

Wave transformation and attenuation along the west coast of India: measurements and numerical simulations

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Abstract

Waves measured at a few locations along the west coast of India were analysed to study modification and attenuation of wave energy in the nearshore regions. It has been found that the reduction in wave height is relatively lower (less than 10%) between two nearshore depths off Goa (25m and 15m) and Ratnagiri (35 m and 15 m), central west coast of India and is higher (22%) off Dwarka (30 m and 15 m), northwest coast of India. It is observed that the diurnal variation in waves decreases from north to south along the coast, as the intensity of sea breeze decreases from north to south. Swell attenuation due to opposing winds (from NE) is observed along the Ratnagiri coast during NE monsoon. The growth of wind seas (from NE) towards offshore and their modification by opposing swells (from SW/SSW) significantly contributed to the reduction in wave heights at shallow water depths off Dwarka. The role of opposing winds in the attenuation of swells along the west coast of India during NE monsoon season is significant. Numerical simulations were carried out to study the wave transformation between the depths 100, 50, 20, 10 and 5 m off Mumbai, Goa and Kochi. Diurnal variation is evident during the pre-monsoon season, and the magnitude of variation decreases from north to south.

Keywords: wave spectra; wave attenuation; wave propagation; diurnal variations; wind waves; sea breeze.

1. Introduction

Wave-induced current is the major driving force for nearshore circulation and sediment transport in the surf zone and inner continental shelf [Wright *et al.*, 1991]. In shallow water, refraction and shoaling induce variations in the wave height. The most important physical processes which affect the waves in shallow waters are wave energy dissipation due to bottom friction [Shemdin *et al.*, 1980], bottom induced wave breaking [Battjes and Janssen, 1978] and wave-wave interaction [Madsen and Sorensen, 1993]. 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]. Vortex ripples and their feedback on the waves through enhanced bottom roughness determine the dissipation of wave energy in the bottom boundary layer [Zhukovets, 1963]. Dissipation due to bottom friction is the primary wave attenuation mechanism in swell dominated conditions over a wide continental shelf [Ardhuin *et al.*, 2003]. Baba *et al.* [1983, 1985] reported that nearshore wave energy decreases from south to north along the southwest (SW) coast of India.

Waves along the west coast of India are dominated by swells during southwest (SW) and northeast (NE) monsoon seasons and by wind seas during pre-monsoon season [Vethamony *et al.*, 2011; Kumar *et al.*, 2000; Rao and Baba, 1996]. Kurian and Baba [1987] showed the importance of shelf slope in controlling spatial contrasts in bottom frictional attenuation and consequently the coastal energy regime. Wave heights along the west coast of India are generally low during NE and pre-monsoon seasons, and higher during SW monsoon [Aboobacker *et al.*, 2011; Vethamony *et al.*, 2009; Kumar and Kumar, 2008].

Waves along the west coast of India are generally multi-peaked [Kumar *et al.*, 2003], which is due to co-existence of swell and wind sea [Vethamony *et al.*, 2009]. The role of winds on transforming the properties of swells is not well understood. However, wind seas are modified by swells and wind sea slope is preserved during their interactions [Hansen and Phillips, 1999]. Aligned swells can shorten and attenuate the wind seas [Chu *et al.*, 1992]. The present study aims at understanding (i) diurnal variation in wave parameters and wave transformation at various locations along the west coast of India (WCI) and (ii) modification of wave parameters due to opposing/aligned winds and wind seas.

Lack of adequate reliable wind and wave data has long been recognized as the limiting factor for coastal, port and harbour operations. Global winds such as NCEP (National Centers for Environmental

Prediction, USA) re-analysis winds and IFREMER/CERSAT (French Research Institute for Exploration of the Sea / Centre for Satellite Exploitation and Research, France) blended winds are generally adequate for the prediction of wave conditions around the globe. In the present study, IFREMER/CERSAT blended winds were applied to re-produce the wave characteristics in the Indian Ocean. Waves measured at nearshore depths off Goa, Ratnagiri and Dwarka (2 locations each) along with numerical model results have been used to study wave energy modification and attenuation along the WCI for different seasons.

2. Study area

Study region is presented in Figure 1. The prevailing seasons over this region are: SW monsoon (June – September), NE monsoon (October – January) and pre-monsoon (February – May). Large scale winds are weaker and sea breeze is prevalent along the west coast of India during pre-monsoon season [Aparna *et al.*, 2005]. The strength of the large scale winds during pre-monsoon season is 3-5 m/s; they become weaker while sea breeze prevails - reach upto 5 m/s along the central west coast of India [Dhanya *et al.*, 2010]. Shamal swells generated due to the action of Shamal winds in the Arabian Sea can influence the west coast of India during NE and early pre-monsoon seasons [Aboobacker *et al.*, 2011]. Shamal winds are the NW winds associated with an extra-tropical weather system prevailing over the Arabian Peninsula during winter as well as summer [Hubert *et al.*, 1983].

Pre-monsoon season is characterized by the sea breeze-land breeze system along the west coast of India [Dhanya *et al.*, 2010; Rani *et al.*, 2010; Subrahamanyam *et al.*, 2001]. They observed that the sea breeze is blowing from the NW and the land breeze is from northeast or north. The sea breeze is usually blows perpendicular to the coastline, however, along the west coast of India sea breeze blows with an inclined angle. Though the coastal topography plays a major role in maintaining the NW direction for the sea breeze, the actual phenomena is not yet completely understood. Vethamony *et al.*, (2011) indicate that the waves along the west coast of India are influenced by sea breeze during the active sea-breeze period (day hours), after the cessation of the sea breeze the waves revert back to the prevailing swell conditions, and hence a diurnal pattern in the wave parameters is noted. The land breeze (from NE) is low in magnitude and does have minor impact on the predominant swells from SW (both swells and land breeze are in opposite direction). Sea breeze characteristics along the east coast of India are not consistent as seen along the west coast of India, though there exist sea breeze-land breeze system at

different seasons. Srinivas *et al.*, (2006) observed sea breeze activity along the east coast of India during pre-monsoon season (May), and the direction varies between 140 and 180°. Simpson *et al.* (2007) observed diurnal patterns in wind speed and direction along the Chennai coast during SW monsoon season caused by sea breeze during the day hours (08 h to 17 h local time) and SW monsoon winds (magnitude is low along the east coast of India) rest of the hours. The sea breeze blows from 140° (with an inclination of approximately 45° to the coast, as seen along the west coast of India) and SW monsoon winds blows from approximately 260°. Wind direction and wave direction described here are with respect to the north (0°) and indicated as “coming from”.

<Figure1>

3. Data used

Wave measurements have been carried out at nearshore depths off Goa (at 25 and 15 m), Ratnagiri (35 and 15 m) and Dwarka (30 and 15m) (Fig. 1b) using Directional Wave Rider Buoys [Datawell, 2001]. The details of location and duration of measurements are given in Table 1. The wave rider buoy can function within -20 to +20 m of surface elevation with an accuracy of 3% within the wave period of 1.6 to 30.0 s. The direction accuracy is within 0.5° to 2.0° depending on the latitude. The sampling duration is 20 minutes during which waves with frequencies 0.025 and 0.58 Hz are measured in the form of wave spectra. Wind sea and swell parameters were separated from the spectra using the methodology given by Gilhousen and Hervey [2001], where the separation frequencies are dynamic in each observation; vary between 0.1 and 0.26 Hz.

<Table 1>

Simultaneous wind measurements were carried out with a sampling period of 10 minutes using Autonomous Weather Station (AWS) of National Institute of Oceanography (NIO, Goa). The AWS was set at a height of 10 m at Dwarka and Ratnagiri coastal stations and at a height of 43.5 m at Dona Paula (Goa) coastal station. Dwarka AWS station is not fully exposed to the open coast and hence, some of the relevant information is missing in the wind data. Further, winds at 43.5 m height (Goa region) were reduced to 10 m height using logarithmic wind profile [Roland, 1988] as follows:

$$U(z) = \frac{U_s}{z} \ln(z/z_0) \dots\dots\dots (2.1)$$

where, U is the wind speed measured at the height $Z=43.5\text{m}$, U_* the surface friction velocity, $Z_0(=0.22\text{m})$ the aerodynamic roughness length (the AWS is placed on top of the NIO building – approximately 300 m away from the sea, and the area is surrounded by low lying trees) and $\kappa(=0.4)$ is the von Karman constant.

4. Model setup

Numerical wave model was set up to simulate waves during 2005 and Dec 2007 – Feb 2008 using MIKE 21 SW, a third generation spectral wave model developed by DHI Water & Environment, Denmark [DHI, 2009]. The model simulates growth, decay and transformation of wind waves and swells in offshore and nearshore areas. The model includes wave growth by action of wind, non-linear wave-wave interaction, dissipation by white-capping, dissipation by wave breaking, dissipation due to bottom friction, refraction due to depth variations, and wave-current interaction. Please note that the effect of surface currents were not included in the present simulations. The formulation is based on the wave action conservation equation [Komen *et al.*, 1994; Young, 1999], where the directional-frequency wave action spectrum is the dependent variable. An unstructured mesh technique has been used on the geographical domain. The discretization of the governing equation is geographical and spectral space is performed using cell-centered finite volume method. The time integration is performed using a fractional step approach where a multi-sequence explicit method is applied for the propagation of wave action [DHI, 2009].

The model domain (Indian Ocean) is bounded between 65°S to 30°N (latitude) and 20°E to 125°E (longitude). A triangulated mesh is generated with a maximum size of triangles: 1.5° (south Indian Ocean), 0.75° (north Indian Ocean), 0.25° (coastal region), 0.09° (approx. 10 km, along the west coast of India) and 0.014° (approx. 1.5 km, select coasts such as Goa, Ratnagiri, Mumbai, Dwarka and Kochi). The model bathymetry was generated using ETOPO5 data ($5'$ interval) obtained from NGDC (National Geophysical Data Center, Colorado, USA) for deep water region and improved bathymetric data sets for Indian coasts by Sindhu *et al.* [2007] for shallow water region. IFREMER/CERSAT blended surface winds [Bentamy *et al.*, 2006, 2009] available for every 6 hours with a spatial resolution of $0.25^\circ \times 0.25^\circ$ were applied as the input parameter. These winds are obtained by blending QuikSCAT winds to the operational ECMWF winds over the global oceans. The quality of this data has been checked with buoy

winds and the match is very good [Bentamy et al., 2007]. Aboobacker *et al.* [2011] used these winds to study the Shamal wind characteristics in the Arabian Sea.

Initial conditions to the model were applied using the JONSWAP fetch growth formulation [Komen *et al.*, 1994]. The model results such as significant wave height (H_s), mean wave period (T_m) and mean wave direction (θ) have been obtained for every 1hour. The model was previously validated for Ratnagiri and Goa regions for the same study period [Aboobacker *et al.*, 2011; Vethamony *et al.*, 2011]. 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) were extracted and analysed to study the wave attenuation.

Though the dissipation term in the third generation models is a combination of cumulative and inherent wave-breaking dissipation, dissipation due to interaction with turbulence in the air-sea interface with the adverse wind etc.; attention should be given to each individual process. The model used in this study is capable of resolving the issues such as superimposition of multi-directional waves [e.g., Vethamony *et al.*, 2011] and effect of opposing winds on swells to some extent. However, traditional tuning of source would be insufficient to completely justify the actual mechanism. In this view Zieger *et al.*, [2011] implemented an observation-based dissipation and input terms in a third generation wave model, and tested satisfactorily for the wave hindcasting in the Lake Michigan, though it needs further improvements before general implementation.

5. Results and discussion

5.1 Wave observations

Variations in significant wave heights at the nearshore depths and wind direction off Goa, Ratnagiri and Dwarka are shown in Figure 2, and the relative dominance of directional swell and wind sea parameters at deeper depth in each location are shown in Figure 3. Since the measurements were carried out during fair weather season, we assume that wave height attenuation is very less at larger depths (>25 m). Wave height attenuation at 15 m depth off Goa and Ratnagiri is relatively less (< 10%) compared to Dwarka (22%) (Table 2). The gradient in water depths caused this reduction to some extent; other factors are opposing wind, wind sea, etc.

<Table 2>

<Figure2>

<Figure3>

Figure 4 shows winds along the coasts of Goa, Ratnagiri and Dwarka during the wave measurement period. During pre-monsoon season, the prevailing sea breeze generates local wind seas (from NW) which grow progressively towards the coast off Goa [Vethamony *et al.*, 2011]. In this region, swells approach from SW (approx. 225°) and wind seas NW (approx. 315°), that is, approximately with 90° inclination between swells and wind seas. The swells are least attenuated (4.7%), and a reduction of about 16% (Table 2) is obtained for wind seas, which is significant (3 times the swell attenuation), though the prevailing conditions are favorable for wind sea growth towards the coast. Since the attenuation of long-period swells is much lower than that of short-period wind seas, the reduction in wind sea height cannot be attributed to the wave-bottom interaction alone. In a similar study, Sheremet and Stone [2003] pointed out that large reduction in short wind seas could happen if very high suspended sediment is present. It may be noted that suspended sediment concentration (SSC) off Goa during the measurement period is not available to support the above hypothesis. Masselink and Pattiaratchi [1998] found that sea breeze can cause sediment re-suspension in the nearshore regions. However, muddy waters are not present off the Goa coast. Another reason for wind sea attenuation could be interaction of wind seas with sea breeze-induced currents. It may also be noted that wind sea and current are in the same direction (to SE) during this period, and it is possible that following current might have reduced the wind sea height. Since there are no current measurements during the study period, we have not included wave-current interaction in the present study.

<Figure 4>

The attenuation in swell heights (10.6%) and wind sea heights (9.0%) off Ratnagiri are moderate during the measurement period. Considering the interaction of aligned/opposite wind, wind sea and swell, the following processes are significant in the wave transformation: (i) suppression of wind sea growth by aligned swell [e.g., Donelan, 1987; Shyu and Phillips, 1990; Chen and Blecher, 2000] and (ii) attenuation of swell by opposite wind [e.g., Mitsuyasu and Yoshida, 2005]. Similar scenario is observed off Ratnagiri while analyzing the wave transformation. During winter season (NE monsoon and early pre-monsoon), waves along the west coast of India are influenced by Shamal winds [Aboobacker *et al.*, 2011]. Figure 4b shows the presence of Shamal winds along the Ratnagiri coast with wind speed

ranges between 4 and 9 m/s and wind direction between NW and N. Apart from Shamal winds, NE monsoon winds (from NE) are also accountable. It has been found that wind sea heights are nearly the same at both the depths (35 m and 15 m) during Shamal events. Also, both swells and wind seas were observed in the same direction (between NW and N). Even though there exist relatively stronger winds, further growth in wind seas towards the coast was not occurred. This could be due to the interaction of wind seas with aligned swells, during which the wind sea growth is suppressed by aligned swell, supporting the findings of Chu *et al.* [1992] and Hanson and Phillips [1999] that the wind seas are shortened and attenuated by aligned swells.

The attenuation of swells off Ratnagiri is primarily due to wave-bottom interaction. However, the reduction in swell heights is relatively low during Shamal events. This gives rise to the possibility of swell growth in aligned winds, since the wind is sufficiently high to alter the swell characteristics. Mitsuyasu and Yoshida [2005] found that the growth rate of swell caused by aligned wind is almost same as the magnitude of the attenuation rate of swell by an opposing wind. This is true with the attenuation of SW swells in the prevailing NE wind conditions, where the winds oppose the swells, irrespective of the Shamal conditions. Wave attenuation is higher for the swells during this period. Energy and momentum fed from the opposing wind will get trapped at the crest of swells, which contribute significantly to the attenuation of the swell [Mahony, 1977].

Three different conditions prevailed off Dwarka during NE monsoon season: (i) dominance of NE wind seas due to strong NE winds (Figure 5a), (ii) dominance of NW wind seas due to local sea breeze (Figure 5b) and (iii) dominance of S/SSW swells due to weakening of local wind seas (Figure 5c). The growth in NW wind seas is represented in Figure 5d. Figure 6 shows typical NE monsoon winds over the Arabian Sea. NE wind seas grow while moving away from the coast (15m water depth off Dwarka is very close to the coast, and the available fetch for NE wind seas is very limited) as the winds are blowing from land to sea, during which the wind seas and swells are nearly in the opposite direction. The NE wind causes swell attenuation (from S/SSW) to a considerable amount; conversely, the swell intensifies the NE wind sea due to increase in wind shear stress. In the presence of opposing swell, the surface drag coefficient (C_D) increases by more than a factor of 4 [Sullivan *et al.*, 2008; Donelan *et al.*, 1997]. In this scenario, the attenuation of swells (15.6%) can be attributed to the effect of opposing wind as well as wave-bottom interaction. In fact, the growth of wind seas towards offshore (27.8%

increase at 30 m depth compared to 15 m depth) and their modification by opposing swells could be conveniently contributed to the reduction in wave heights at shallow water depths (Table 2).

<Figure5>

NE monsoon winds are normally weak in the Arabian Sea. However, when these winds get intensified, they spread over the entire Arabian Sea with wind speeds ranging upto 15m/s (Figure 6). These winds not only attenuate the opposing (S/SSW) swells, but also generate NE swells (the swell generation and propagation are away from the coast). S/SSW swells become prominent as NE wind weakens; however, NW wind seas are generated due to local sea breeze, which in turn dominates upon intensification by the sea breeze. This was evident while analysing the wave heights at two depths off Dwarka (Figure 2). For example, the wave data during 12 – 22 Dec 2007 represents NE wind sea dominated condition, whereas, that during 23 – 30 Dec 2007 indicates a NW wind sea dominated condition. Available fetch is sufficiently high for the NW wind compared to NE wind, and hence, the waves from NW are relatively higher compared to the NE wind sea dominated condition. Since the wind sea (NW) growth is towards the coast, their attenuation between 30 and 15 m depths are considerably less. Effects of following swell or opposing wind are negligible for the NW wind seas. Multi-directional peaks (from NE and NW) were observed in the wind sea spectrum at several occasions (Figure 5a). This represents the simultaneous occurrence of two local wave systems; one developed at a nearby area of the measurement location (peak energy from the NW), and the other formed within the region itself (peak energy from the NE). The peak frequencies of the NW wind sea energy vary between 0.15 and 0.35 Hz and that of NE wind sea energy between 0.30 and 0.55 Hz.

<Figure6>

NE wind sea peaks become negligible as the NE winds weaken, hence SSW swells are the dominating wave systems over this region (Figure 5c). However, NW wind seas are present in the wave spectrum. As these wind seas are due to sea breeze activity, the peak energy of these wind seas varies according to the sea breeze development and intensity in a diurnal cycle (Figure 5d).

5.2 Model results

The wave model has been validated with the measurements off Goa, Ratnagiri and Dwarka. Figure 7 shows the comparison between measured and modeled significant wave height and mean wave period. The modeled wave parameters show reasonably good comparison with the measurements. Table 3

shows the statistical parameters such as correlation coefficient, bias, r.m.s. error and scatter index between the model and measurements which shows that model results are in good agreement with the measurements. The correlation coefficient for the significant wave height ranges between 0.63 and 0.85, and that for the mean wave period ranges between 0.54 and 0.77. The biases and r.m.s errors are within the acceptable limits. The scatter index is reasonably good, except for Dwarka.

<Figure 7>

<Table 3>

Modeled H_s at various depths (100, 50, 30, 20, 10 and 5 m) off Mumbai, Goa and Kochi (Figure 8) indicate that the waves in the nearshore regions have undergone significant transformation. The above three locations represent three sectors (northwest coast, central west coast and southwest coast) of the entire west coast of India. Attenuation due to bottom friction is high at depths below 10 m for low and moderate waves. Larger waves (during SW monsoon) are attenuated at intermediate depths (between 10 and 30 m). If we take a particular depth (between 100 and 5m), we found that H_s decreases from Mumbai to Kochi (north to south). For example, the maximum H_s observed at 100 m depth off Mumbai, Goa and Kochi are 6.2, 5.2 and 4.1 m, respectively (all of them represent the same event). Similarly, wave height attenuation is in the decreasing order of magnitude from Mumbai to Kochi. During the post-monsoon season (October –January), the wave heights are in decreasing order from north to south. NE monsoon winds are significant at the north; hence, the wave heights at deeper locations off Mumbai are higher compared to Goa and Kochi.

<Figure8>

Significant wave heights off Mumbai, Goa and Kochi during pre-monsoon season are illustrated in Figure 9. The diurnal variations have been observed at all depths off Mumbai, Goa and Kochi. Vethamony *et al.* [2011] identified that waves off Goa exhibit diurnal variations during pre-monsoon season which is due to superimposition of wind seas with pre-existing swells. The present study not only supports their findings but also gives evidence for the existence of diurnal patterns all along the west coast of India during pre-monsoon season. It reveals that the superimposition of wind seas with pre-existing swells and the associated diurnal characteristics are typical for the west coast of India. However, order of variation decreases towards the south (least variations observed off Kochi). The wind data also present a decreasing trend in sea breeze towards the south [Figure 9]. The seaward extent of

sea breeze varies along the west coast of India - lower at the south (160 km off Kochi) and higher at the north (210 km off Mumbai) during the pre-monsoon season (Aparna et al., 2005). We have also analysed the wave parameters along the east coast of India, which however show diurnal pattern though they are not similar to the conditions prevailing along the west coast of India. During pre-monsoon season, diurnal variations can be seen along the east coast of India with increasing magnitude from south to north.

<Figure9>

Seasonal and annual statistics (mean and standard deviation) of significant wave heights at various depths off Mumbai, Goa and Kochi are listed in Table 4. The seasonal variations in mean H_s are graphically represented in Figure 10. Significant reduction in wave heights due to bottom dissipation has been observed at shallow depths. The mean H_s are nearly the same during pre-monsoon and NE monsoon seasons. 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 the effect is highly visible off Mumbai and Goa regions.

<Table 4>

<Figure10>

6. Conclusions

Wave data collected off Goa, Ratnagiri and Dwarka were analysed to study the modification and attenuation in wave energy in the nearshore depths. Short wind seas off Goa were highly attenuated compared to the longer swells during the pre-monsoon season. The diurnal variations in wave parameters observed during pre-monsoon season are typical for the west coast of India as evident from the modelling results. However, the magnitude of variation decreases from north to south along the coast, as the intensity of sea breeze decreases from north to south. Higher reduction in wave heights is associated with high wind speeds indicating that role of refraction process is significant. The study on reduction in wind seas off Goa during pre-monsoon season will be taken up as future research. A detailed field study is planned to investigate the mechanism involved in the short wave attenuation along this part of the coast.

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Table captions

Table 1. Wave measurement location, water depth, duration and data interval.

Table 2. Mean H_s and % reduction at various measurement locations along the west coast of India (for one month period as given in Table 1).

Table 3. Statistical parameters between measured and modelled significant wave height and mean wave period off Goa, Ratnagiri and Dwarka

Table 4. Seasonal and annual mean and standard deviation of significant wave heights at various depths off Mumbai, Goa and Kochi

Figure captions

Figure 1. (a) Study area, (b) Bathymetry contours and measurement locations off Goa, Ratnagiri and Dwarka.

Figure 2. Significant wave heights measured at the nearshore depths off: (a) Goa, (b) Ratnagiri and (c) Dwarka and Autonomous Weather Station winds measured at (a) Goa, (b) Ratnagiri and (c) Dwarka.

Figure 3. Significant wave heights and directions for the swell and wind sea parameters at (a) 25 m depth off Goa (b) 35 m depth off Ratnagiri and (c) 30 m off Dwarka.

Figure 4. Wind rose: (a) Goa during 01-21 May 2005, (b) Ratnagiri during 24 Jan – 25 Feb 2008 and (c) Dwarka during 05 Dec 2007 – 05 Jan 2008.

Figure 5. Wave energy spectra off Dwarka: (a) NE wind sea dominated, (b) NW wind sea dominated, (c) SSW swell dominated conditions, and (d) spectra showing NW wind sea growth. WS – wind speed; WD – wind direction and MWD – mean wave direction. Both WD and MWD indicate “coming from”.

Figure 6. Dominating NE monsoon winds (IFREMER/CERSAT) over the Arabian Sea during 14 December 2007.

Figure 7. Comparison between measured and modeled (a) significant wave height and (b) mean wave period off Goa, Ratnagiri and Dwarka.

Figure 8. Significant wave heights simulated at various water depths off Mumbai, Goa and Kochi during 2005.

Figure 9. Diurnal variations in significant wave heights simulated and wind speed at various water depths off Mumbai, Goa and Kochi during pre-monsoon season (May 2005).

Figure 10. 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.

Tables

Table 5. Wave measurement location, water depth, duration and data interval.

Region	Location	Water depth (m)	Duration	Season	Data interval (h)
Goa	15.488° N, 73.700° E (B2)	25	01 - 21 May 2005	Pre-monsoon	1.0
	15.423° N, 73.749° E (B3)	15	06 - 21 May 2005	Pre-monsoon	0.5
Ratnagiri	17.004° N, 73.120° E (B4)	35	24 Jan - 25 Feb 2008	NE monsoon	0.5
	17.007° N, 73.250 °E (B5)	15	24 Jan - 25 Feb 2008	NE monsoon	0.5
Dwarka	22.088° N, 69.040° E (B6)	30	05 Dec 2007 - 05 Jan 2008	NE monsoon	0.5
	22.088° N, 69.090° E (B7)	15	05 Dec 2007 - 05 Jan 2008	NE monsoon	0.5

Table 6. Mean H_s and % reduction at various measurement locations along the west coast of India (for one month period as given in Table1).

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)	
	Mean H_s (m)	0.86	0.78	0.96	0.87	0.50	0.39
	Difference (m)	0.08		0.09		0.11	
Resultant wave	% reduction	9.3		9.4		22.0	
	Mean H_s (m)	0.64	0.61	0.66	0.59	0.32	0.27
	Difference (m)	0.03		0.07		0.05	
Swell	% reduction	4.7		10.6		15.6	
	Mean H_s (m)	0.56	0.47	0.67	0.61	0.36	0.26
	Difference (m)	0.09		0.06		0.10	
Wind sea	% reduction	16.1		9.0		27.8	

Table 7. Statistical parameters between measured and modelled significant wave height and mean wave period off Goa, Ratnagiri and Dwarka.

Parameters	Locations	Correlation coefficient	Bias	RMS error	Scatter Index
Sign. Wave height	Goa	0.65	0.03	0.18	0.22
	Ratnagiri	0.85	0.02	0.20	0.20
	Dwarka	0.63	0.05	0.21	0.42
	Goa	0.77	0.19	0.81	0.19
	Ratnagiri	0.67	0.50	0.76	0.17
	Dwarka	0.54	-0.42	0.73	0.29

Table 8. 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

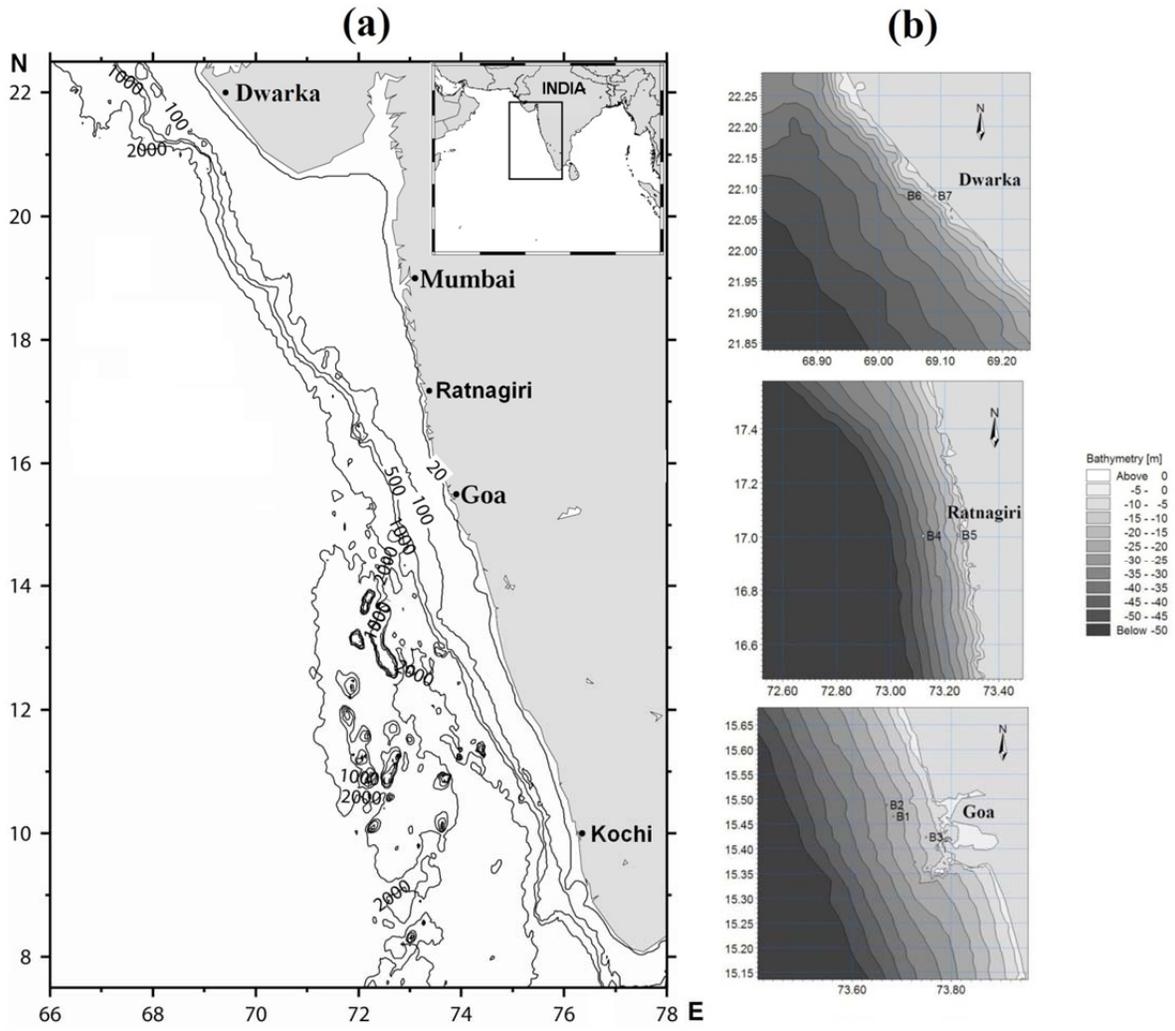


Figure 1

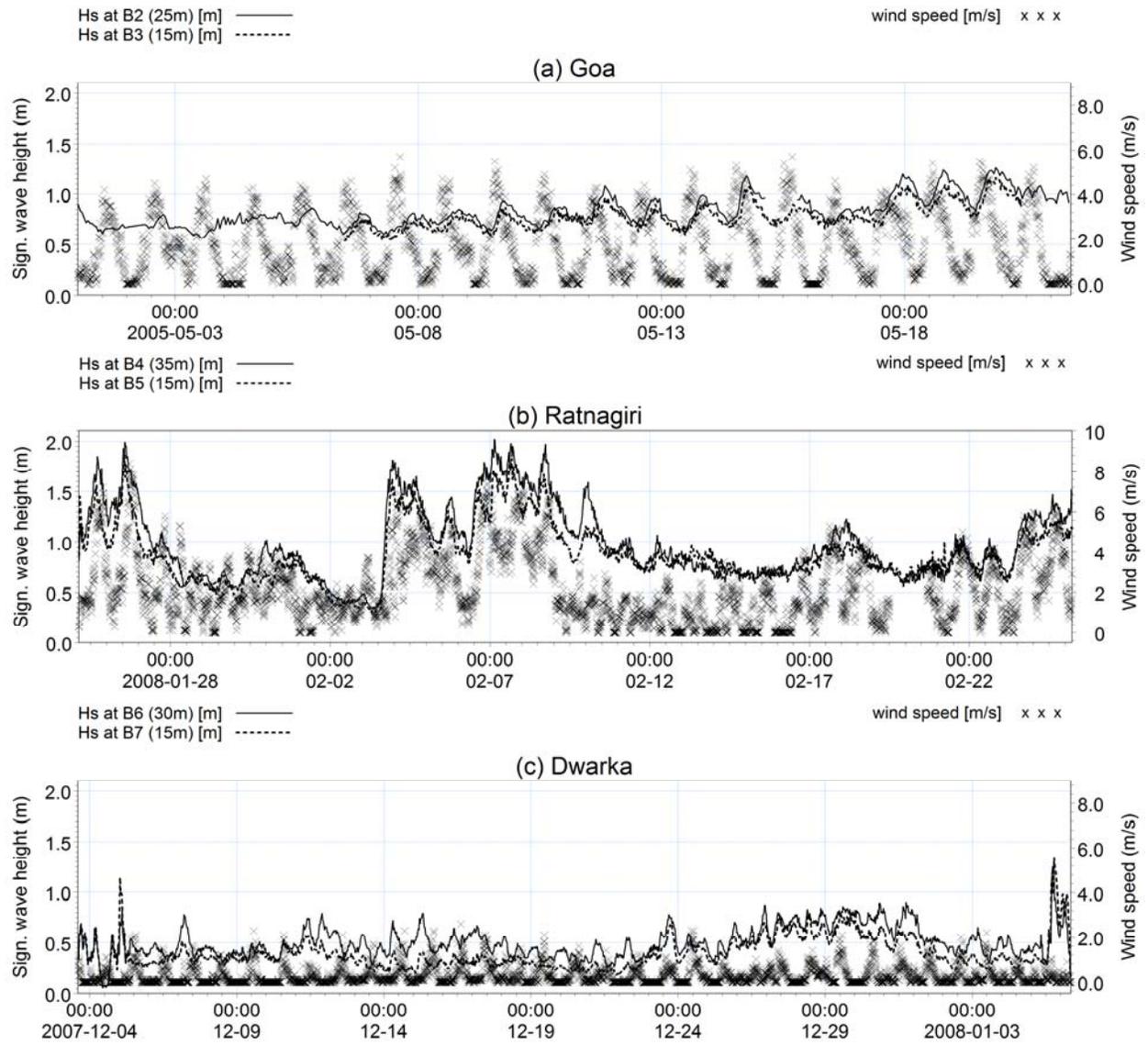


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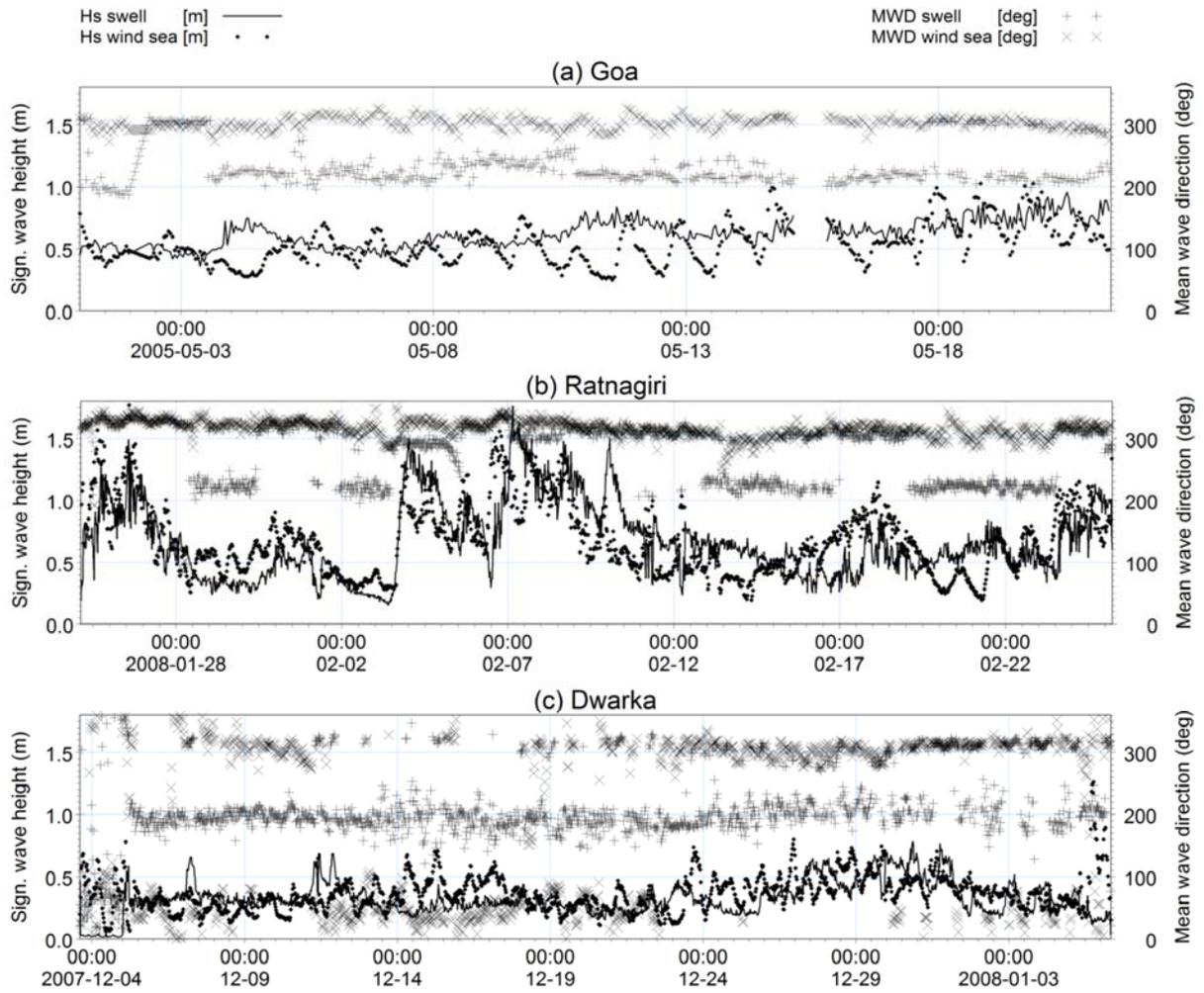


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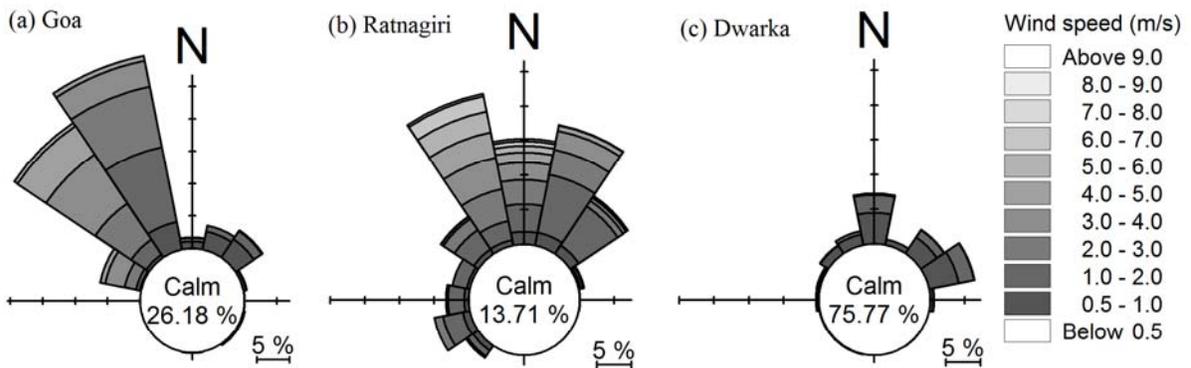


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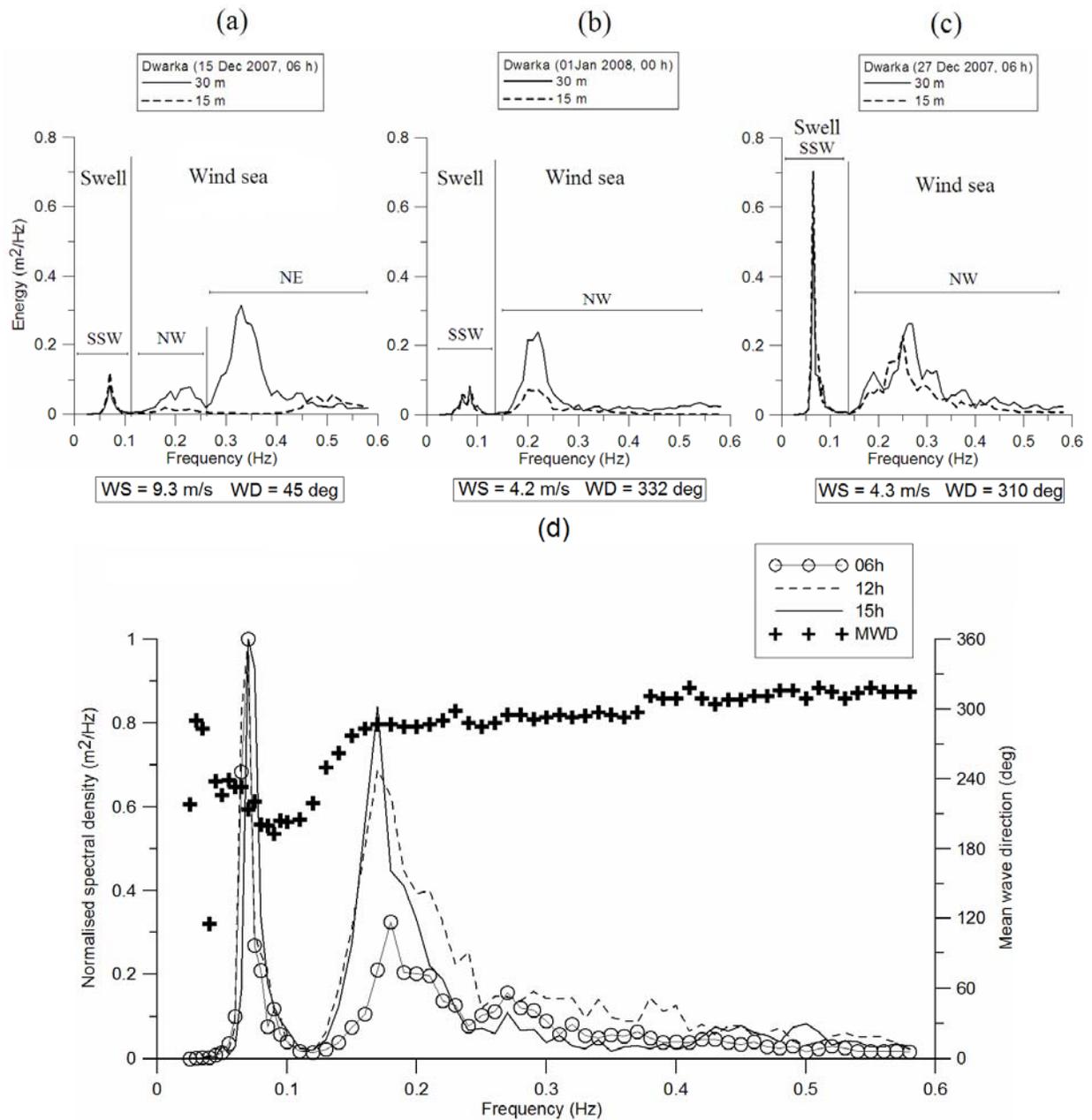


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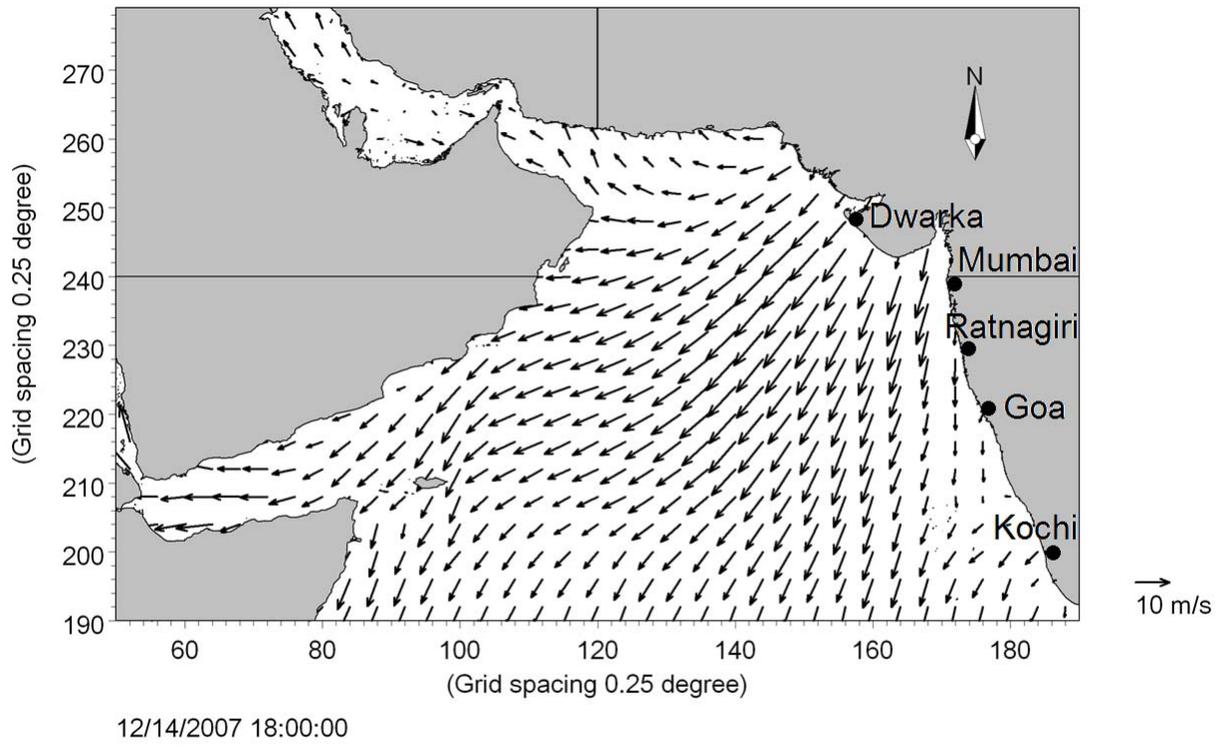
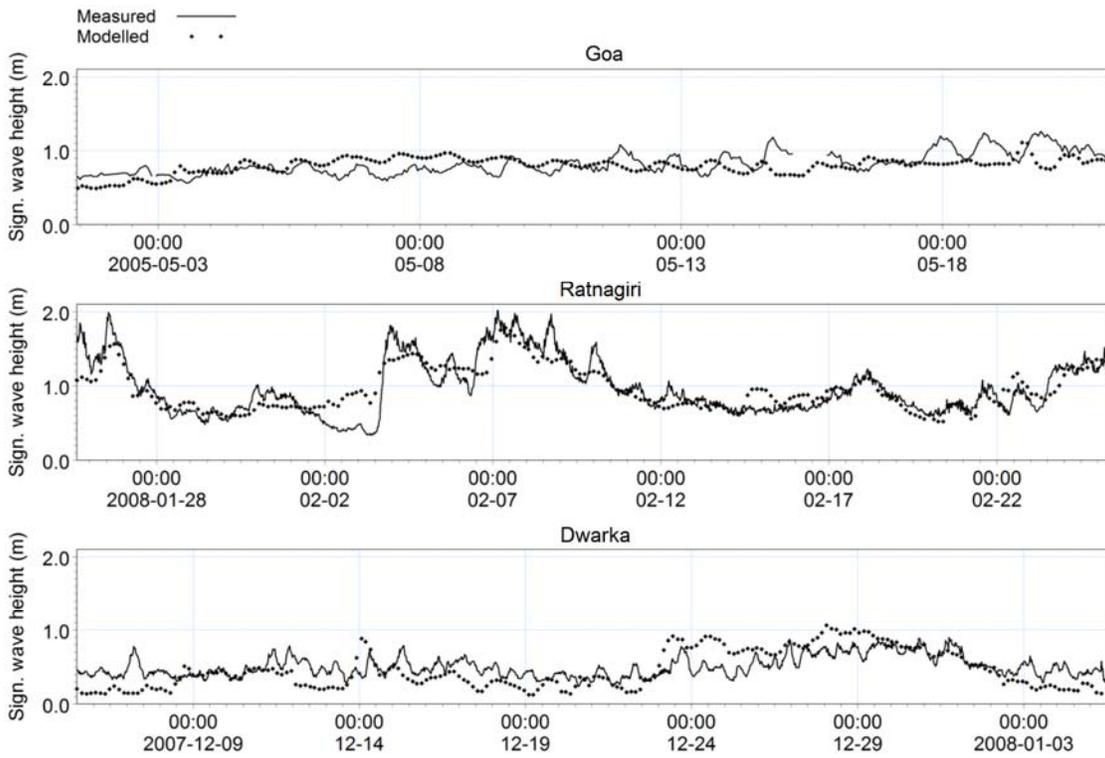


Figure 6

(a) Significant wave height



(b) Mean wave period

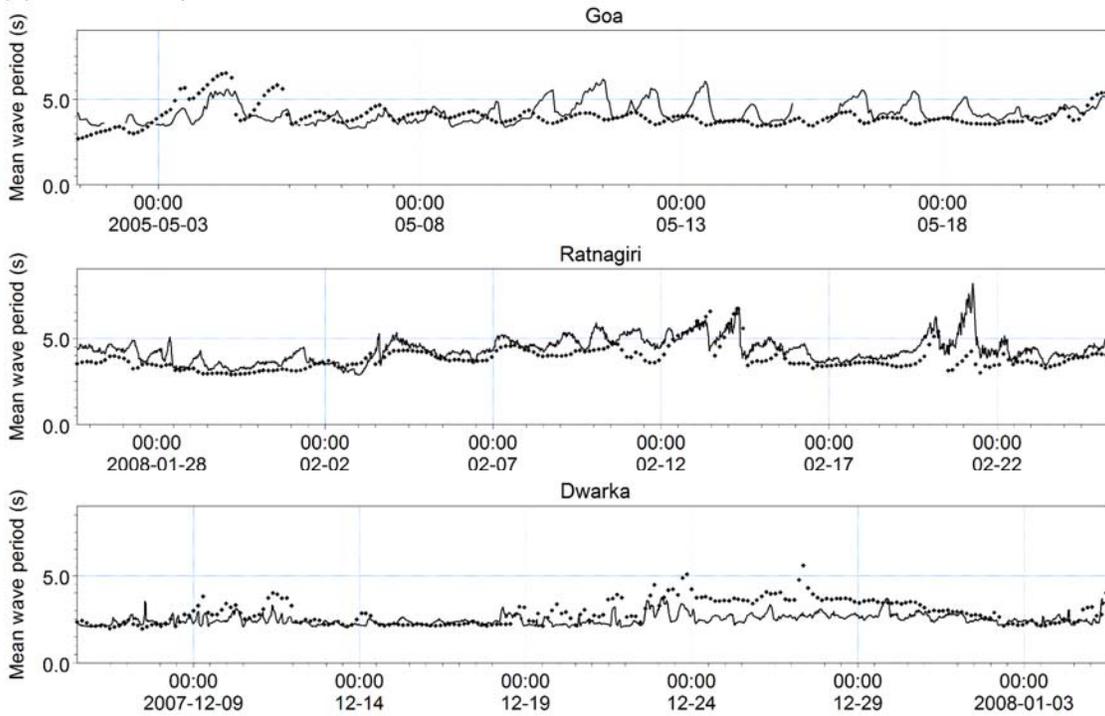


Figure 7

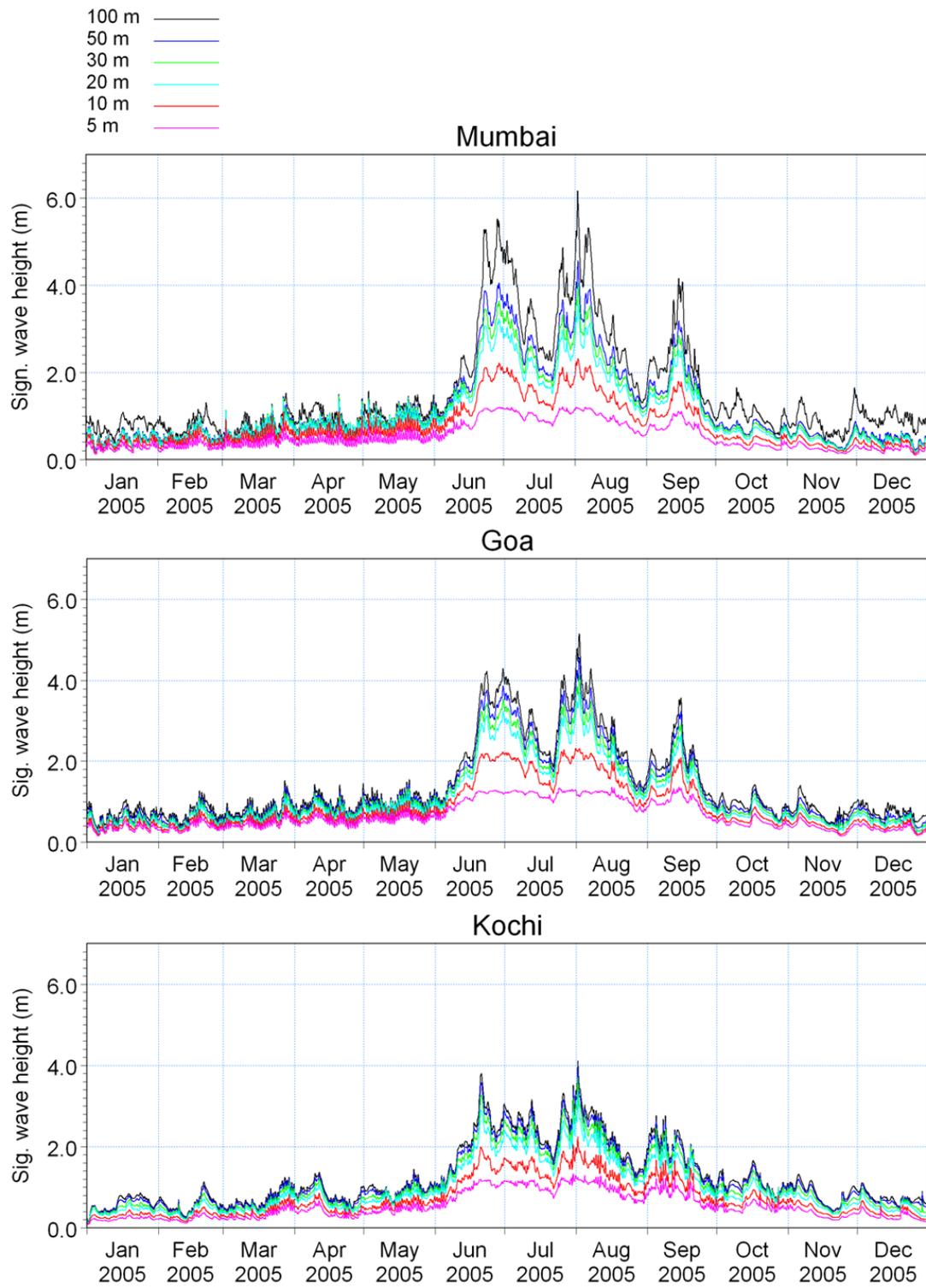


Figure 8

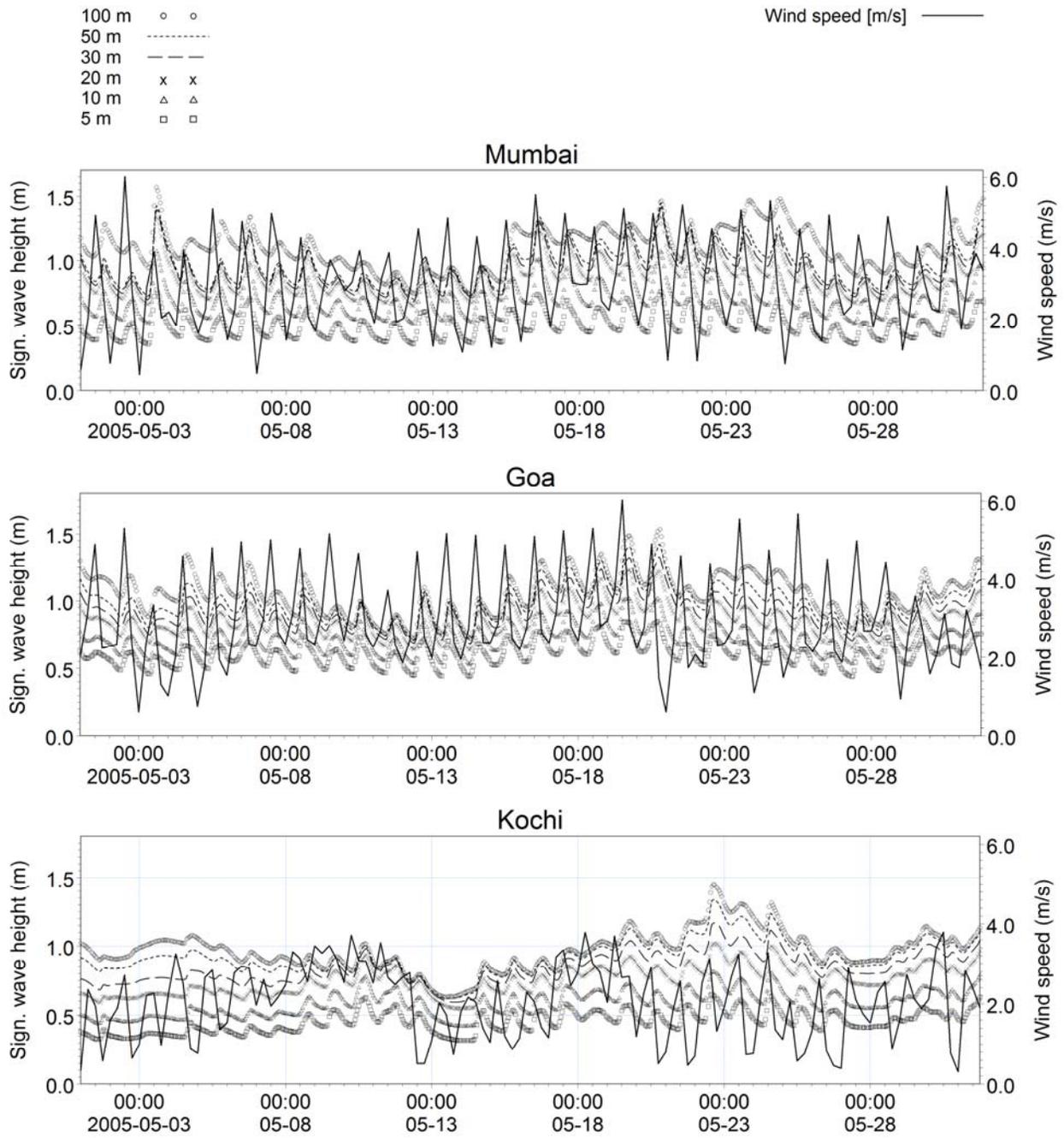


Figure 9

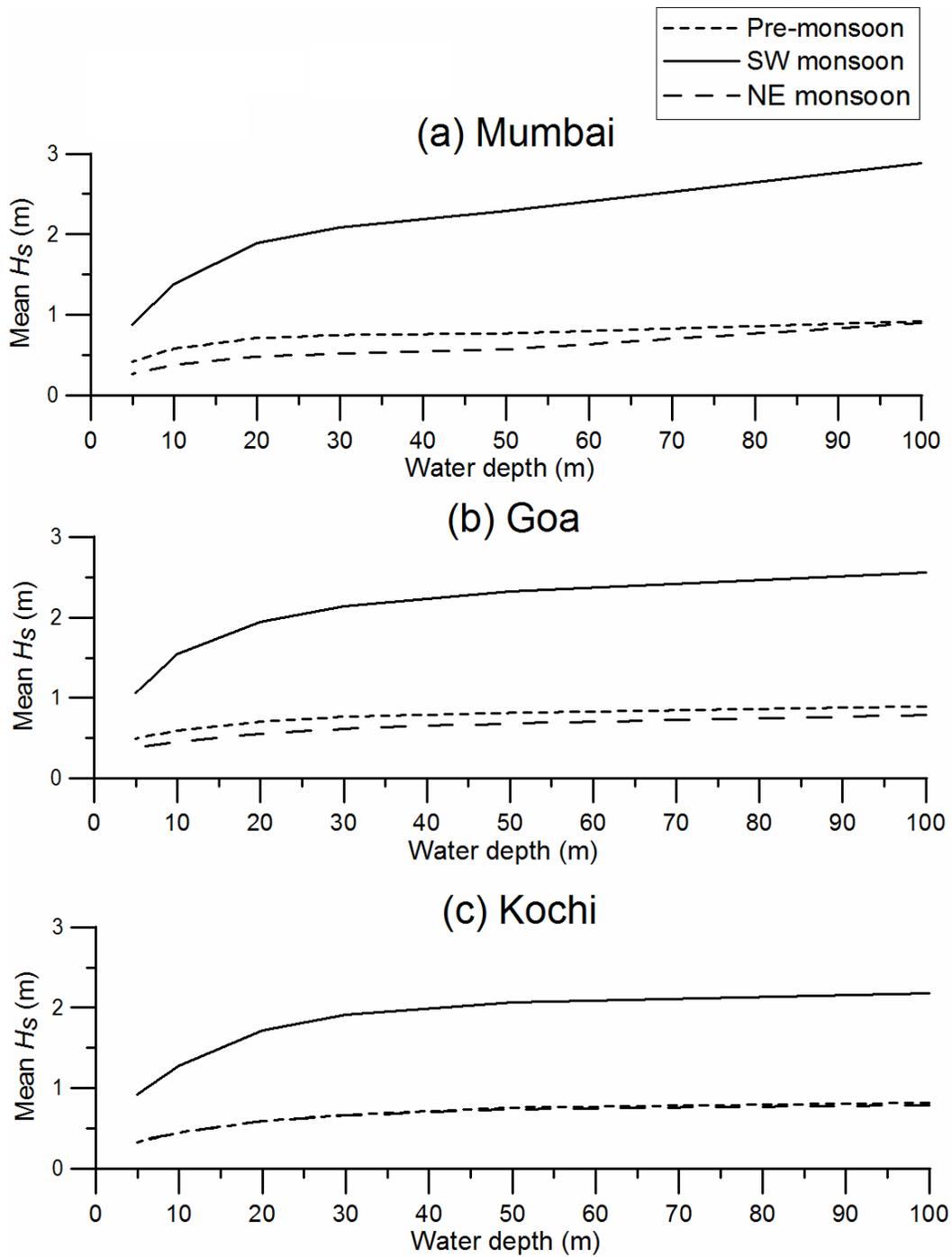


Figure 10