
Chapter 5

Wave transformation along open coasts and semi-enclosed regions

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5.1. Introduction

Wave transformation along select open coasts and semi-enclosed regions has been studied using in situ, model and remote sensing wave data have been used in the analysis. Significant wave heights obtained from Jason-1 altimeter (Quilfen et al, 2004) have been analysed to study the deep water wave characteristics. Since, the above data are not reliable at nearshore regions, results from numerical simulations were taken into account. Sec. 5.2 describes wave transformation along select open coasts, and Sec. 5.3 describes the transformation along semi-enclosed areas, which are naturally and artificially protected. Furthermore, a case study has been carried out to revise the inland vessel's limit (IVL) of Mormugao Port based on the distribution of significant wave heights, which illustrates the applicability of a wave transformation model in the nearshore regions. The results are analysed and discussed in Sec. 5.4.

5.2. Wave transformation along open coasts

In order to study wave transformation in the intermediate waters, altimeter data, model results and measured data have been used, depending on the data availability. However, for the nearshore region, measurements and model results have been used as satellite data (altimeter) has inherent limitations.

5.2.1. *Deep water waves from Jason-1*

Significant wave heights obtained from Jason-1 altimeter during 2005 were analysed to understand the deepwater wave characteristics. Two regions were selected: off Goa (along the west coast of India) and off Paradip (along the east coast of India). At each region, significant wave heights from two grid points were selected. One grid is close to the coast and the other one is approximately 450 km away from the coast (Figure 2-3).

Jason-1 significant wave heights off Goa and off Paradip at deep waters during 2005 are shown in Figure 5-1. Significant wave heights off Goa are relatively low (< 2.0 m) during pre-monsoon and post-monsoon seasons and higher (reach upto 4.6 m) during SW

monsoon. Sanil Kumar et al. (2000) reported that waves along the west coast of India are higher during southwest monsoon. Significant wave heights off Paradip are low (< 2.0 m) during pre-monsoon and NE monsoon seasons and higher (reached up to 3.6 m) during SW monsoon. However, extreme events such as cyclones are more prevalent in the Bay of Bengal, and during such event, higher waves prevail along the east coast of India (Sanil Kumar et al., 2004c; Prasad Kumar et al., 2000 and Aboobacker et al., 2009). Since, the temporal resolution of Jason-1 data is very coarse, the extreme events are not well represented. There are no significant changes in wave heights between the grids G1 and G2 off Goa or between the grids P1 and P2 off Paradip.

The major limitations of Jason-1 data are: (i) data cannot be used at a region very close to the coast, and (ii) its temporal resolution is very coarse (alternate 3 and 4 days). Therefore, wave measurements and modelling results are considered to study wave transformation in shallow waters.

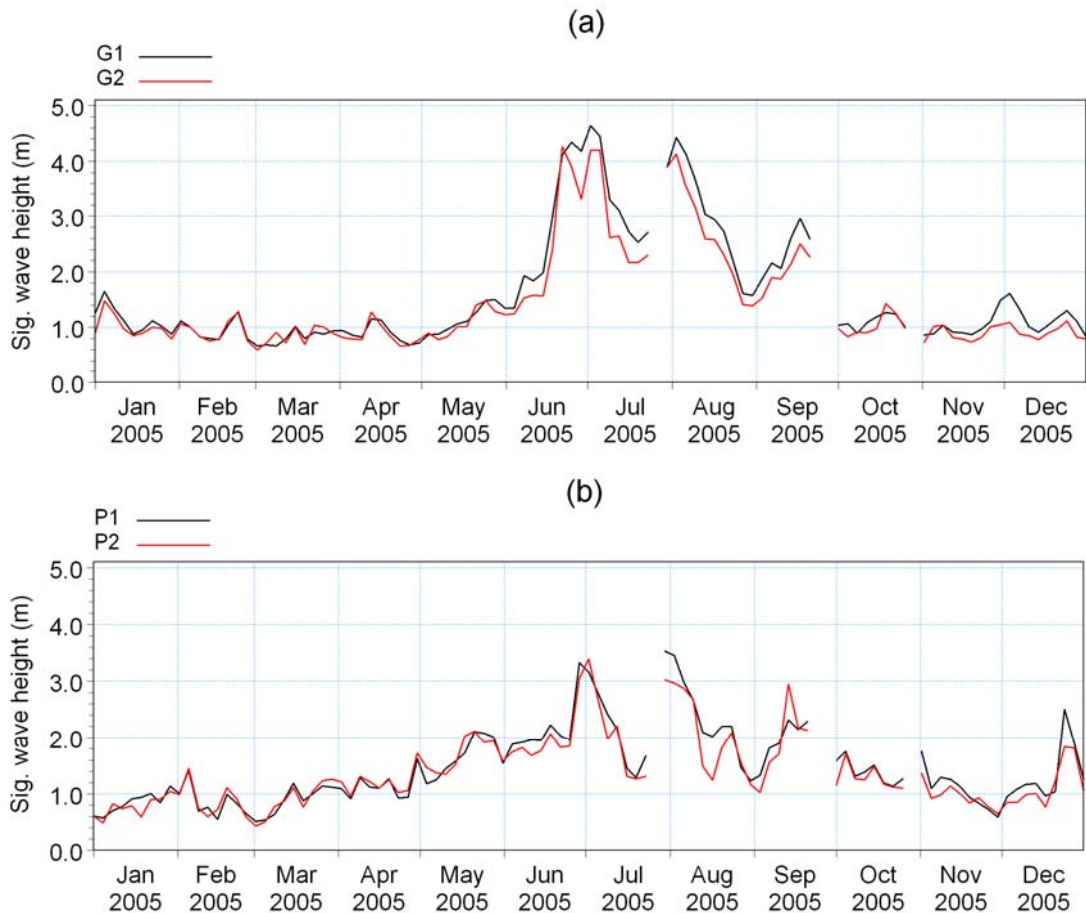


Figure 5-1. Jason-1 significant wave height distribution during 2005: (a) off Goa and (b) off Paradip.

5.2.2. *Waves along nearshore regions*

Local winds such as seas breeze play a major role in generating wind seas at the nearshore regions. Interaction of these wind seas with pre-existing swells modulates the waves in the nearshore regions. However, the resultant waves propagate into shallow waters. Once they begin to feel the bottom, significant changes occur in wave characteristics because of shoaling, refraction, etc.. To understand the characteristic changes that occur due to wave transformation, measured and modelled wave parameters at 2 different depths normal to coast are analysed. The results are discussed in the following sections.

5.2.2.1. *Measurements*

Wave data measured at two depths each off Goa, Ratnagiri and Dwarka have been analysed to study transformation in nearshore depths. Measurement points and bathymetry contours at each location are shown in Figure 5-2. Significant wave heights at these two depths off Goa, Ratnagiri and Dwarka are shown in Figure 5-3. It is found that gradients in water depths (offshore to nearshore) led to reduction in wave heights to some extent. But, the patterns are similar, since the bathymetry contours are nearly parallel to the coast at the measurement locations.

Wave attenuation at each location is estimated and given in Table 5-1. Mean values of significant wave heights, differences and percentage reduction in wave heights are calculated separately for wind sea, swell and resultant wave. The reduction in wave heights at 15m depth off Goa (9.3%) and Ratnagiri (9.4%) are nearly the same, whereas, it is much higher off Dwarka (22%). It has been found that the waves off Dwarka are dominated by wind seas during the study period, and the predominant wind seas are from NE (land to sea). The 15m depth contour off Dwarka is very close to the coast, and the fetch available is very limited. However, a fetch of approx. 9 km is available for NE winds at 30m depth, which is sufficient to generate moderate wind seas. Hence, wind seas in the NE direction (away from the coast) resulted in increase in H_s at 30 m depth.

The reduction in swell and wind sea heights at each location has been analysed. The least reduction in swell heights among the two water depths is observed off Goa (4.7%) and higher off Dwarka (15.6%). The reduction in swell H_s off Ratnagiri is 10.6%. This wave height reduction is explained only partially by refraction of waves that propagate onshore at large oblique angles (approx. 45°) with the depth contours (predominant swells are from SW/SSW). As described earlier (in Chapter 4), these are the longer swells propagating from south Indian Ocean. Interaction of waves with bottom produces a boundary layer,

which results in the loss of wave energy to the bed due to bottom friction (Bagnold, 1946). Small-scale bottom features contribute to the roughness of the bottom and determine the dissipation of wave energy in the bottom boundary layer (Zhukovets, 1963). Formation of vortex ripples and their feedback on the waves through enhanced bottom roughness are the primary mechanisms for wave attenuation across a sandy continental shelf. Sediments along the central west coast of India vary between fine sand and medium sand (Sanil Kumar et al., 2003c). The large reduction in wave heights off Dwarka indicates that bottom attenuation is higher compared to Ratnagiri and Goa regions.

The reduction in wind sea H_s off Goa, Ratnagiri and Dwarka are 16.1%, 9.0% and 27.8%, respectively. During sea breeze period, the waves off Goa are dominated by winds seas from NW (as described in Chapter 4). The reduction in short-period wind seas off Goa is much higher than the reduction in long-period swells (it is only 4.7% for swells). This suggest that the reduction is not due to direct wave-bottom interactions, but possibly due to heavy sediment suspension over the entire water column affecting the hydrodynamics of short-period waves (Sheremet and Stone, 2003). Since the observations have been made during pre-monsoon season, the prevailing sea breeze activity can cause sediment re-suspension (Masselink and Pattiaratchi, 1998). However, this has to be confirmed through detailed field study of distribution of bottom sediments and suspended sediments during pre-monsoon season. The large reduction in wind seas off Dwarka is attributed to the generation of NE wind seas, and their growth is towards offshore. Sufficient fetch is available at 30 m depth for NE wind seas compared to 15 m water depth.

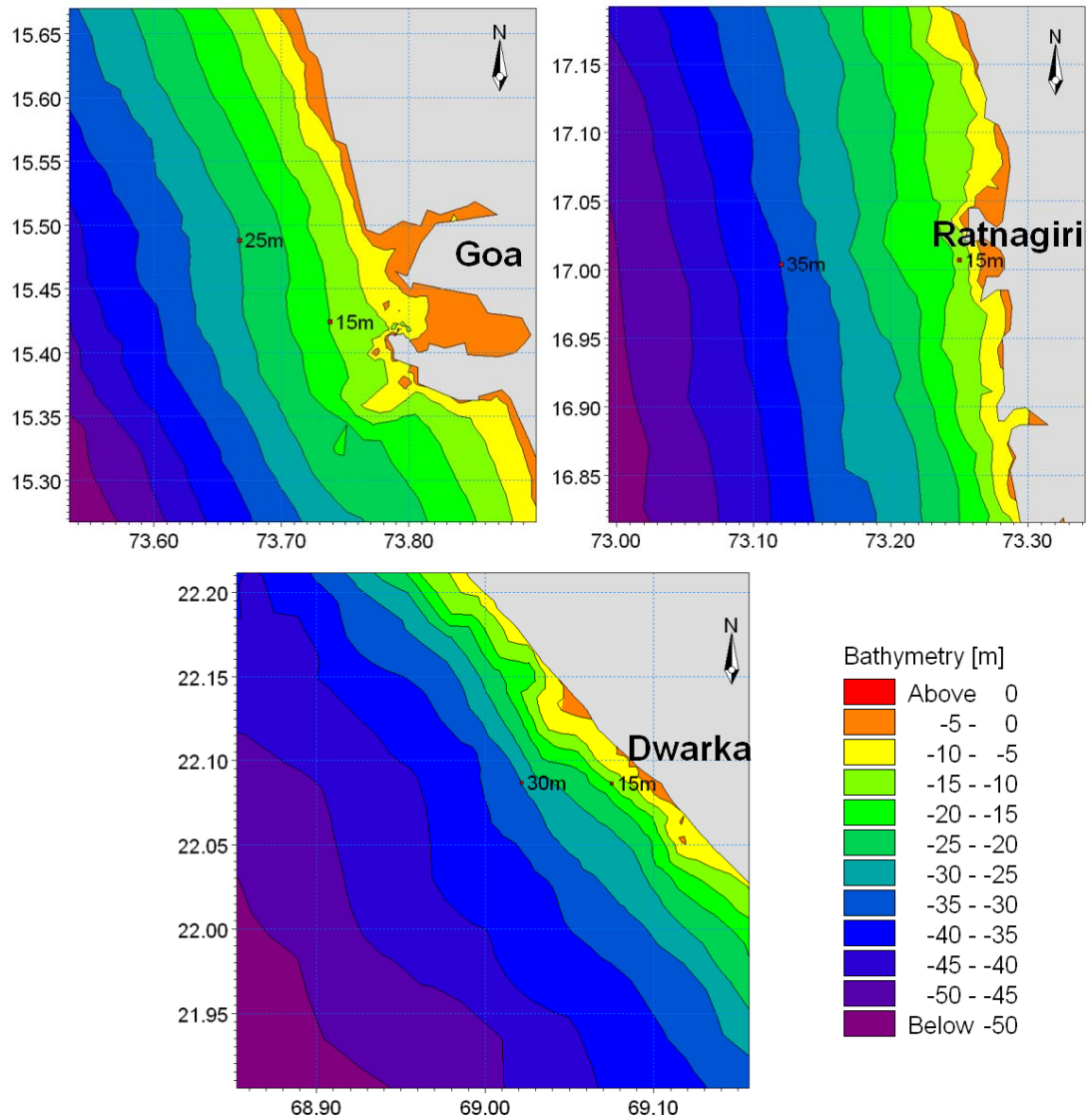


Figure 5-2. Measurement locations and bathymetry contours off Goa, Ratnagiri and Dwarka.

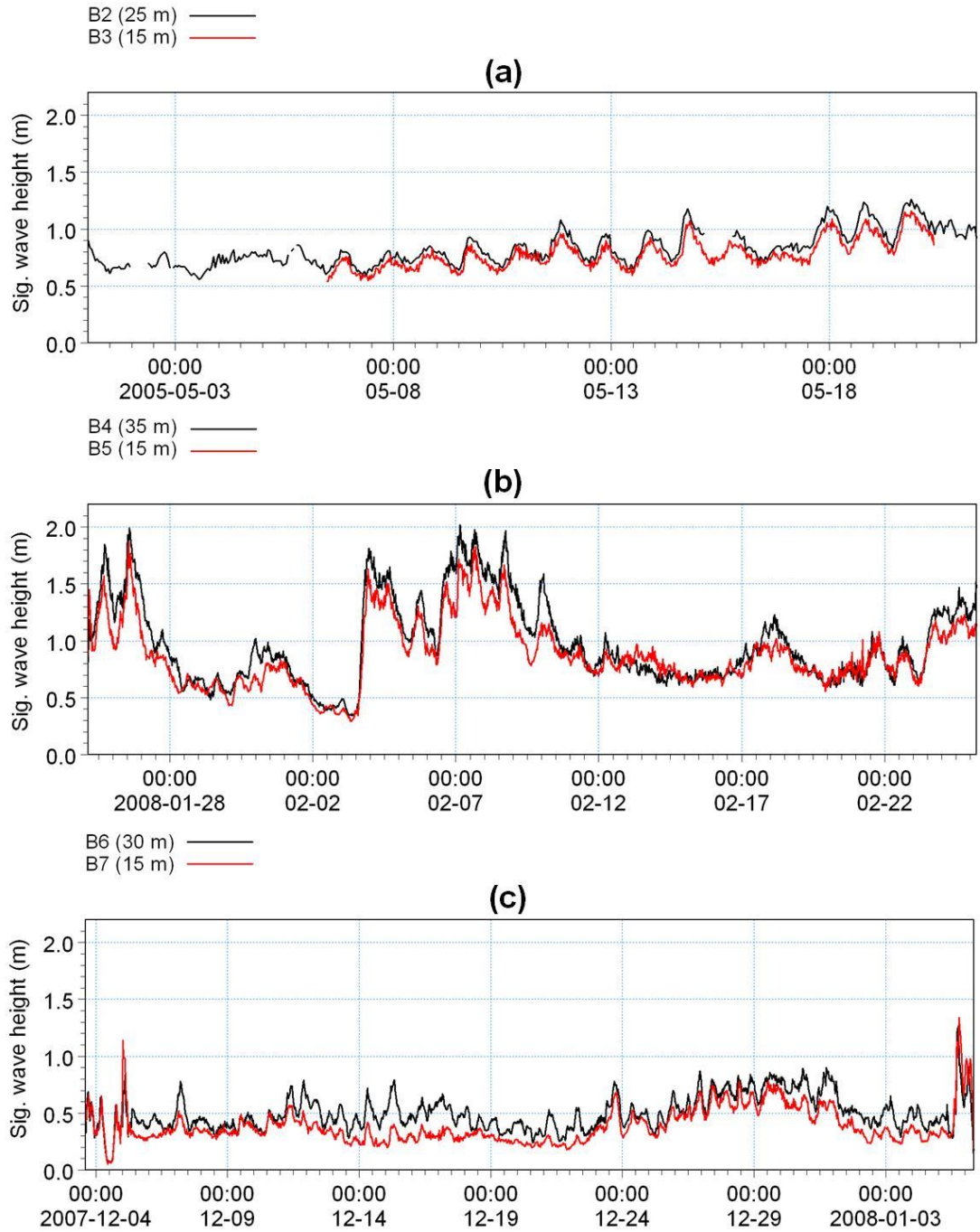


Figure 5-3. Significant wave heights measured at nearshore depths off: (a) Goa, (b) Ratnagiri and (c) Dwarka (locations are marked in Figure 2-2).

Table 5-1. Mean H_s and % reduction at various measurement locations along the west coast of India.

Regions		off Goa		off Ratnagiri		off Dwarka	
Locations		B2 (25 m)	B3 (15 m)	B4 (35 m)	B5 (15 m)	B6 (30 m)	B7 (15 m)
Resultant wave	Mean H_s (m)	0.86	0.78	0.96	0.87	0.50	0.39
	Difference (m)	0.08		0.09		0.11	
	% reduction	9.3		9.4		22.0	
Swell	Mean H_s (m)	0.64	0.61	0.66	0.59	0.32	0.27
	Difference (m)	0.03		0.07		0.05	
	% reduction	4.7		10.6		15.6	
Wind sea	Mean H_s (m)	0.56	0.47	0.67	0.61	0.36	0.26
	Difference (m)	0.09		0.06		0.10	
	% reduction	16.1		9.0		27.8	

5.2.2.2. *Modelling results*

Modelled wave parameters at various depths (100 m, 50 m, 30 m, 20 m, 10 m and 5 m) off Mumbai, Goa and Kochi (along the west coast of India) and off Nagappattinam, Visakhapatnam and Paradip (along the east coast of India) were analysed. Figure 5-4 shows significant wave heights at various depths off Mumbai, Goa and Kochi during 2005. The pattern of wave transformation is nearly the same. During the southwest monsoon, the significant wave heights show an increasing trend from the south to the north (Kochi to Mumbai). The wave dissipation between deep and shallow depths (100 m and 5 m) is higher for larger waves, since these waves start feeling the bottom at relatively deeper depths. Significant reduction in wave height is occurred at shallow depths for moderate and small waves. Kurian et al. (2009) reported that the sediments along the southwest coast of

India are fine sands (0.25 mm), and further north they are confined to the fine to medium sand (0.5 mm) category. It has been found that the reduction in wave height is minimum off Kochi and maximum off Mumbai, which is attributed to the varying bottom attenuation. This supports the observations by Kurian and Baba (1987) that the frictional attenuation increases towards north, though their study is limited to Kerala coast.

Significant wave heights off Mumbai, Goa and Kochi during pre-monsoon season are further illustrated in Figure 5-5. The diurnal variation in wave heights is found during pre-monsoon season (as described in Chapter 4) at all depths off Mumbai, Goa and Kochi, which is typical for the west coast of India. However, magnitude of variation reduces from the north to the south, indicating that sea breeze and its effect on wind sea generation decreases from the north to the south.

Seasonal and annual statistics (mean and standard deviation) of significant wave heights at various depths off Mumbai, Goa and Kochi are listed in Table 5-2. The seasonal variations in mean H_s are graphically represented in Figure 5-6. Significant reduction in wave heights due to bottom dissipation has been observed at shallow depths. Large waves off Mumbai and Goa, and relatively lower waves off Kochi are observed. The mean H_s during pre-monsoon and NE monsoon seasons off Kochi are nearly the same and relatively low compared to the SW monsoon waves as well as waves off Goa or Mumbai. However, H_s is marginally higher off Goa and Mumbai during the pre-monsoon season compared to NE monsoon waves. It is evident that sea breeze adds up sufficient energy to the waves prevailing in the nearshore region off the west coast of India during pre-monsoon season, and it is highly visible off Mumbai and Goa regions.

Significant wave heights at various water depths off Nagappattinam, Visakapattinam and Paradip during 2005 are shown in Figure 5-7. Waves are small during pre-monsoon season and higher during SW and NE monsoon seasons. Significant wave height is maximum (around 3.0 m) during southwest monsoon season. Wave patterns are nearly the same all along the east coast of India. Wave heights show increasing trend during pre-monsoon and SW monsoon seasons, and decreasing trend during NE monsoon season (October – January) from south to north (Nagappattinam to Paradip). During extreme events, the wave heights are even higher. Sanil Kumar et al. (2004c) found that during the passage of a cyclone in November 1998, the maximum wave height observed off Visakhapatnam was 5.74 m. Aboobacker et al (2009) reported that significant wave height off Paradip during another cyclone in May 1996 was 4.2 m.

During the NE monsoon season, the wind wave grows towards south due to energy transfer from NE winds to the waves. Hence, higher waves are observed along the southeast coast of India during the NE monsoon season. Significant reduction in wave height due to bottom dissipation is noticed when the significant wave heights at depths 100, 50, 30, 20, 10 and 5 m off Nagappattinam, Visakapattinam and Paradip are analysed. However, the reduction among various depths is relatively less as compared to those along the west coast of India, as the depth contours along the east coast of India are more closer than those along the west coast of India (continental shelf is narrow along the east of India). Bottom dissipation causes higher reduction in wave heights over a wide continental shelf (Ardhuin et al., 2003).

Figure 5-8 shows the significant wave heights off Nagappattinam, Visakapattinam and Paradip during pre-monsoon season. Even though, there are variations in wave heights, a well-defined diurnal pattern (as seen along the west coast of India) is not present along the east coast of India during the pre-monsoon season.

Seasonal and annual mean and standard deviation of significant wave heights at various depths off Nagappattinam, Visakapattinam and Paradip are listed in Table 5-3. Seasonal distribution of mean H_s is graphically represented in Figure 5-9 also. The mean H_s is relatively low at all locations along the east coast of India compared to those along the west coast of India. Significant reduction due to bottom dissipation is occurred at lower depths (below 20 m) during all the seasons. The waves off Paradip and Visakapattinam are higher during SW monsoon season, and waves off Nagappattinam are higher during the NE monsoon season. It is evident that wave heights are in the increasing order of magnitude during SW monsoon season from Nagappattinam to Paradip (south to north), and in the decreasing order of magnitude during NE monsoon season. A slight increase in wave height is noticed from south to north during pre-monsoon season.

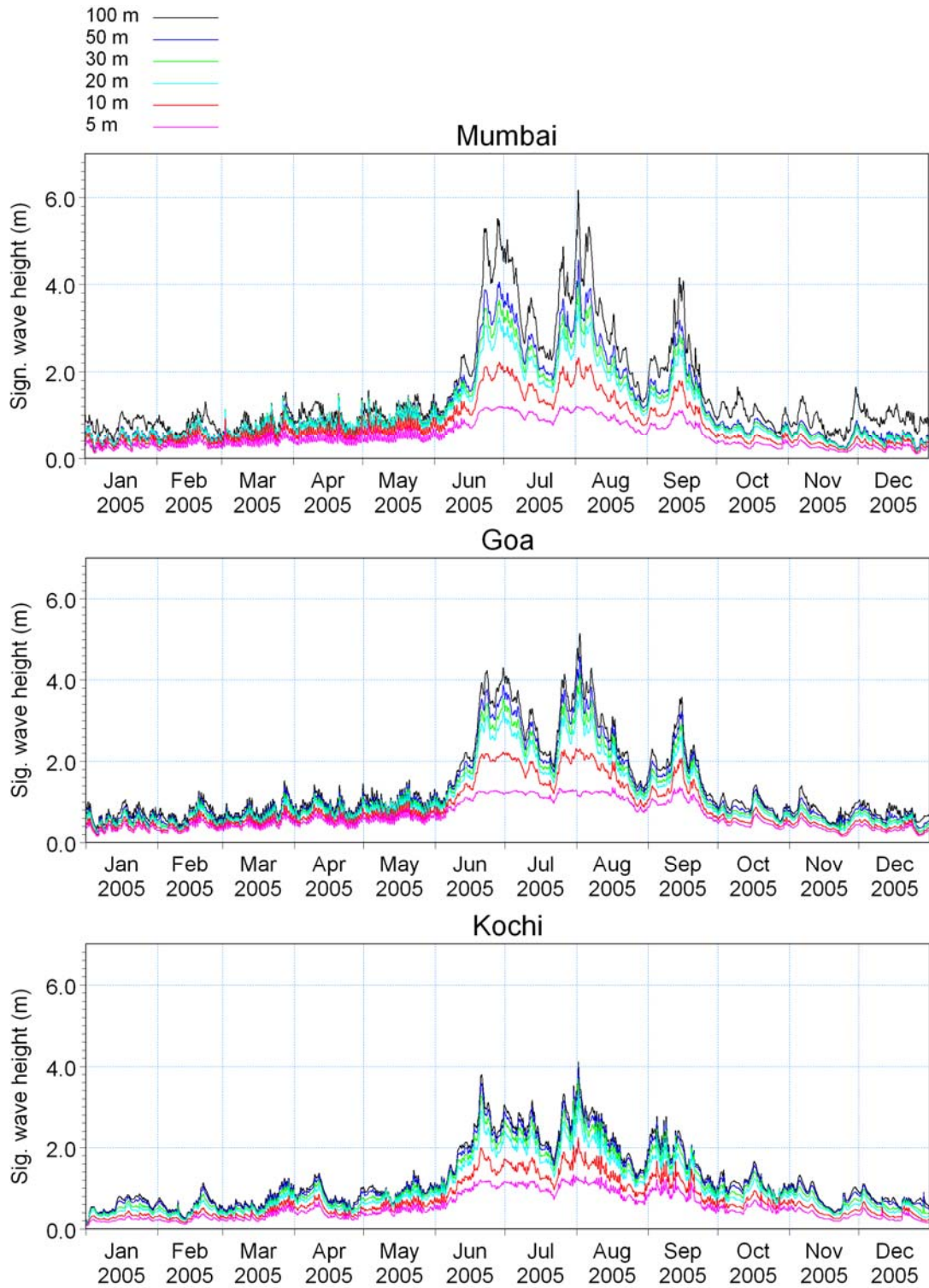


Figure 5-4. Significant wave heights at various water depths off Mumbai, Goa and Kochi during 2005.

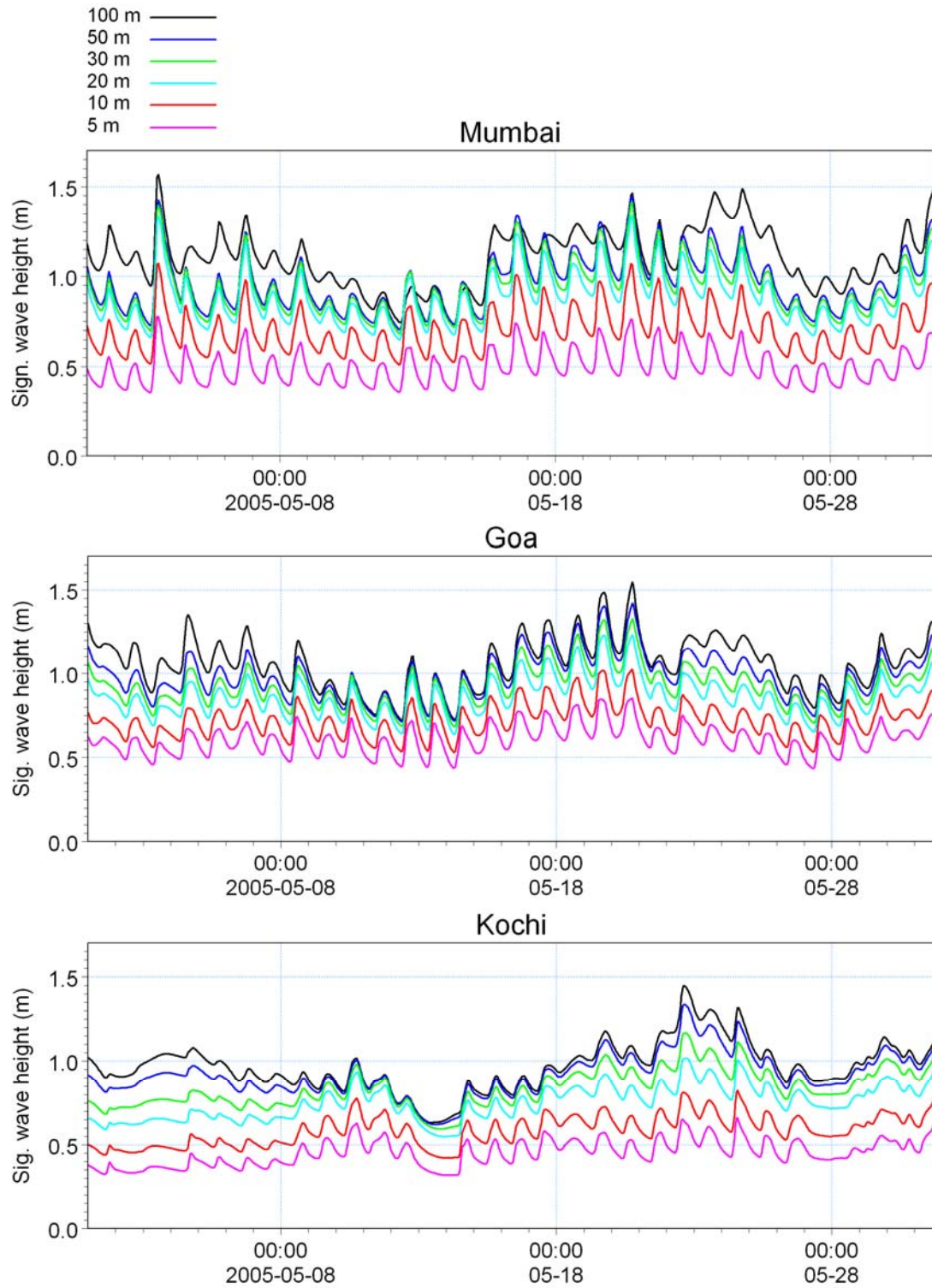


Figure 5-5. Diurnal variations in significant wave heights at various water depths off Mumbai, Goa and Kochi during pre-monsoon season (May 2005).

Table 5-2. Seasonal and annual mean and standard deviation of significant wave heights at various depths off Mumbai, Goa and Kochi.

Seasons	Water depth (m)	Significant wave height (m)					
		Mumbai		Goa		Kochi	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
Pre-monsoon	100	0.92	0.24	0.89	0.22	0.79	0.24
	50	0.77	0.22	0.81	0.21	0.74	0.23
	30	0.75	0.21	0.76	0.20	0.66	0.21
	20	0.71	0.20	0.70	0.18	0.59	0.19
	10	0.58	0.15	0.59	0.15	0.45	0.15
	5	0.42	0.11	0.49	0.13	0.34	0.12
SW monsoon	100	2.88	1.19	2.56	0.96	2.18	0.63
	50	2.29	0.86	2.33	0.84	2.07	0.59
	30	2.09	0.75	2.14	0.76	1.91	0.55
	20	1.89	0.66	1.95	0.69	1.72	0.49
	10	1.38	0.44	1.55	0.47	1.28	0.34
	5	0.89	0.22	1.07	0.20	0.93	0.21
NE monsoon	100	0.90	0.23	0.78	0.20	0.82	0.27
	50	0.57	0.16	0.68	0.18	0.76	0.26
	30	0.52	0.15	0.61	0.16	0.67	0.24
	20	0.48	0.13	0.55	0.15	0.59	0.21
	10	0.38	0.10	0.45	0.13	0.45	0.17
	5	0.27	0.07	0.37	0.10	0.33	0.13
Annual	100	1.57	1.18	1.42	1.00	1.26	0.77
	50	1.21	0.93	1.27	0.91	1.19	0.74
	30	1.12	0.83	1.17	0.83	1.08	0.69
	20	1.03	0.74	1.07	0.76	0.97	0.63
	10	0.78	0.51	0.86	0.57	0.72	0.46
	5	0.52	0.30	0.64	0.34	0.54	0.32

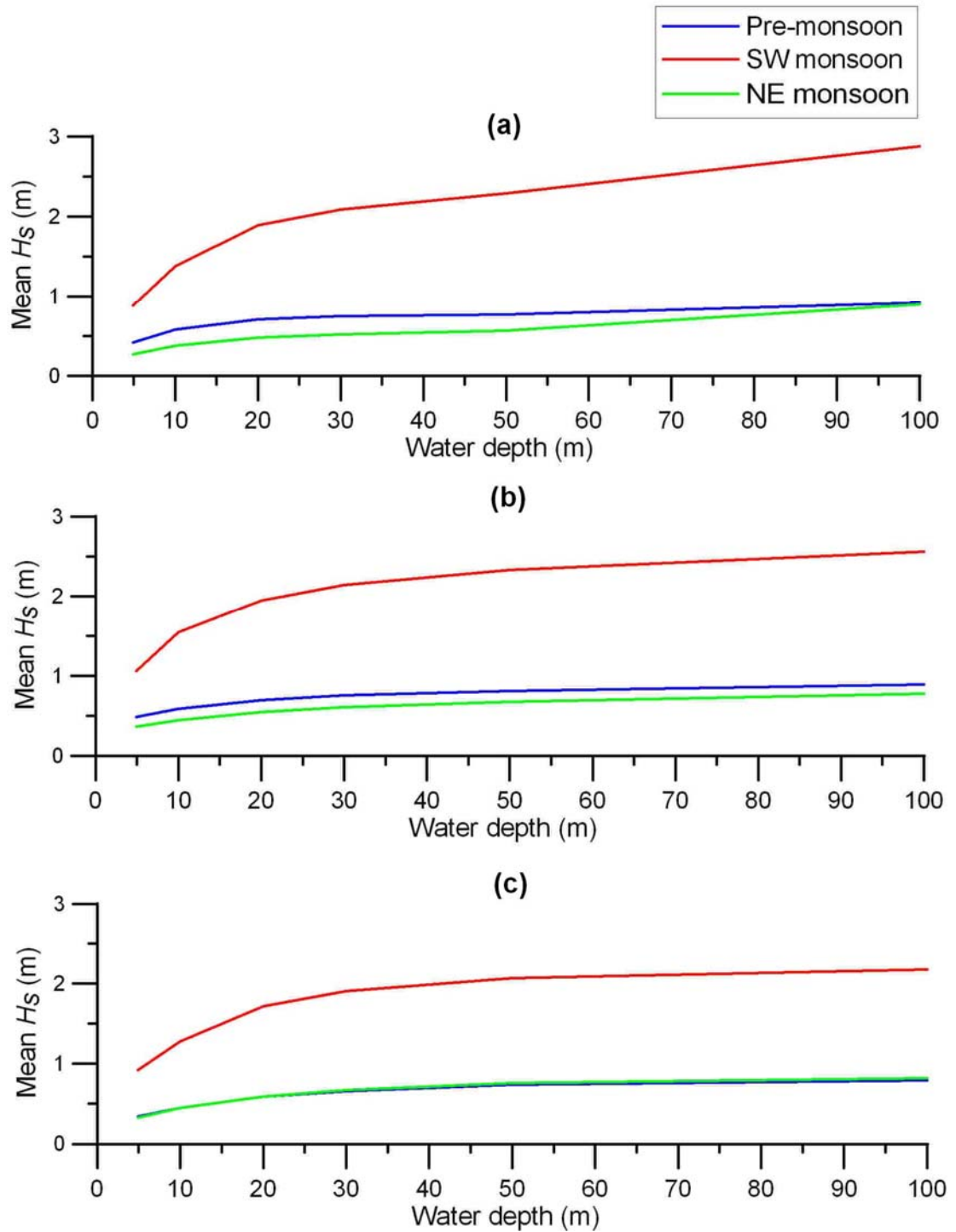


Figure 5-6. Mean H_s at various depths ranging from 100 to 5 m during pre-monsoon, SW monsoon and NE monsoon seasons off: (a) Mumbai, (b) Goa and (c) Kochi.

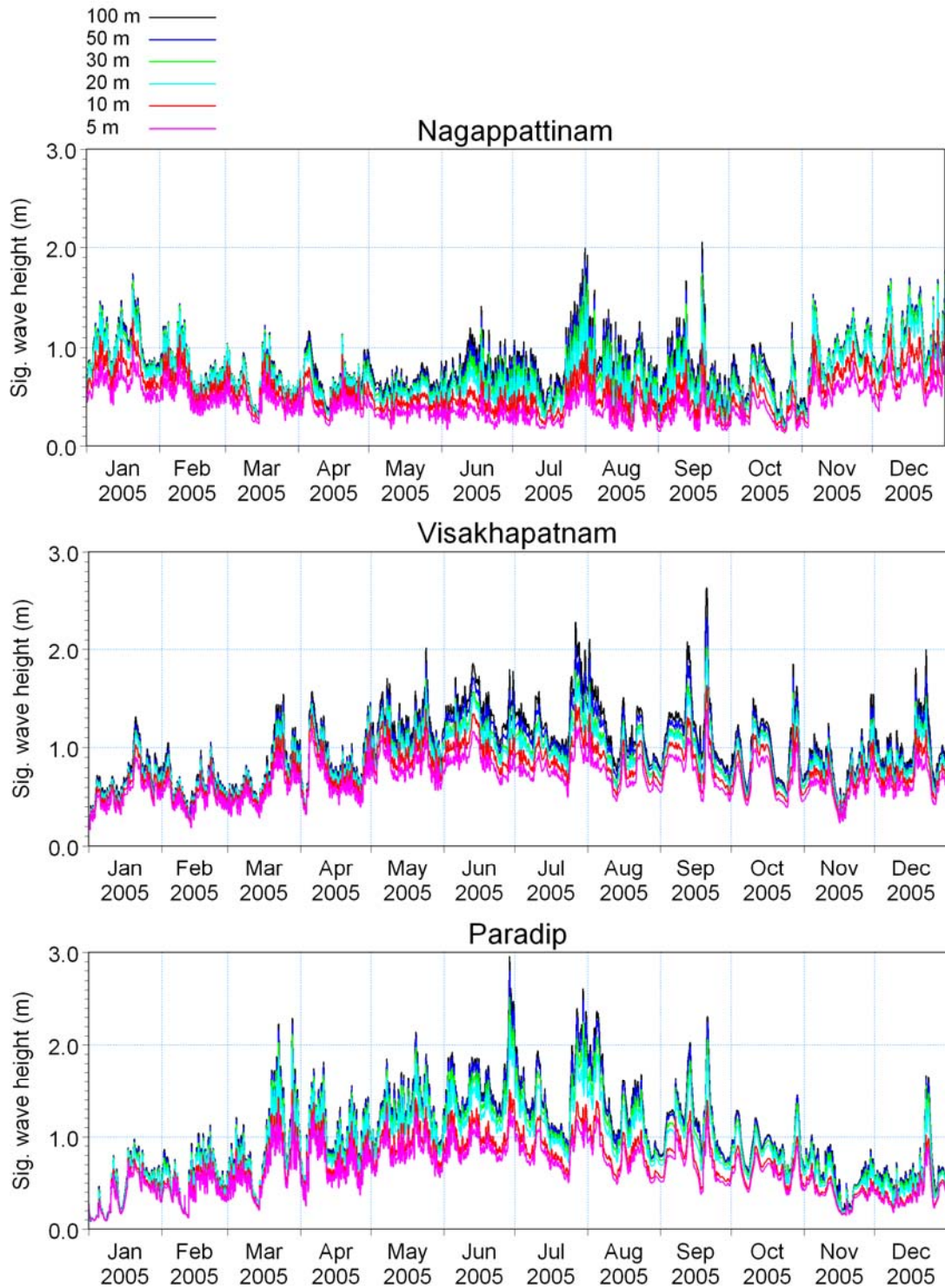


Figure 5-7. Significant wave heights at various water depths off Nagappattinam, Visakhapatnam and Paradip during 2005.

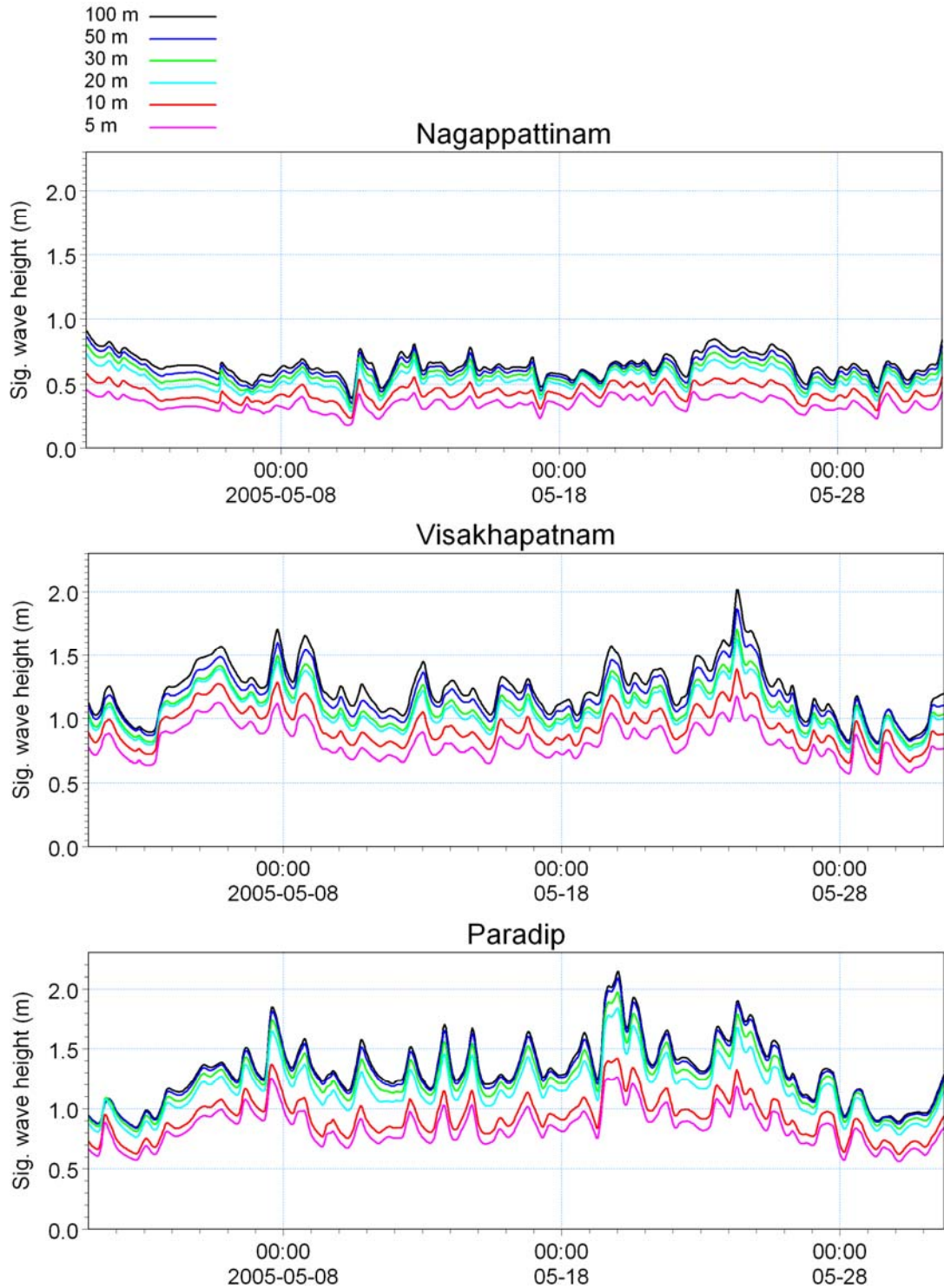


Figure 5-8. Significant wave heights at various water depths off Nagappattinam, Visakhapatnam and Paradip during pre-monsoon season (May 2005).

Table 5-3. Seasonal and annual mean and standard deviation of significant wave heights at various depths off Nagappattinam, Visakapattinam and Paradip.

Seasons	Water depth (m)	Significant wave height (m)					
		Nagappattinam		Visakapattinam		Paradip	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
Pre-monsoon	100	0.71	0.18	0.89	0.32	0.99	0.41
	50	0.69	0.18	0.86	0.30	0.97	0.40
	30	0.66	0.18	0.82	0.28	0.93	0.37
	20	0.63	0.17	0.80	0.27	0.88	0.35
	10	0.53	0.15	0.72	0.23	0.72	0.27
	5	0.43	0.12	0.64	0.20	0.66	0.24
SW monsoon	100	0.82	0.26	1.27	0.31	1.41	0.41
	50	0.76	0.24	1.18	0.27	1.37	0.39
	30	0.69	0.22	1.08	0.24	1.27	0.35
	20	0.61	0.20	1.03	0.23	1.17	0.31
	10	0.45	0.15	0.91	0.19	0.90	0.22
	5	0.34	0.11	0.79	0.16	0.80	0.20
NE monsoon	100	0.94	0.30	0.89	0.29	0.65	0.28
	50	0.92	0.30	0.84	0.26	0.64	0.28
	30	0.89	0.30	0.80	0.24	0.61	0.26
	20	0.84	0.29	0.77	0.23	0.57	0.24
	10	0.67	0.23	0.69	0.19	0.47	0.20
	5	0.53	0.18	0.61	0.16	0.43	0.18
Annual	100	0.83	0.27	1.02	0.36	1.02	0.48
	50	0.79	0.27	0.96	0.32	0.99	0.47
	30	0.75	0.26	0.90	0.28	0.94	0.43
	20	0.69	0.25	0.87	0.27	0.87	0.39
	10	0.55	0.20	0.77	0.23	0.69	0.29
	5	0.43	0.16	0.68	0.19	0.63	0.26

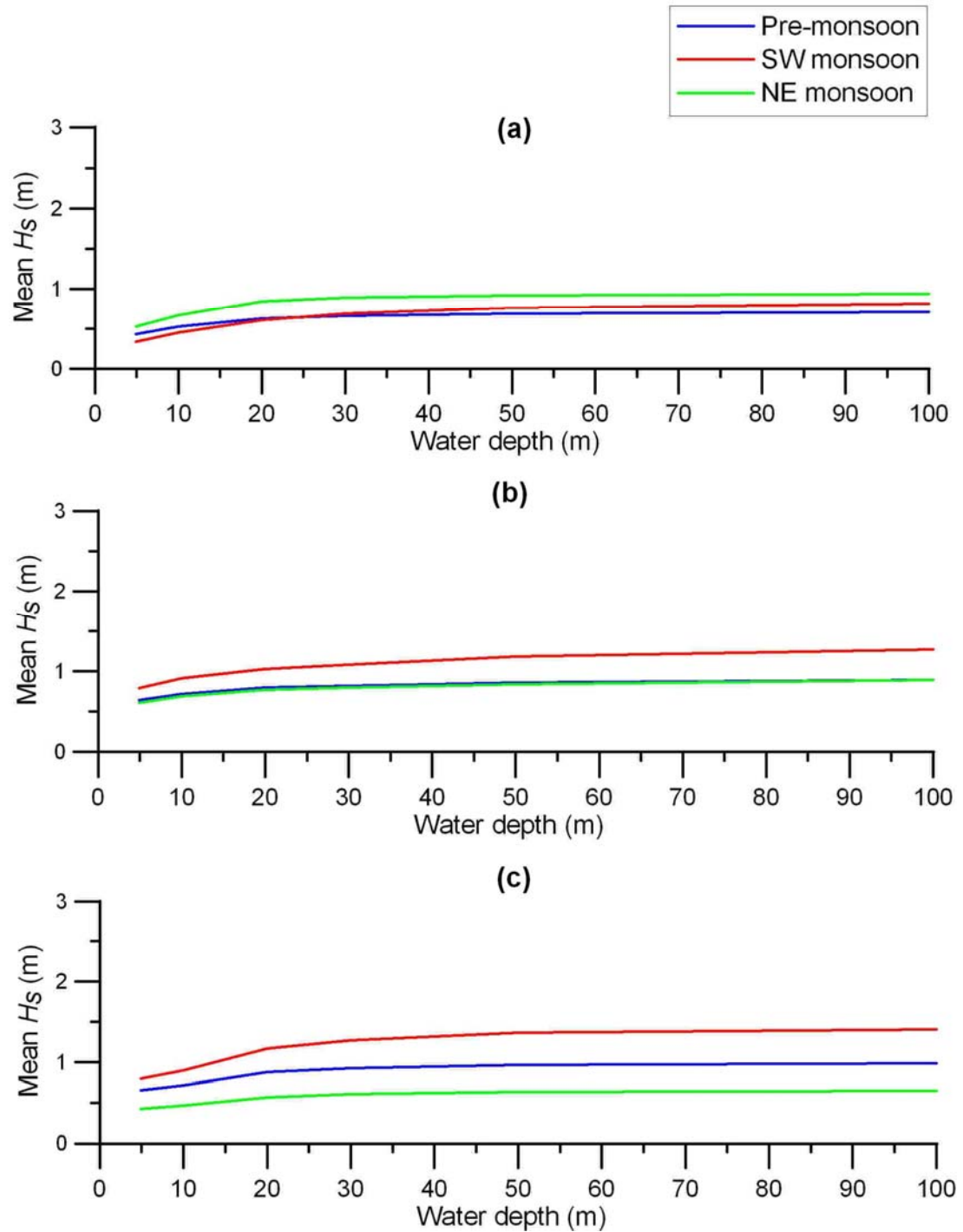


Figure 5-9. Mean H_s at various depths ranging from 100 to 5 m during pre-monsoon, SW monsoon and NE monsoon seasons off: (a) Nagappattinam, (b) Visakapattinam and (c) Paradip.

5.3. Wave transformation at semi-enclosed regions

Wave transformation at two semi- enclosed areas, Dhamra Port (naturally protected), situated on the east coast and Mormugao Port (artificially protected), located on the west coast, has been studied. Non-directional wave gauge data available for the inner channel of the Dhamra Port during 12 July – 13 Aug 2005 has been used for validation; no measurements are available inside the Mormugao Port. Numerical model has been set up for the Dhamra Port and the Mormugao Port regions by including diffraction effects.

5.3.1. *Dhamra Port – naturally protected area*

Dhamra Port is situated along the northern part of the east coast of India (Figure 1-5). Figure 5-10 show flexible mesh and bathymetry of the Dhamra region. The Port and inner channel are sheltered from the direct impact of waves due to the Dhamra River Delta (Kanika sands), which acts as a natural breakwater. Hence, major part of the wave energy gets dissipated at the delta and the remaining energy propagates towards the Port and surrounding areas.

Waves off Dhamra have been simulated for 2005 (model domain is shown in Figure 3-4b in Chapter 3). The two measurement locations, offshore (B10) and inner channel (C1), are marked in Figure 5-10. A comparison between measured and modelled wave parameters at B10 is shown in Figure 5-11, and the match is very good. Similarly, measured and modelled wave parameters at the inner channel (C1) have been compared, and the match is good (Figure 5-12). This experiment indicates that the model simulates waves in the semi-enclosed regions very accurately.

Wave parameters at three different locations, namely, an open area south of Gahirmatha at 12 m water depth (B10), an open area outside the channel at 11 m depth (O1) and a sheltered area at the inner channel at 6 m water depth (C1), have been analysed. Figure 5-13 shows the significant wave height and mean wave direction at locations B10, O1 and C1. Gahirmatha beach and surrounding mangrove areas prevent the waves fully from SSE to SSW, and partially from ESE to SE direction to reach the Port region. The Kanika sands in front of the Dhamra region, prevent the waves (fully) from ENE to E and the waves (partially) from NNE to NE entering the Port (SW to N are covered by land). It is seen from Figure 5-13 that the waves at an offshore location, say B10, are predominantly from S during pre-monsoon and SW monsoon seasons and between NE and E during NE monsoon season. Waves from these directions are obstructed by the above land forms and mangrove areas. They undergo diffraction while propagating towards the Port region. Hence, the

diffracted waves are predominantly observed at the Port and the inner channel (C1). Due to diffraction and bottom friction, large amount of wave energy gets dissipated, and hence the waves with low heights are observed at C1. The waves at C1 are least attenuated during the NE monsoon season and most attenuated during SW monsoon season.

At O1, the predominant waves are between ESE and SSE during pre-monsoon and SW monsoon seasons and between NE and E during NE monsoon season. Gahirmatha land prevents the waves from S and SW to reach at O1. The bathymetry contours near O1 is normal to ENE direction, and hence large waves will refract and propagate normal to the bathymetry contours. During pre-monsoon season, the predominant waves in deep water location are from S and undergo refraction at O1 upto 30° deviation (from S to SSE). During SW monsoon, the waves are even larger and undergo significant refraction at O1 upto 40° (from S to SE). These waves will refract further while moving towards C1, and in combination with diffraction, a large reduction in wave height has been observed during pre-monsoon and SW monsoon seasons.

During NE monsoon season, the waves are relatively small. Wave heights are nearly the same at locations B10 and O1, since the bottom effects are minimum at these depths for small waves. Significant reduction in wave heights due to diffraction and refraction have been observed at C1, and the predominant propagation directions are between NNE and NE. Maximum, mean and standard deviation of significant wave heights at B10, O1 and C1 are listed in Table 5-4. The maximum values observed at B10, O1 and C1 are 2.3, 1.2 and 0.38 m, respectively, and the mean values are 0.74, 0.4 and 0.07 m with standard deviations of 0.38, 0.19 and 0.06 m, respectively. This indicates that the significant wave heights are reduced significantly while propagating from offshore to the inner channel off Dhamra, mainly due to diffraction and bottom dissipation caused by the natural protection such as Kanika sands and mangroves in the vicinity of Dhamra region.

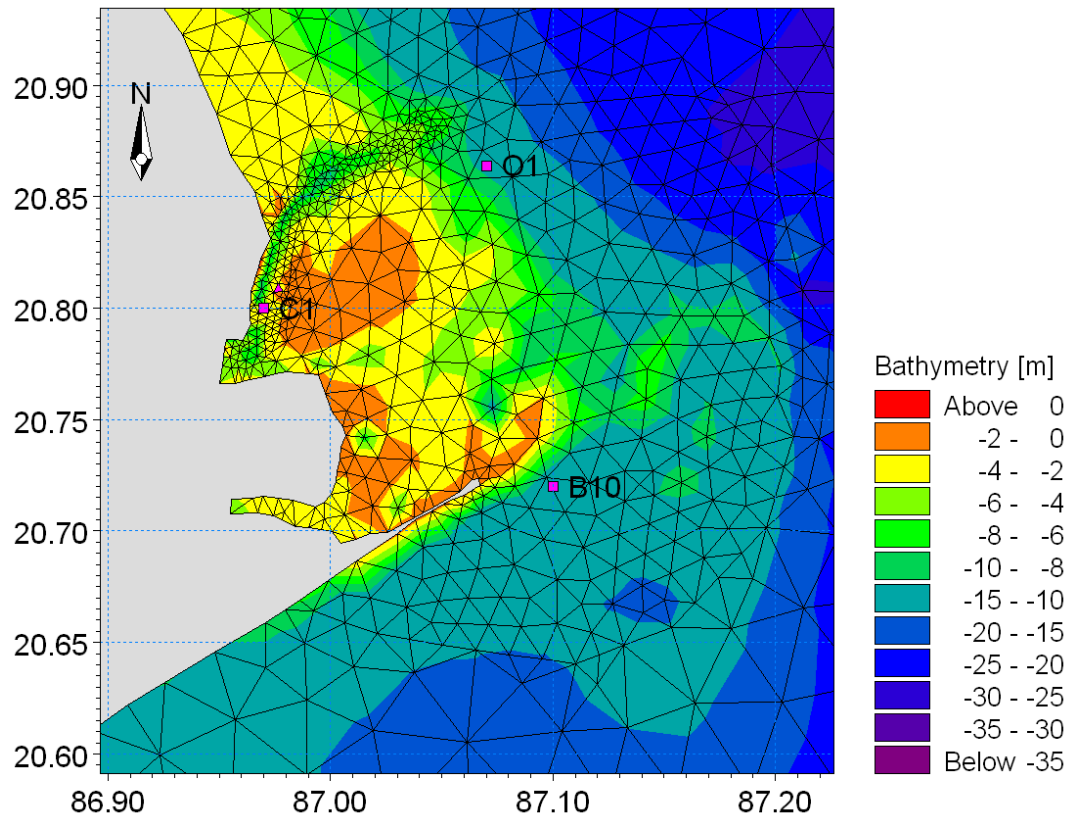


Figure 5-10. Flexible mesh and bathymetry close to the Dhamra region.

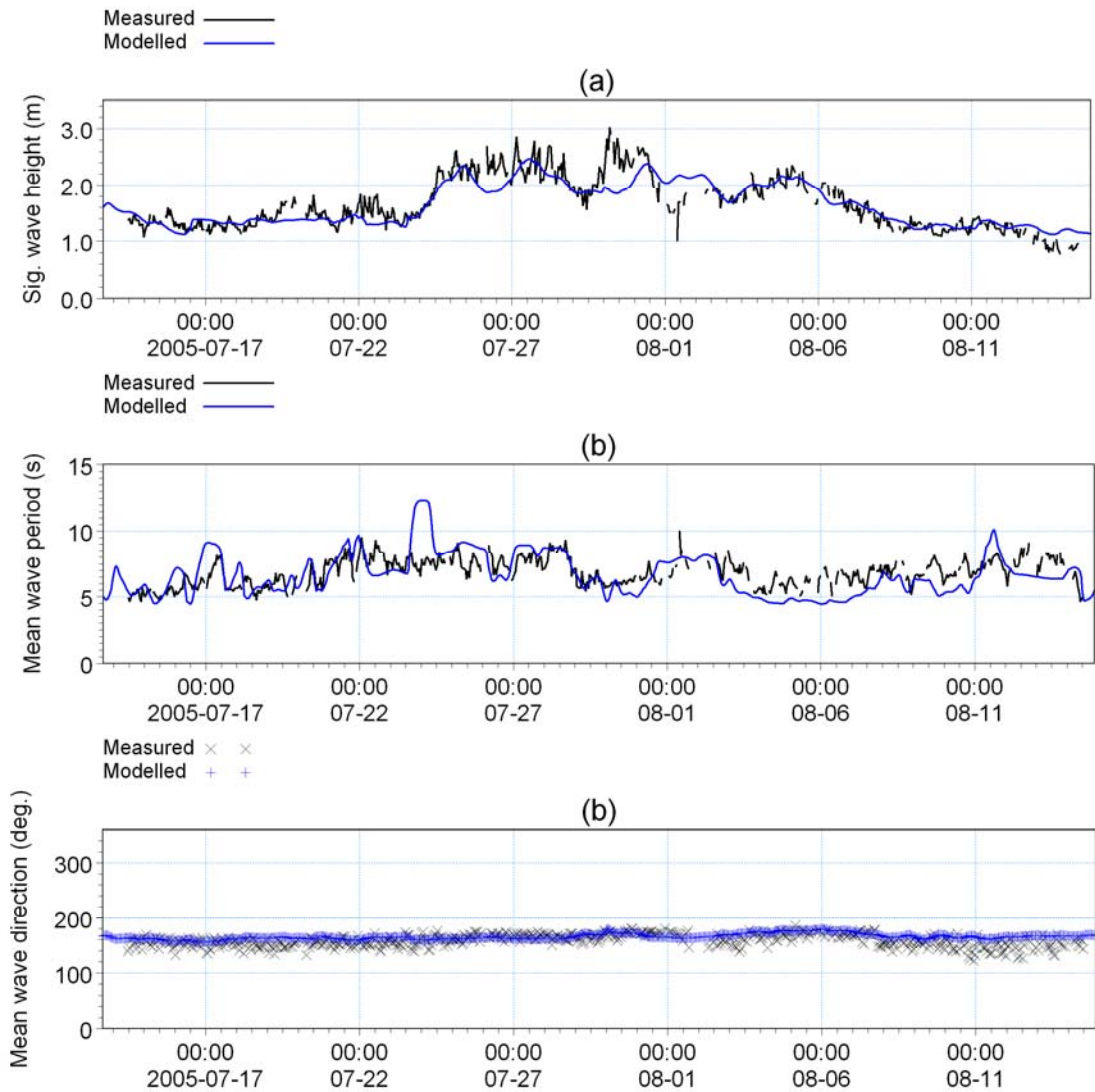


Figure 5-11. Comparison between measured and modelled wave parameters at location B10: (a) significant wave height, (b) mean wave period and (c) mean wave direction.

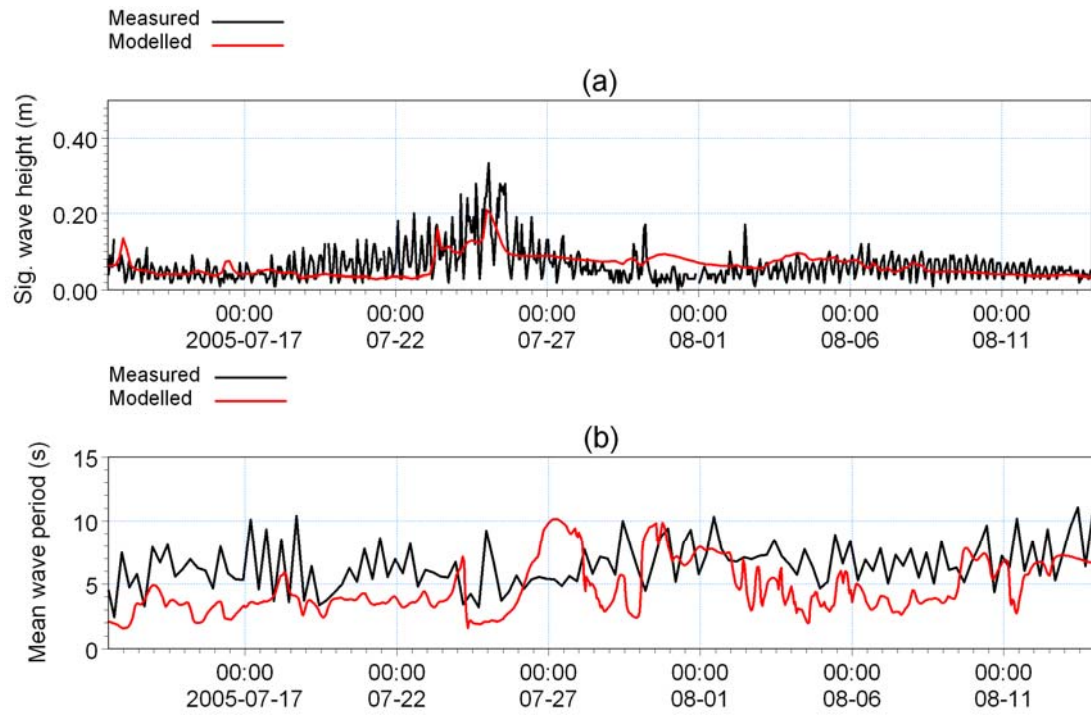


Figure 5-12. Comparison between measured and modelled (a) significant wave height and (b) mean wave period off Dhamra (at C1).

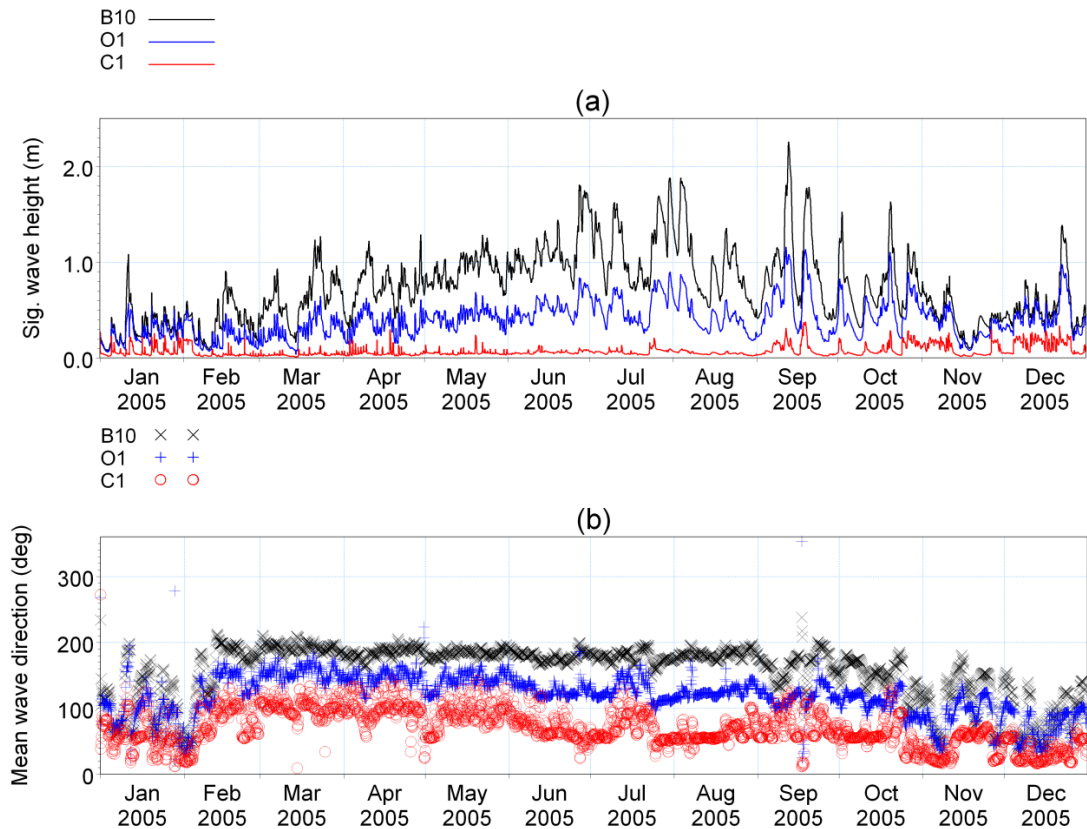


Figure 5-13. (a) significant wave height and (b) mean wave direction, at locations B10, O1 and C1 during 2005.

Table 5-4. Maximum, mean and standard deviation of significant wave heights during 2005 in the vicinity of Dhamra Port.

Location	Significant wave height (m)		
	Maximum	Mean	Standard deviation
B10	2.30	0.74	0.38
O1	1.20	0.40	0.19
C1	0.38	0.07	0.06

5.3.2. *Mormugao Port – artificially protected area*

Mormugao Port is protected from direct impact of waves due to breakwaters (Figure 1-4b). The breakwaters help to dissipate the wave energy in front of the port; minimum wave

energy only propagates to the area inside the port, which is mainly caused by diffraction. Features like reflection and overtopping are not incorporated in the numerical study.

Since, there are no measurements available inside the Port, the sensitivity of the model has been tested with available data at nearshore depths; measured data at B2 (25 m) and B3 (15 m). Model domain was selected considering the west open boundary at 25 m depth contour; measured data at B2 was used as the boundary conditions. The other two open boundaries (north and south) are considered as symmetrical. Figure 5-14 shows the model domain and flexible mesh bathymetry used for the wave transformation simulations off Mormugao Port region. The waves at B2 during 01-21 May 2005 are subject to transformation. The modelled wave parameters at B3 were extracted and compared with measurements (Figure 5-15) and the match is excellent.

Considering the measured wave parameters at B1 during Feb 1996 – May 1997 as boundary conditions, the waves at Mormugao Port region were simulated to study the transformation in all seasons. The wave parameters at three different locations, outside the breakwater (OP) and inside the Port (IP1 and IP2), were extracted. The extraction locations are marked in Figure 5-14b.

Figure 5-16 shows the significant wave height and mean wave direction at locations B1 (the boundary data), OP, IP1 and IP2 during Feb 1996 – May 1997. The location B1 is open to the waves from all directions, and OP is open to the waves between SW and NW. Diffracted and refracted waves from other directions also propagate towards OP. Since water depth at OP is shallow (9 m), larger waves will get dissipated due to bottom friction to some extent. The bottom contours at OP are normal to the west. Hence, the waves tend to travel in the W direction due to refraction. Even though, significant reduction in wave heights occurs at OP, the waves are still larger for carrying out the port operations. Diffraction takes place around the breakwater and diffracted waves with low energy propagate into the port. Wave heights at IP1 and IP2 are significantly low during any season and extreme events. The highest significant wave height observed at 23 m depth off Goa during a tropical cyclone in the Arabian Sea is 5.8 m. However, simulations show that the associated significant wave heights at OP, IP1 and IP2 are 2.62, 0.89 and 0.33 m, respectively. Maximum, mean and standard deviation of the significant wave heights during February 1996 – May 1997 at locations OP, IP1 and IP2 are given in Table 5-5. The mean significant wave heights at OP, IP1 and IP2 are 0.66, 0.23 and 0.08 m, respectively, and the corresponding standard deviations are 0.47, 0.17 and 0.06, respectively.

Larger waves are experienced during southwest monsoon and relatively low during pre-monsoon and post-monsoon seasons. The waves at B1 during SW monsoon are predominantly in the WSW direction. Due to refraction, it has been aligned to W at OP with a mean deviation of 10° . During pre-monsoon and NE monsoon seasons, the waves at B1 are predominantly in the SW and NW directions. The mean deviations in the predominant direction at OP are 20° from SW to WSW and 10° from NW to WNW, which are due to refraction (bathymetry contours are oriented to W).

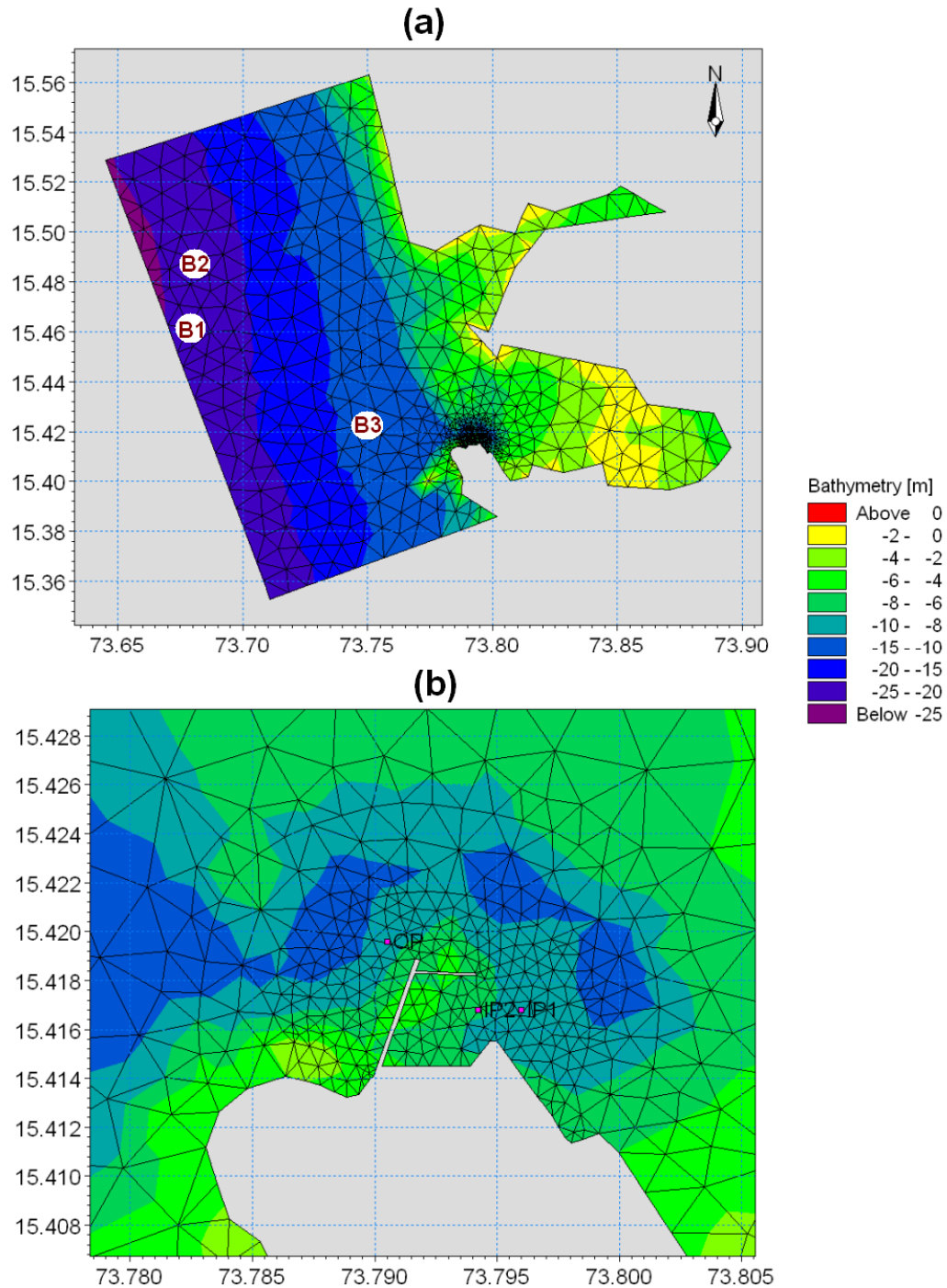


Figure 5-14. (a) Model domain and flexible mesh selected for the wave transformation simulations off Goa and (b) Flexible mesh and bathymetry close to the Port and extraction locations - outside breakwater (OP) and inside breakwater (IP1 and IP2).

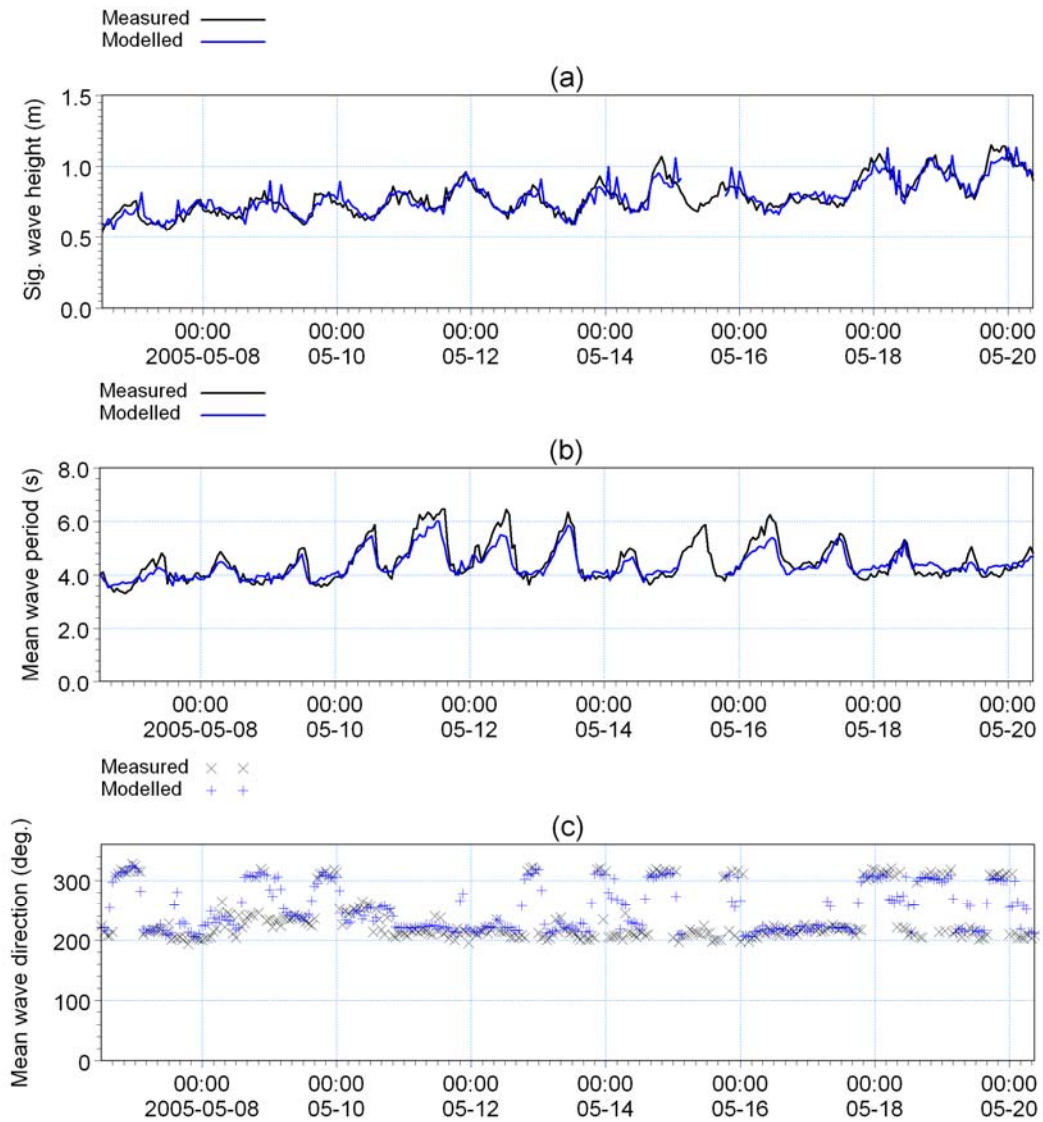


Figure 5-15. Comparison between measured and modelled wave parameters at location B3.

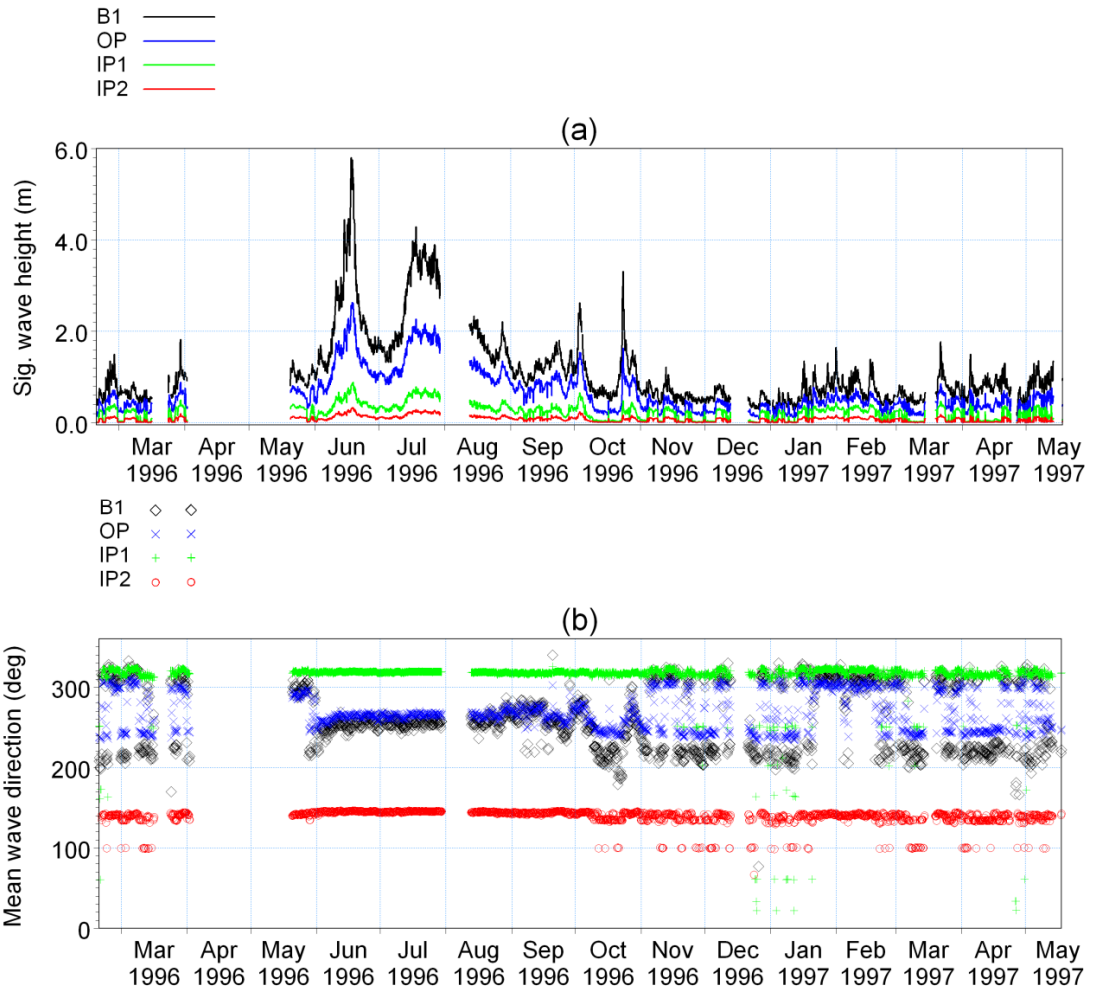


Figure 5-16. Significant wave height and mean wave direction obtained at locations OP, IP1 and IP2 during Feb 1996 – May 1997.

Table 5-5. Maximum, mean and standard deviation of significant wave heights during February 1996 – May 1997 in the vicinity of Mormugao Port.

Location	Significant wave height (m)		
	Maximum	Mean	Standard deviation
OP	2.62	0.66	0.47
IP1	0.89	0.23	0.17
IP2	0.33	0.08	0.06

5.4. Inland vessel's limit off Mormugao Port – a case study

5.4.1. Introduction

Winds, waves and currents are the important driving forces which generate several oceanic phenomena in the coastal and open ocean. Information on winds and waves are very essential for activities such as exploitation of natural resources, ship-routing, design of harbours, breakwaters and jetties, loading & unloading of products from the vessels and navigation of different types of vessels in the coastal region. The lack of adequate reliable wind and wave data has long been recognized as a major limiting factor to such activities along the Indian coast and port & harbour regions. The Ministry of Shipping desires to revise the IVL (inland vessels' limit) notification based on scientific rationale for the following reasons: (i) area of operation of ports has been extended towards the offshore and (ii) new major and minor ports have been developed since 1972. One of the objectives of this initiative is to improve the safety of vessels and onboard personnel. This limit is necessary to prevent damage to any vessel or loss of life.

The study region including the Mormugao Port limit is shown in Figure 1-4a (Chapter 1). The port of Mormugao is formed by a breakwater and a mole. It provides 11 alongside berths and several mooring buoys. The Mandovi river flows into the head of Aguada Bay. The bar at the Mandovi river mouth is subject to frequent change. During southwest monsoon, large breakers break across the bar and river mouth, and makes navigation in and out across the mouth very difficult. The present work is primarily concerned with finding out significant wave heights of the region off Mormugao port. AWS winds, moored buoy winds, NCEP analysed winds and NCMWRF winds are used as input to MIKE 21 - OSW and NSW models.

5.4.2. Data and Methods

In order to get an overall picture of the waves off Goa, the wave data measured off Mormugao (at B1) during February 1996 - May 1997 are analysed. The waves measured off Goa during May 2005 at B2 and B3 are used to study the wave transformation and to analyse the effect of local winds on the generation of wind seas over the region. Moored buoy data, which consists of wind and waves, at a deep water location (DS1) during July - November 1999, May - July 2000, January 2001 and May - September 2001 and at a shallow water location (SW3) during May - September 2001 and October 2004 - March 2005 are also utilised in this study. The location details are given in Table 2-1 and Table 2-2 and marked in Figure 2-3 (in Chapter 2).

AWS winds measured at Dona Paula coastal station during May - September 2004 and April - May 2005 have been analysed to study wind characteristics off Goa during pre-monsoon and SW monsoon periods. In order to predict offshore waves in the north Indian Ocean, the NCEP reanalysis winds and NCMRWF winds are utilised.

Regional (MIKE 21 OSW) and local model (MIKE 21 NSW) domains are selected as given in Figure 3-2 and Figure 3-5 (described in Chapter 3). The wave parameters for the boundary of local model are extracted from the regional model outputs. Significant wave heights derived from simulations have been used to draw IVL limit as follows: (i) regions where significant wave heights (H_s) < 0.6m, (ii) regions where $0.6\text{m} \leq H_s \leq 1.2\text{m}$ and (iii) regions where $1.2\text{m} \leq H_s \leq 2.0\text{m}$.

5.4.3. *Results and Discussion*

Table 5-6 shows monthly variations in the significant wave height and mean wave period off Goa during February 1996–May 1997. The analysis shows that H_s vary from 0.16 to 5.85 m throughout the measurement period. The highest H_s value of 5.85 m and the maximum wave height of 10.47 m were observed in June 1996 when a monsoon depression was formed over the Arabian Sea. An analysis of waves measured at 25 and 15 m water depths off Mormugao, Goa, during May 2005 shows that H_s varies from 0.56 to 1.26 m and from 0.54 to 1.16 m, and mean wave period from 4.4 s to 9.3 s and from 4.4 s to 8.6 s, respectively. The relative changes in wave parameters at these two locations could be attributed to wave transformation due to refraction, shoaling and bottom friction.

A few typical 3 h interval wave spectra for 13 May 2005 are shown in Figure 5-17. The two major peaks present in the wave spectra at two different frequency bands can be attributed to wave trains coming from two different directions. This is a combination of short period wind seas generated due to local winds and long period swells generated far away. Vethamony and Sastry (1986), Rao and Baba (1996) and Sanil Kumar et al. (2004) also observed multi-peaks in wave spectra along the Indian coast.

It has been found from the analysis of AWS winds during May–September 2004 and April–May 2005 that the local winds dominate in pre-monsoon period (April and May), and there exists diurnal variations in wind speed and direction due to localized convective activity. A typical case for 12 May 2005 was highlighted in Figure 4-24. It is evident from the analysis of local winds measured at the coastal station and wave spectra measured off Goa that the diurnal variations in the wave parameters are mainly due to the co-existence of locally generated wind seas over the pre-existing swells.

Table 5-7 shows the statistics of significant wave heights exceeding 2.0 m during southwest monsoon of various years of measurements. Table 5-8 shows the ranges of H_s derived from available moored buoy data off Goa. It has been observed that H_s exceeds 2.5 m during June - August 2004, whereas it is below 2.0 m in September and does not exceed 1.2 m during October 2004 - May 2005. The highest value of 4.30 m obtained in May 2001 was due to an extreme event prevailed in the region. H_s are the highest during June - August and below 2.0 m during the rest of the period. Hence, it is very evident that Mormugao port and Panaji coastal region are safe from large waves, except during June - August.

Figure 5-18 shows a typical H_s distribution off Mormugao port during southwest monsoon. It is very clear that most of the region is influenced by large monsoon waves having H_s greater than 2.5 m. As the inland vessels are smaller in size and they are permitted to ply only during non-monsoon months, especially when H_s are less than 2.0 m, IVL is required to be fixed for non-monsoon months. The outer boundary of the 2.0 m decides the extreme IVL. Accordingly, IVL contours were fixed for all the months. These results will be used by the Ministry of Shipping (MoS) for implementing the IVL. A typical H_s distribution along with IVL contours for a non-monsoon month is shown in Figure 5-19. The existing smooth and partially smooth waterlines (practiced now by the inland vessels) and the port limit are also shown in Figure 5-19. The present study gives hope for larger area of movement for the vessels as seen by the existing waterlines and the proposed IVL.

Table 5-6. Monthly variations in the significant wave height and mean wave period off Goa during February 1996 - May 1997.

Year	Month	Significant wave height (m)	Mean wave period (s)
1996	February	0.33 - 1.50	3.0 - 5.0
	March	0.42 - 1.82	3.0 - 5.7
	April	--	--
	May	0.75 - 1.37	3.7 - 6.3
	June	0.93 - 5.85	4.6 - 9.1
	July	1.32 - 4.29	5.2 - 8.7
	August	1.20 - 3.25	4.4 - 7.5
	September	0.80 - 1.80	4.1 - 8.0
	October	0.47 - 3.31	3.6 - 6.9
	November	0.36 - 1.20	3.1 - 6.5
	December	0.29 - 0.96	2.7 - 6.5
	1997	January	0.27 - 1.65
February		0.38 - 1.39	3.1 - 5.3
March		0.39 - 1.77	3.1 - 5.7
April		0.16 - 1.50	2.8 - 5.7
May		0.38 - 1.36	2.9 - 6.1

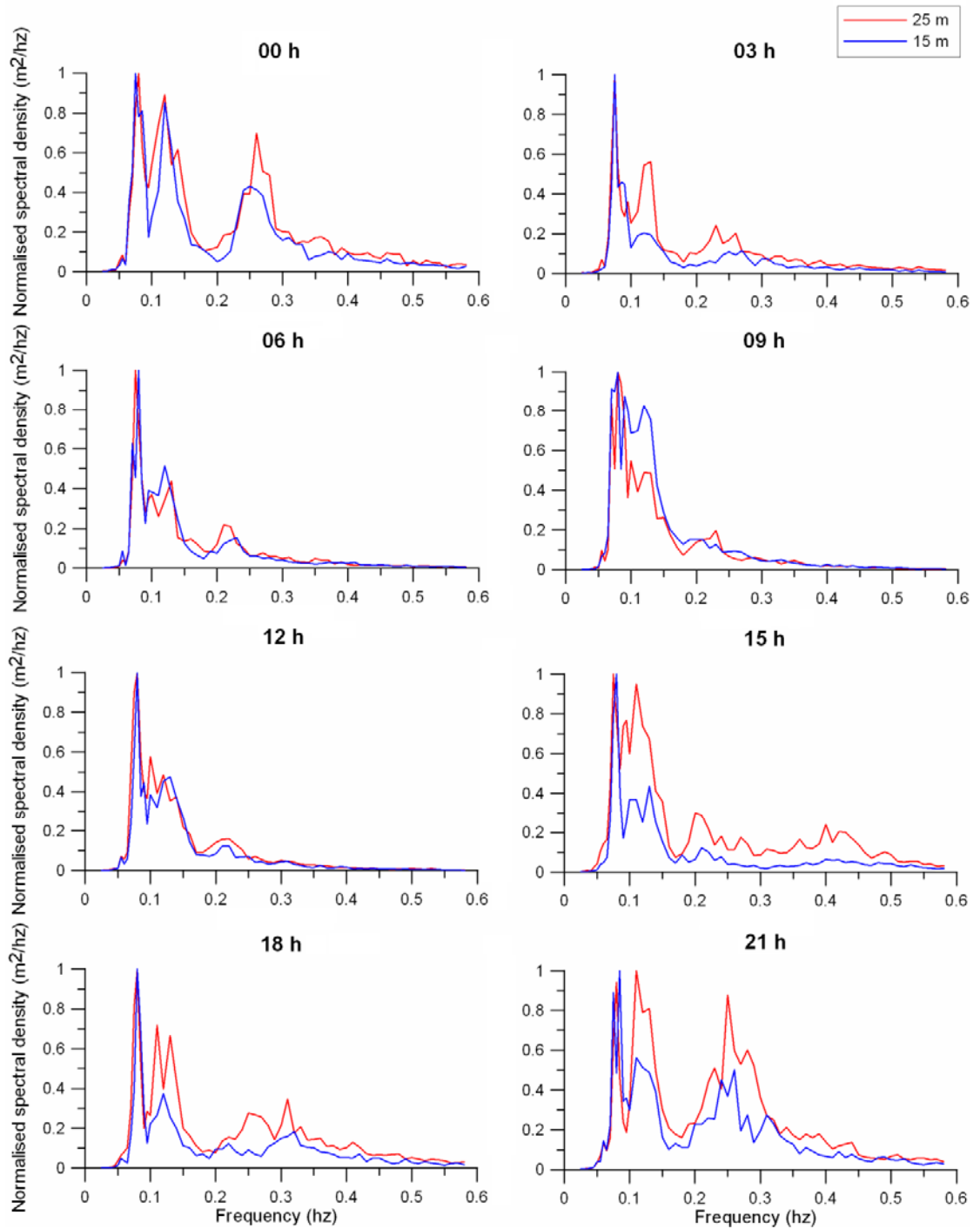


Figure 5-17. Typical wave spectra at 2 locations off Goa during 13 May 2005 (00 h, 03 h, 06 h, 09 h, 12 h, 15 h, 18 h, 23 and 21 h respectively).

Table 5-7. Statistics of significant wave heights exceeding 2.0 m during SW monsoon season.

Month	May		June			July		Aug.		Sep.
Year	2001	2004	2001	2002	2003	2001	2003	2001	2003	2001
Total wave heights	237	247	178	124	240	145	246	218	118	230
$H_s > 2.0$ m	59	20	120	36	151	71	228	78	52	0
% of $H_s > 2.0$ m	24.9	8.1	67.4	29	62.9	49	92.7	35.8	44.1	0

Table 5-8. Range of significant wave height derived from available moored buoy data off Goa.

Months	Years				
	2001	2002	2003	2004	2005
Jan		0.23 -1.41	0.33 -1.15	0.23 -1.25	0.33 -1.8
Feb	0.31 -1.41	0.31 -1.41	0.38 -1.50	0.39 -1.02	0.35 -1.45
Mar	0.31 -1.56	0.47-1.09	0.30 -1.87	0.16 -1.17	0.41-1.21
Apr				0.55 -1.17	
May	0.55 - 4.30	0.53 -1.87	0.46 -1.53	0.63 -2.27	
Jun	0.80 - 3.91	0.96 - 4.41	0.78 -3.80		
Jul	1.48 - 2.81		1.61 -3.78		
Aug	1.56 - 2.97		1.26 -2.52		
Sep	0.55 -1.88				
Oct	0.39 -1.48	0.42 - 1.42		0.31-1.31	
Nov	0.31 - 0.78	0.38 -0.76		0.29 -1.05	
Dec	0.23 - 0.70	0.30 -1.29	0.23-1.02	0.31-0.96	

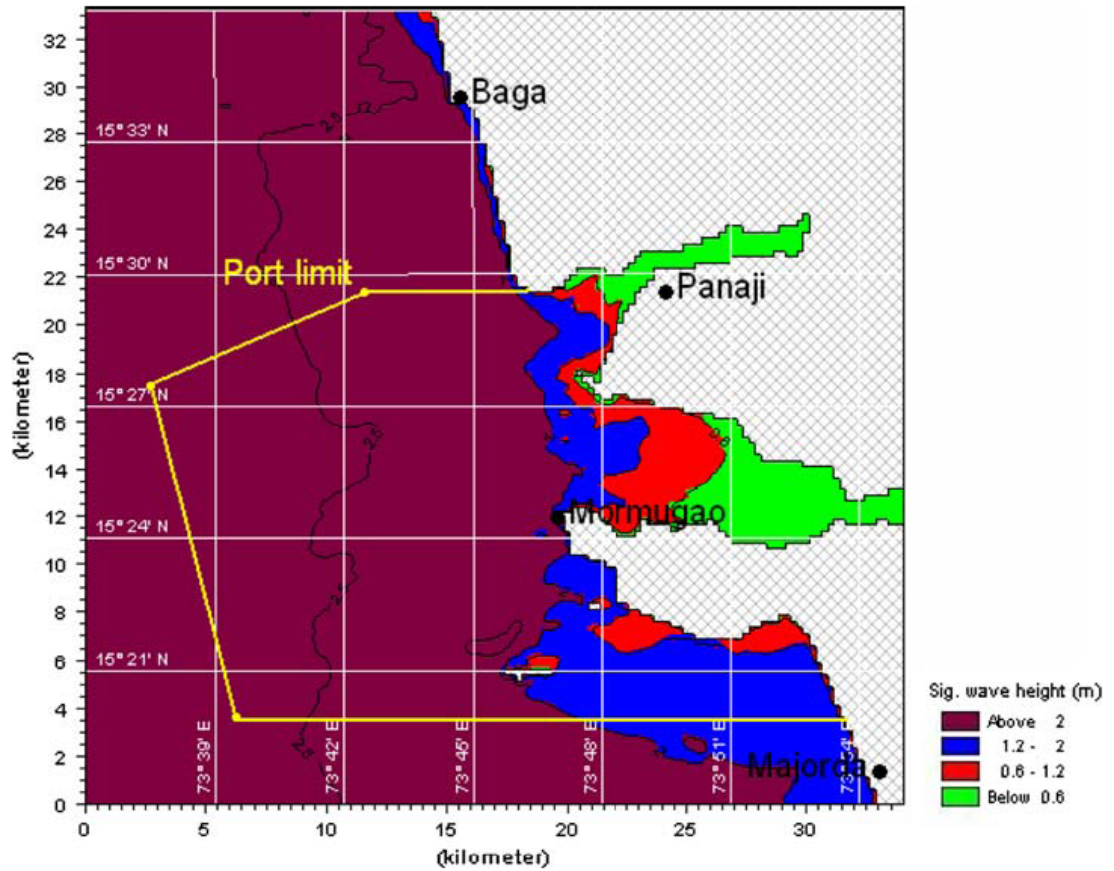


Figure 5-18. Typical significant wave height distribution off Mormugao Port during southwest monsoon (region showing the Mormugao Port limit is marked).

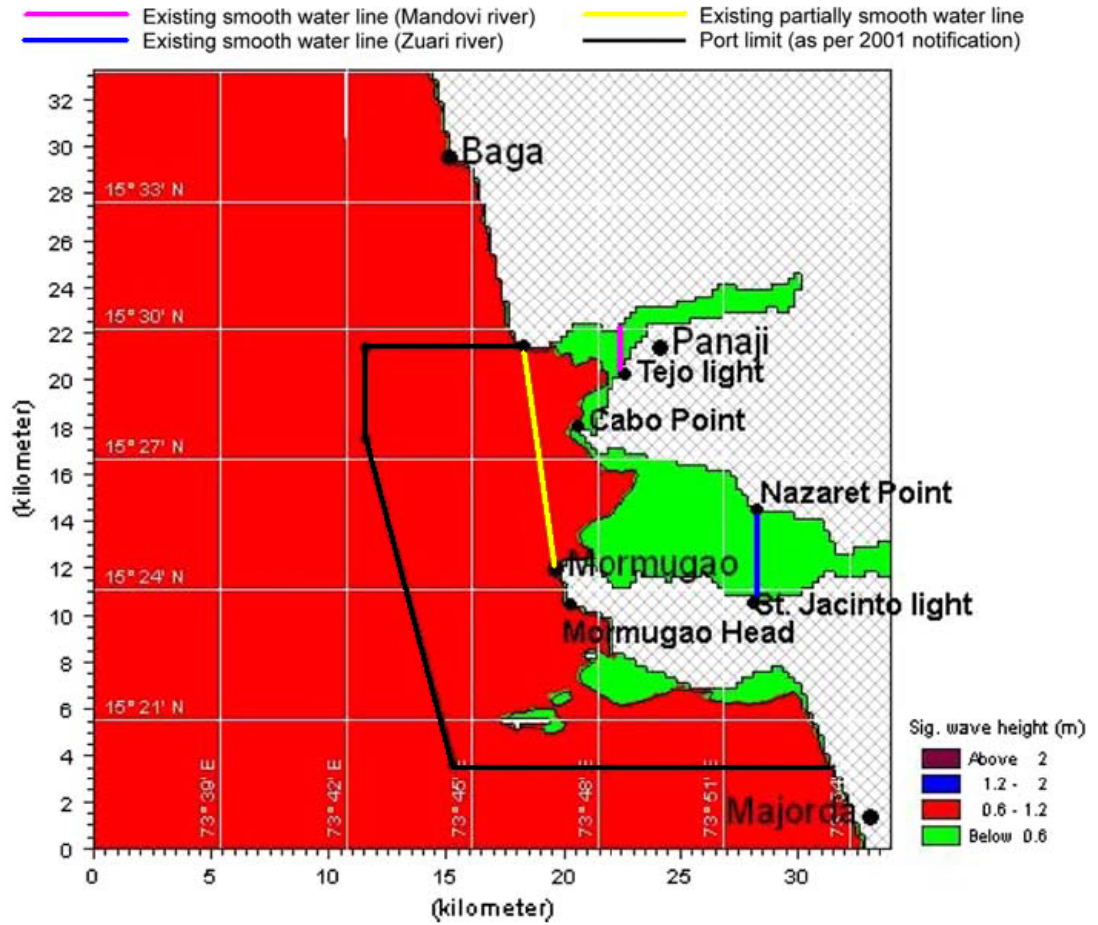


Figure 5-19. IVL regions demarcated based on wave heights (April 2005) with existing smooth and partially smooth waterlines.