

Sea breeze-induced wind sea growth in the central west coast of India

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Abstract

Fine resolution wind data is required in wave models to study the interaction between wind seas generated by coastal currents and swells. In the present study, a mesoscale model, MM5, which is capable of reproducing fine details of sea breeze characteristics, has been used to simulate winds along the central west coast of India during pre-monsoon season, and these winds are used in the wave model. Our analysis shows that sea breeze induced wind seas are generated roughly around 210 km off Goa in the northwest direction, and grow progressively while propagating towards the coast. Relationships between wind speed and wind sea height have been derived, and they fairly explain the generation of wind seas by the sea breeze system. Since, the land breeze is weak and available fetch is very limited, the land breeze has no significant effect on wind sea generation from the northeast direction.

Keywords: sea breeze; wind seas; MM5; numerical modelling; pre-monsoon; coastal processes.

Introduction

The sea breeze circulation system – a common mesoscale meteorological phenomenon – has a profound effect on the meteorology and oceanography of coastal areas (Simpson, 1994). It occurs along about two-thirds of the earth's coastline, especially in the tropics and sub-tropics (Sonu et al., 1973). The sea breeze system begins at some distance offshore from the coast and expands further offshore (Laughlan, 1997). As the intensity of the wave activity depends on fetch length, the seaward extent of the sea breeze is important for wind sea generation. Aparna et al. (2005) studied the seaward extent of sea breeze along the west coast of India utilising QuikSCAT scatterometer winds (Ebuchi et al., 2002), and found that the maximum seaward extension is about 180 km off Goa, the central west coast of India. However, due to constraints in temporal and spatial resolutions, QuikSCAT winds are not useful to study the sea breeze characteristics very close to the coast. Moreover, fine resolution winds are necessary to model the waves, and understand the effect of land-sea breeze on wind-sea generation in the coastal regions (Vethamony et al., 2011). Earlier, Dhanya et al. (2010) modelled the land-sea breeze circulation along the central west coast of India using the mesoscale model, MM5, which was developed by the Pennsylvania State University / National Centre for Atmospheric Research (PSU/NCAR). It provides fine details of winds in reasonable temporal and spatial resolutions (Grell et al., 1994).

Theoretical study and experimental verification of wind wave generation and evolution focus generally on ideal conditions of steady state and quiescent initial background, of which the ideal fetch-limited wind wave growth is an important benchmark. In the study of ocean surface wind stress, the growth function expressed as the dimensionless dependence of wave variance on wave frequency is invoked to make comparison among different expressions of the drag coefficient or dynamic roughness [e.g., Pierson and Moskowitz, 1964; Toba et al., 2001; Jones and Toba, 2001; Hwang, 2005b,]. Wave growth data are usually reported at 10 m elevation, serving as the scaling wind velocity; several growth functions are proposed. The discrepancies in the proposed functions are due to stability conditions and combination of field and laboratory data in some of the analyses [e.g., Hasselmann, et al., 1973; Kahma and Calkoen, 1992, 1994; Young, 1999], the spatial variability of the wind field caused by the proximity of land [Dobson et al., 1989; Donelan et al., 1992] and the difference in wave development stages in individual data sets [Hwang and Wang, 2004]. After sorting out the stability conditions, excluding laboratory data from the analysis, and using the average wind speed between measuring stations as the scaling wind velocity, Kahma and Calkoen [1992, 1994] found that many of the discrepancies could be reconciled.

Waves along the west coast of India have been studied using measurements and models by several researchers (For example, Kurian and Baba, 1987; Baba et al., 1989; Chandramohan et al., 1991; Kumar et al., 2000; Samiksha et al., 2012; Vethamony et al., 2013; Rashmi et al., 2013; Aboobacker et al., 2013). Measured wave energy spectra off Goa (part of the central west coast of India) show the presence of two different wave systems – wind sea and swell, during pre-monsoon season (Vethamony et al., 2009); they superimpose with pre-existing swells and generate diurnal variations in the wave parameters (Vethamony et al., 2011). Swells observed off Goa are primarily from SSW/SW direction generated in the south Indian Ocean. Sea breeze activity is predominant during pre-monsoon season (Aparna et al., 2005), and this influences the wave characteristics off Goa (Neetu et al., 2006). The present study aims at understanding the role of sea breeze in the generation and growth of wind seas along the central west coast of India. We have utilised Mesoscale Model (MM5) winds along the central west coast of India during May 2005 to reproduce wind seas off Goa using the model, MIKE21 SW.

Data used

Wave measurements were carried out at 25 m (B1) and 15 m (B2) water depths off Goa (Figure 1) during May 2005 using Datawell directional wave rider buoys (Datawell, 2006). The wave rider buoy can function within -20 to +20 m of wave height, with an accuracy of 3% within the wave period range of 1.6 to 30 s. The direction accuracy is within 0.5 to 2° depending on the latitude. The wave data consists of wave energy spectra and wave parameters such as significant wave height (H_s), mean wave period (T_m) and mean wave direction (θ). Wind sea and swell parameters have been separated using the methodology given by Gilhousen and Hervey (2001)(Figure 3), which is based on the wave steepness algorithm which partitions the wave spectrum into wind sea and swell components. The details of this methodology are discussed in our earlier study (Rashmi et al., 2013). The peak frequency (f_x), of steepness parameter (ratio between wave height and wavelength) of each frequency is calculated to estimate the separation frequency (f_s), $f_s = C f_x$, where $C = 0.75$ is an empirically determined constant (Gilhousen and Hervey, 2001). The wind sea and swell part of the spectra have been separated using f_s , and accordingly, significant wave height, mean wave period and mean wave direction of wind seas and swells were calculated from the moments. 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, installed at a height of 43.5 m at Dona Paula (Goa) coastal station (Figure 1). These winds were reduced to 10 m height using logarithmic wind profile (Roland, 1988).

Simulation of winds using MM5

MM5 is a three dimensional, limited area, non-hydrostatic model designed to simulate atmospheric circulation (Grell et al., 1994). Nested model domains were selected in the Arabian Sea, covering Goa region (finest grid) with spatial resolutions of 27 km, 9 km and 3 km (Figure 1); wind vectors for every 1 hour have been simulated, and these MM5 winds were validated with AWS measurements. Comparison between measured and modelled wind velocity vectors (u and v components) shows that the match is reasonably good (Figure 2). Correlation coefficient for the zonal component is 0.86, whereas it is 0.59 for the meridional component (Table 1). If we refer to Figure 2, we find that on an average v component is about 3 m/s and RMSE 0.69, and the error is $\approx 23\%$. In an earlier study (Dhanya et al., 2010), where MM5 model has been used, a RMSE of 1.26 m/s has been reported. The poor correlation of meridional component is mainly due to irregular topographic features of the region. Moreover, Sea breeze system along the west coast of India is mainly represented by the onshore velocity component (u-component) of wind and the model could reproduce the same reasonably good (Table 1). Also, point measurements from the AWS station cannot be truly compared with the smoothed spatial data from the model. However, we can observe main features of sea breeze (such as onset timing and maximum offshore extension) from the simulated sea breeze characteristics (Figure 6), and these are in consistent with the earlier studies (Aparna et al., 2005; Dhanya et al., 2010).

Wave modelling

MIKE 21 SW, spectral wave model developed by DHI Water & Environment (DHI, 2008) simulates growth, decay and transformation of wind waves and swells in offshore and shallow regions. The model considers wave growth by wind, non-linear wave-wave and wave-current interactions, dissipation by white-capping, wave breaking and bottom friction, and refraction and shoaling due to depth variations. 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. The discretization of the governing equation in geographical and spectral space is performed using cell-centered finite volume method. An unstructured mesh technique has been used on the geographical domain. 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].

MIKE 21 SW model includes two different formulations: a directional decoupled parametric formulation and a fully spectral formulation of the wave action balance equation. The first formulation is suitable only for nearshore conditions, whereas the second one is applicable to both nearshore and offshore regions. In the fully spectral formulation the source functions are based on the WAM Cycle 4 formulation (Komen et al., 1994). The source term for depth limited wave breaking is based on the formulation by Battjes and Janssen (1978). A short description of the source term can be found in Sorensen et al. (2004). Wave simulations in the present study have been carried out under the fully spectral formulations.

Figure 4 shows model domain and bathymetry; an unstructured flexible mesh was generated with varying resolutions. In the offshore region, the size of the triangulated mesh was taken as 20 km and 7.5 km at the outer and inner zones, respectively, and 1.5 km off the Goa coast. In an early study (Samiksha et al, 2012), a larger domain, extending the southern boundary from 5° north to 60° south was considered to accommodate swells coming from the south Indian Ocean. As the primary objective of the present work is to study the impact of sea-breeze on the wind seas (hence, ignored the swells), we have separated wind seas from swells, and only the wind sea component is used for the discussion. Hence, we have restricted the southern boundary to 5° N.

The shallow water Etopo5 bathymetry data (National Geophysical Data Centre, Colorado, USA) was supplemented with digitised hydrographic chart data, interpolated to each element of the mesh in the model domain. In our earlier study, we have simulated waves in the Indian Ocean using NCEP (National Centers for Environmental Prediction, USA) re-analysis winds (Aboobacker et al., 2009). The spatial resolution of NCEP winds, which is available in 2.5° x 2.5° grid for every 6 hour, is very coarse and insufficient to get a better understanding of coastal wind regime, though enough for predicting open ocean swells.

Results and discussion

Comparison between measured and modelled (NCEP and MM5) wind sea parameters (H_s , T_m and Θ) shows reasonably good model performance (Figure 5). Statistical parameters estimated for measured and modelled wind sea heights and periods at B1 are given in Table 2. Correlation (0.70) is fairly good for wind sea H_s , and not for T_m ; biases are 0.09 m for H_s and 0.4 s for T_m ; r.m.s. errors are 0.16 m for H_s and 0.52 s for T_m ; wind sea H_s and T_m are underestimated in the model. The model has reasonably reproduced the wave heights, but not the wave periods (for example, rmse of wind sea period is within

≈20% of the measured wave period). It may kindly be noted that prediction of wave periods has attained a reasonable level of accuracy in regions, where swells dominate (e.g., open ocean in the Arabian Sea (Aboobacker et al., 2011)). Sea breeze induced wave periods are yet to be computed accurately from models, especially, in the coastal regions. Figure 6 shows the scatter between measured and modelled wind sea H_s and T_m at B1. There is a good linear fit for H_s , even though a few points are widely scattered. Most of the scatter points of T_m are closely packed between 2 and 3 s. In fact, these are the wind sea periods that we find off Goa during pre-monsoon season (Kumar et al., 2010). During shamal events (post-monsoon and early pre-monsoon seasons) also, we come across wind seas with periods of the order of 2 to 4 s when shamal winds extend to the west coast of India (Aboobacker et al., 2011).

The MM5 modelled winds clearly shows the distribution of sea breeze – land breeze system along the central west coast of India during pre-monsoon season (Figure 7). In a diurnal cycle, sea breeze starts around 11 h, and continues to blow in the NW direction with the maximum wind speed during 15 to 18 h, and gradually reduces thereafter (Vethamony et al., 2011). As the sea breeze weakens, the wind speed decreases (as seen at 00h in Figure 7) and a clear land breeze (from NE) is established by 0600 h (Fig 6). The magnitude of land breeze is relatively low and its extension towards offshore is limited to a few kilometres only (20 to 30 km) from the coast. We observed that the maximum offshore extension of the sea breeze is between 140 and 180 km, which is in consistence with the earlier studies (Aparna et al., 2005; Dhanya et al., 2010).

The wind seas simulated using MM5 winds are more accurate than those simulated using NCEP winds. For instance, MM5 wind provides a correlation coefficient of 0.70 (Table 2) between measured and modelled wind sea H_s , while NCEP wind gives a correlation coefficient of 0.63 (Vethamony et al., 2011). This indicates that accuracy can be improved if the local wind conditions are properly incorporated in the wave model. Vethamony et al. (2011) noticed that waves off Goa during pre-monsoon season show diurnal variations due to superimposition of wind seas with pre-existing swells. The wind seas generated off Goa clearly show the diurnal variations as seen in the sea breeze pattern. These wind seas sufficiently contribute to the total waves in such a way that during active sea breeze period, the waves are dominated by wind seas; however, as sea breeze weakens it reverts to the pre-existing swell conditions.

Wave model results indicate that wind seas grow gradually towards the coast during the active sea breeze period. However, it takes around 3 hours from the start of the sea breeze to obtain sufficient

growth in the wind sea. Hence, the maximum wind sea H_s is obtained between 18 h and 21 h (whereas, maximum wind speed is measured between 15 h and 18 h). This is further explained below. For example, Figure 8 shows a snapshot of typical wind sea H_s vectors simulated during 06 May 2005. During the initial phase of the sea breeze, wind seas are low (Figure 8a), of the order of 0.4 m, and they are generated in the area relatively closer to the coast. However, the area that the wind seas occupy increases further offshore, the sea breeze intensifies and the wind seas grow sufficiently. Wind sea H_s (max), of the order of 0.8 m, is observed around 19 h closer to the Goa coast (Figure 8b). That is, maximum wind sea values are observed 3 h after peak sea breeze speeds, and decays progressively as sea breeze weakens. As explained earlier, waves simulated off Goa indicate that coastal region is dominated by wind seas during the active sea breeze period, waves reach the maximum after the cessation of the sea breeze and revert back to the swell condition subsequently. Since, the land breeze is weak and available fetch is very limited, the land breeze has no significant effect on the wind sea generation from NE direction.

Figure 9 shows the time series of wind sea H_s extracted at locations A, B, C, D and E along the shore perpendicular transect (pls refer to Figure 4 for the locations). It has been found that location A is not significantly influenced by the sea breeze, whereas a gradual growth is observed from B to E. The high impact of sea breeze is noticeable at locations close to the coast (D and E). This indicates that wind sea is generated around the area closer to B (approximately 150 km from the coast), and wave height increases while propagating towards the coast depending on available fetch, sea breeze duration and intensity of wind. The diurnal variations are evident and a phase shift of approximately 3 h has been observed between A and E. The wind sea H_s is low and nearly the same at all the locations when the sea breeze is absent.

We derived a relation between wind speed (U) and wind sea height (H_{ws}) for the sea-breeze induced waves along the central west coast of India. For this purpose, mean wind speed and mean wind sea height during the active sea breeze period (averaged during 11h and 22 h on 06 May 2005) over the domain were estimated. A NW transect leading to the Goa coast from the western boundary (Figure 10a) with 5 km grid spacing has been extracted. It has been found that there is a gradual increase in wind speed due to sea breeze at a distance of approximately 210 km (perpendicular distance of 150 km) from the Goa coast in the NW profile. The wind sea heights along the NW profile also show significant changes from 210 km to the Goa coast (marked as the sea breeze zone in Figure 10b). It is evident from

the spatial mean wind speed that a distance of 150 km is nearly consistent throughout the central west coast of India.

The wind sea growth along the NW profile is gradual and can be split into two relationships: (i) an exponential growth over a distance of 160 km, and (ii) and a nearly linear growth over the next 60 km closer to the coast. This indicates that the sea-breeze induced wind sea reaches the fully developed stage after a fetch of 160 km. However, the maximum wind speed is within the 60 km of the coast. The estimated relationships between the wind sea height and wind speed are:

$$H_{ws1} = 0.028 U^{1.68} \dots\dots\dots(1)$$

$$H_{ws2} = 0.145U^{0.7} \dots\dots\dots(2)$$

Where, H_{ws1} and H_{ws2} are the wind sea heights at stage 1 (exponential growth) and stage 2 (near linear growth), respectively. The above wind sea heights (from Equations (1) and (2)) agree well with the model wind sea height within the sea breeze zone (Figure 10b) with a correlation coefficient of 0.99 and 0.98 for H_{ws1} and H_{ws2} , respectively.

Conclusions

Coastal winds along the central west coast of India during pre-monsoon season were simulated using a mesoscale model MM5. Modelled winds were successfully applied in the simulation of wind seas. Model results indicate that the accuracy of the coastal wind sea prediction along the west coast of India has improved significantly when fine resolution MM5 model winds were used, compared to earlier model predictions. Sea breeze induced wind seas are generated ~ 210 km off Goa coast along the NW, and grow progressively while propagating towards the coast. The wind sea starts to grow around 11 h, and maximum wind sea H_s is observed between 18 h and 21 h. Relationships between wind speed and wind sea heights for such scenarios have been derived, and they explain fairly well ‘the generation of wind seas by the sea breeze system’.

Acknowledgements

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Table captions

Table 1. Correlation coefficient, bias and r.m.s. error between measured and modelled winds off Goa (May 2005).

Table 2. Correlation coefficient, bias and r.m.s. error between measured and simulated wind seas off Goa (May 2005).

Figure captions

Figure 1. Model domain used for nested MM5 simulations . Wind (AWS) and wave (B1 and B2) measurement locations are marked.

Figure 2.(a) Comparison between measured and modelled wind velocities and (b) Scatter between measured and modelled wind velocities.

Figure 3. Distribution of (a) significant wave height and (b) mean wave direction for the wind sea and swell for May 2005.

Figure 4. Model domain and bathymetry used for wave simulations. Wave measurement location (B1 and B2), AWS location and profile extraction locations (A to E) are marked (see Figure 9 for more details).

Figure 5. Comparison between measured and modelled wind sea parameters: (a) significant wave height, (b) mean wave period and (c) mean wave direction.

Figure 6. Scatter between measured and modelled (a) wind sea H_s and (b) wind sea T_m .

Figure 7. Typical wind vectors off Goa for every 6 hour simulated during pre-monsoon season (13 May 2005).

Figure 8. Wind sea H_s :(a) at the developing phase (11 h) and (b) at the maximum (19 h) 06 May 2005.

Figure 9. Wind sea H_s simulated at points A to E during May 2005 (please see Figure 3 for their locations).

Figure 10.(a) NW profile towards Goa coast and (b) Modelled and derived wind sea heights along the NW profile.

Tables

Table 1. Correlation coefficient, bias and r.m.s. error between modeled and measured winds off Goa (May 2005).

Items	Correlation coefficient	Bias (m/s)	r.m.s. error (m/s)
u-velocity	0.86	-0.56	0.76
v-velocity	0.59	0.13	0.69

Table 2. Correlation coefficient, bias and r.m.s. error between modeled and measured wind seas off Goa (May 2005).

Location	Parameters	Wind sea	
		H_s (m)	T_m (s)
B1	Correlation coefficient	0.70	0.39
	Bias	0.09	0.40
	r.m.s. error	0.16	0.52
	Scatter Index	0.30	0.17

Figures

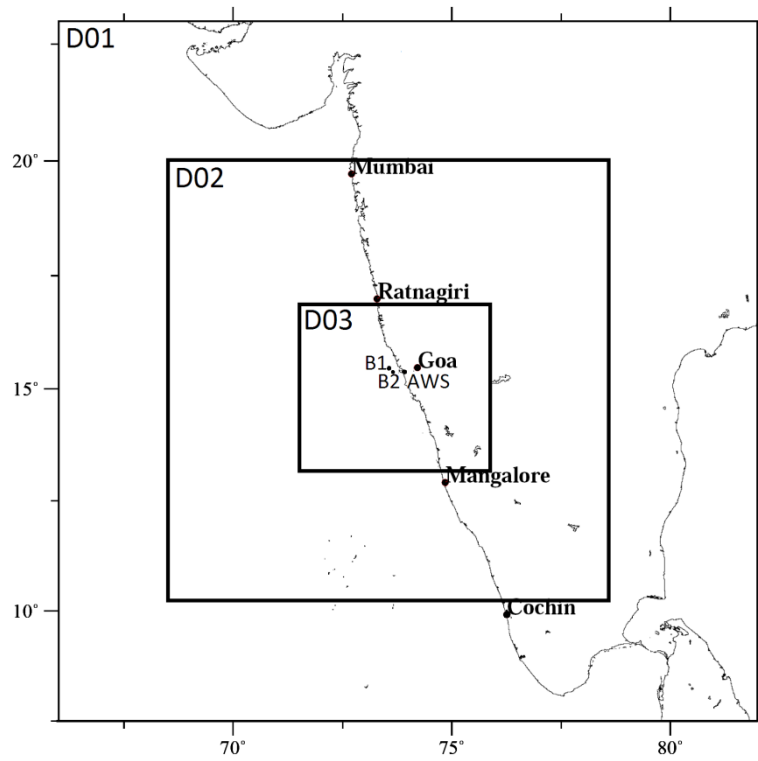


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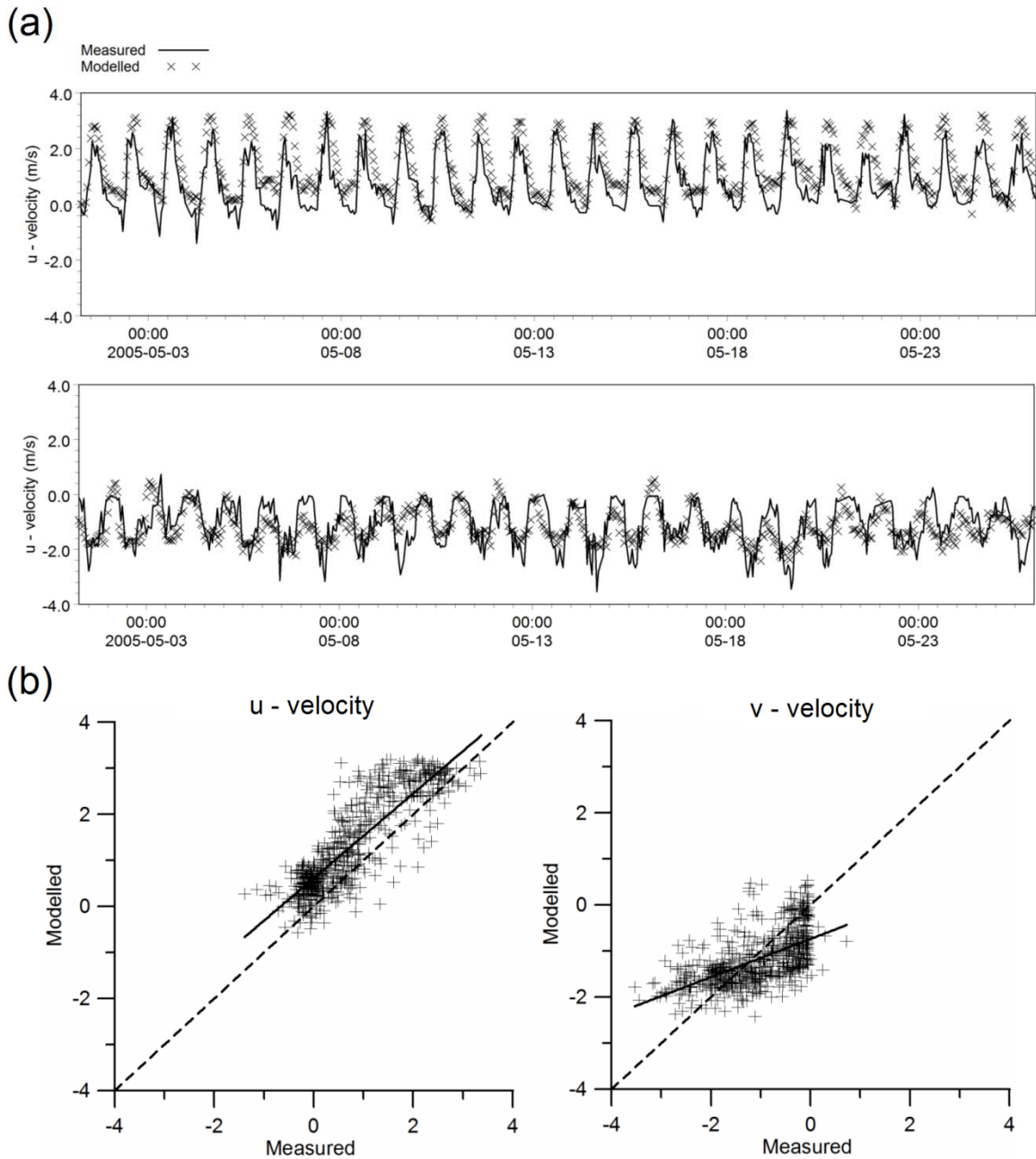


Figure 2.(a) Comparison between measured and modelled wind velocities and (b) Scatter between measured and modelled wind velocities.

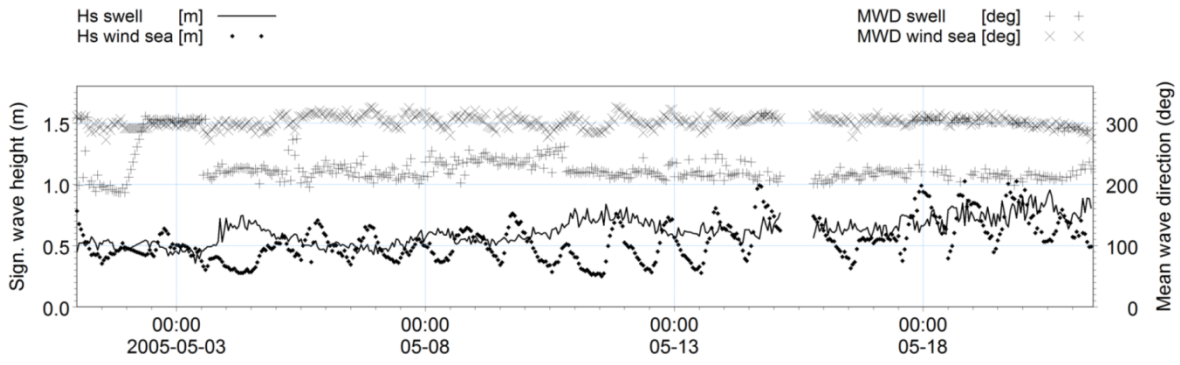


Figure 3. Distributions of wind sea height, swell height, wind sea direction and swell direction during May 2005.

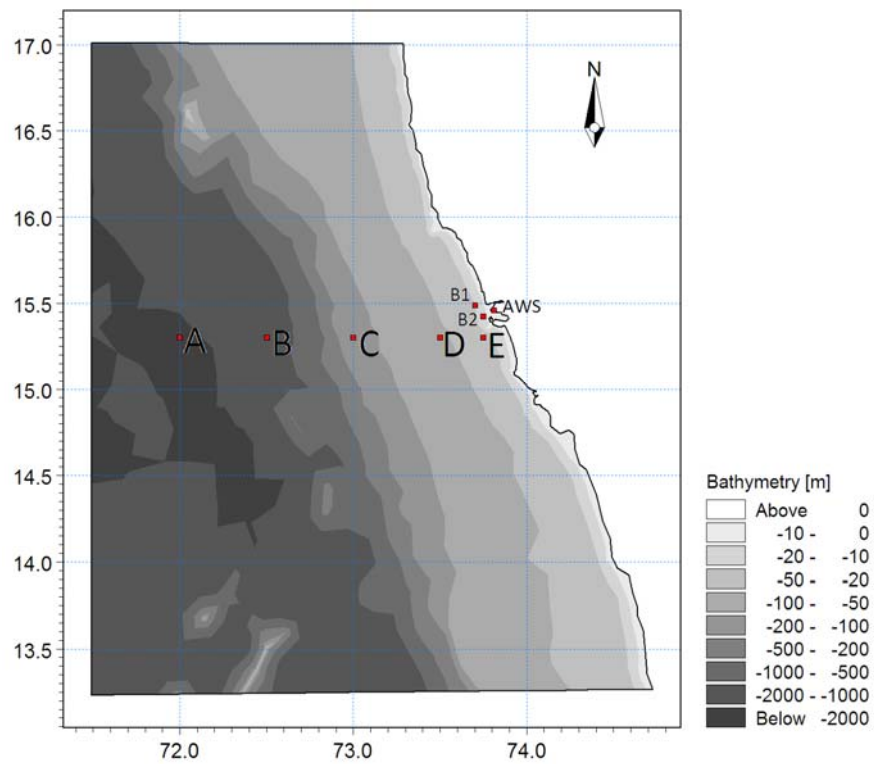


Figure 4. Model domain and bathymetry used for wave simulations. Wave measurement locations (B1 and B2), AWS location and profile extraction locations (A to E) are marked (please see Figure 9 for more details).

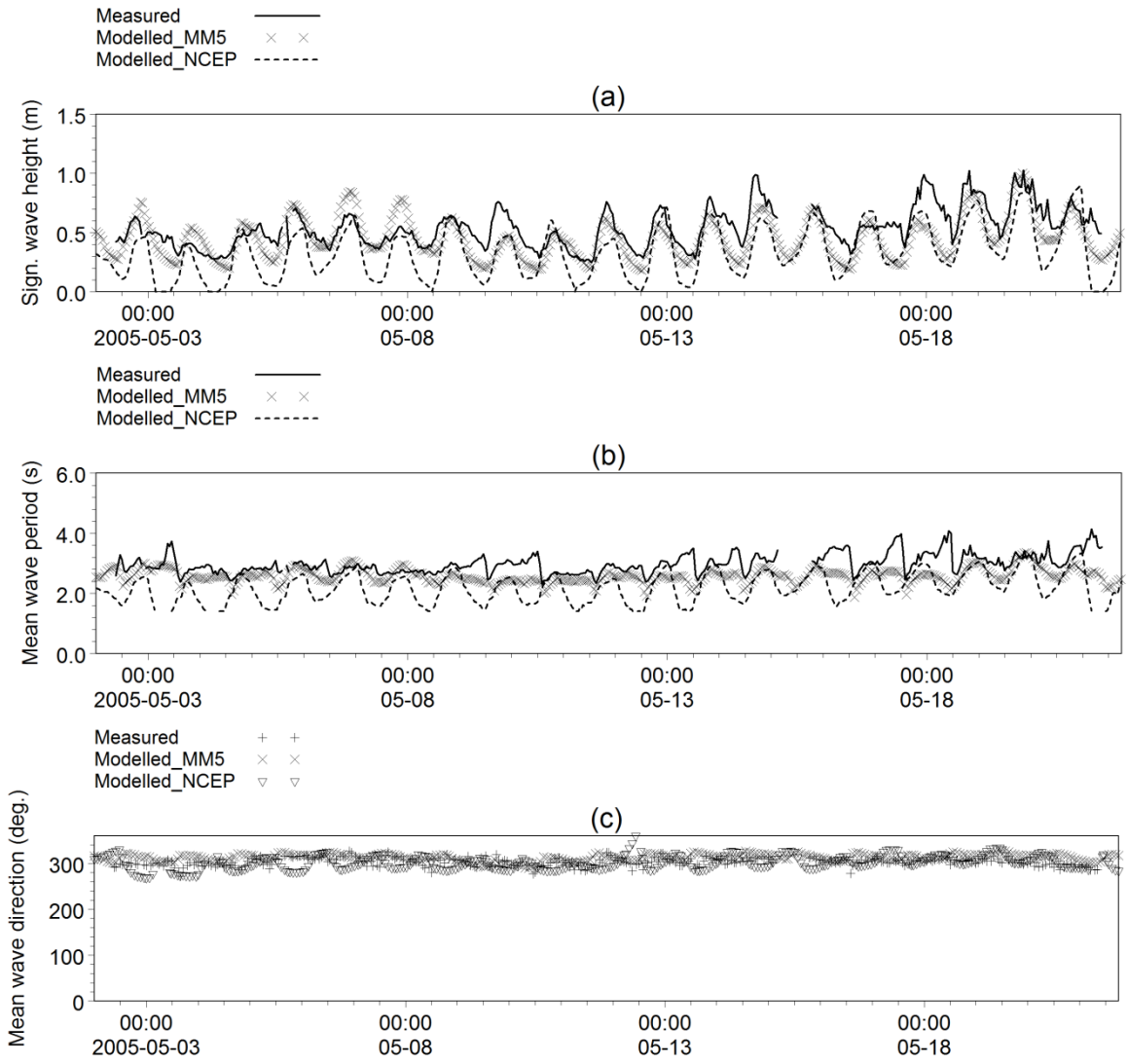


Figure 5. Comparison between measured and modelled (NCEP & MM5) wind sea parameters: (a) significant wave height, (b) mean wave period and (c) mean wave direction.

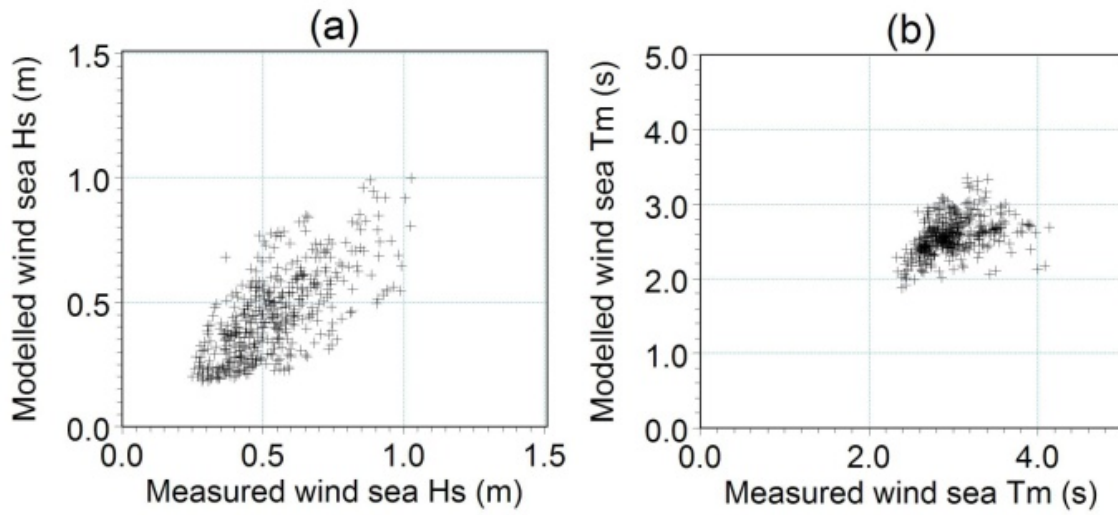


Figure 6. Scatter between measured and modelled (a) wind sea H_s and (b) wind sea T_m .

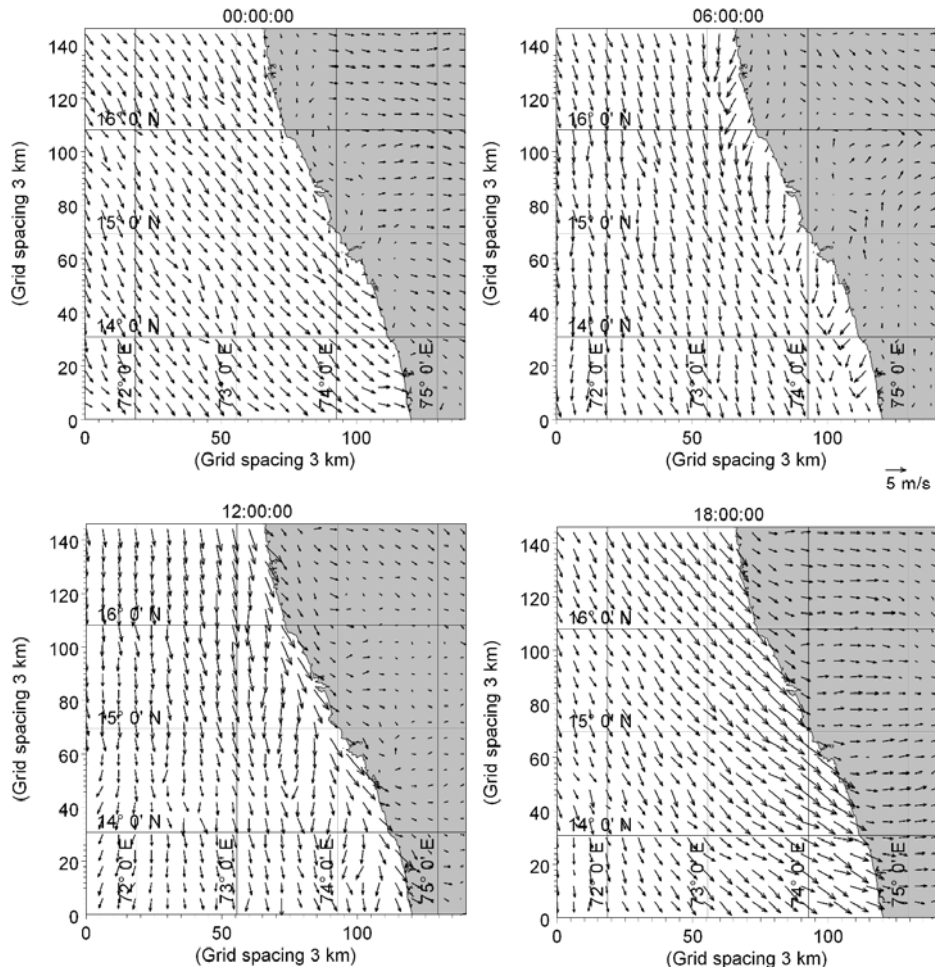


Figure 7. Typical wind vectors off Goa for every 6 hour simulated during pre-monsoon season (13 May 2005).

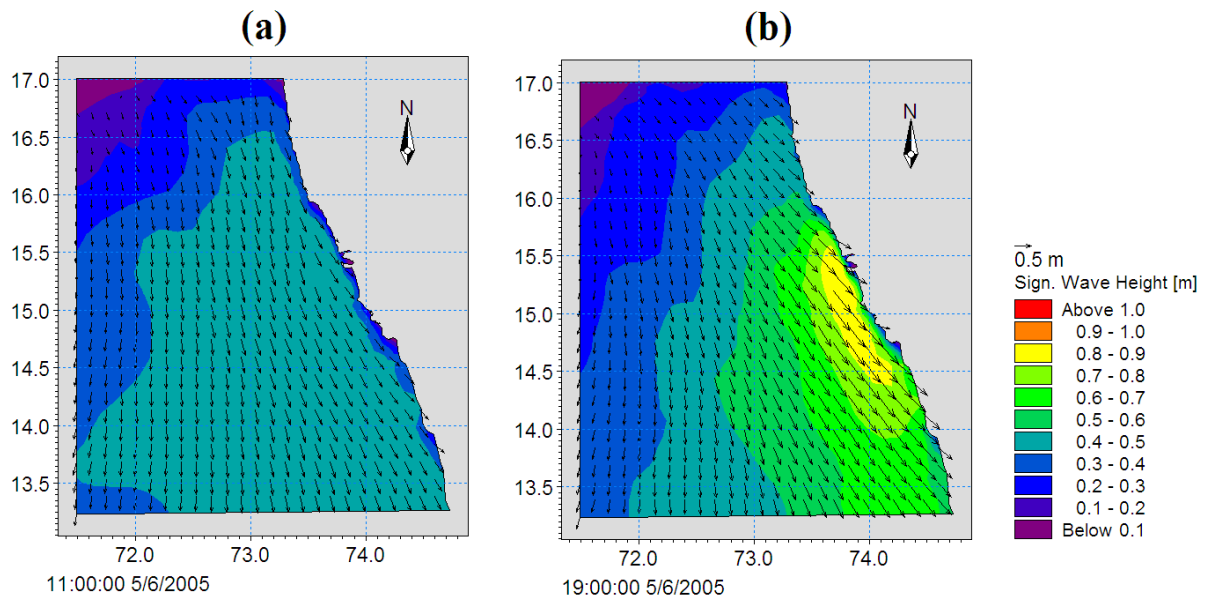


Figure 8. Wind sea H_s :(a) at the developing phase (11 h) and (b) at the maximum (19 h) on 06 May 2005.

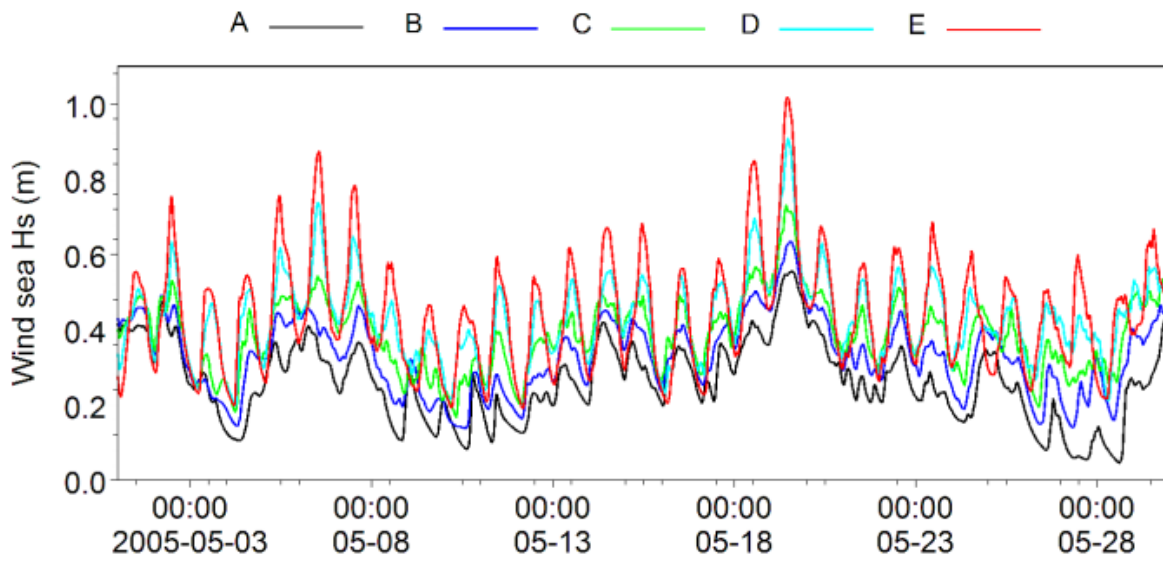


Figure 9. Wind sea H_s simulated at points A to E during May 2005 (please see Figure 3 for their locations).

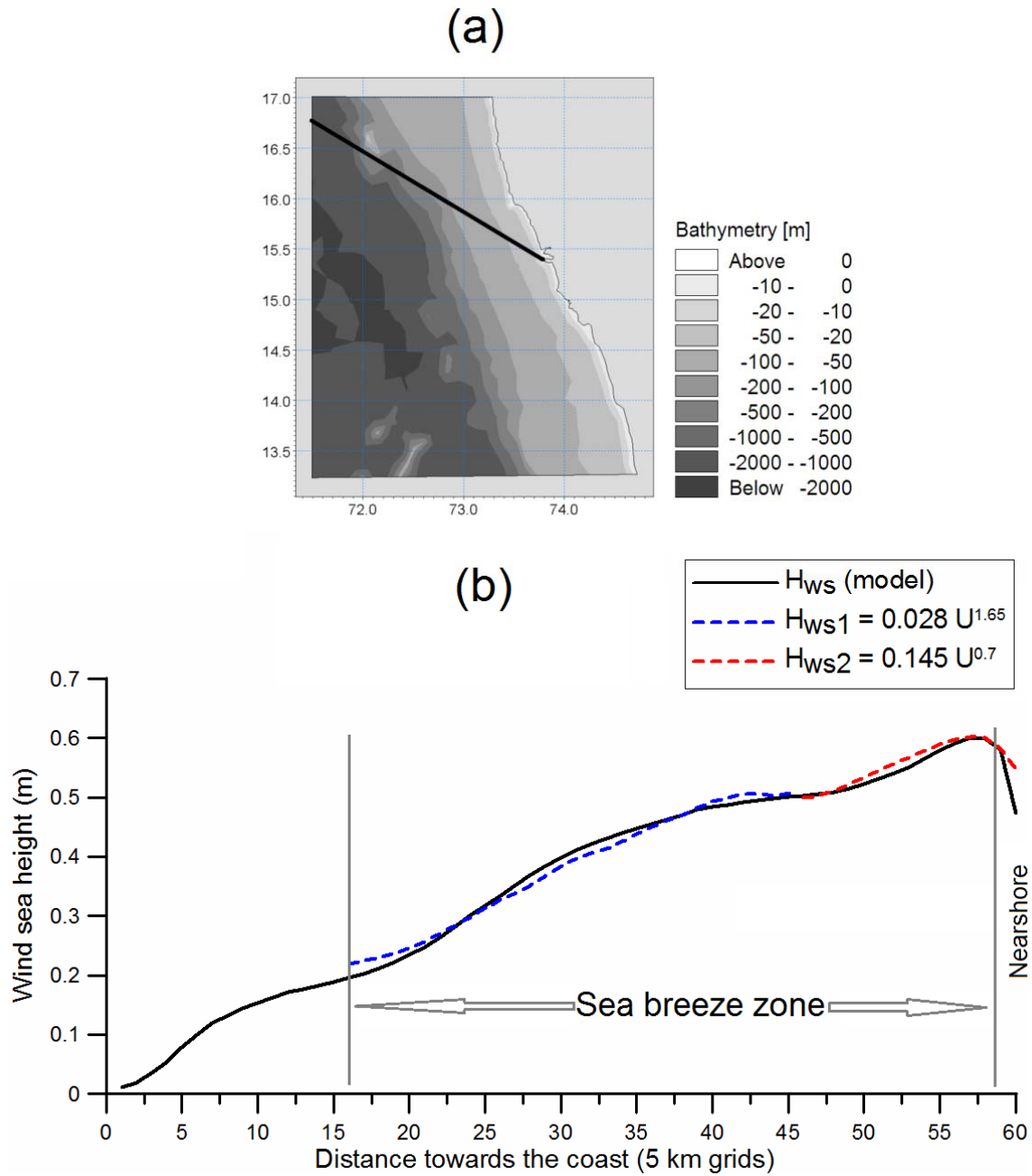


Figure 10. (a) NW profile towards Goa coast and (b) Modelled and derived wind sea heights along the NW profile.