings on spectrum forms and growth, Acta Oceanol. Sin., 8, 15–39, 1989.

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Table 1. Details of data source.

Location	Longitude (E)	Latitude (N)	Water depth (m)	Duration
Goa (late pre-monsoon)	73° 42′ 1.2″	15° 29′ 18″	25	1–21 May 2005
(May 2005)	73° 44′ 55″	15° 25′ 24″	15	6–21 May 2005
Ratnagiri (early pre-monsoon)	73° 07′ 17.3″	17° 00′ 15.1″	35	24 Jan–25 Feb 2008
(Jan–Feb 2008)	73° 15′ 00.7″	17° 00′ 25.4″	15	24 Jan–25 Feb 2008
Dwarka (post-monsoon)	69° 01′ 8.24″	22° 05′ 15.7″	30	3 Dec 2007–6 Jan 2008
(Dec 2007–Jan 2008)	69° 05′ 24.0″	22° 04′ 7.85″	15	3 Dec 2007–6 Jan 2008

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Table 2. Percentage of swell, wind sea and mixed sea with comparable energy during non-monsoon season.

Location	Water depth (m)	No. of observations	Dominance (%) Swell	Wind sea	Mixed sea with comparable energy
Goa	25	463	54	20	26
(May 2005)	15	717	71	11	19
Ratnagiri	35	1524	39	44	17
(Jan–Feb 2008)	15	1523	39	48	14
Dwarka	30	1485	38	45	17
(Dec 2007–Jan 2008)	15	1483	61	24	15

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Table 3. Percentage of intermodal distance (ID) along the west coast of India.

Location	Water depth (m)	No. of observations	Mean ID values (observations in %)		
			ID-I	ID-II	ID-III
Goa	25	463	0.28(14)	0.54(85)	0.72(1)
(May 2005)	15	717	0.28(4)	0.54(95)	0.72(1)
Ratnagiri	35	1524	0.1(57)	0.55(40)	0.71(3)
(Jan–Feb 2008)	15	1523	0.1(56)	0.54(41)	0(3)
Dwarka	30	1485	0.14(14)	0.59(60)	0.73(26)
(Dec 2007–Jan 2008)	15	1483	0.24(5)	0.56(75)	0.76(20)

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Table 4. Distribution of young, mature and old swells along the west coast of India.

Location	Water depth (m)	Young swell (%)	Mature swell (%)	Old swell (%)
Goa	25	6.05	92.01	1.94
(May 2005)	15	1.53	90.94	7.53
Ratnagiri	35	39.7	30.31	29.99
(Jan–Feb 2008)	15	29.42	32.57	38.01
Dwarka	30	8.48	38.73	52.79
(Dec 2007–Jan 2008)	15	0	12.61	87.39

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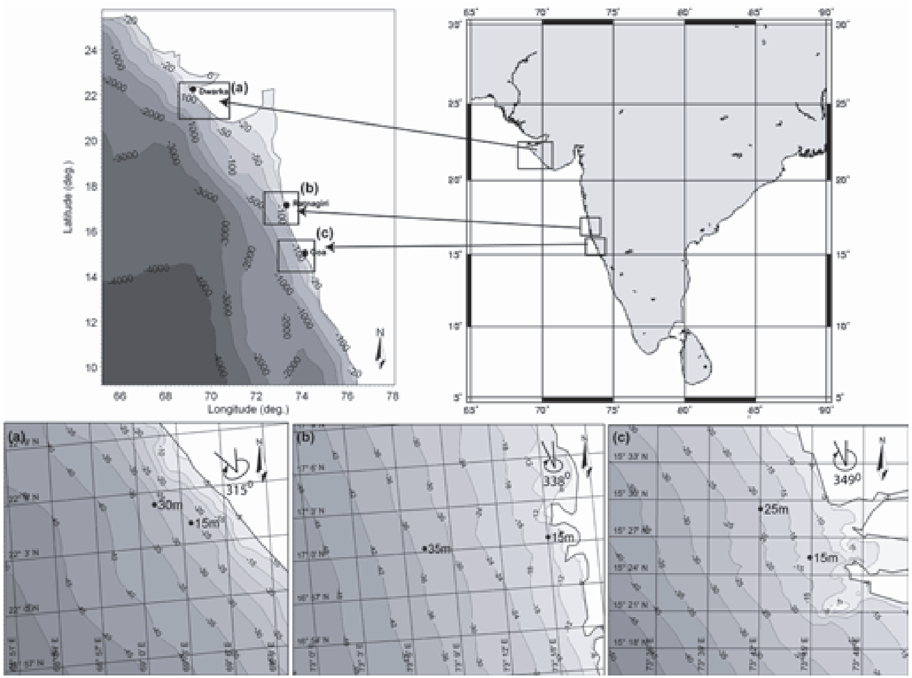

Fig. 1. Wave measurement location and its bathymetry contours along the west coast ofIndia. Angles mentioned in the figures are the orientation of the coastline w.r.t north.

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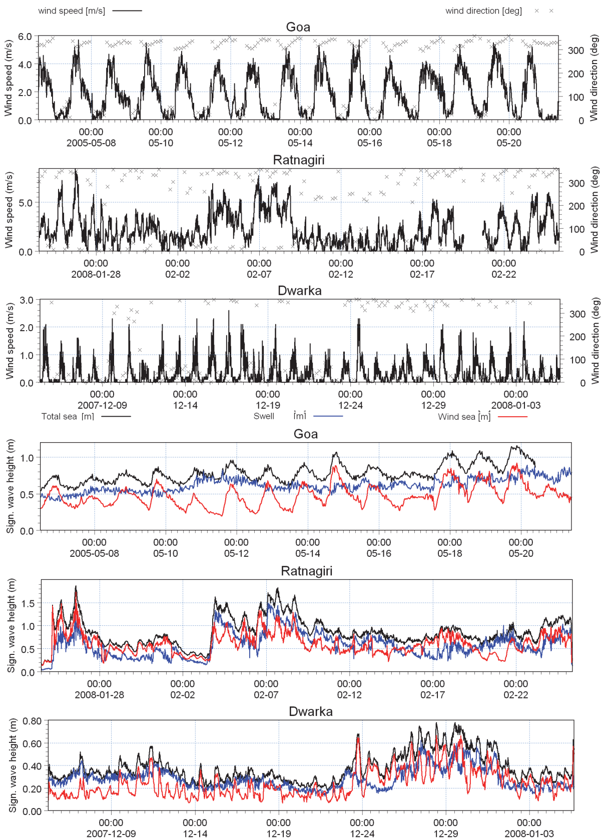

Fig. 2. Wind parameters (wind speed and direction) and significant wave height (total sea – black, swell – blue and wind sea – red) off Goa, Ratnagiri and Dwarka.

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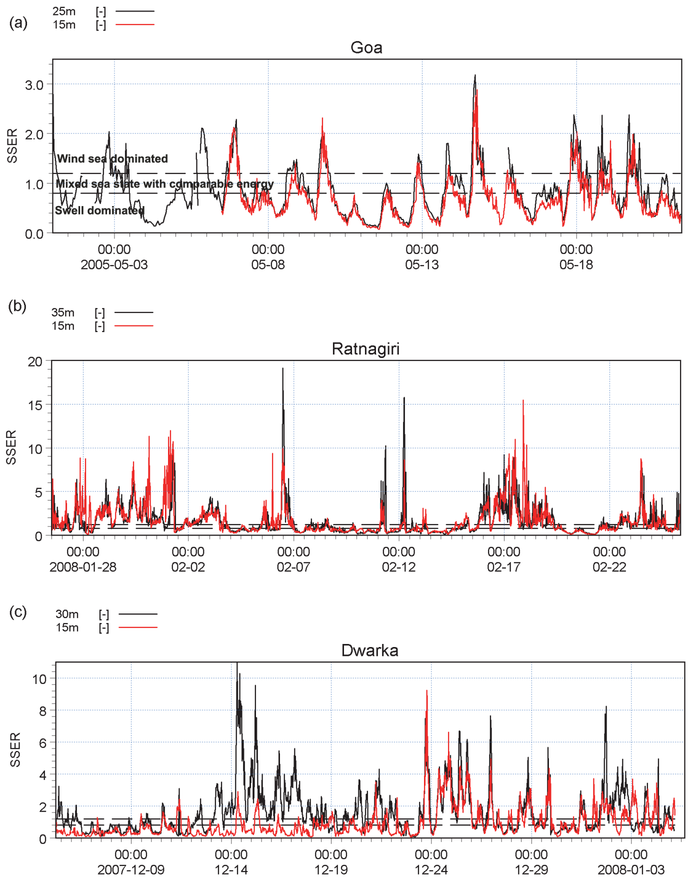

Fig. 3. SSER of wind sea, mixed sea and swell: **(a)** 15 m and 25 m depths off Goa, **(b)** 15 m and 35 m depths off Ratnagiri and **(c)** 15 m and 30 m depths off Dwarka.

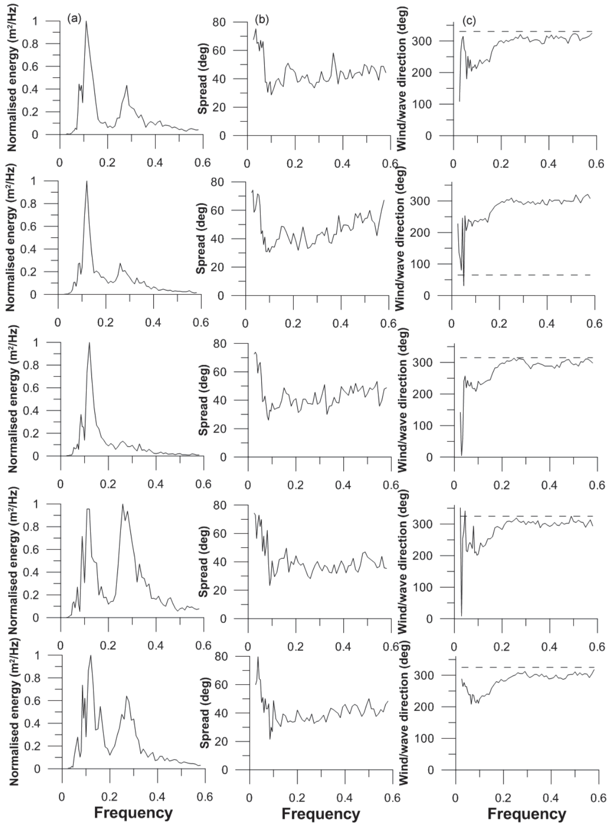

Fig. 4. (a) Wave energy spectrum **(b)** wave spread and **(c)** mean wave (solid line) andwind (dashed line) directions at 00:00 h, 06:00 h, 12:00 h, 18:00 h and 23:00 h offGoa during 9 May 2005.

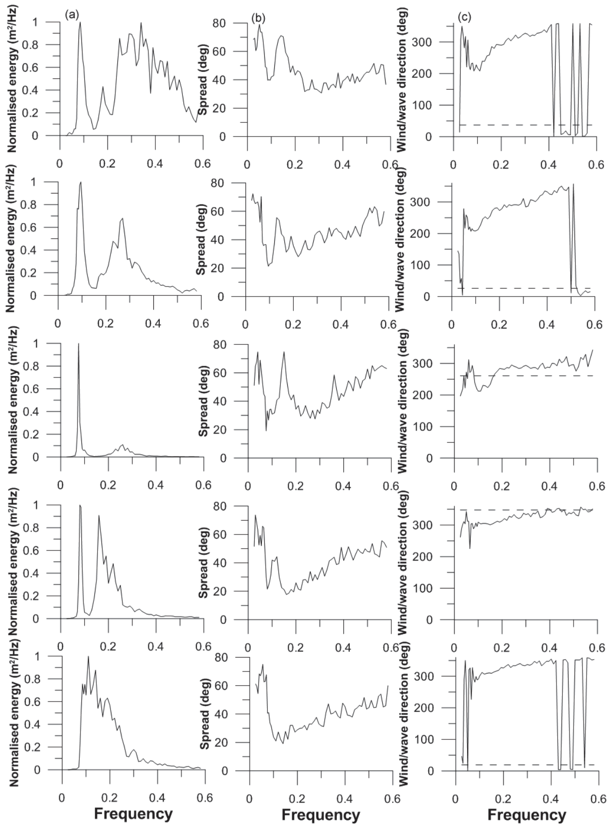

Fig. 5. **(a)** Wave energy spectrum **(b)** wave spread and **(c)** mean wave (solid line) and wind (dashed line) directions at 00:00 h, 06:00 h, 14:00 h, 19:00 h and 23:00 h off Ratnagiri during 3 February 2008.

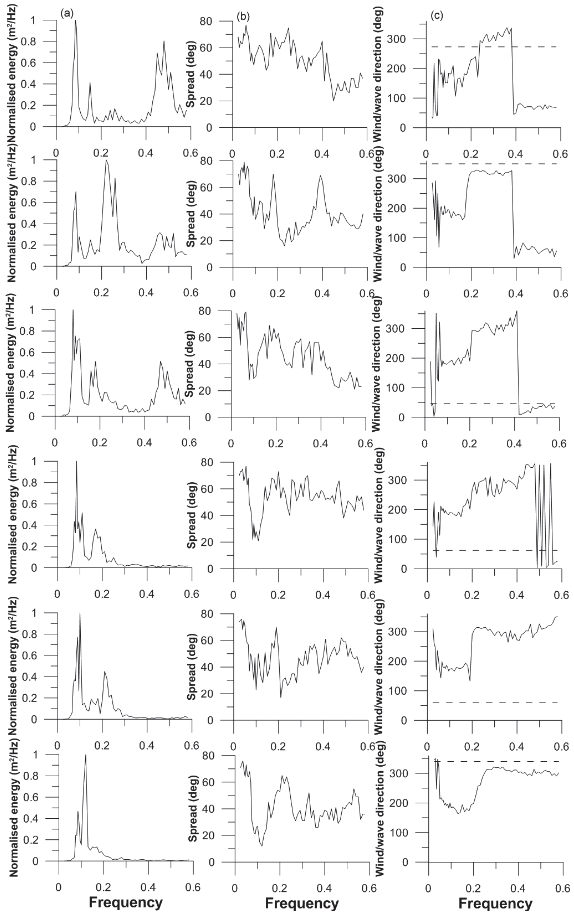

Fig. 6. (a) Wave energy spectrum **(b)** wave spread and **(c)** mean wave (solid line) and wind (dashed line) directions at 00:00 h, 06:00 h, 11:00 h, 13:00 h, 17:00 h and 23:00 h off Dwarka during 22 December 2007.

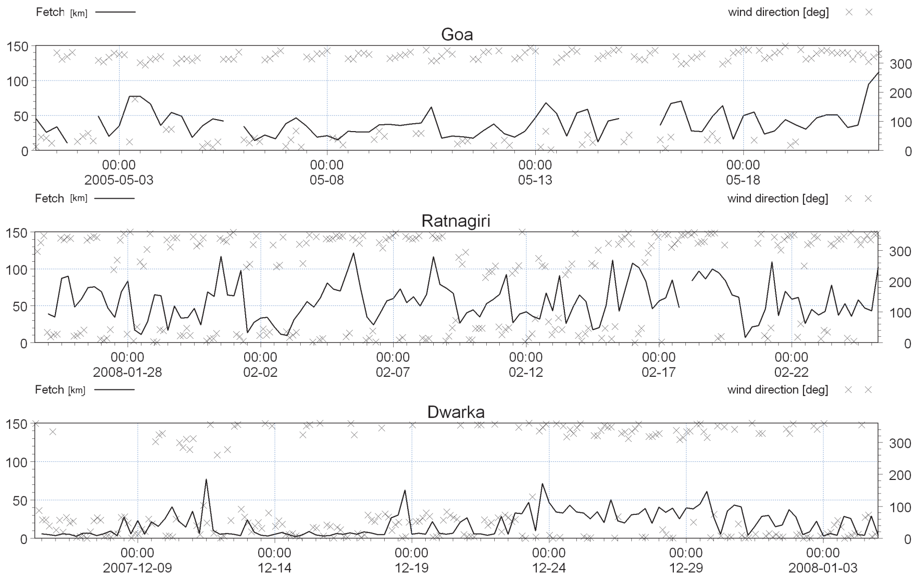

Fig. 7. Fetch and wind direction off Goa, Ratnagiri and Dwarka along the west coast of India.

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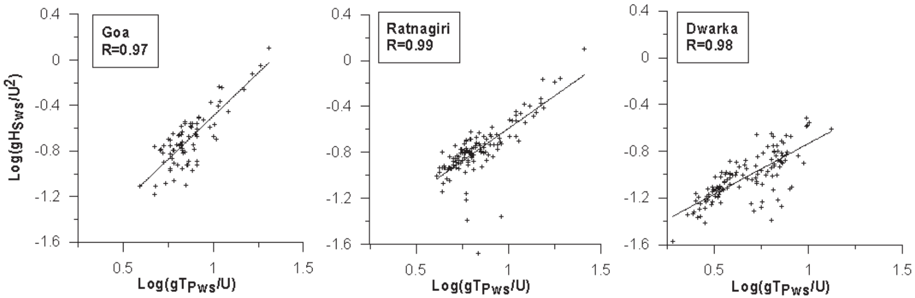

Fig. 8. Scatter between $\log(gH_{sws}/U^2)$ and $\log(gT_{pws}/U)$ at different locations along the west coast of India.