
Chapter 4

Seasonal response of coastal waves along the Indian coast: spectral approach

Chapter 4

Seasonal response of coastal waves along the Indian coast: spectral approach

4.1. Introduction

Spectral characteristics of nearshore waves have been analysed using time series wave data measured at select locations along the Indian coast. The directional spectra distinctly separate out the wave conditions prevailed at various locations along the Indian coast during pre-monsoon, SW monsoon and NE monsoon seasons and extreme weather events. Further, dominance of swells and wind seas along the west coast of India has been studied in detail. Potential swell regions, which affect the west coast of India during various seasons, were identified from the analysis of global wind data and wave observations. The findings have been substantiated through numerical simulations. The characteristics of “Shamal swells” have been studied based on measured wave data off Ratnagiri during winter season. Numerical simulations reproduced the generation and propagation of the Shamal swells in the Arabian Sea. Superimposition of pre-existing swells with wind seas generated by the sea breeze during pre-monsoon season has been studied to understand the nature of coastal waves prevailing along the west coast of India.

4.2. Wave characteristics during monsoons and extreme events

Wave data measured at locations B1 (off Goa) and B8 (off Paradip) have been used to study the spectral characteristics of the nearshore waves during monsoons and extreme weather events along the west coast and east coast of India, respectively. Measurements are available for the periods Feb 1996 – May 1997 at B1 and May 1996 – Jan 1997 at B2. Numerical simulations have also been carried out to reproduce the wave characteristics in the Indian Ocean during the measurement periods.

4.2.1. *Along the east coast of India*

Indian Daily Weather Report (IMD, 1996) reveals the presence of 4 storms/depressions in the Bay of Bengal during the study period. The pressure level data from the Cyclone Detection Radar Centre at Paradip indicates that the pressure dropped from 1003.1 to 996.9 mb during 26–30 May 1996, from 1008.0 to 994.2 mb during 10–21 June 1996 and from

1003.0 to 991.2 mb during 18–26 July 1996 (Figure 4-1), leading to extreme wave conditions. The fourth depression could not intensify, though the pressure level decreased from 1012.3 to 1000.4 mb during 24–28 October 1996. Pressure data from IDWR (IMD, 1996) also indicate the presence of depressions over the region. JTWC reported four storms in the Bay of Bengal during the study period: 11 – 18 June 1996, 21 – 29 Oct 1996, 01 – 07 Nov 1996 and 20 Nov – 07 Dec 1996. However, all of them did not impact the Paradip coast (except the storm during 11 – 18 June 1996), as the tracks were far away from the study region.

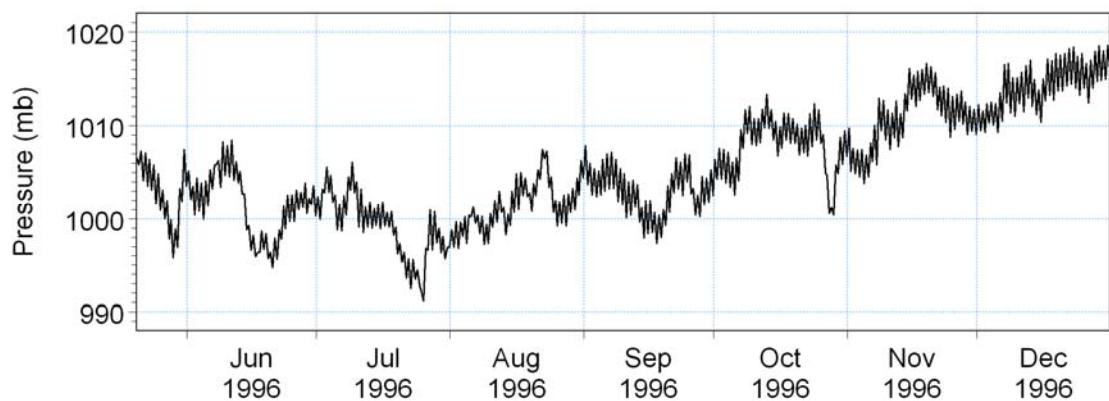


Figure 4-1. Pressure levels during May 1996–December 1996.

In May 1996 (pre-monsoon season), the predominant wave direction was between SSW and SSE with significant wave heights varying between 0.9 and 2.7 m (Figure 4-2). The depression during 26–30 May, 1996 caused the waves to grow and the significant wave height reached up to 2.7 m on 28 May in the SSW direction. On 29 May, the wave direction shifted to S and subsequently wave height reduced. The predominant wave direction during SW monsoon season (June–September) was between S and SSE, and the significant wave height reached a maximum value of 3.8 m and 4.2 m on 16 June and 25 July, respectively. This includes waves during the two depression periods. In NE monsoon (November–January), the predominant wave direction was between SE and NE, and the maximum significant wave height observed was 2.1 m (SE direction) on 28 October due to the depression that occurred in the Bay of Bengal (24–29 October, 1996). Even though the pressure level decreased from 1012.3 to 1000.4 mb, the depression could not intensify further and generate high waves. For the rest of the year, the waves were below 0.8 m in height, and varied between S and SSE directions.

An analysis of several years of wave data from the Bay of Bengal shows that wave parameters such as significant wave height, wave period and mean wave direction vary significantly in various seasons. In general, during fair weather season off Paradip significant wave heights are below 1.0 m, during monsoon below 3.5 m and during extreme weather events of the order of 5.0–7.0 m.

Frequency-energy spectra during extreme events are single peaked, and the maximum energy distribution is in a narrow frequency band (Figure 4-3a) with an average directional spreading of 20° . Spectra for other seasons are multi-peaked, and energy is distributed over a wide range of frequencies (Figure 4-3b and 4-3c) in different directions. The type of spectra shown in Figure 4-3b and 4-3c represent the seasonal variation of wave conditions in the Bay of Bengal in the absence of extreme events. Wave spectra of extreme events are distinctly different from that of monsoon or fair weather season. In general, wave spectra along the Indian coast are multi-peaked, often with two peaks (Harish and Baba 1986; Vethamony and Sastry 1986; Rao and Baba 1996). Greenslade (2001) found that when energy shifts from one portion of the spectrum to another, the spectral peak suddenly jumps to a different frequency.

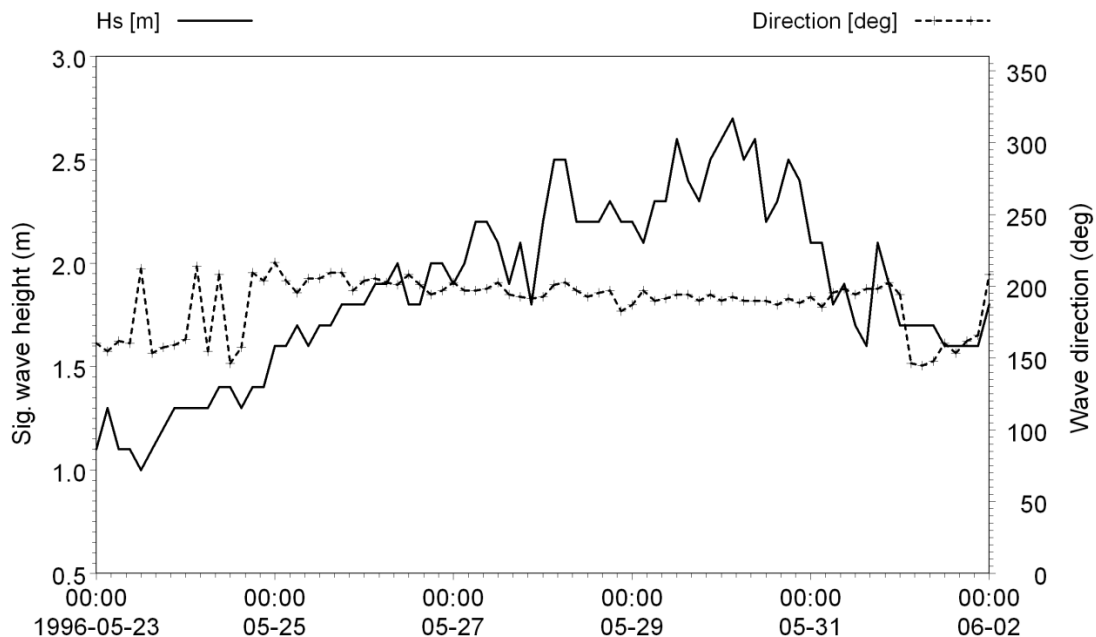


Figure 4-2. Significant wave height pattern during an extreme event (23 May – 02 June, 1996) indicating wave growth and decay.

Sanil Kumar et al. (2004) found that wave spectra during extreme sea states are mainly single-peaked, and the percentage of occurrence of double-peaked spectra is higher for low sea states. In the present case also, the spectra are single-peaked, and the maximum energy is centered in a narrow frequency band. The maximum spectral energy during the two depressions are $30.33 \text{ m}^2/\text{Hz}$ (15 June) and $31.25 \text{ m}^2/\text{Hz}$ (26 July), which are very high compared to the energy during normal monsoon months (e.g. $7.63 \text{ m}^2/\text{Hz}$ (13 June) and $5.68 \text{ m}^2/\text{Hz}$ (28 July)). It is evident from the spectra that wave energy is higher during SW monsoon season than the NE monsoon. Typical measured directional energy spectra representing SW and NE monsoon seasons are shown in Figure 4-4 and Figure 4-5, respectively.

Bathymetry contours off Paradip are parallel to the coast, and the slope is very gentle. In general, winds are either southwesterlies or northeasterlies. Sufficient fetch is available for both the winds.

During extreme events, long waves with higher amplitudes are generated and most of the energy is concentrated in the low frequency region. So, typically the spectra will be single-peaked. When swells reach the region where the locally generated waves are present, the spectra show double- or multi-peaks. Normally during fair weather season, the sea states are swell dominated. Hence, the primary peak will be in the low-frequency region and secondary peak will be in the high-frequency region, depending on the locally generated wind seas.

During monsoons, the sea off Paradip is usually 'sea' dominated. Distant swells from different directions also propagate to this region and form a complex sea state. Hence, the peak energy shifts from low- to high-frequency region depending on the strength of the prevailing winds.

Modelled directional energy spectra during 26 July are shown in Figure 4-6. The spectra show single-peakedness as in the measured spectra due to extreme event prevailed in the region. The modelled wave directions are between SSW and SSE from May to September and between N and NW in November and December. Mean wave period ranges from 4 to 10 s in SW monsoon and from 2 to 8 s in NE monsoon. The highest measured significant wave height is 4.2 m, whereas the corresponding modelled value is 3.4 m (22 July 1996, due to the extreme event that prevailed in the region).

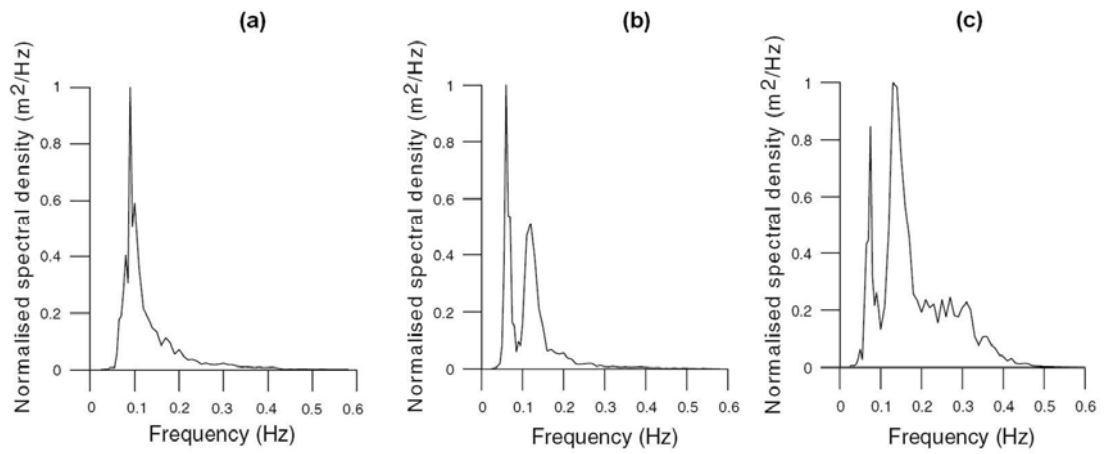


Figure 4-3. Typical wave spectra during (a) 26 July at 09 h, (b) 3 Aug 1996 at 09 h and (c) 3 July 09 h.

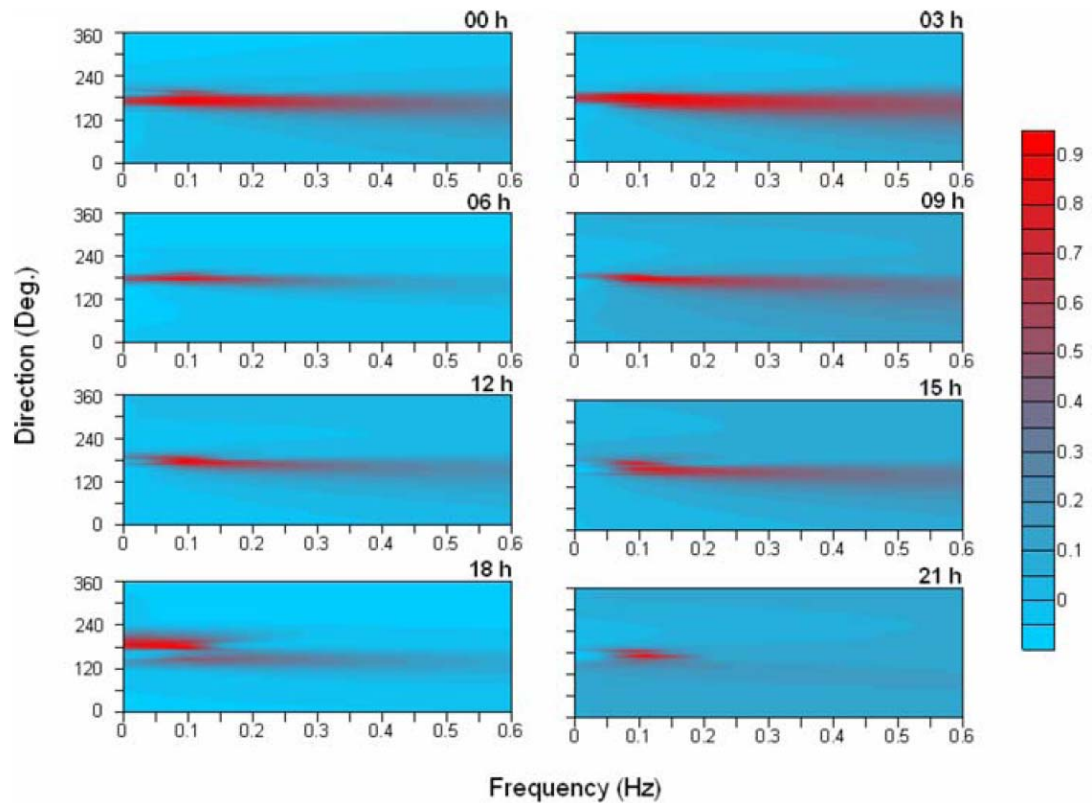


Figure 4-4. Measured directional energy spectra from 00 h to 21 h (for every 3 h) on 26 July 1996.

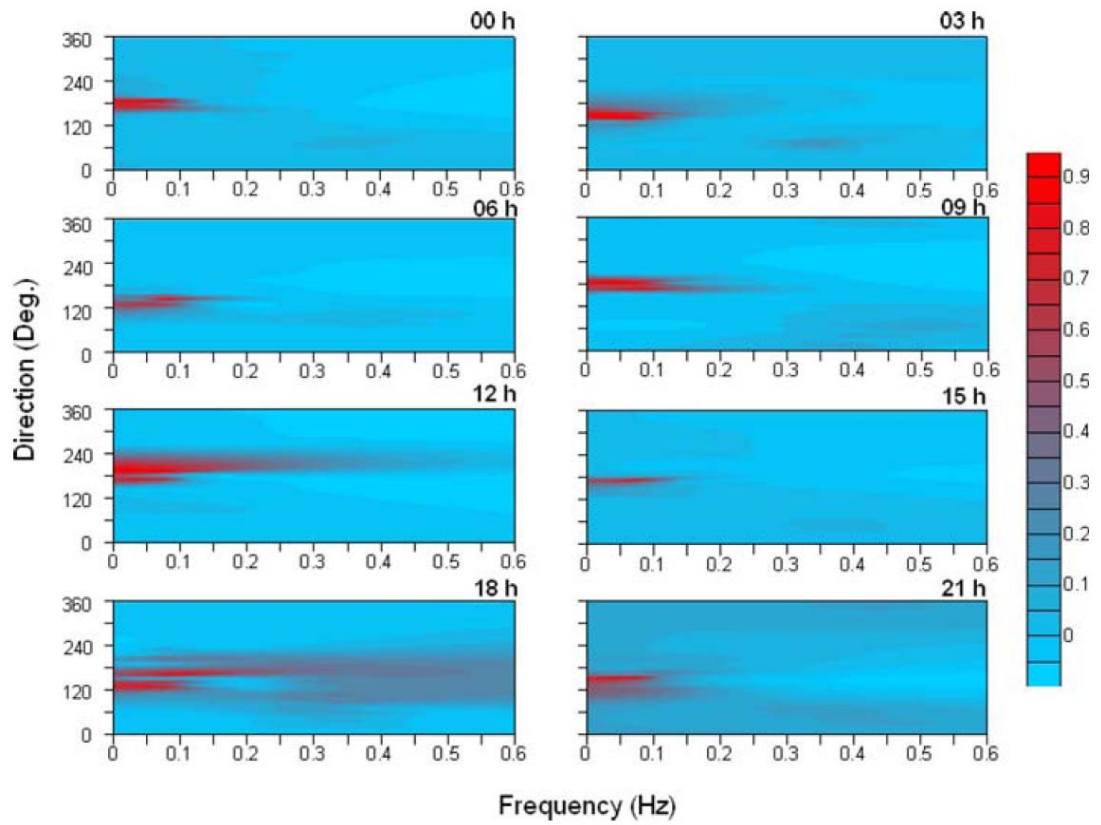


Figure 4-5. Measured directional energy spectra from 00 h to 21 h (for every 3 h) on 15 November 1996.

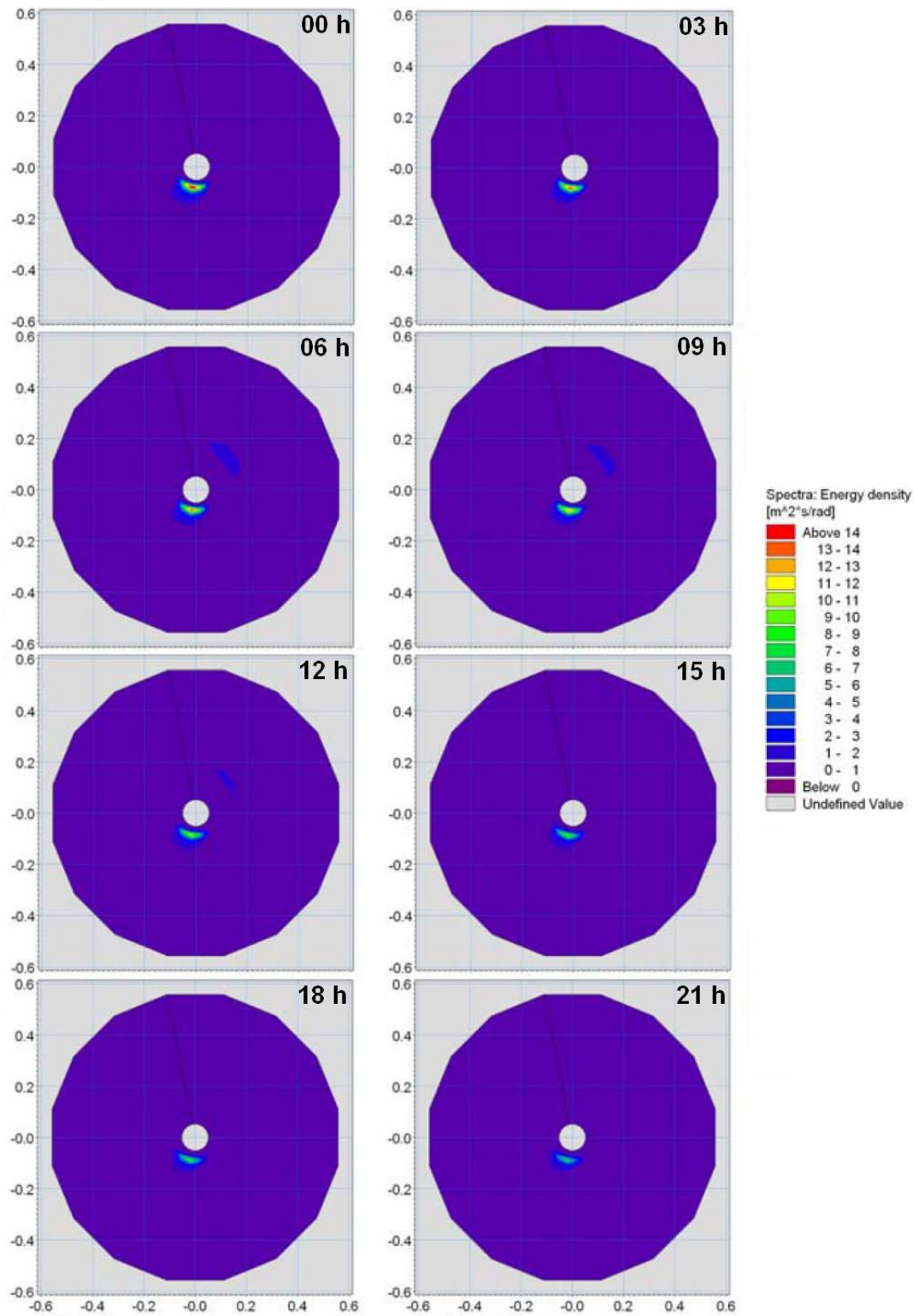


Figure 4-6. Modelled directional energy spectra on 26 July for every 3 h simulations (from 00 h to 21 h).

4.2.2. *Along the west coast of India*

The analysis shows that the wave energy spectra, in general, consist of two/multiple energy peaks - one in the low frequency region (associated with swell) and the other(s) in the high frequency region (associated with seas) indicating the presence of two or more distinct wave systems prevailing in the region. The frequency range of primary and secondary peaks in the spectra varies according to the dominance of different wave systems. During extreme events, the spectra are primarily single-peaked.

The distribution of significant wave height (H_s), mean wave period (T_m) and mean wave direction (θ) of wave, swell and sea for the period February 1996 to May 1997 is shown in Figure 4-7. The maximum H_s observed is 5.85 m and the corresponding T_m is 9.1 s. The maximum swell H_s is 5.53 m and $T_m = 11.3$ s. The maximum wind sea H_s and corresponding T_m are 2.3 m and 4.8 s, respectively. The waves are predominantly from SW, WSW and NW directions. Major part of the swells are from SW, NW and WSW directions with 27%, 23% and 20%, respectively, which constitute 70% of the total swells, whereas, wind seas are distributed over NW, W and WNW directions with 41%, 20% and 16%, respectively, which constitute 77% of the total seas. We find that waves during June – September (SW monsoon season), primarily follow the swell pattern as waves generated in the Arabian Sea/southern Indian Ocean by the strong SW monsoon winds propagate towards the Goa coastal region as swells. During pre-monsoon and NE monsoon seasons, waves follow either swell or wind sea pattern depending on their dominance.

Monthly variations in significant wave height (H_s) and mean wave period (T_m) for the swell and wind sea are presented in Table 4-1. The maximum swell and sea H_s are observed in June, and minimum in December. Larger waves associated with wind seas during January to April, November and December, indicate the influence of local winds on wind sea generation. Long-period swells ($T_m > 12$ s) are observed during March to May, September, November and December, and these are the swells propagated from higher latitudes (south Indian Ocean). Mean periods of wind seas are generally above 2 s, whereas, those of swells are above 5 s. The observed maximum mean periods are 6.2 s (September) and 13.8 s (December) for wind sea and swell, respectively.

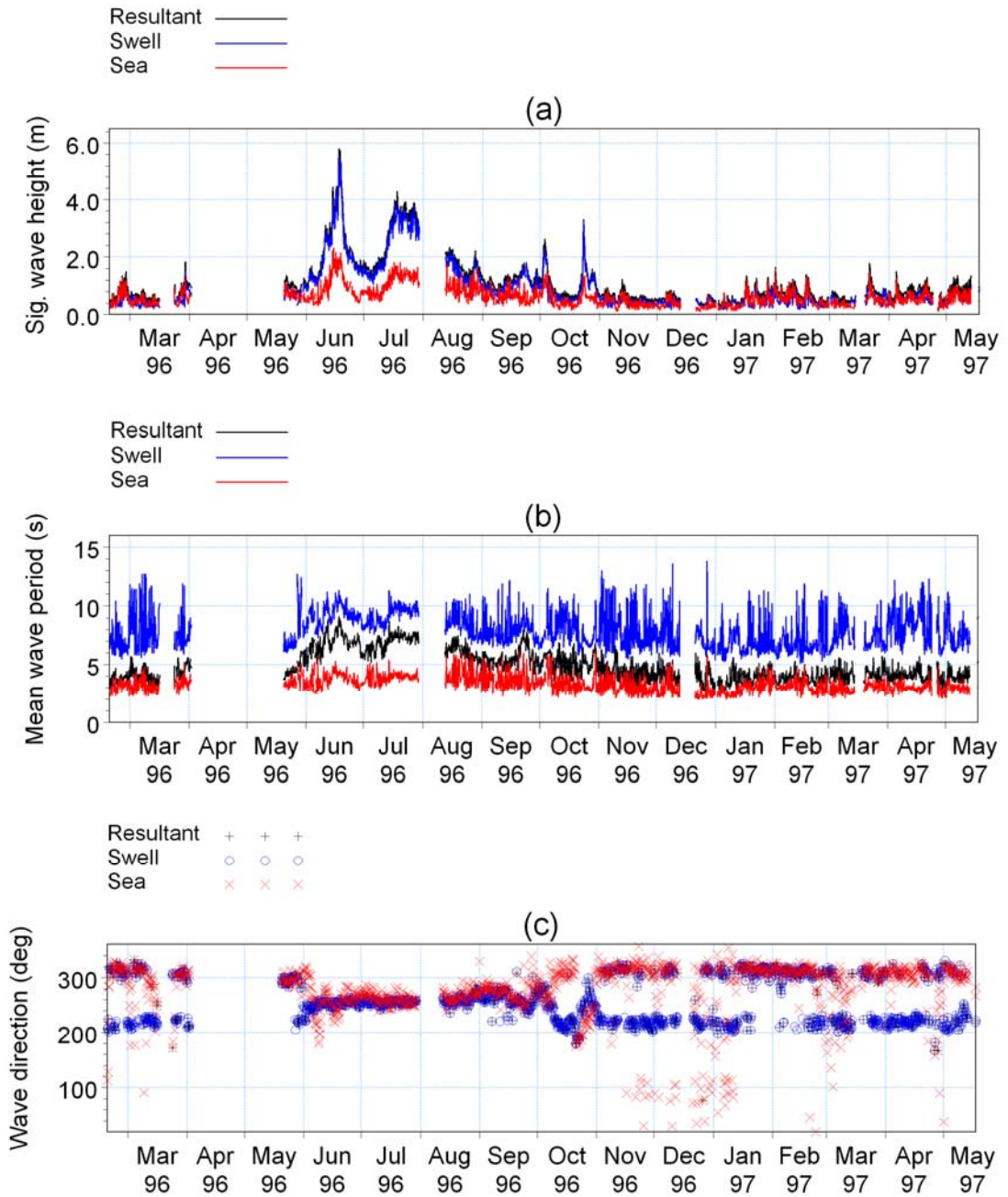


Figure 4-7. Distribution of (a) significant wave height, (b) mean wave period and (c) mean wave direction for the resultant wave, swell and wind sea during February 1996 to May 1997.

Table 4-1. Monthly variations of H_s and T_m for the swell and sea.

Parameters	Significant wave height (m)		Mean wave period (s)	
	Swell	Sea	Swell	Sea
January	0.16 - 1.10	0.13 - 1.56	5.3 - 11.3	2.0 - 4.9
February	0.16 - 0.94	0.16 - 1.27	5.1 - 11.9	2.1 - 4.9
March	0.20 - 1.50	0.19 - 1.50	5.6 - 12.7	2.1 - 5.1
April	0.13 - 0.97	0.10 - 1.27	5.7 - 12.3	2.1 - 4.9
May	0.28 - 1.13	0.20 - 1.10	6.0 - 12.7	2.1 - 5.1
June	0.75 - 5.53	0.31 - 2.30	7.3 - 11.3	2.5 - 5.6
July	1.04 - 3.87	0.44 - 1.81	7.5 - 11.3	2.9 - 5.4
August	0.53 - 2.18	0.37 - 1.74	6.7 - 11.0	2.6 - 6.1
September	0.18 - 1.77	0.28 - 1.28	6.3 - 12.2	2.3 - 6.2
October	0.33 - 3.22	0.15 - 1.50	5.8 - 11.5	2.2 - 6.1
November	0.21 - 0.87	0.11 - 0.88	5.5 - 13.0	2.1 - 5.0
December	0.16 - 0.76	0.11 - 0.80	5.4 - 13.8	2.0 - 5.7

In addition to the observations by Kumar and Anand (2004), inferences are made on the seasonal scenario of the nearshore wave characteristics. The mean period of the waves during SW monsoon is generally above 5 s, and it is below 5 s during pre-monsoon and NE monsoon seasons (Figure 4-7). Lower wave periods during pre-monsoon and NE monsoon seasons indicate superimposition of local wind seas with the pre-existing swells. Such effects are relatively less during SW monsoon, and hence waves follow the swell pattern. Figure 4-8 shows typical directional wave energy spectra and wind roses off Goa during pre-monsoon, SW monsoon and NE monsoon seasons. The predominant winds are from

NW, NNW and N directions during pre-monsoon season, from WSW, W and WNW directions during SW monsoon season (swells are mainly from W/WSW) and from NNW and E directions during NE monsoon season. However, swells are mainly from SW /SSW direction (and also from NW), and the predominant wind seas are from NW direction (this is attributed to the local sea breeze, which is absent in the coarse resolution NCEP winds) during pre-monsoon and NE monsoon seasons. Occasionally, low period (and low energy) wind seas from NE and ENE are also present during NE monsoon season.

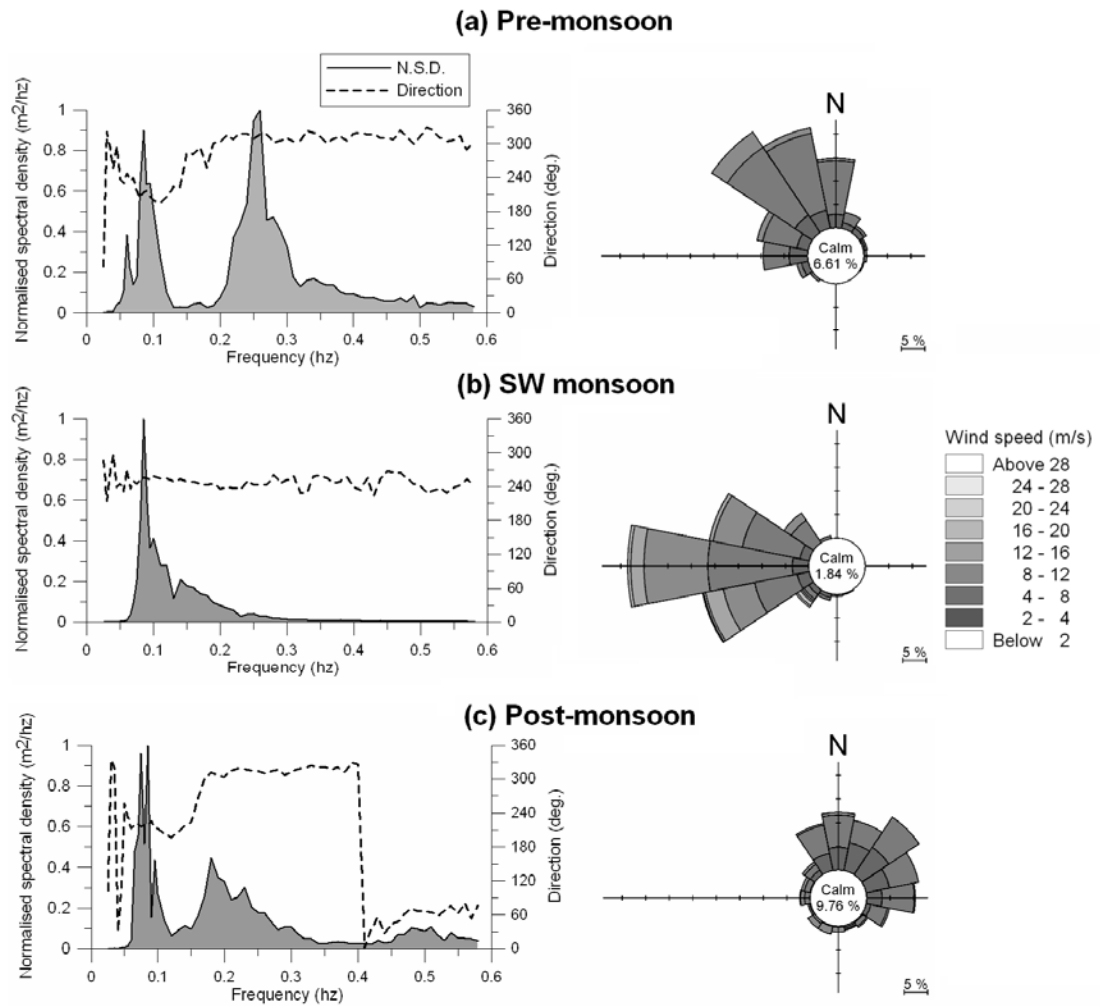


Figure 4-8. Typical directional wave energy spectra and wind rose during (a) pre-monsoon, (b) SW monsoon and (c) NE monsoon seasons.

Joint Typhoon Warning Center (JTWC) reported two extreme events (15 -25 June 1996 and 14 October – 2 November 1996) in the Arabian Sea in 1996. These are subtropical storms of Category 1 with maximum wind speed of 34 m/s. The first storm developed at an

offshore location off Goa; it moved towards north, and changed its direction towards west, and finally hit the Gujarat coast after 3 days. The maximum intensity of the storm was on 19 June 1996, and weakened while travelling further towards the subcontinent. The second storm developed in the Bay of Bengal, moved across the subcontinent towards west and crossed the region between Goa and Mangalore. The maximum speed was observed off Ratnagiri (approx. 200 km north of Goa) on 23 October 1996.

NCEP winds show that wind speeds in the Arabian Sea are of the order of 20 – 34 m/s during the tropical storms (i) 15 -25 June 1996 and (ii) 14 October – 2 November 1996). During evolution of the storms, a gradual increase in wave height is observed along with an increase in wave period (Figure 4-7). Following the peak intensity of the event, maximum H_s of 5.85 m and 3.32 m and maximum T_m of 9.1 s and 6.8 s were observed for the storms (i) and (ii), respectively. The swell H_s are nearly the same as that of waves and the waves follow the pattern of swells. The correlation coefficient between swell H_s and resultant H_s is 0.99, whereas, correlation coefficient between wind sea and resultant swell H_s during both the storm events is 0.87. Since storm-1 is associated with SW monsoon, the propagation direction of the waves remained the same (SW). Prior to storm-2, the predominant wave direction was W. However, with the evolution of the storm, the wave direction had changed to SSW, and further to SW, following a sudden shift in the cyclone track.

Measured and modelled significant wave heights show very good match during the tropical storm events. For storm-1, the correlation coefficients between measurements and modelling for resultant H_s , swell H_s , and wind sea H_s are 0.93, 0.79 and 0.74, respectively, whereas they are 0.80, 0.74 and 0.7, respectively for storm-2. The swells of storm-1 resemble the same pattern (in terms of propagation direction) of the SW monsoon swells; swells of storm-2 are in different directions (mainly SSW and SW). Off Goa (in deep waters), the significant swell height reached above 6.5 m (Figure 4-9) and mean swell period were 11 -13 s during storm-1. The wave reaches a maximum H_s of 7.9 m at an offshore location off Ratnagiri during storm-1 and 3.6 m off Mumbai during storm-2.

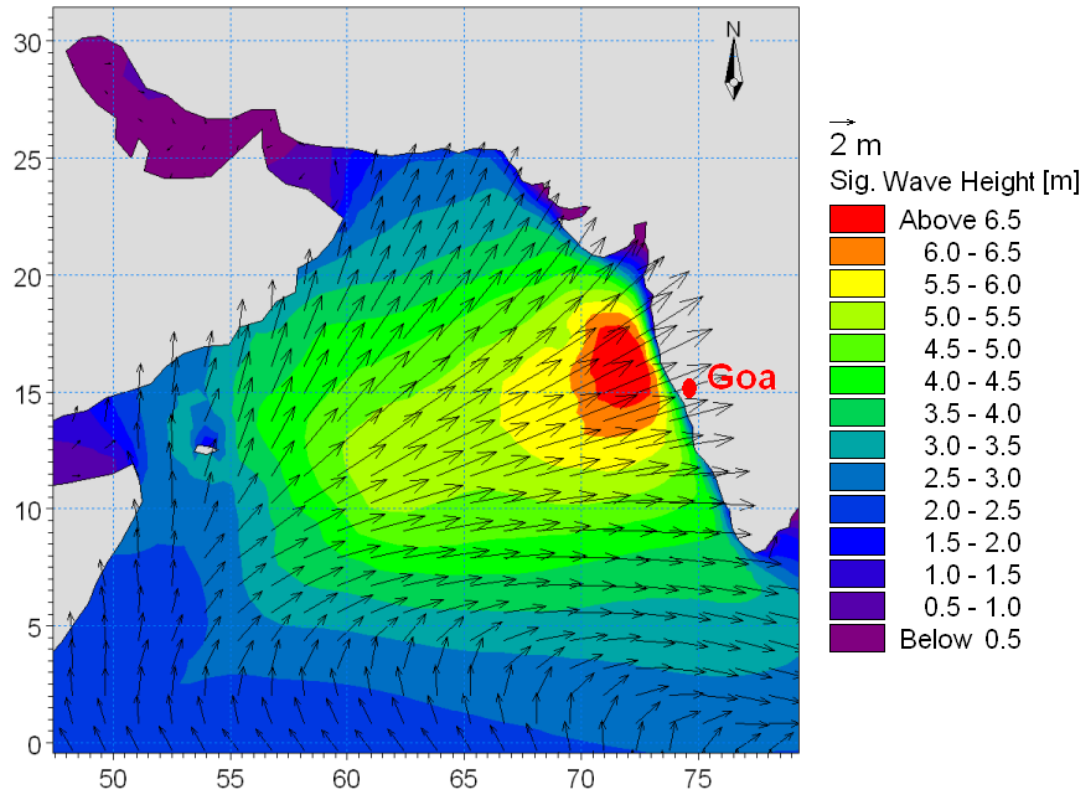


Figure 4-9. Swell patterns during a tropical storm in the Arabian Sea.

4.3. Dominance of swells along the west coast of India

Dominance of wind seas and swells were analysed based on the measured wave data off Goa during Feb 1996 – May 1997. For this purpose, wind sea and swell parameters were calculated from the measured wave energy spectra and analysed.

Monthly dominance of swell and wind sea is presented in Table 4-2. Swells are predominant (above 50 %) during March to December, and wind seas are predominant during January and February. Even though, swells are predominant during March to May, November and December, the role of wind seas is significant (the percentage dominance of wind seas is above 30 % during the above months). Hence, the influence of wind seas along the west coast of India during pre-monsoon and NE monsoon seasons is highly remarkable. During June to July, the waves are fully dominated by swells due to the effect of strong SW monsoon winds. Dominance of wind sea is maximum during February (63 %). Annually, around 70% of the waves are swell dominated. Swells are predominant during SW monsoon and NE monsoon seasons (93 % and 67 %, respectively), whereas, wind seas are predominant during pre-monsoon season (51 %). The dominance of wind

seas during pre-monsoon season is primarily due to prevailing sea breeze along the west coast of India. Numerical experiments could be done for understanding the interaction of wind seas with pre-existing swells, but it requires fine resolution coastal winds.

Figure 4-10 shows the scatter of resultant H_s against swell H_s and wind sea H_s during pre-monsoon, SW monsoon and NE monsoon seasons. The correlation coefficient between wind sea H_s and resultant H_s during pre-monsoon season is 0.85; whereas, it is 0.79 between swell H_s and resultant H_s . The correlation coefficient between swell H_s and resultant H_s during SW monsoon is 0.99, whereas it is 0.83 between wind sea H_s and resultant H_s . Even though the wind seas contributed sufficiently to the wave, swell contribution exceeds that of seas due to the arrival of SW monsoon swells. The correlation coefficients for swell H_s and wind sea H_s with resultant H_s during NE monsoon season are 0.93 and 0.82, respectively. The swell contribution is higher than that of wind sea, and hence it follows mostly the same pattern of swell during the NE monsoon season. It has been noted that irrespective of seasons, the correlation coefficient between the wind seas and wave is 0.82 to 0.85, and this indicates that wind seas are consistent in all seasons. However, the swell contribution varies from season to season.

Figure 4-11a shows the locations of NCEP winds extracted in the Arabian Sea and Figure 4-11b shows wind speed and direction off Goa (at W1) during February 1996 – May 1997. The selected locations are at 72.5° E, 15° N (W1); 65° E, 12.5° N (W2) and 55° E and 5° N (W3). The NCEP winds at W1 during February 1996 – May 1997 have been used to analyse the correlation with wave parameters. At W1, Wind direction varies according to seasons - between west-southwest (WSW) and north (N) during pre-monsoon, between northwest (NW) and east (E) during NE monsoon and between SW and NW during SW monsoon. We find that wind sea direction matches very well with the wind direction in all seasons, except when winds from NE and E are present. Since the measurement location is close to the coast, these winds can contribute only to the wave generation towards offshore (away from measurement location). Hence, wind seas from NE and E are not present at the measurement location. However, these winds (NE/E) could have influenced on the generation and propagation of swells towards the southwestern Arabian Sea.

Table 4-2. Monthly percentage dominance of swell and sea.

Month	Swell dominance (%)	Sea dominance (%)
January	48.5	51.5
February	36.8	63.2
March	55.7	44.3
April	50.5	49.5
May	52.9	47.1
June	99.6	0.4
July	100.0	0.0
August	87.0	13.0
September	85.7	14.3
October	87.9	12.1
November	60.0	40.0
December	69.6	30.4

Figure 4-12 produces scatter diagrams of (i) wind speed against wind sea H_s and (ii) wind direction against wind sea direction. Wind speed gives good linear fit with wind sea H_s and a correlation coefficient of 0.72 is obtained between wind speed and wind sea H_s (Figure 4-12a), which indicates that major part of the local wind contribution to the wind sea generation off the Goa coast has been captured in the NCEP winds. A very good match is obtained between wind and wind sea directions, except when land breeze from N and NE dominates - indicating the influence of local winds on wind sea generation. There exist two distinct wind directions: (i) between SW and N and (ii) between N and E. Major part of wind seas is between SW and N. Though there exists wind between N and E, wind seas from these directions are not present (winds are from land to sea and wave rider buoy was

deployed very close to the coast). It may be noted that NE monsoon winds are not very active over this part of the coast. Hence, low energy waves generated due to NE winds are only present during NE monsoon season. Detailed investigation on the local wind sea contribution to the wind sea generation in the coastal regions demands the use of fine resolution (both temporal and spatial) wind fields, which are not available during the measurement period.

Figure 4-12b shows that there exist wind seas in the NW direction, when there was no NW winds (as seen in NCEP winds), and this may be due to sea breeze, which is hardly captured in NCEP because of its coarse spatial resolution. The offshore extension of the local winds controls the wind sea generation mechanism along the west coast of India. The winds during pre-monsoon season along the west coast of India are dominated by sea breeze. According to Aparna et al. (2005), the seaward extension of the sea breeze is 180 km off Goa during February – April. The selected NCEP grid (close to the coast) covers the entire limit of the sea breeze extension. Neetu et al., (2006) observed that the peak sea breeze speed at Goa coast during pre-monsoon season is 5 m/s and sea breeze generated wind seas have considerable amount of energy in the wave spectra. Masselink and Pattiaratchi (1998) observed that sea breeze typically produces a 1 – 1.5 m high wave with periods ranging between 6 and 9 s.

Figure 4-13 shows the scatter between swell H_s and wind sea H_s during pre-monsoon, SW monsoon and NE monsoon seasons. The correlation coefficients between swell H_s and wind sea H_s are 0.36, 0.74 and 0.56 during pre-monsoon, SW monsoon and NE monsoon seasons, respectively. It is evident that during SW monsoon season, the wind sea also follows the same pattern of the swell (Figure 4-7); however, the energy associated with swells is much higher than that of wind seas. Major part of the swells during pre-monsoon season is propagating far from the southern Indian Ocean in the SW direction, and occasionally from northern Arabian Sea in NW direction. However, the local wind seas are mainly from NW direction. The swells are generally weak during pre-monsoon and NE monsoon seasons. It may be noted that sea breeze is very active during pre-monsoon season. Hence, the weakening of distant swells together with effect of sea breeze on wind sea generation results in the dominance of wind seas along the west coast of India during pre-monsoon season. The moderate correlation during NE monsoon season indicates that even though there exist long period swells propagating from the southern Indian Ocean, there are swells from other areas (swells propagating from NW) in which the directions of swells and wind seas coincide. Hence, there exist multi-directional swells and local wind

seas concurrently. The dynamics associated with the interaction between the multi-directional swells and the superimposition of these swells with the local wind seas is to be investigated in detail.

Waves along the entire west coast of India follow the same distribution in all seasons to a large extent (Figure 4-14). Since Goa is in the central west coast, measurements from this region are taken as representative data for the entire west coast for validation: modelled wave parameters match very closely with measurements. Hence, modelled wave parameters at various other locations along the west coast of India have been extracted and analysed for their distributions. Figure 4-14 shows the modelled significant wave heights at 25m depths off Kochi, Mangalore, Goa, Ratnagiri and Mumbai during pre-monsoon, SW monsoon and NE monsoon seasons. It has been found that the significant wave heights follow nearly the same pattern at all locations in any season though there are time lags due to arrival times of the swells. Hence, it is concluded that swell dominates during SW monsoon and NE monsoon seasons and wind sea dominates during pre-monsoon season at all locations along the west coast of India and their distribution (swell and wind sea) is relatively the same at all locations as observed in the Goa region.

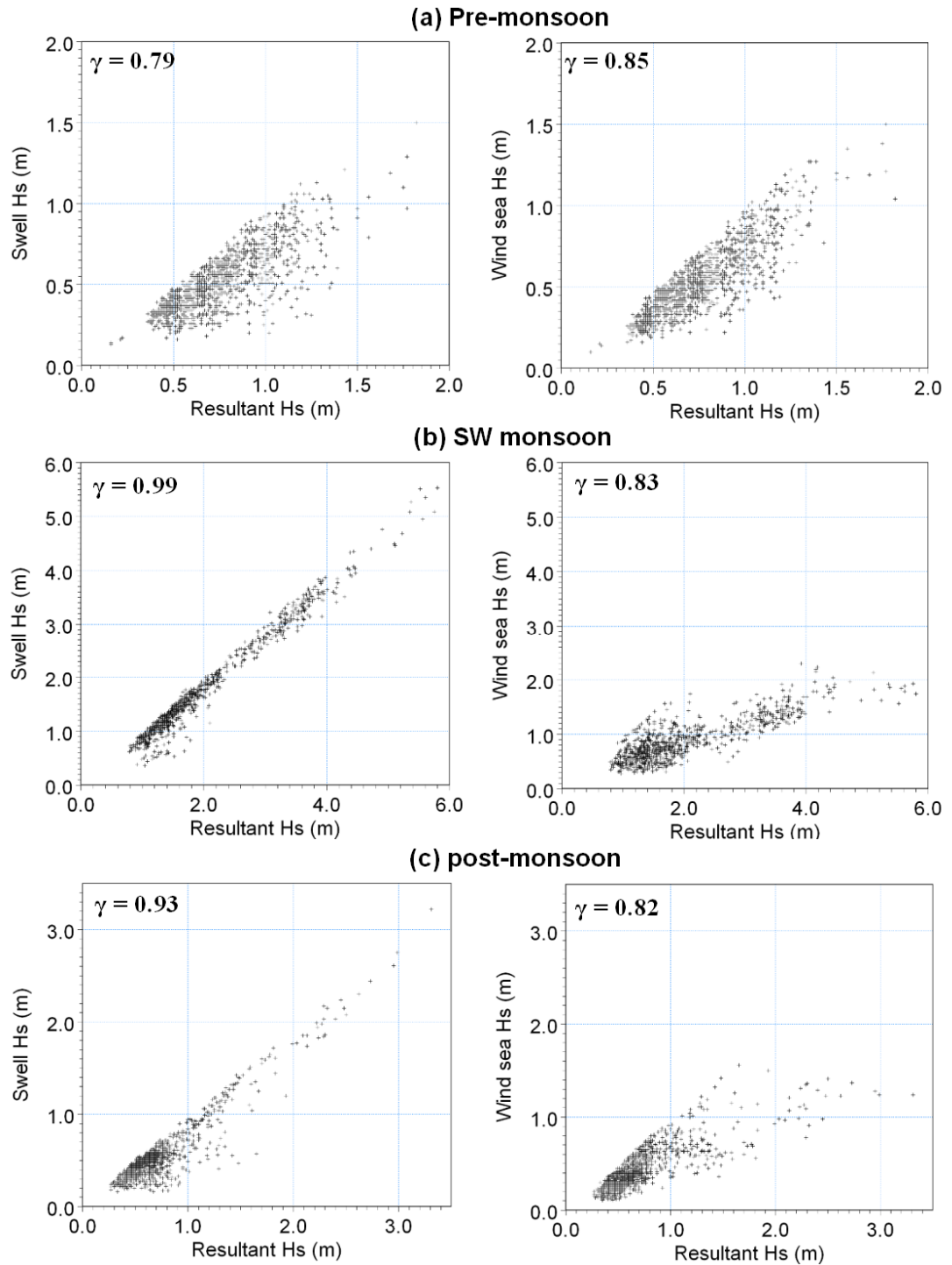


Figure 4-10. Scatter diagrams of resultant H_s vs. swell H_s and resultant H_s vs. wind sea H_s during (a) pre-monsoon, (b) SW monsoon and (c) NE monsoon seasons.

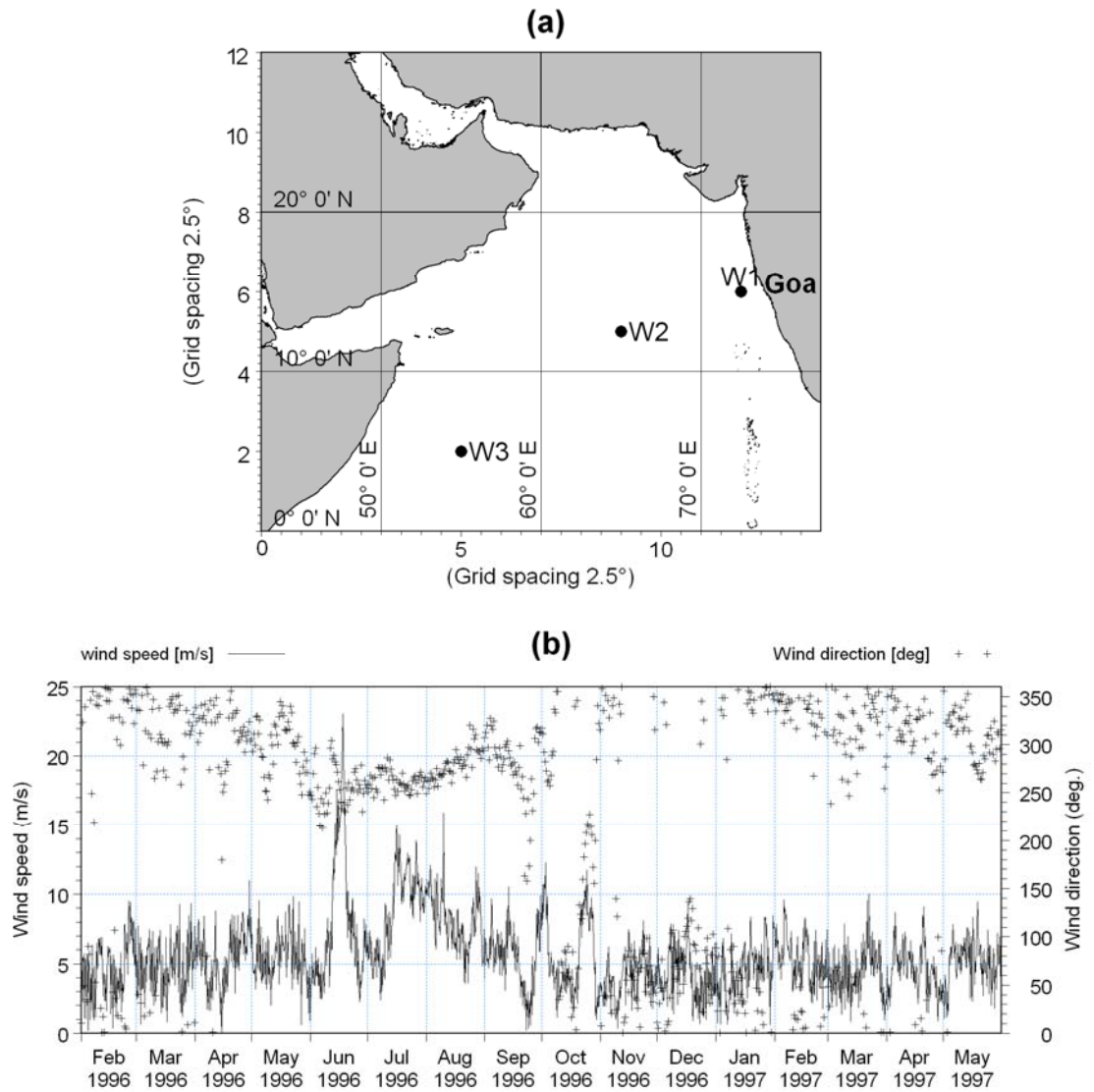


Figure 4-11. (a) Locations of NCEP wind extracted and (b) wind speed and direction at W1 (off Goa) during Feb 1996 to May 1997.

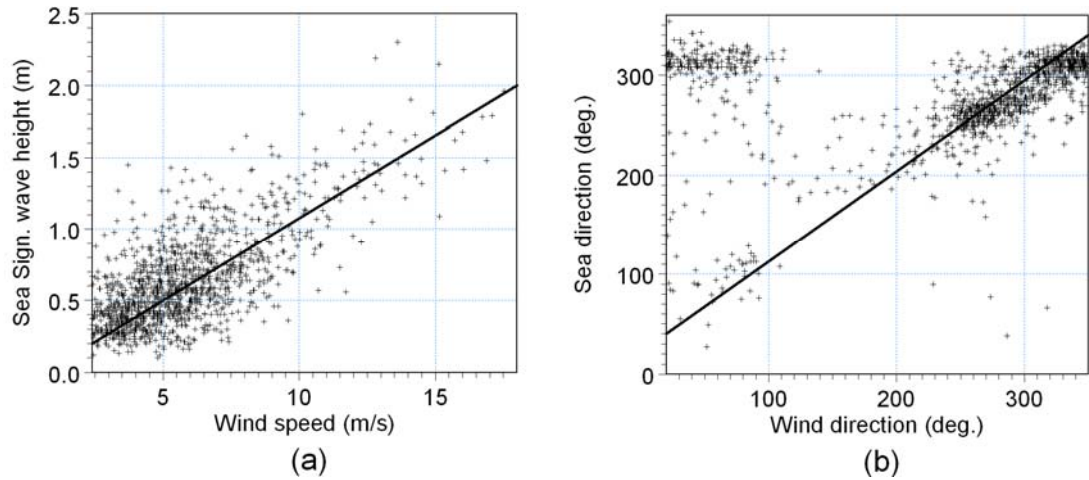


Figure 4-12. Scatter diagrams (a) wind speed vs. wind sea H_s and (b) wind direction vs. wind sea direction.

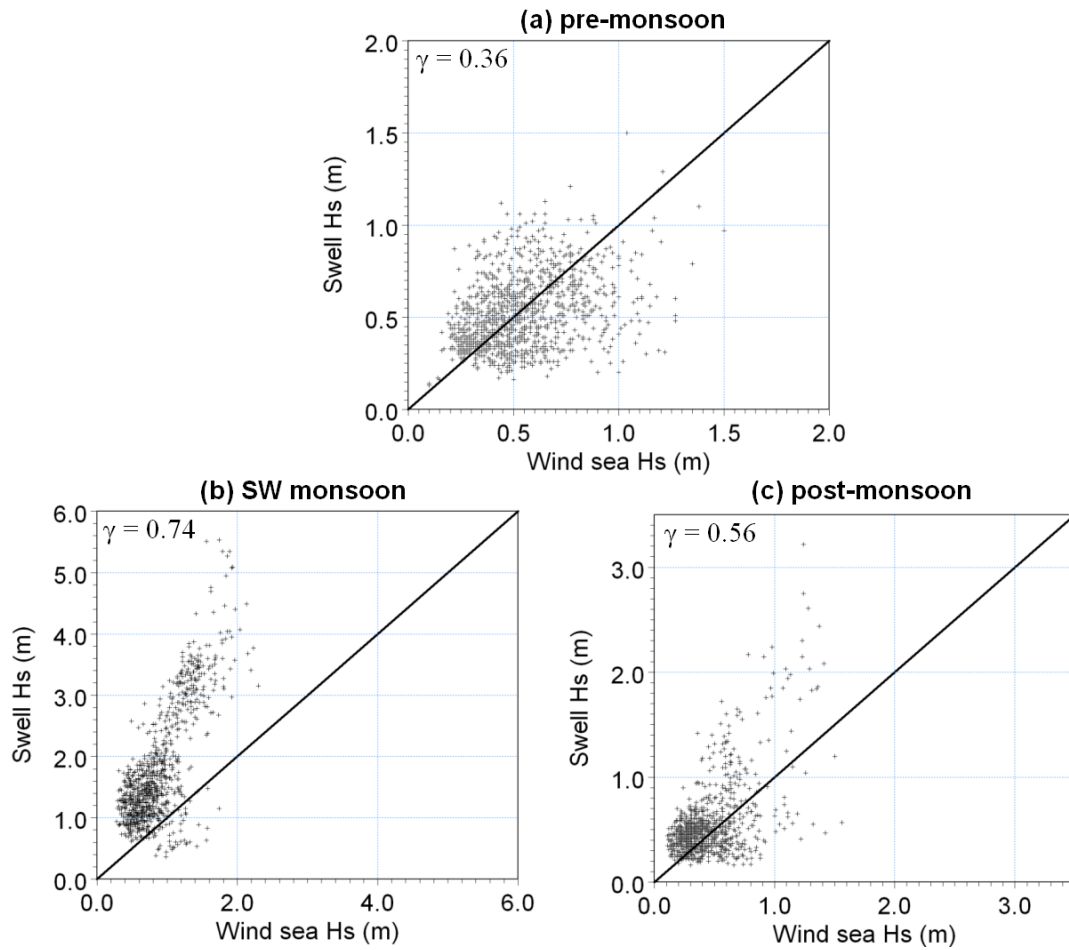


Figure 4-13. Scatter diagram of significant wave heights showing the dominance of wind sea and swell during (a) pre-monsoon, (b) SW monsoon and (c) NE monsoon seasons.

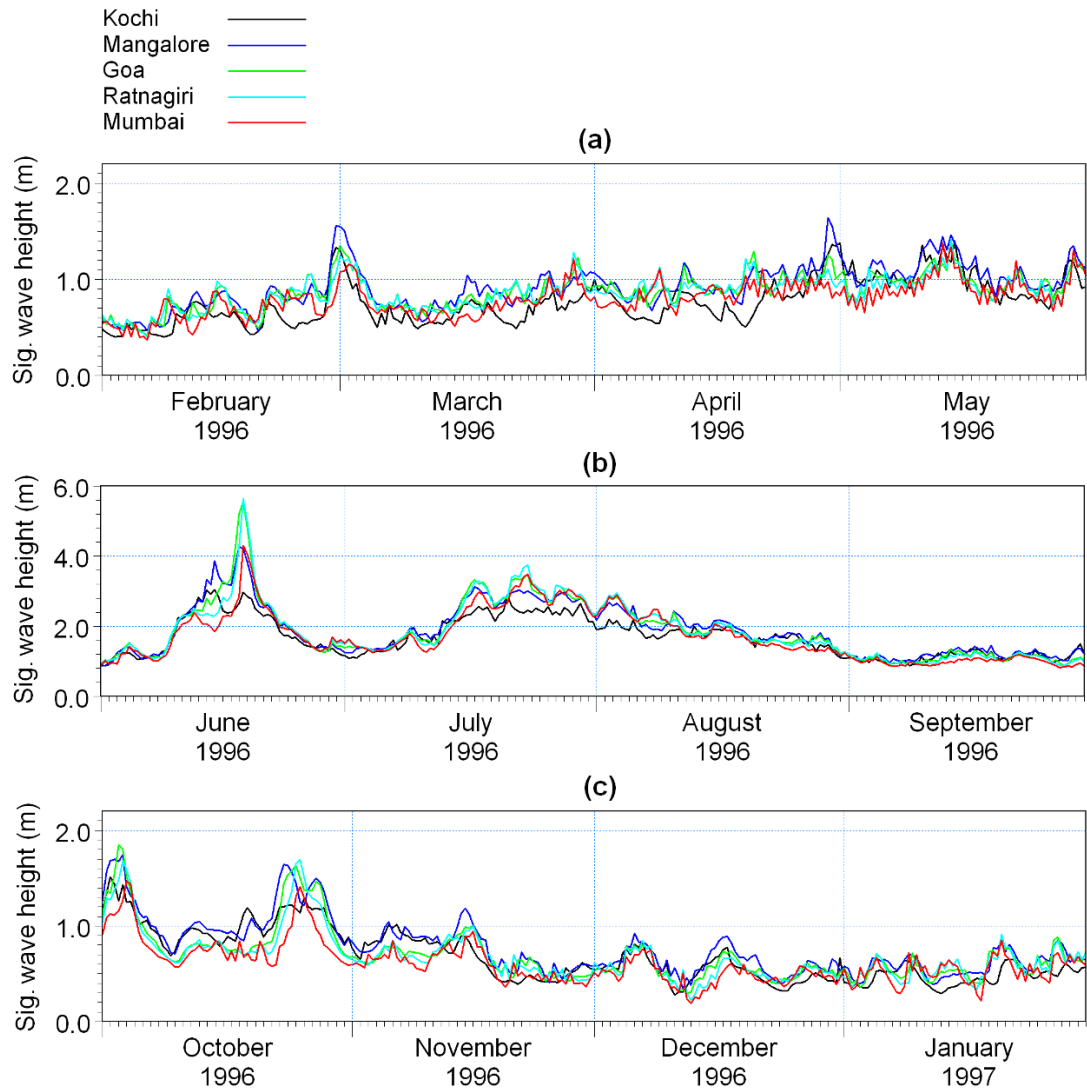


Figure 4-14. Significant wave heights off Kochi, Mangalore, Goa, Ratnagiri and Mumbai during (a) pre-monsoon, (b) SW monsoon and (c) NE monsoon seasons.

4.4. Potential swell generation regions

In this section, winds over the Indian Ocean have been analysed to identify potential areas which generate the swells that influence the west coast of India. These potential swell generation areas have been identified and confirmed through numerical modelling. Propagation of these swells to the west coast of India has been discussed below.

4.4.1. *Wave observations*

In order to identify potential swell originating areas, NCEP winds at 3 cells, namely, W1, W2 and W3 (Figure 4-11a) have been analysed. During SW monsoon season, wind direction at W3 is predominantly between SW and WSW, at W2, between SW and W with dominating WSW direction and at W1, between SW and NW with dominating W direction. Winds in the south Indian Ocean, say around 20° S, are predominantly in SE direction during SW monsoon season, which generate swells in SE direction. Below 40° S, winds from W are predominant and SW/SSW winds are rarely occur during SW monsoon season, hence SW/SSW swells from these areas are relatively weak as compared to those generated in the north Indian Ocean. Wave measurements show that swells off Goa are predominantly between WSW and W with dominating WSW direction during June – Sept. This indicates that the potential swell generating area during SW monsoon season is between W3 and W2, probably around 60° E, 10° N. The mean swell periods are predominantly 8 to 10 s during June – July, and 7 to 9 s during August – September, which also shows that the swell generating area during the second half of the season are relatively closer to the Goa coast, since these swells are generated over a relatively small fetch.

During pre-monsoon season, winds at W3 (Figure 4-11a) are predominantly between NNE and E in February – April and between SW and WNW in May; at W2, between N and NE in February – March and between W and NE in April – May, and at W1, between W and N with dominant NW direction. Two distinct swells from SW or SSW and NW were observed off Goa during pre-monsoon season. The mean swell periods associated with SW or SSW swells are predominantly 8 to 11 s, whereas, those associated with NW swells are 6 to 8 s. The swells generated by the winds from N, NE and E could not reach the west coast. Hence, swells generated by winds from SW or SSW and NW could impact well. The observed longer period waves also indicate that these swells are generated at an area, probably around 40° S, where large fetch is available for stronger SW or SSW winds with relatively longer duration. It has been found that NW winds are present throughout the season at location W1. Whenever NW winds dominate over the northern Arabian Sea, the generated swells propagate to the Goa coast with relatively low periods (6 to 8 s), since the generation area is relatively close to the measurement location. The potential generation area for NW swells is probably around 65° E, 20° N.

During NE monsoon season, winds at W3 and W2 are predominantly between N and E and at W1, between NW and E. Similar to the observations during pre-monsoon season, there are two distinct swells; SW or SSW and NW swells. The mean periods associated with SW

swells are 8 to 12 s, whereas those associated with NW swells are 6 to 8 s. The long-period SW or SSW swells are generated in the south Indian Ocean, whereas NW swells are generated in the northern Arabian Sea, as observed during pre-monsoon season.

4.4.2. Numerical model results

Wave simulation has been carried out during Feb 1996 – May 1997 (for the same measurement period) using NCEP winds. Swell patterns in the Indian Ocean obtained from the simulations have been analysed. Figure 4-15 shows the typical swell patterns in the Arabian Sea during pre-monsoon and NE monsoon seasons. The simulations indicate that the predominant swells off the west coast of India are from SW or SSW and NW directions during pre-monsoon and NE monsoon seasons. There are various swell systems (other than SW or SSW and NW) in the Arabian Sea during pre-monsoon and NE monsoon seasons which may not propagate towards the west coast as the propagation direction is away from the west coast. NW swells are stronger during pre-monsoon season, as compared to those during NE monsoon season. During SW monsoon season, the predominant swell in the Arabian Sea is from SW and WSW due to the prevailing winds in the same directions. It does have high impact on the nearshore regions off the west coast of India (significant swell heights reach above 4.0 m in the Arabian Sea). The significant swell heights are generally below 2.0m in the Arabian Sea during pre-monsoon and NE monsoon seasons.

The potential swell areas are identified from the simulated swells in the Indian Ocean. It has been found that the SW and SSW swells generated in the area covered by 40° E to 70° E and 30° S to 50° S propagate towards the west coast as long-period swells during pre-monsoon and NE monsoon seasons. However, these swells are relatively weak as compared to those generated in the Arabian Sea during SW monsoon season. Hence, the predominant swells during SW monsoon season are generated in the area covered by 52.5° E to 62.5° E and 5° N to 15° N. During pre-monsoon season, apart from SW swells from southern Indian Ocean, NW swells from northern Arabian Sea have been also found, which are propagating towards the Goa coast. It has been found that these swells are generated in the area bounded by 60° E to 67.5° E and 17.5° N to 25° N. It is evident from wave measurements that wind sea energy dominates over swell energy during pre-monsoon season.

During NE monsoon season, the distant swells play major role in the dominance of swells along the west coast of India. It is clear from Figure 4-15 that the swell patterns in the south Indian Ocean during pre- and NE monsoon seasons are basically the same. However, they

could be distinguished by the influence of NE winds over the north Indian Ocean during NE monsoon season. As explained elsewhere, NE winds cannot generate swells along the west coast of India due to fetch limitation. Majority of the swells during NE monsoon season are generated in the south Indian Ocean, especially in the area bounded by 40° E to 70° E and 30° S to 50° S. Wind sea energies during NE monsoon season are relatively weaker compared to pre-monsoon season. Hence, a well-defined swell dominance has been obtained along the west coast of India during NE monsoon season.

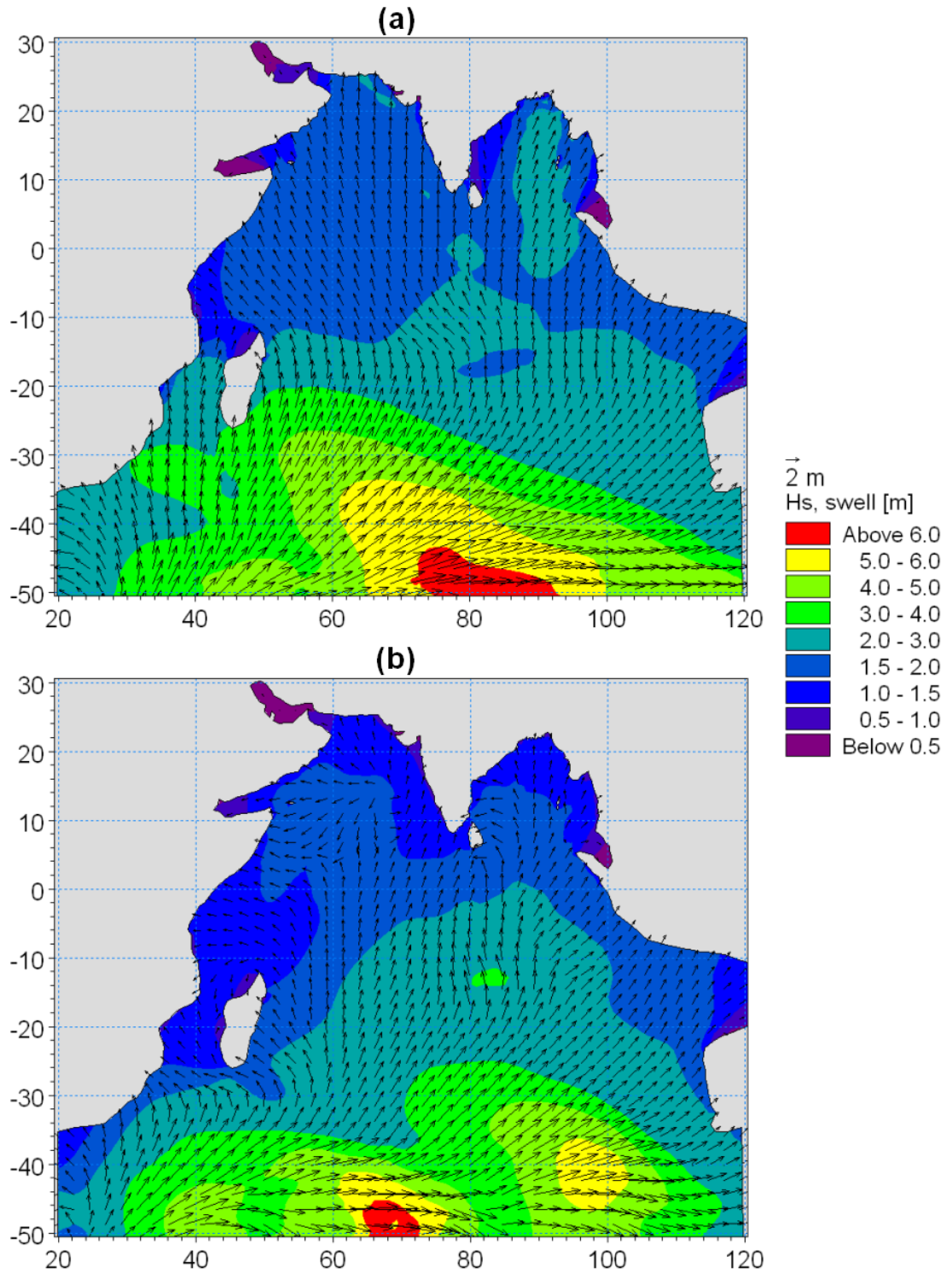


Figure 4-15. Typical swell patterns in the Arabian Sea during (a) pre-monsoon season (12 April 1997) and (b) NE monsoon season (10 December 1996).

4.5. “Shamal” swells in the Arabian Sea

4.5.1. *Introduction*

Shamal winds are meteorological events associated with winds, which normally occurs in the Arabian Peninsula, especially during the winter season. The word “Shamal” literally means “north” (in Arabic literature) and the winds during Shamal events are named as Shamal winds. Onset, duration and strength of the Shamal winds in winter or summer vary according to the dynamic interaction of the upper air jet streams and the distribution of lower tropospheric pressure zones (Ali, 1994). The summer Shamal events are not very common and the intensity is relatively low. However, the winter Shamal events have high impact on the meteorological conditions over the Arabian Peninsula. The winter Shamal occurs during November to March and is associated with mid-latitude disturbances travelling from west to east (Hubert et al., 1983). It usually occurs following the passage of cold fronts and is characterized by strong northwesterly winds. Based on the intensity, the periodicities are classified as follows: (i) 24 to 36 hours and (ii) 3 to 5 days. The associated wind speeds during the events are higher, of the order of 20 m/s. It can generate surface waves as high as 3.0 – 4.0 m in the Persian Gulf (Arabian Gulf).

Studies on the wave characteristics and storm surges due to Shamal winds are very limited and restricted to the Arabian/Persian Gulf region only (e.g., El-Sabh, 1989 and Parvaresh et al., 2005). Impacts of Shamal events on the Arabian Sea or along the west coast of India are not studied so far. It could have significant role on the meteorological and oceanographic conditions of the Arabian Sea. Rapid changes in wind patterns during the Shamal events can alter the associated wave characteristics in the Arabian Sea. This motivated us to take up the present study with the following objectives: (i) generation and propagation of “Shamal” swells in the Arabian Sea, and (ii) influence of “Shamal” swells on the wave characteristics along the west coast of India. Figure 4-16 shows the study area and wave measurement locations (B1, B4 and B6).

The general swell patterns in the Arabian Sea are known from the literatures (e.g., Sanil Kumar et al. 2000; Rajkumar et al., 2009 and Kurian et al., 2009). The predominant swells are from the SW or S directions, propagating from the south Indian Ocean. On several occasions we have observed weaker swells propagating from the northwest.

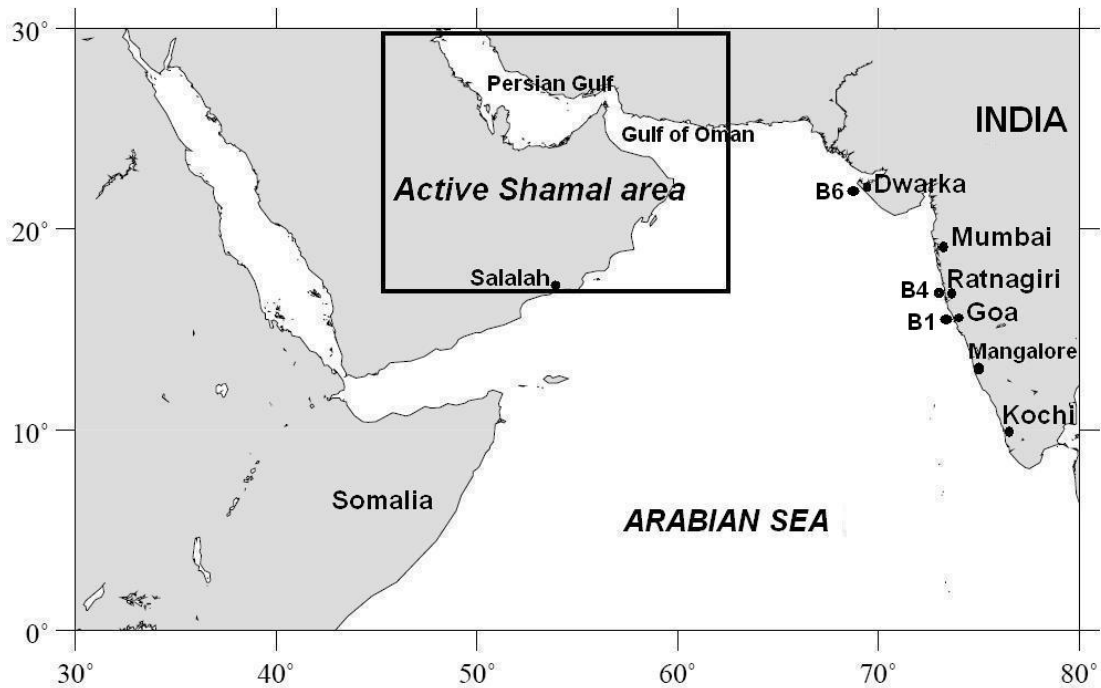


Figure 4-16. Study area and measurement locations.

4.5.2. Characteristics of “Shamal” swells

Measured waves off Ratnagiri show systematic variations in the wave parameters during several occasions (Figure 4-17). During NE monsoon and early pre-monsoon seasons, nearshore waves along the west coast of India are generally low (say, < 1.0 m). However, in 2008 waves with significant wave heights of the order of 1.0 - 2.0 m were observed at several occasions. Further analysis shows that wave parameters exhibit distinct characteristics: increase in wave heights associated with decrease in swell period and a common propagation direction (NW) for wind sea, swell and waves (Figure 4-17a, 4-17b and 4-17c). Measured winds at Ratnagiri coast also show systematic variations during the above periods (Figure 4-17d). The systematic features observed in the wind and wave parameters are indicated as (1) to (6), during which the significant wave heights are in the range 1.0 to 2.0 m, mean swell periods between 6.0 and 8.0 s and predominant wind and wave directions in NW.

The directional energy spectra show peak energies in the swell region, and most of the energies are concentrated between the frequencies 0.1 and 0.2 Hz in the NW direction, contrary to the normal swell conditions along the west coast of India, wherein energy is distributed between 0.05 and 0.15 Hz in the direction SW or S (e.g., Vethamony et al.,

2009). Typical directional energy spectra measured off Ratnagiri during Shamal period and non-Shamal period are shown in Figure 4-18a and 4-18b. Swells from the south Indian Ocean (S or SW direction) are generally observed along the west coast of India, which are mostly “old swells”. However, NW swells generated at the northern Arabian Sea can propagate to the west coast within relatively shorter duration, and that is the reason for observing mostly “young” or “matured” swells from the NW direction. On an average, “young”, “matured” and “old” swells (NW swells) are 76%, 21% and 3% respectively, during the study period.

The predominant winds in the Arabian Sea during NE monsoon and early pre-monsoon seasons are from NE, and the wind speeds are in the order of 5 to 10 m/s. On several occasions, it was observed that the NE winds become weak, and NW winds become stronger, especially in the north-western Arabian Sea and in the Arabian Peninsula. These NW winds are associated with Shamal events (active Shamal area is marked in Figure 4-16). Typical wind vectors in the Arabian Sea during NE monsoon and associated Shamal events are shown in Figure 4-19a and 4-19b. The wind speeds associated with Shamal events normally range between 10 and 20 m/s. As evident from the AWS winds at Ratnagiri coast (Figure 4-17d), at times, Shamal winds extend upto the west coast of India, though the magnitudes are relatively less along the coastal regions. These winds are stronger at the northern part of the west coast of India extending up to Karachi in Pakistan. The period as well as duration of the Shamal events closely matches with the systematic features observed in the measured wave parameters and AWS winds. Considering the above facts, it has been concluded that the systematic features observed in the wave parameters are primarily due to the impact of Shamal winds, which generate strong waves and propagate to the west coast of India as swells. These swells are hereafter named as “Shamal” swells.

Waves measured at B1 (off Goa) during Feb 1996 – May 1997 also shows similar features. Such well-defined features are observed between November and March, and more frequently in January and February. These features are not evident in other seasons. Winds associated with summer Shamal events are relatively weaker, and their impact on the wave characteristics along the west coast of India is negligible due to the prevailing stronger SW monsoon winds, and the corresponding larger waves during this season.

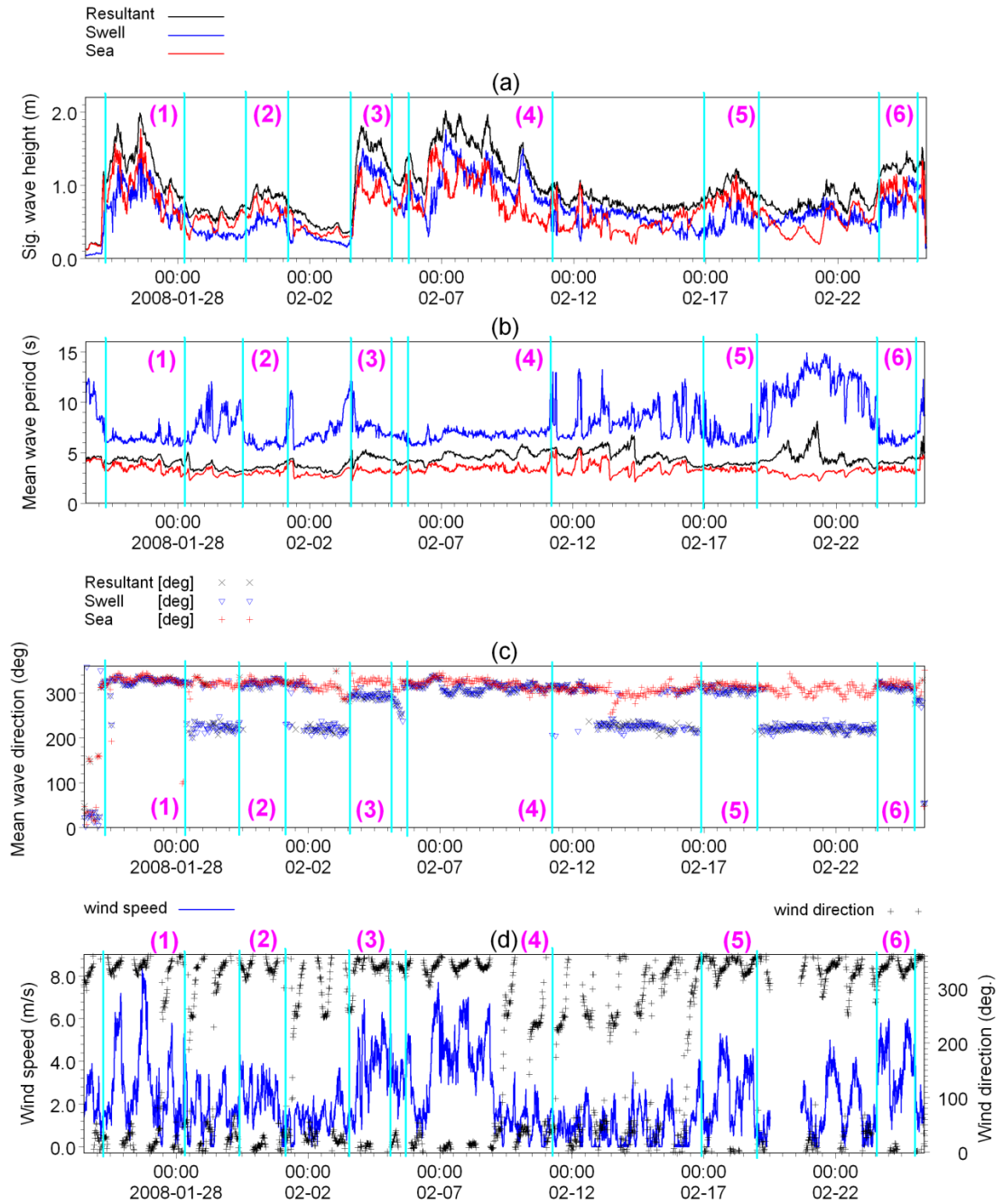


Figure 4-17. Measured wave and wind parameters off Ratnagiri; (a) significant wave height, (b) mean wave period, (c) mean wave direction and (d) AWS wind speed and direction. Well-defined features on wave and wind parameters are marked from (1) to (6).

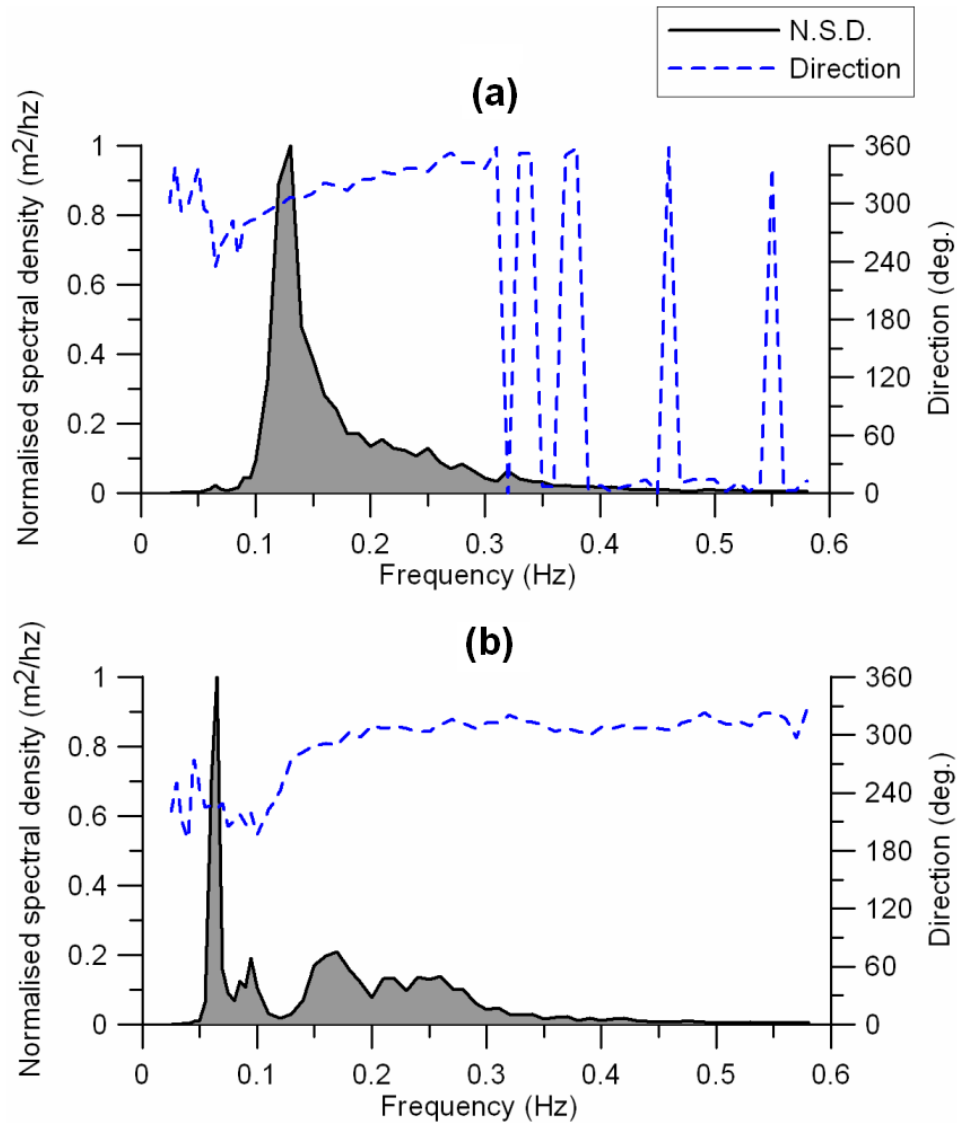


Figure 4-18. Typical directional energy spectra during (a) Shamal period and (b) non-Shamal period.

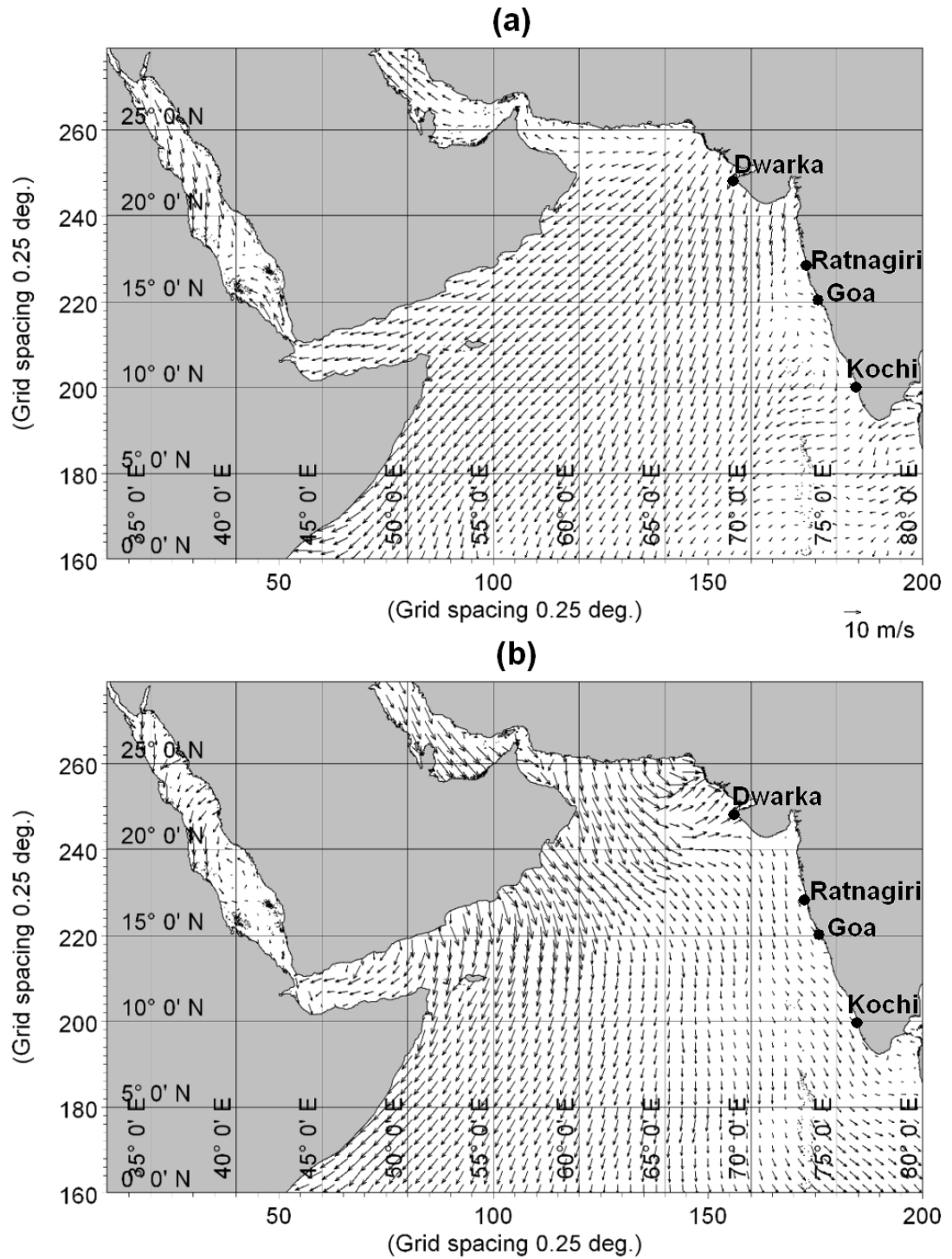


Figure 4-19. Typical wind vectors over the Arabian Sea associated with (a) NE monsoon and (b) Shamal event.

4.5.3. *Generation and propagation*

Numerical simulations carried out using IFREMER/CERSAT blended winds during Jan – Feb 2008 reproduced the generation and propagation characteristics of Shamal swells in the Indian Ocean. The analysis indicates that waves generated due to strong Shamal winds at the northwestern Arabian Sea propagate in the NW direction towards the west coast of India. A gradual wind wave growth has been observed with respect to the increase in wind speed during Shamal events. Significant wave height reaches upto 4.3 m in the Persian Gulf. However, propagation of the waves generated in the Persian Gulf to the rest of the Arabian Sea is obstructed at Hormuz Strait due to narrow opening and low water depths. It has been found that the Shamal winds generate higher waves in NW direction at the northwestern Arabian Sea (excluding Persian Gulf). The associated significant wave height reaches upto 3.7 m within a fetch of around 300 km. Once leave the generating area, they propagate in NW direction as Shamal swells.

Figure 4-20 shows significant wave height vectors in the Arabian Sea, representing the generation and propagation of Shamal swells for every 12 h during 02-04 Feb 2008. It is evident that larger waves are generated in the Persian Gulf, Gulf of Oman and off the east coast of Oman due to strong Shamal winds. The swells generated in the Gulf of Oman and east coast of Oman propagate in the NW direction. Another swell system also formed at an offshore area close to the Salalah coast (Figure 4-20) and propagates in the NNW direction. Since, the present study aims at understanding the influence of Shamal swells along the west coast of India, importance is attached to the NW swells generated in the northwestern Arabian Sea (Gulf of Oman and off the east coast of Oman).

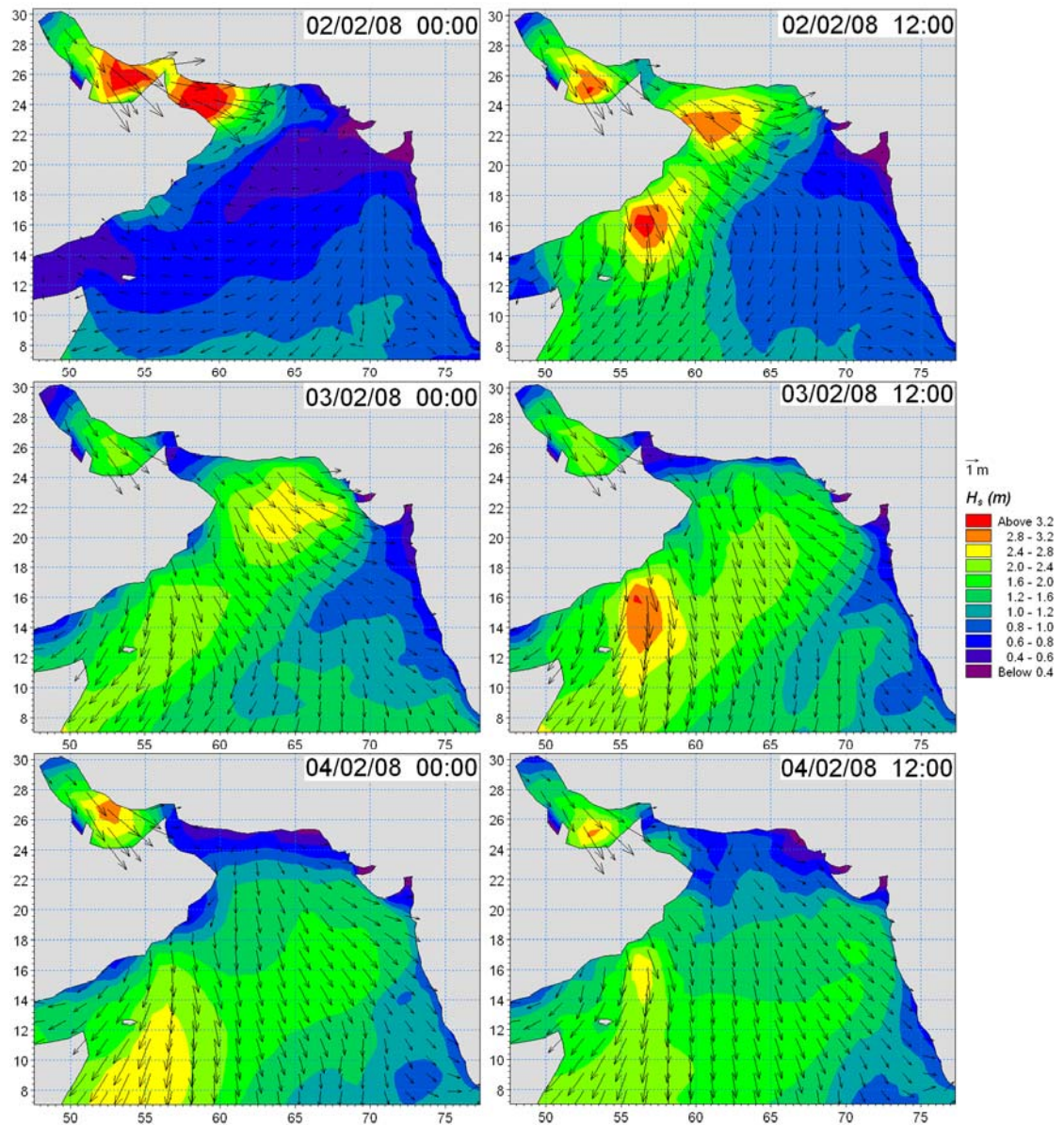


Figure 4-20. Significant wave height vectors in the Arabian Sea during 02-04 Feb 2008 representing the generation and propagation of Shamal swells.

It is evident that the Shamal swells propagate towards the west coast of India in the NW direction. They arrive at different times depending on the distance of propagation to various locations along the west coast of India. The swells reach first (in less than 20 h) along the Gujarat coast and later (around 48 h) along the Kerala coast. The swells observed off Gujarat coast have higher energy than those observed in the Kerala coast, indicating that the coastal region of Gujarat would be having high impact due to Shamal swells. The

Shamal swells measured off Ratnagiri coast has a mean period around 7 s and a wavelength of approximately 76 m. The travel distance of swell to the Ratnagiri coast is around 1200-1500 km. Hence, it takes 30-38 h to reach the Ratnagiri coast.

4.5.4. Influence along the west coast of India

Swell heights extracted from the simulation results at 25 m water depth off Kochi, Mangalore, Goa, Ratnagiri, Mumbai and Dwarka during the study period are presented in Figure 4-21. Variations in swell heights associated with Shamal events indicate that all the above locations along the west coast of India are influenced by the Shamal swells, though there are changes in patterns and heights according to the intensity and duration of the event. The swell heights are higher off Dwarka, indicating that the coast of Gujarat is highly influenced by the Shamal swells. Similar pattern is observed off Mumbai, but swell heights are relatively low compared to those off Dwarka. The swell pattern off Ratnagiri, Goa, Mangalore and Kochi are nearly the same, but with time lags as discussed earlier.

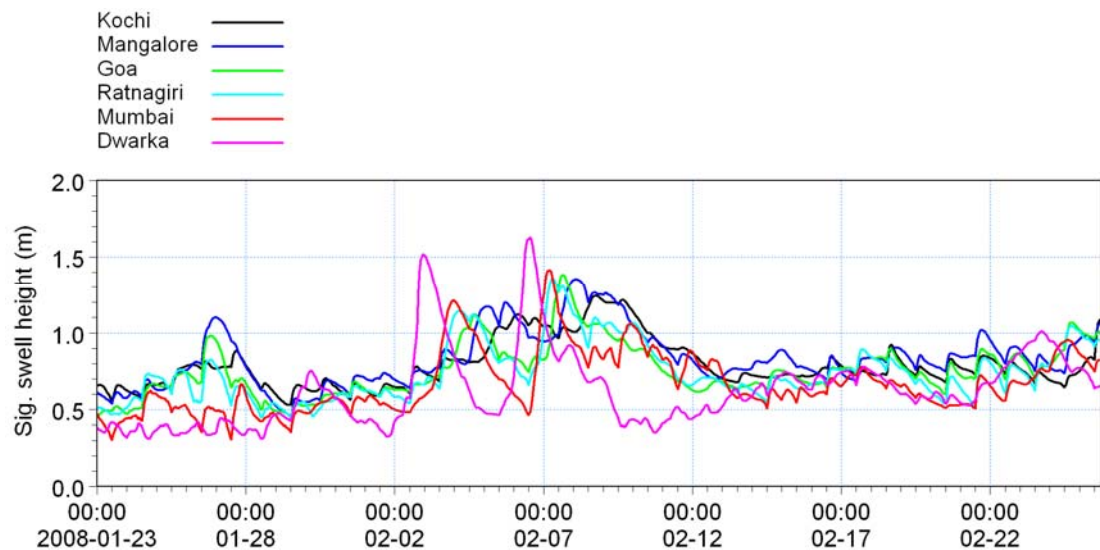


Figure 4-21. Significant swell heights off Kochi, Mangalore, Goa, Ratnagiri and Mumbai at 25 m water depth, extracted from the simulation results.

An analysis of measured waves off Dwarka (at B6) during 05 Dec 2007 – 05 Jan 2008 indicates that the Shamal swells are present, but relatively weaker compared to those during 24 Jan – 25 Feb 2008 (Figure 4-22). The predominant swells during this period are from S or SSW direction. However, short duration (< 24 h) Shamal swells have been observed in the NW direction; the swell heights are significantly higher and the mean swell

periods are between 6 and 8 s. It has been found from measurements that wind seas are dominated off Dwarka during non-Shamal events.

Figure 4-23 shows the wave parameters off Goa (at B1) during January 1997. Increase in wave height associated with decrease in swell period and propagation of wind sea and swell in the NW direction are prominent during the Shamal events. Even though Shamal swells exist, at times, the wind sea energies in NW direction (generated by Shamal winds) dominate over the swell energies, which provide an indication to the extension of Shamal winds up to the west coast of India. However, this has to be confirmed through detailed investigations.

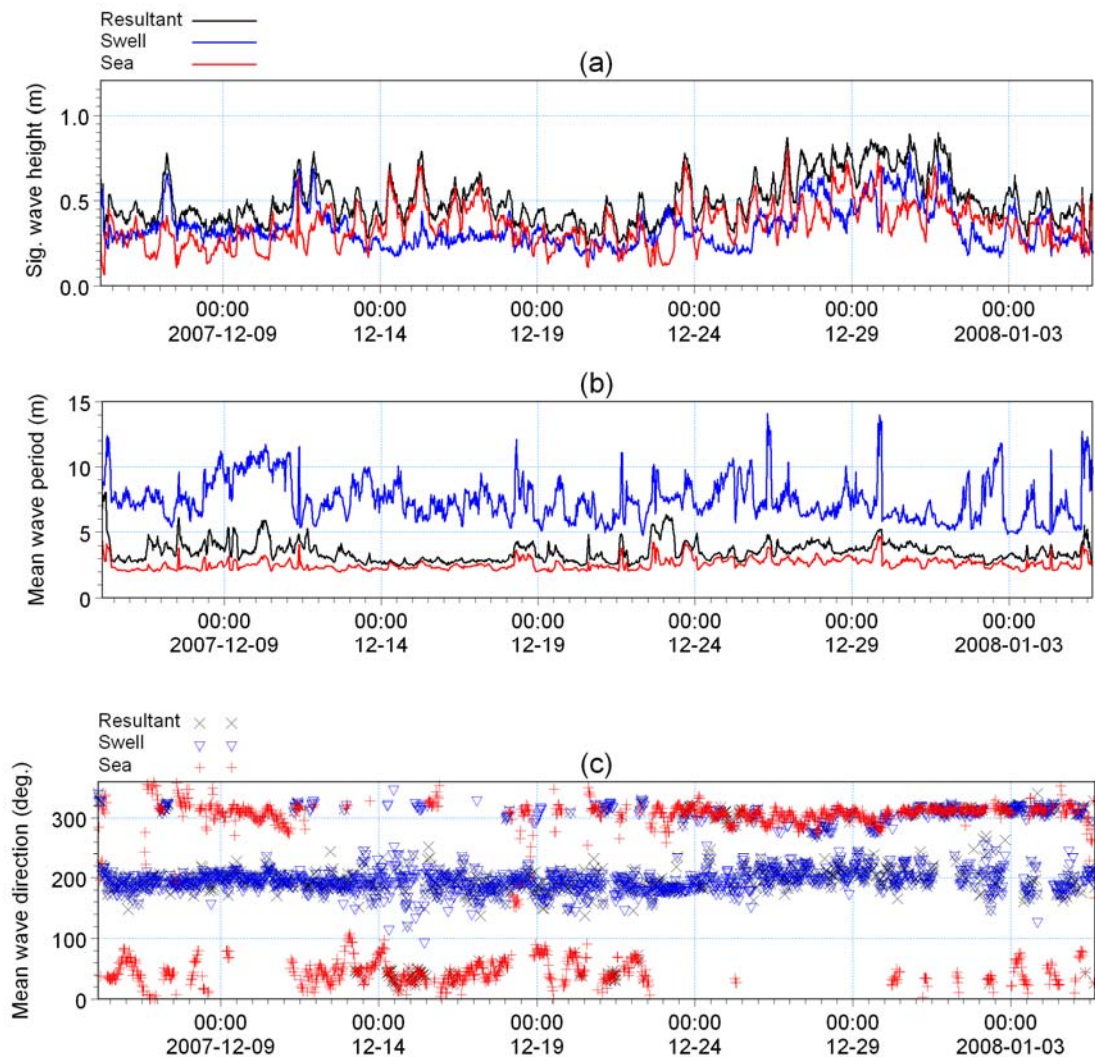


Figure 4-22. Measured wave parameters off Dwarka at B6 during 05 Dec 2007 – 05 Jan 2008: (a) significant wave height, (b) mean wave period and (c) mean wave direction.

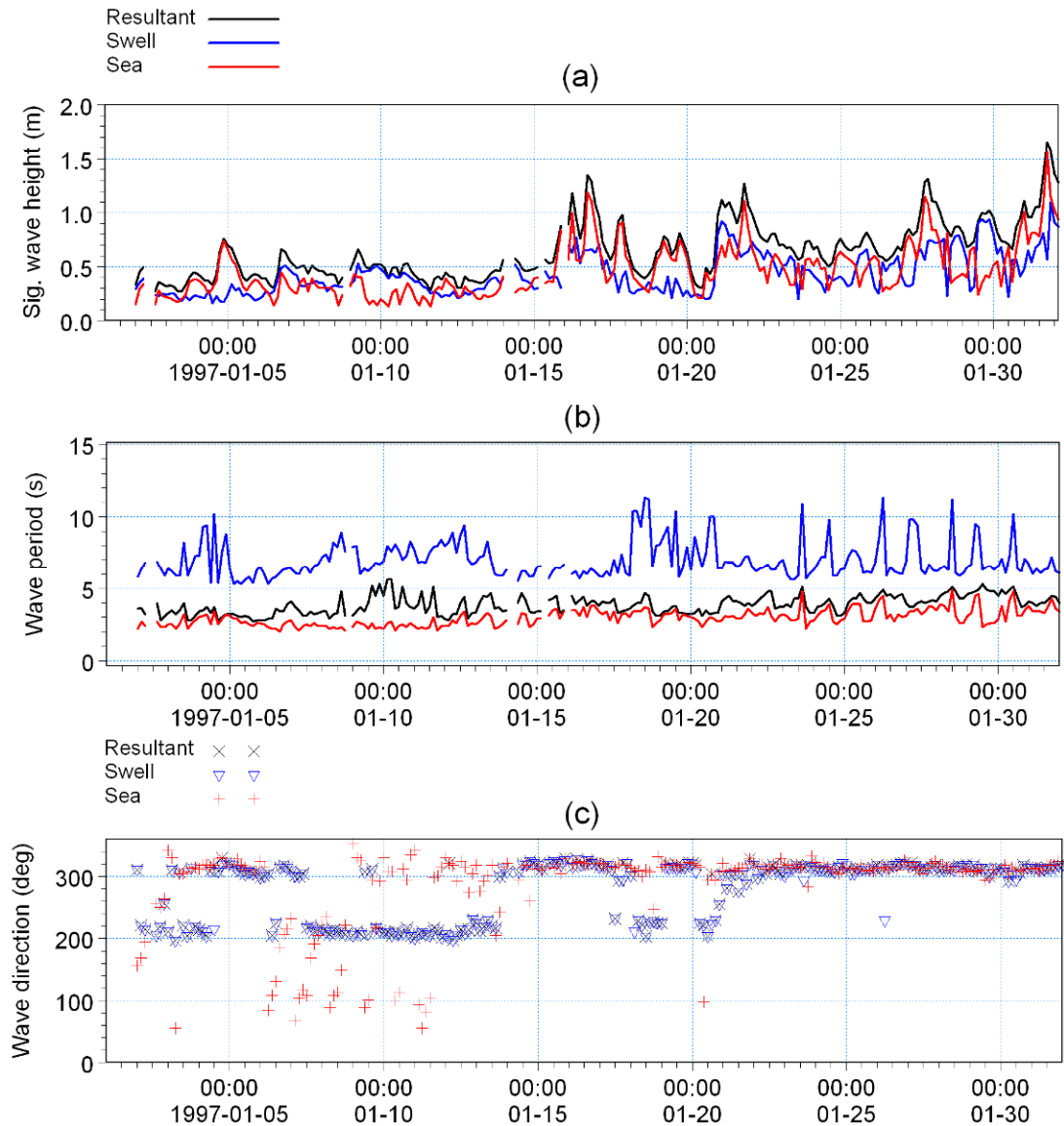


Figure 4-23. Measured wave parameters off Goa at B1 during January 1997: (a) significant wave height, (b) mean wave period and (c) mean wave direction.

4.6. Superimposition of coastal wind seas on pre-existing swells

It has been found that wind seas are dominated along the west coast of India during pre-monsoon season. Sea breeze has prominent role in the generation of relatively stronger wind seas along the west coast. Superimposition of these wind seas with pre-existing swells leads to typical variations in the waves on a diurnal cycle. To understand these variations, wind and wave data measured off Goa, west coast of India, during May 2005 have been analysed.

Masselink and Pattiaratchi [1998] studied the effect of sea breeze on wave characteristics of the coastal regions of Sydney and found that during sea breeze, the addition of locally generated short-period wind waves to the background swell, resulted in an increase in wave height, a decrease in wave period and an intensification of nearshore currents. After the cessation of the sea breeze, the wind-wave energy level gradually decreased and the associated wind-wave period increased. Ten hours after the sea breeze had stopped blowing, significant amount of wind-wave energy was still present. Sonu et al. (1973) noticed that after the onset of sea breeze, the wave height increases, wave period decreases and wave direction changes. Interestingly, similar variations have been found in the wave data measured off Goa at B2 and B3 during May 2005.

4.6.1. *Sea breeze along the west coast*

The west coast of India is characterized by sea breeze and land breeze systems which are prominent in calm seasons especially during pre-monsoon months (Aparna et al., 2005). The seaward extension of the sea breeze is around 180 km off Goa, while it is 160 km and 190 km off Kochi and Mangalore, respectively during February – April, and the speed decreases towards offshore.

Winds from the AWS for the coastal region off Goa show nearly semi-diurnal variations both in their magnitude and direction (Figure 4-24). The prominent wind directions are NW (from sea to land) and NE (from land to sea). The speeds are relatively higher for northwesterlies. The sea breeze and land breeze systems are nearly perpendicular to each other, the former is roughly parallel and the latter is perpendicular to the orientation of the Goa coast. Sea breeze starts around 11h, and continues to blow in the NW direction; wind speed is maximum between 15h and 18h. Very early in the morning, the wind shifts its direction to NE (land to sea) and continues till 11h; wind speeds are relatively lesser compared to sea breeze. These variations are found to be systematic throughout the study period, and consistent with the results of earlier studies (e.g., Masselink and Pattiaratchi, 1998). In general, the maximum wind speeds are observed around 15h and the minimum around 06h. The maximum wind speed observed during the study period (in May 2005) was 4.6 m/s in the NW direction. On several occasions no wind is observed in the early hours of the day.

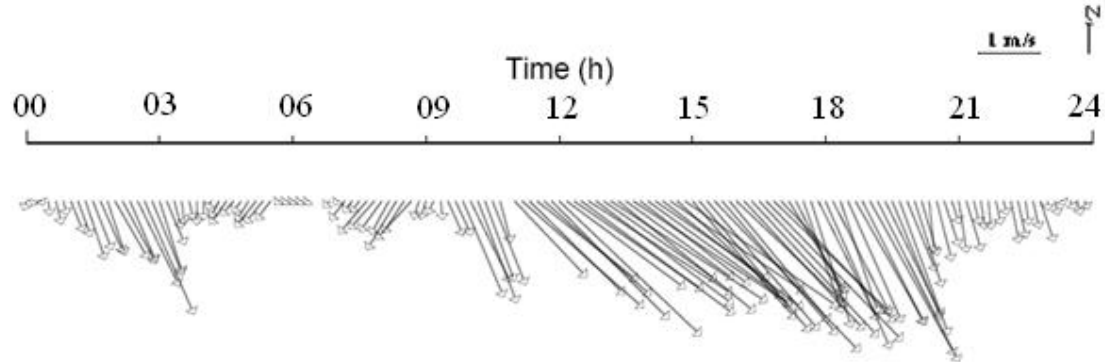


Figure 4-24. AWS wind distribution at Dona Paula during 12 May 2005.

Six-hourly NCEP reanalysis wind data present the existence of two different wind systems in this region: (i) relatively stronger southwesterlies / westerlies in the open ocean throughout the day and (ii) relatively weaker northwesterlies in the coastal region. The analysis of wind speeds obtained from QuikSCAT along a section upto 200 km from the coast (Figure 4-25) indicates that wind speeds increase towards the coast in a constant NW direction. Since QuikSCAT data is available twice daily, i.e., 06h and 18h (local time) and data is not accurate within 25 km from the coast, the land breeze effect could not be noticed. Wind at 06h from the coastal AWS station is NE and relatively weaker, and that at 18h is NW and stronger. A typical vector plot (6-hourly) of the IFREMER/CERSAT blended winds in and around Goa during 05 May 2005 is shown in Figure 4-26. Weaker winds from N and NE (land breeze) are present close to the coast during 00h and 06h, whereas stronger NW winds (sea breeze) are observed during 18h. The speed of northwesterly winds is found to be lower between 00h and 06h as seen in the measurements (Figure 4-24) and direction remains nearly constant throughout the day.

The modelled MM5 winds, clearly show the sea breeze – land breeze distribution at the Goa coast during pre-monsoon season. Figure 4-27 shows the typical wind vectors plotted for every 6 hour. The initial phase of the sea breeze generation is clearly visible around 12h, increases the magnitude with the maximum around 18h and gradually decreases towards 24h (00h). It is evident that NW winds (sea breeze) are stronger at the Goa coast around 18h. Gradual increase in the intensity of the sea breeze towards the coast from offshore area has been observed. While entering the land, sea breeze gets weakened due to the topographic effects. The extension of sea breeze over the land area is clearly visible during this time. Land breeze is observed along the coast around 06h. The magnitude of

land breeze is relatively low and its extension towards offshore is limited to a few kilometer from the coast.

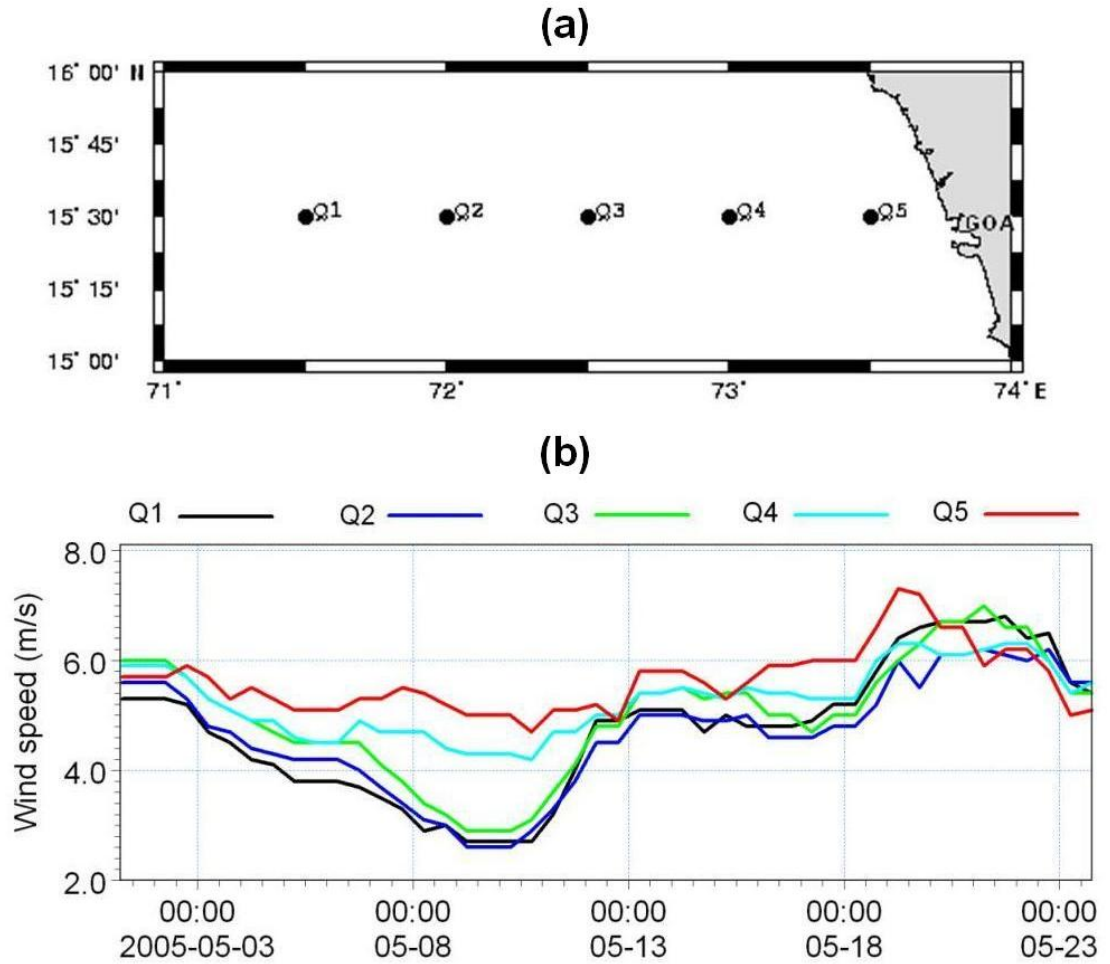


Figure 4-25. QuikSCAT winds off Goa: (a) locations from offshore to coast (Q1 to Q5) and (b) wind speed distribution at the locations Q1 to Q5.

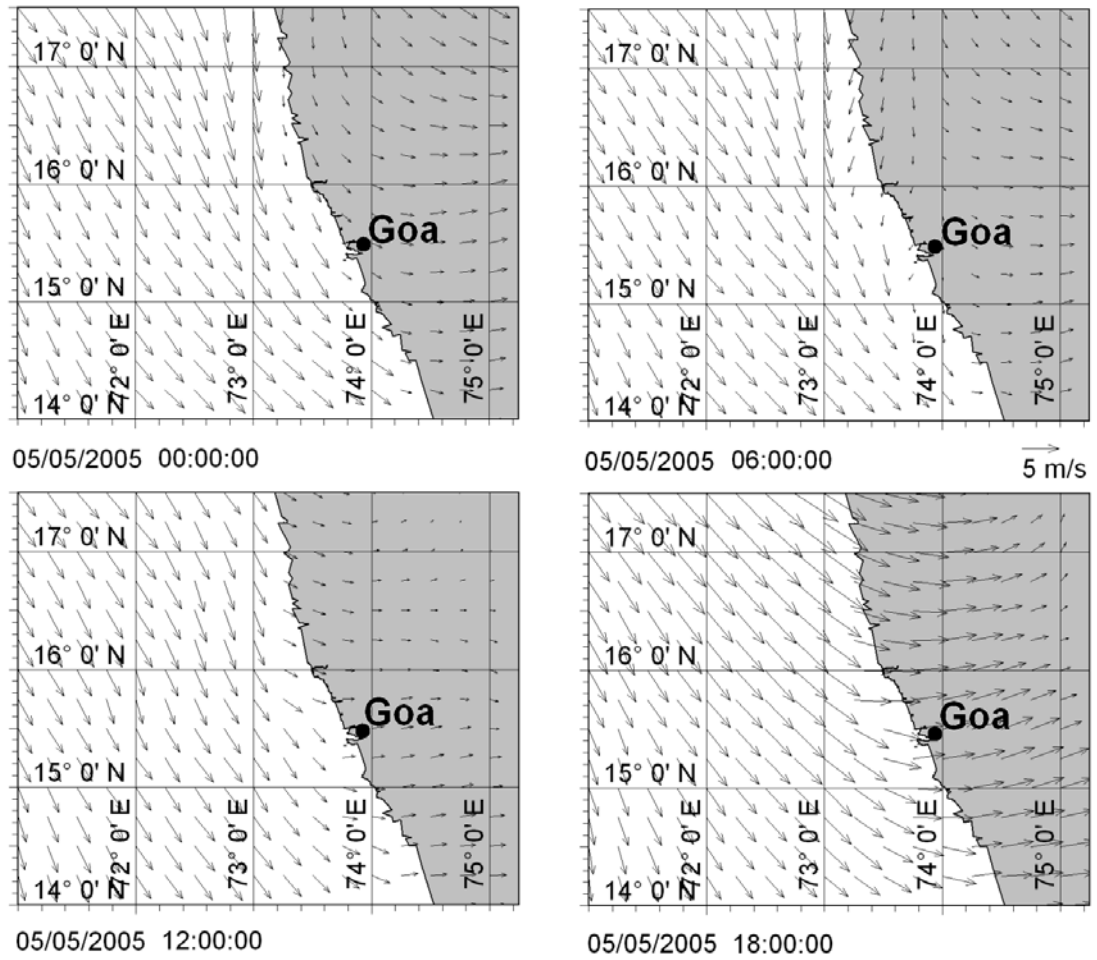


Figure 4-26. Typical wind vectors (CERSAT/IFREMER blended winds) in and around Goa region during 05 May 2005.

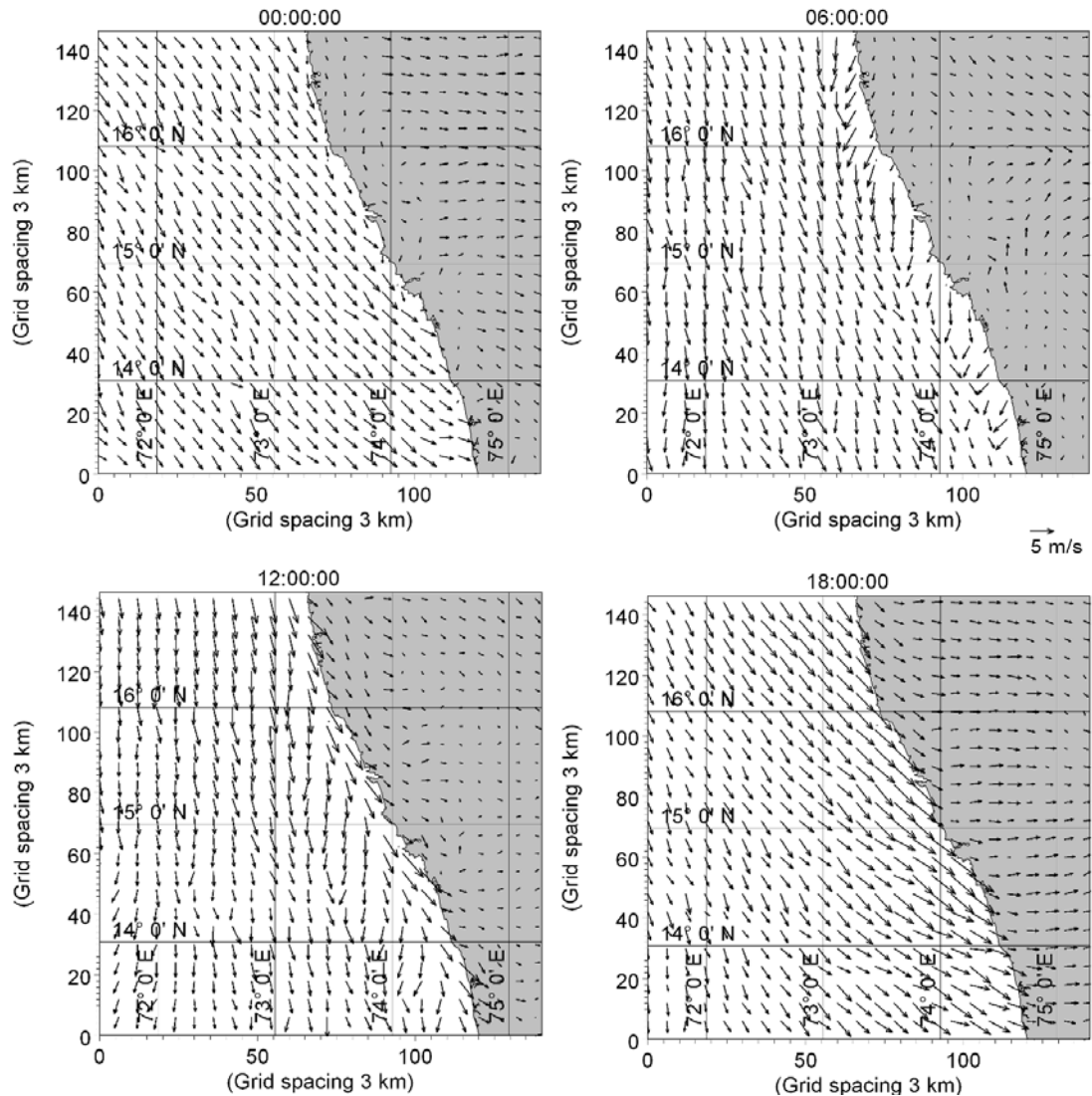


Figure 4-27. Typical wind vectors on a daily cycle during pre-monsoon season, as simulated in MM5.

4.6.2. Diurnal variations in the nearshore waves

The sea-land breeze system leads to a typical cycle of local waves. Following the onset of sea breeze, a wind wave system grows in time, following the progressive extension of the sea breeze area towards offshore. While, once begun, the wind speeds present close to the coast remain relatively constant, the consequent increase of fetch with respect to the coastal area leads to an increase of the derived wave height (Figure 4-28 and Figure 4-29). Although relatively limited, the increase of significant wave height shows that the local wind sea has energy comparable to or larger than the permanent background swell.

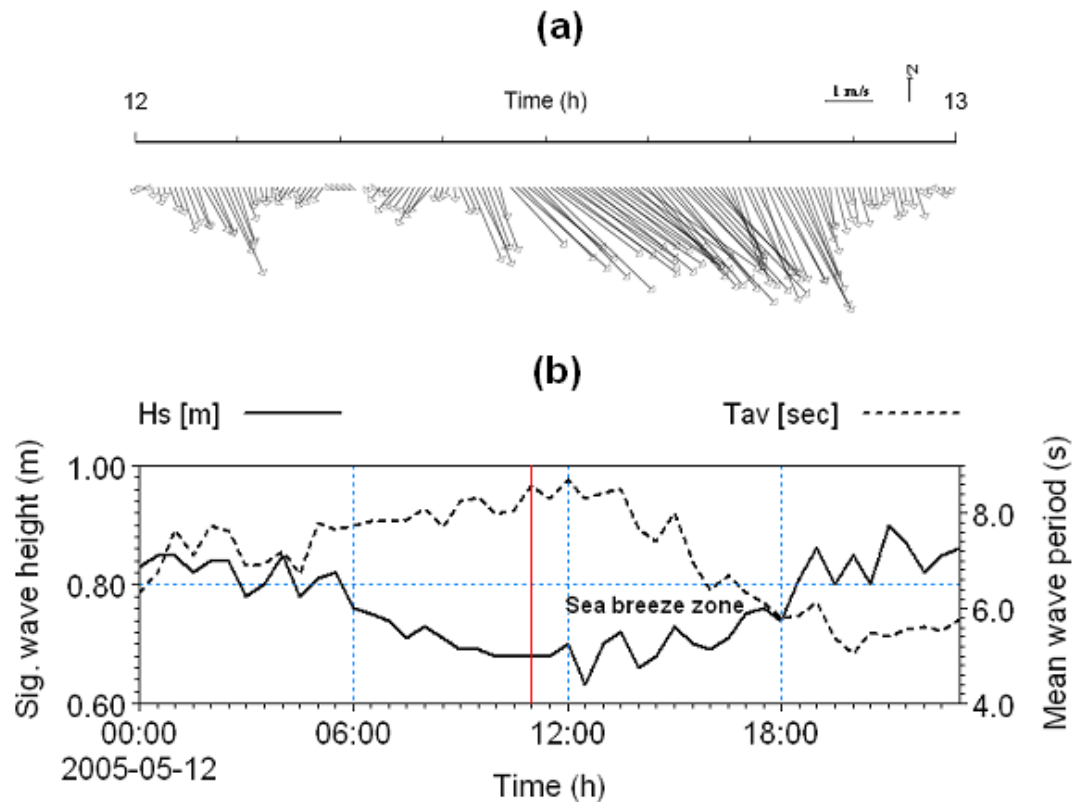


Figure 4-28. (a) AWS wind distribution at Dona Paula and (b) significant wave height and mean wave period at B2 during 12 May 2005.

The time evolution of the sea breeze implies a time lag between the onset of the sea breeze and the maximum wave conditions experienced along the coast. Interestingly, the local experience has led to a practical rule used by the local mariners, indicating that the maximum H_s is reached between 3 and 4 hours after the sea breeze begins, as seen clearly in the measurements (Figure 4-28 and Figure 4-29). Combined with the wave generation rules (see, e.g., SWAMP group, 1985), this suggests a substantial offshore extension of the area, which is affected by the sea breeze.

An indication of the offshore extension where the sea breeze is strong enough to generate waves, is derived from the decay of the wave conditions. During a typical daily cycle, the wave height reaches its peak early in the afternoon, then it decays progressively back to the swell conditions within 5 or 6 hours. Given the typical sea breeze speed between 4 and 5 m/s, the wind sea has a significant wave height (not the overall significant wave height) of the order of 0.5 – 0.6 m. This is very close to the fully developed conditions (for the breeze speed) requiring a minimum fetch of 40 - 50 km. This is not useful for our purpose as the

area affected by the sea breeze is known to be larger. However, another consideration is possible. The typical peak period of sea breeze wave is between 3 and 4 s. This corresponds to about 16 m wavelength (fully consistent with wind sea H_s of 0.5 to 0.6 m), whose energy travels at about 10 km/h. So, the decay time plus the necessary fetch for the most offshore generation suggests an overall extension of the wave generation active zone between 70 and 80 km. An analysis of MM5 winds indicates that the maximum offshore extension of the sea breeze can be around 150-180 km, consistent with the observations of Aparna et al (2005).

Measured spectra clearly show the evidence of the daily cycle of the waves off Goa during pre-monsoon season. Figure 4-30 and Figure 4-31 show the 2D and 1D spectra, respectively. Figure 4-30 clearly shows that at 3-hour intervals, the onset of sea breeze waves around 300° incoming direction, while the swell from $220^\circ - 230^\circ$ are at much lower frequency, and permanently present. The energy associated with the two different wave systems, wind sea and swell, is derived from Figure 4-31. The onset of sea breeze leads to a decrease of mean period. From the maritime safety point of view, the presence of cross-sea conditions (here represented by the SW swell and NW wind sea), is more difficult than a single wave system with the same overall wave height. These cross conditions are typical of the central and southern part of the west coast of India, because of its exposure to long distance swell from the SW direction. No similar conditions are found along the east coast of India (off Paradip and Nagapattinam).

Notwithstanding the limitations of the coarse wind, a first order understanding of the process can be provided by the wave model results obtained using both the large scale NCEP winds and the AWS data for the local area. Figure 4-33 shows a comparison between modelled and measured significant wave heights at location B2. While there are local differences that we associate with the crude wind data (used as input to the wave model), results are consistent with the measured ones, as seen in the related scatter diagram shown in Figure 4-34. The gridded significant wave heights from Jason-1 also match with the modelling and measurements, even though they are averaged (both spatially and temporally).

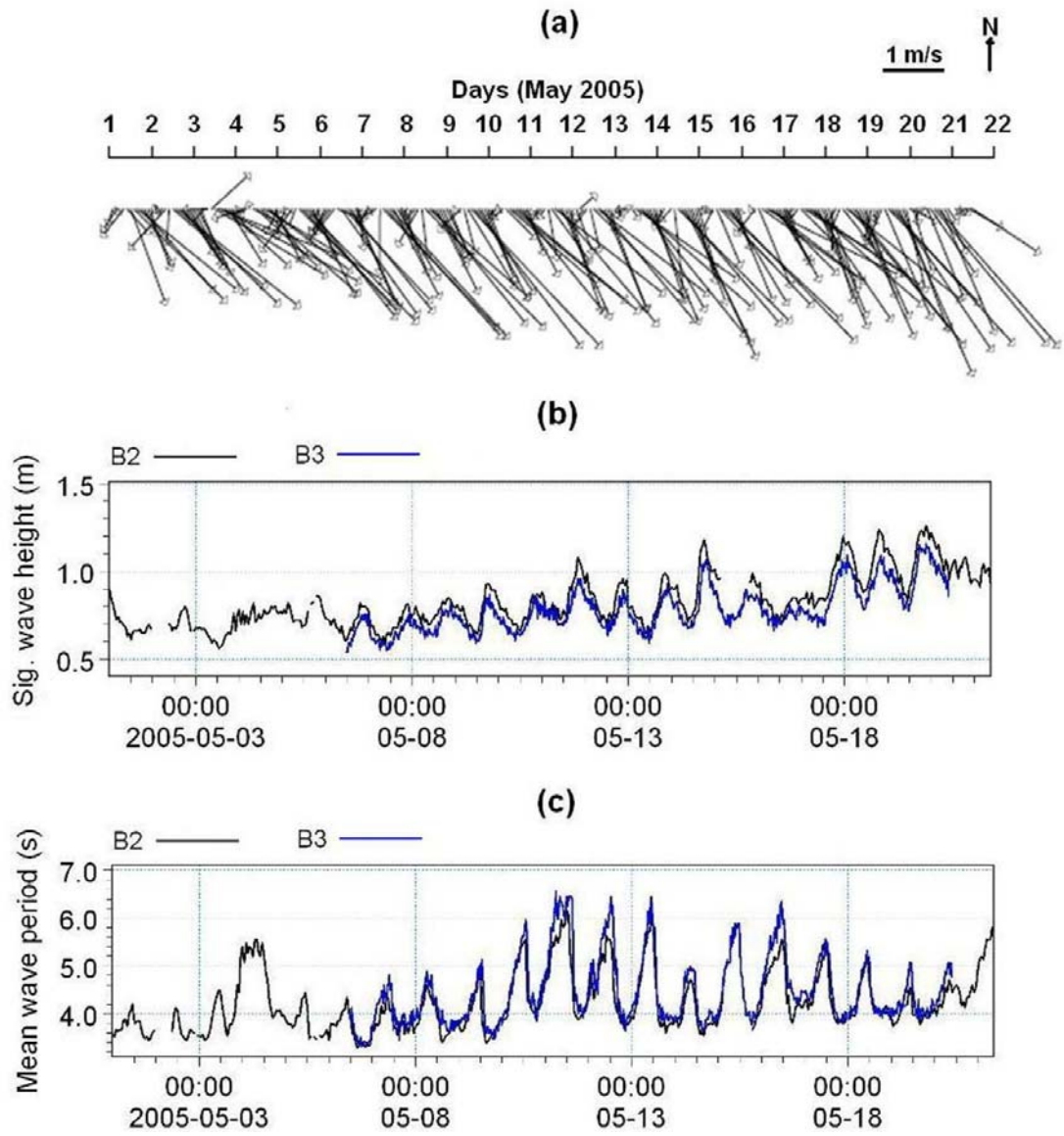


Figure 4-29. Distribution of (a) AWS winds at Dona Paula coastal station, (b) Significant wave height at B2 and B3 and (c) Mean wave period at B2 and B3.

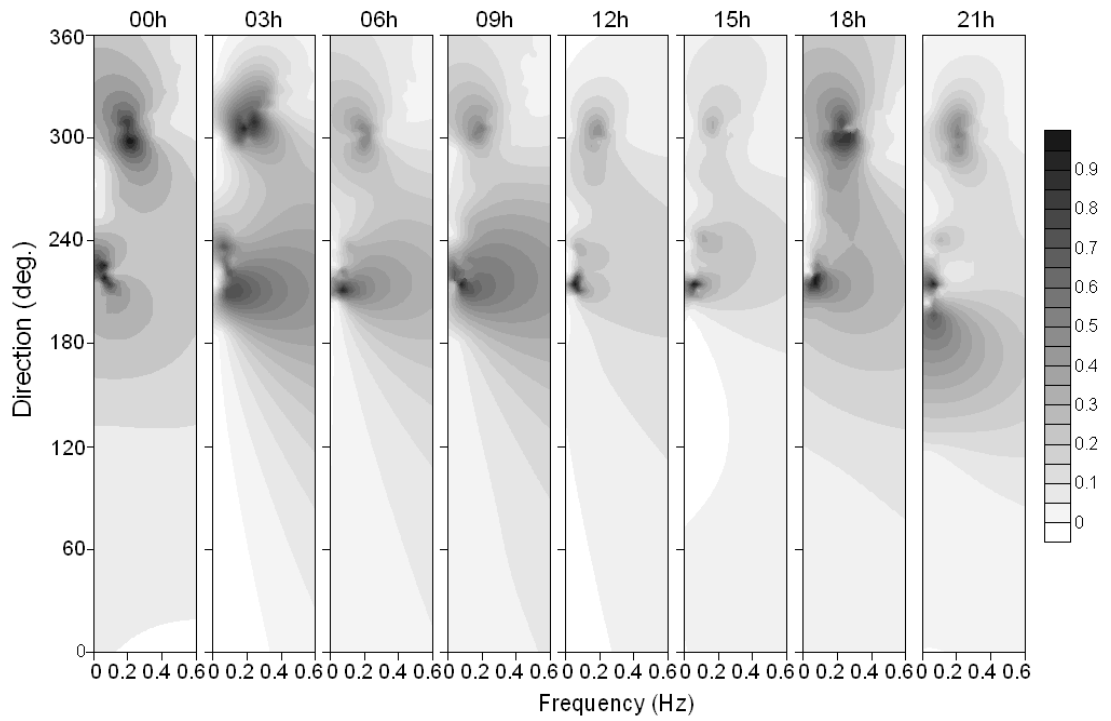


Figure 4-30. Directional energy spectra during 00h to 21h (for every 3 hour) on 19 May 2005.

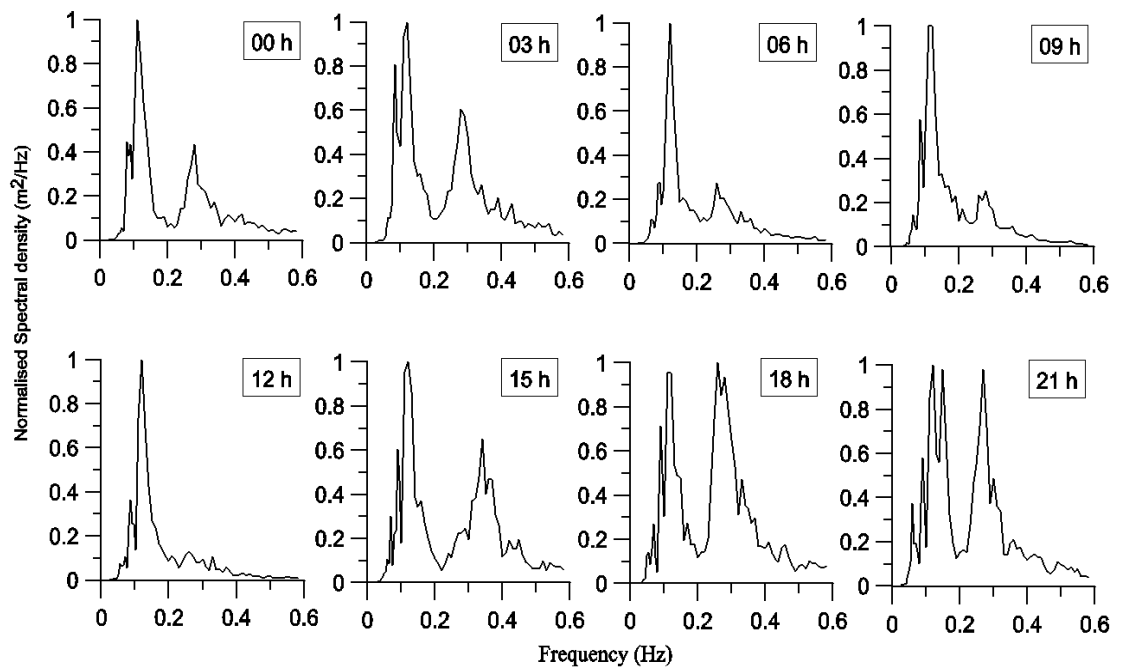


Figure 4-31. Typical 1D spectra during May 2005.

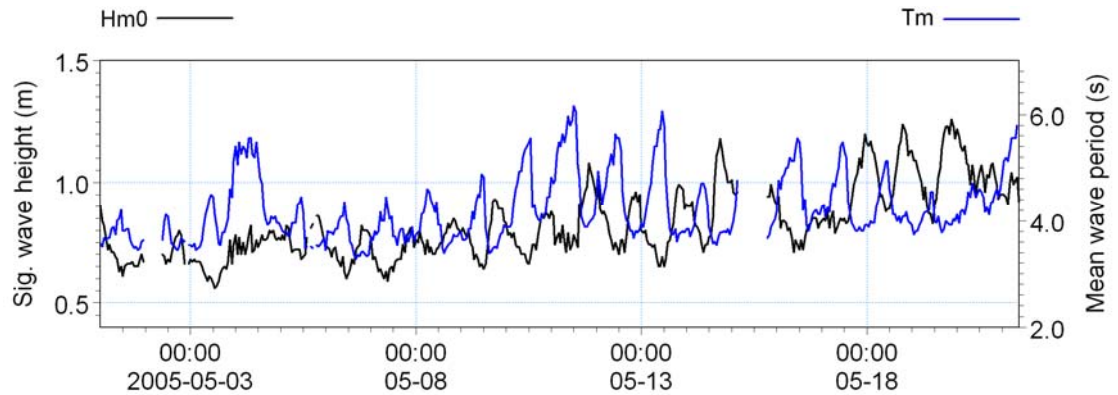


Figure 4-32. Measured significant wave height and mean wave period during May 2005 at B2, showing an inverse proportion among their variations.

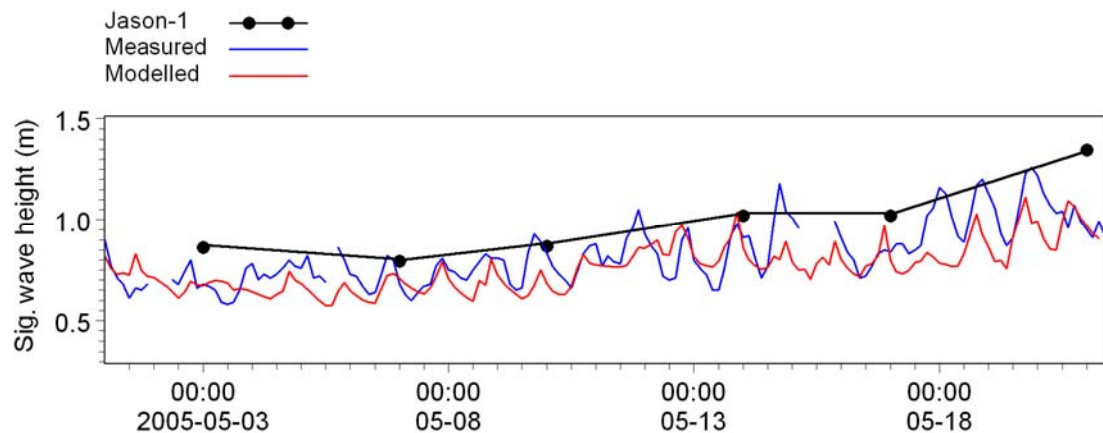


Figure 4-33. Significant wave heights during 1-21 May 2005 : (i) Jason-1 (1 degree x 1 degree grid resolution) extracted at 15° N, 73° E on an alternate 3 and 4 days average, (ii) Measured at B2 (iii) Modelled data extracted at B2.

Clearly, a deeper quantitative analysis of the local generation requires fine resolution winds capable of resolving the details of the wind speed gradient when moving progressively from the Goa coast towards offshore. In this respect, an attempt has been made using MM5 winds to simulate the wind seas off Goa and to analyse the spatial variations according to the wind speed gradient. Figure 4-35 shows the wind sea H_s vectors off Goa during a sea breeze dominated period. It is evident that the wind sea H_s gradually increases toward the coast from offshore, and the maximum wind sea H_s has been observed close to the Goa coast. The wind sea growth towards the coast is proportional to the wind speed gradient, available fetch and sea breeze duration. After cessation of the sea breeze, the associated wind sea energy starts to reduce, and hence a decrease in wind sea H_s has been observed.

The waves simulated by coupling the boundary conditions obtained from the overall simulations for Indian Ocean using NCEP winds, and the MM5 winds for the Goa region, clearly shows diurnal variations in resultant H_s and T_m . A comparison between measured and modelled H_s and T_m at location B2 is shown in Figure 4-36. The interaction of pre-existing swells with the wind seas results in an overall increase of the resultant H_s (as compared to the above wind seas), keeping similar diurnal patterns as observed in the wind seas. However, the diurnal pattern in T_m becomes more systematic for the wave due to the interaction of pre-existing swells. It has been found that the mean wave period decreases, as wind seas dominate. Hence, an inverse proportion has been found between H_s and T_m . Figure 4-37 shows the resultant H_s vectors during sea breeze dominated period, as simulated using MM5 winds and with offshore boundary conditions.

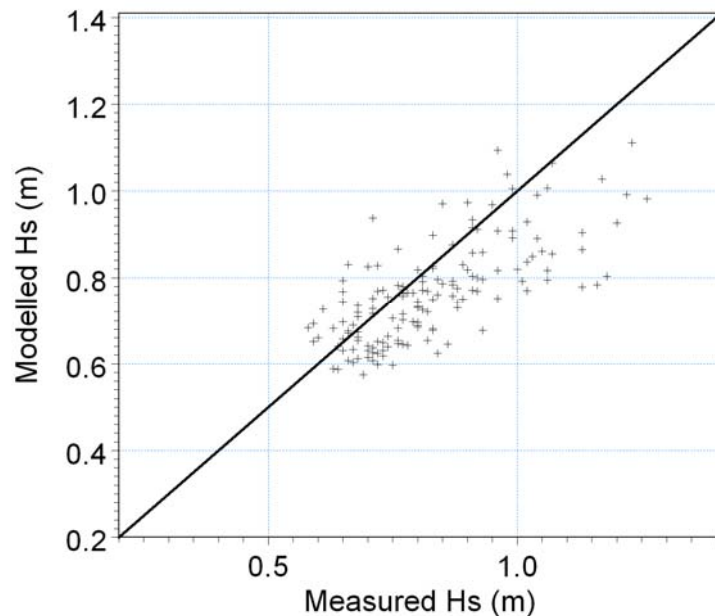


Figure 4-34. Scatter between measured and modelled significant wave heights.

The present theories of wave generation embedded in the various spectral models (e.g., WAM, WAVEWATCH III, etc.) consider the input by wind to a given spectral component (specified in frequency and direction) as independent of energy present in other components. The process of energy transfer from wind to waves is based on a relationship between the wind speed close to the surface and the wave phase speed. However, the latter is bound to change, alternatively in positive and negative direction, when superimposed to a much longer swell. The typical 8 s swell arriving from SW off Goa coast has a

wavelength close to 100m. Therefore, it is likely to affect the local generation of wind waves associated with swell in both wave height and period.

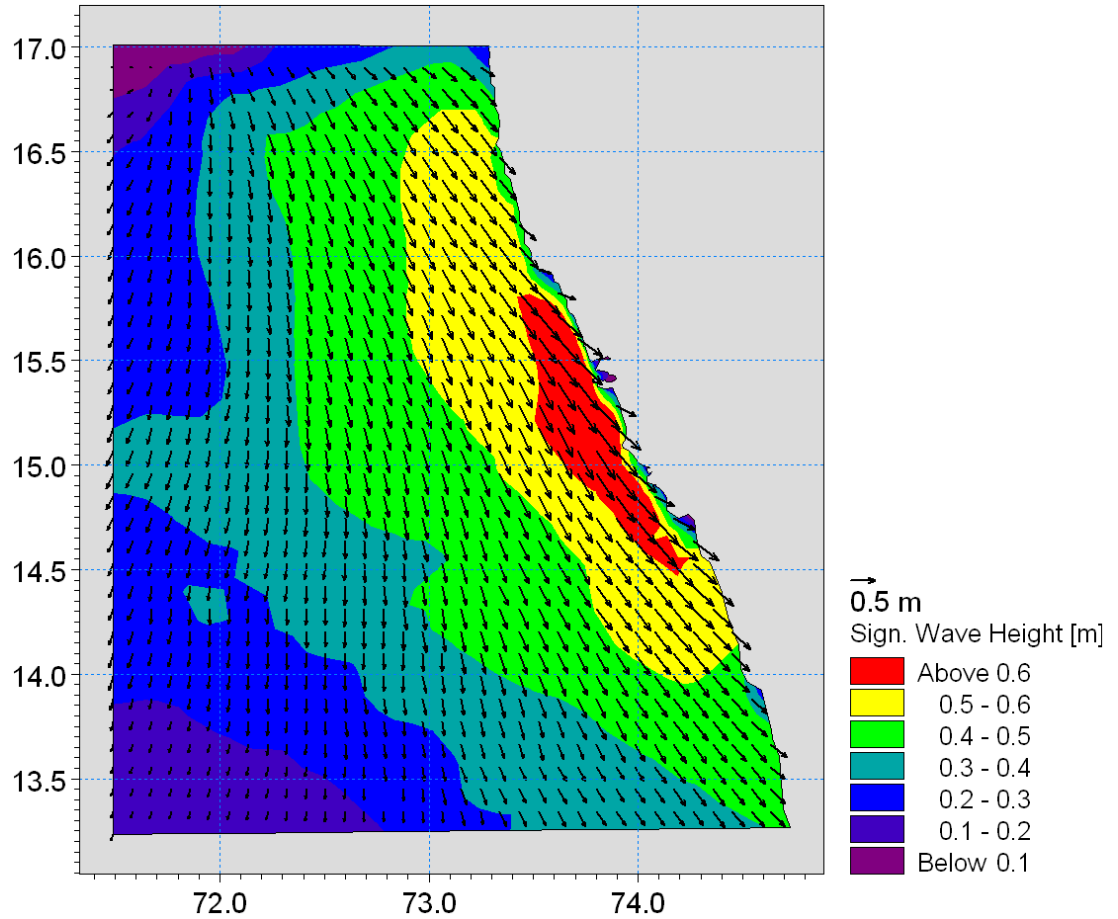


Figure 4-35. Typical wind sea H_s vectors during sea breeze dominated period, simulated using MM5 winds.

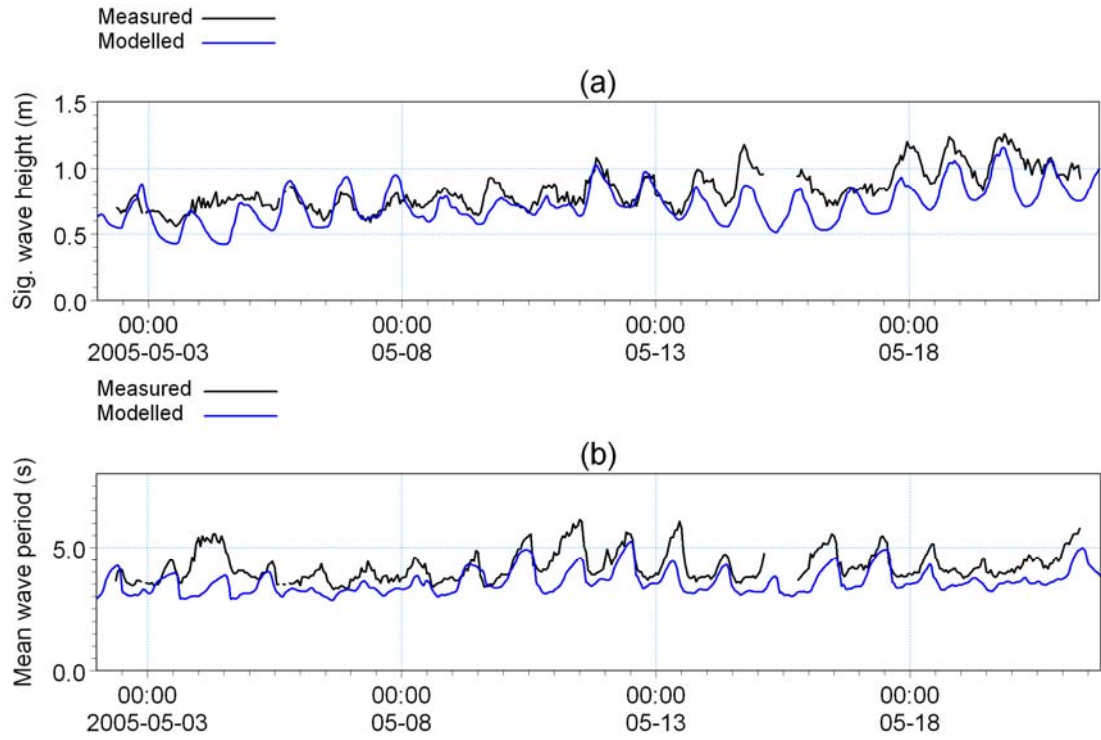


Figure 4-36. Measured and modelled significant wave height and mean wave period at location B2.

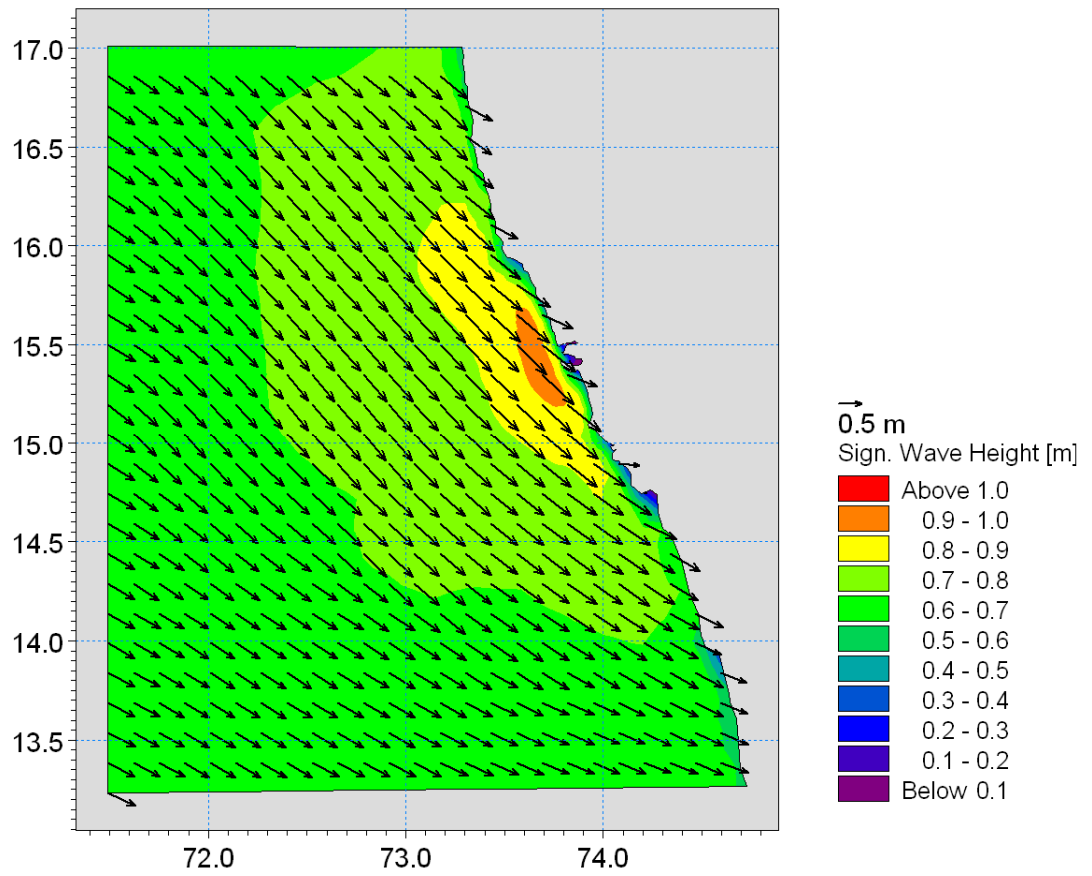


Figure 4-37. Typical H_s vectors during sea breeze dominated period.