Wave hindcast experiments in the Indian Ocean using MIKE 21 SW model

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Wave prediction and hindcast studies are important in ocean engineering, coastal infrastructure development and management. In view of sparse and infrequent *in-situ* observations, model derived hindcast wave data can be used for the assessment of wave climate in offshore and coastal areas. In the present study, MIKE 21 SW Model has been used to carry out wave hindcast experiments in the Indian Ocean. Model runs have been made for the year 2005 using QuickSCAT scatterometer winds blended with ECMWF model winds. In order to study the impact of southern ocean swells, the model has been run in two different domains, with the southern boundary being shifted far south for the Domain 60S model. The model simulated wave parameters have been validated by comparing with buoy and altimeter data and various statistical yardsticks have been employed to quantify the validation. Possible reason for the poorer performance of the model in the Arabian Sea has also been pointed out.

1. Introduction

Ocean wave hindcast and forecast are of paramount importance for the management of offshore structure construction, ship navigation, and naval operations. *In-situ* observations are location-specific and generally sparse. In the Indian Ocean the situation is worse, compared to the Atlantic and Pacific, because long time series data of *in-situ* observations are mostly unavailable. On the other hand, it is simply impossible to estimate the wave climate and extreme sea state without such a long time series. Hence, in recent years, the attention is shifted to the use of numerical wave model generated wave data for the assessment of wave climate. Sverdrup and Munk (1947) were the first to develop operational wave prediction technique. The technique was purely statistical and was based on just one parameter, viz., the significant wave height. In other words, the spectral character of the sea state was completely neglected. Later, the spectral characteristics of waves were taken into account for the development of methods based on wave spectrum. Currently, there are many spectral wave models for wave hindcast and forecast studies in the open ocean as well as in the coastal ocean. In the present study, MIKE 21 SW model has been utilized primarily for hindcast experiments. MIKE 21 SW is a new generation spectral wind wave model, based on unstructured meshes, and is developed by Danish Hydraulic Institute (DHI 2005). The model simulates growth, decay, and transformation of wind generated waves and swells in offshore and coastal areas. As mentioned earlier, the principal objective of the present study is to carry out hindcast experiments with MIKE-21 model in the Indian Ocean and to validate the hindcasts with available *in-situ* and remotely sensed data. As a spin off, we have also studied the impact of southern ocean wave conditions on the wave conditions of north Indian Ocean.

Keywords. Wave modelling; MIKE 21 SW; swell; altimeter.

2. Data and methodology

MIKE 21 SW model is based on flexible mesh, which allows for coarse spatial resolution in the offshore area and high resolution in the shallow coastal waters. 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 near shore conditions, whereas the second one is applicable in both near shore and offshore regions. Hence, in this study the second formulation has been used as the study area contains both shallow 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 Sørensen *et al* (2004). In the present study, the model domain covers the Indian Ocean region, 60°S–25°N; 40°–100°E (figure 1). For the model runs, the spatial resolution has been chosen to be 0.25° in the coastal waters and 1° for the rest of the region. This, however, does not mean that the resolution is constant everywhere in this domain. MIKE 21 SW model uses a flexible mesh for model runs. The flexible mesh allows fine resolution near the coast. In fact, the resolution reaches as fine as 0.003° near the coast in the flexible bathymetry grid used for this study. The bathymetry is from GEBCO (GEneral Bathymetric Charts of the Ocean) produced by Intergovernmental Oceanographic Commission (2003). The resolution of GEBCO bathymetry grid is 1×1 minute. The model has been forced by QuickSCAT scatterometer winds blended with ECMWF model winds. The wind data are obtained from IFREMER, France, and are available at a spatial resolution of 0.25° in longitude and latitude. The quality of the blended winds has been checked by comparing them with buoy winds and the comparison has produced encouraging results. The wind speed correlation coefficients range from 0.80 to 0.90. The RMS difference between buoy winds and blended winds is <2 m/s (Bentamy *et al* 2007). Apart from the forcing data, we have also used wave data derived by moored buoys deployed by the National Institute of Ocean Technology (NIOT) and by JASON-1 altimeter for the purpose of validating the model results. The JASON 1 satellite system carrying a state-of-the-art altimeter sensor, launched on December 7, 2001, is providing wind and wave (besides sea level) information over global oceans regularly. Radar altimeter data have been

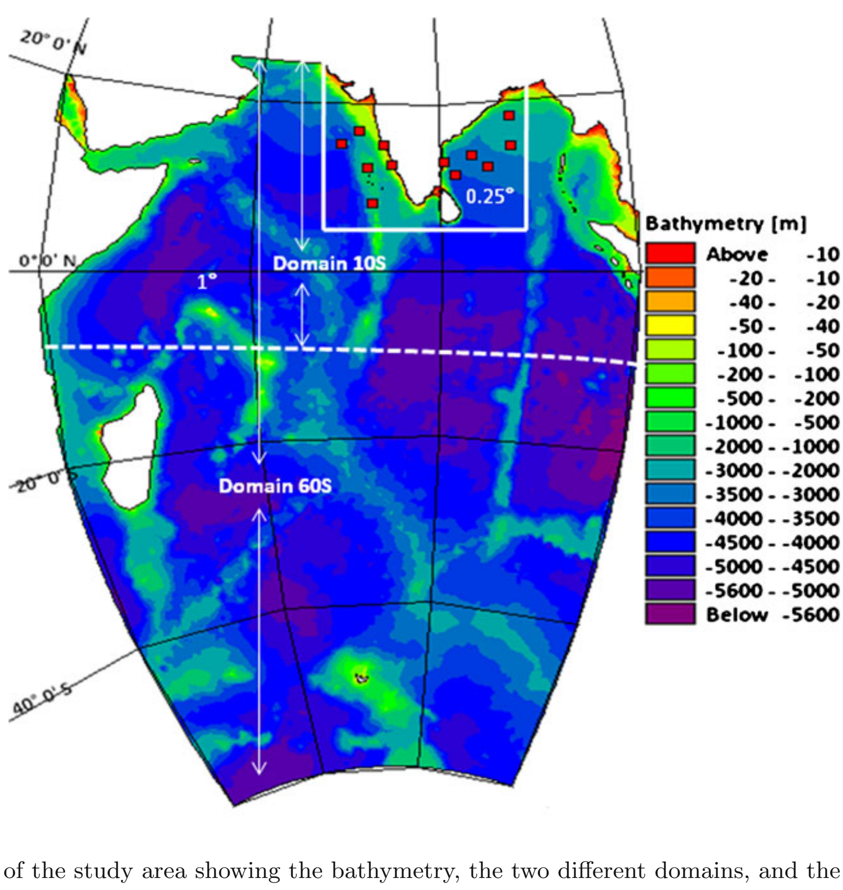

Figure 1. Map of the study area showing the bathymetry, the two different domains, and the buoy locations.

provided by the Delft Institute for Earth-Oriented Space Research Radar Altimeter Database system (http://rads.tudelft.nl/rads/rads.shtml).

3. Model experiments

As mentioned earlier, the basic objective is to carry out hindcasts with MIKE-21 and subsequently to validate the hindcasts. For this purpose, the model has been earlier calibrated using number of *in-situ* data of Indian Ocean region and various model parameters such as breaking parameter, bottom friction and white capping were tuned to provide better wave predictions. In the experiments, wave breaking parameter ($\gamma = 0.5$), bottom friction (Nikuradse roughness) ($K_N = 0.04$ m), and white capping coefficients (Cdis = 3.5) were found to be optimum. And these coefficients have been used in the experiments performed for the present study. However, in order to fulfill the secondary objective of studying the impact of southern ocean waves on the northern ocean wave characteristics, apart from the earlier selected model domain, a smaller one (10°S–25°N, 50°–100°E) was also selected. Spatial resolution for the smaller domain (Domain 10S) model is identical with that for the larger domain (Domain 60S). The model simulations were performed for the year 2005. The wave spectrum is represented by 16 direction bins and 25 frequency bins logarithmically spaced from 0.055 to 0.6 Hz. The model derived wave parameters like significant wave height (Hs), swell wave height (Hss), wind sea height (Hsw), mean wave period (Tm) and mean wave direction (MWD) were compared with similar parameters obtained from NIOT buoys, moored in the Arabian Sea (AS) and Bay of Bengal (BOB). The locations of the buoys and the period of data availability are given in table 1 and the locations of the buoys are also marked in figure 1.

4. Results and discussions

As mentioned earlier, performance of the model was evaluated both in the larger and smaller domains. We evaluated the performance in terms of significant wave height, swell height, wind sea height, mean wave period, mean wave direction in both AS and BOB. In buoy measurements, for sea and swell separation, the wave spectrum measurements between 0.04 and 0.1 Hz is considered low frequency (swell) components and between 0.1 and 0.5 Hz is taken as high frequency (sea) components. Model also follows the same criteria for the sea and swell separation. The definition of mean wave period from the buoy is $\mathrm{Tm} = \sqrt{m_o/m_2}$. Although we compared the simulated and observed wave parameters at six different buoy locations for each of the basins, the results are shown at only one representative location for each of the basins (figure 2a and b). From figure 2(a), one can conclude that the Domain 60S model consistently overpredicts the swell height in the Arabian Sea except for some isolated peaks. This overprediction also affects other wave parameters like mean wave period and Hs and leads to the unexpected result that the error statistics of both the models (Domain 60S one and Domain 10S one) is almost the same. This is a strange result, since the model with the Domain 60S including the southern ocean, should, in principle, have provided simulation of better quality. As seen from figure 2(b), in the case of Bay of Bengal, there is significant difference between the two simulations and the agreement of the Domain 60S result with the buoy data is much better.

A possible clue for the poorer performance of the model in the AS could come from the analysis of mean wave direction (MWD) at a representative buoy location (SW2) in the AS. In figure 2, we show the comparison between simulated and observed MWD. The Arabian Sea experiences three different

Table 1. *Locations of buoys with periods of data availability.*

Buoy	Lat. (N)	Long. (E)	Period of availability
DS1	15.504	69.276	01/01/2005–26/07/2005
DS4	18.443	87.586	01/01/2005–28/06/2005
DS5	13.991	83.248	01/01/2005–31/12/2005
DS7	8.315	72.661	01/01/2005–31/12/2005
OB3	12.498	72.011	01/01/2005–05/09/2005
OB8	11.503	81.473	01/07/2005–31/12/2005
MB10	12.513	84.983	26/09/2005–31/12/2005
MB11	14.997	87.504	01/01/2005–16/05/2005
SW2	16.985	71.099	13/05/2005–31/12/2005
SW3	15.010	73.021	01/01/2005–30/06/2005
SW4	12.936	74.723	01/01/2005–16/06/2005
SW6	13.183	80.392	05/02/2005–23/08/2005

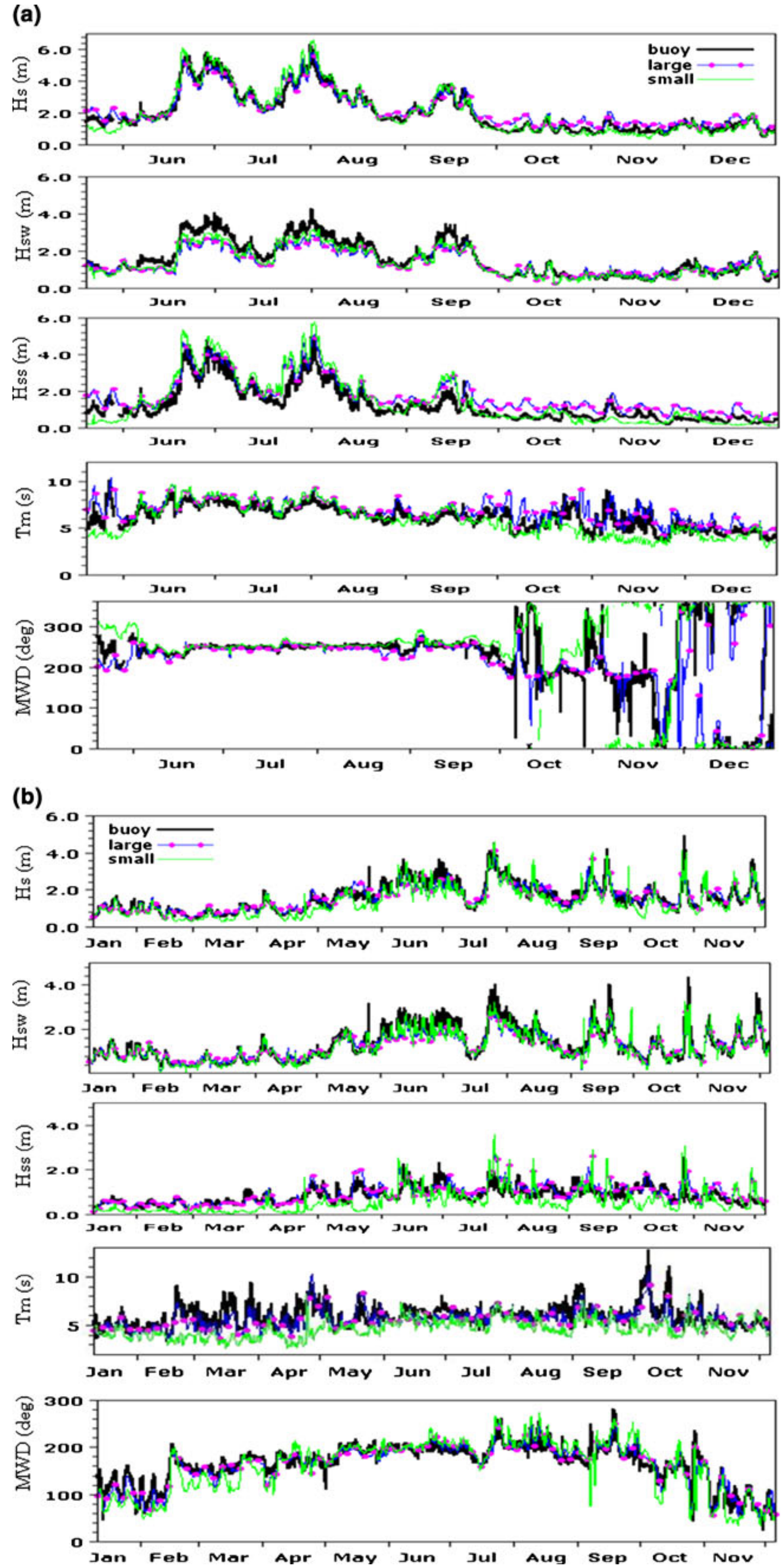

Figure 2. Comparison of model derived wave parameters with buoy derived wave parameters. (**a**) Arabian Sea – representative location SW2 – Off Ratnagiri Port and (**b**) Bay of Bengal – representative location DS5 – Off Machillipatnam.

seasons in a year: pre-monsoon (February–May), southwest monsoon (June–September) and northeast monsoon (October–January). It can be seen that the deviation is more pronounced in pre-monsoon and northeast (NE) monsoon seasons. This finding was true for all the six buoys in the AS. During southwest (SW) monsoon season, the wind seas are dominating and this might be the reason for the change in performance during SW monsoon. During pre-monsoon season, large scale winds are weak and hence sea breeze has an impact on the diurnal cycle of the sea state along the west coast of India (Neetu *et al* 2006). Since this sea breeze has not been taken into account by our model, the simulated MWD does not match the observed one. During NE monsoon season, another mechanism seems to be at work for the poor match of the simulated MWD with observed one. On several occasions, swells propagating from the northwest were observed. A study of 'Shamal' swells carried out by Aboobacker *et al* (2011) showed the impact of northwest swells on wave conditions off west coast of India during NE monsoon. In our study, we have closed the land boundary at 25°N and have not considered the waves entering into the Arabian Sea from the Persian gulf. The above described factors might be the reason for the large deviation observed in mean wave direction off the west coast of India during pre-monsoon and NE monsoon seasons. Thus it is not surprising that even a Domain 60S model has failed to provide simulation of better quality. In the case of BOB the agreement between model-derived MWD and buoy MWD is much better for the Domain 60S model simulation (figure 2b). This agreement is not season- or month-dependent. This supports the conjecture that southern ocean swells cannot be neglected in hindcasts with MIKE-21 model.

Earlier, we have shown only figures for two representative buoy locations. Now we provide the detailed statistics for all the six buoy locations, separately for the AS and BOB. Various statistical measures like Bias, root mean square error (RMSE), scatter index (SI), correlation coefficient (R) are used to assess the model performance by comparing the model derived parameters against the corresponding buoy observations. The formulae for the statistical measures are:

$$\text{Bias} = \frac{1}{n}\sum(m - \text{obs}) \tag{1}$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum(m - \text{obs})^2} \tag{2}$$

$$\text{SI} = (\text{RMSE}) / (\overline{\text{obs}}) \tag{3}$$

$$R = \frac{\sum(m - \overline{m})\left(\text{obs} - \overline{\text{obs}}\right)}{\sqrt{\sum(m - \overline{m})^2\left(\text{obs} - \overline{\text{obs}}\right)^2}} \tag{4}$$

Here $\overline{\text{obs}}$ is the mean value of a particular wave parameter derived by the buoys in a particular basin. $\overline{m}$ is the mean value of the model derived wave parameter.

The statistics has been computed for Domain 60S as well as Domain 10S simulations. In tables 2 and 3, we show the results for the Arabian Sea and the Bay of Bengal. From the statistics of comparison it can be seen that the RMSE of wind speed and swell wave height are high in the case of Arabian Sea. Bay of Bengal statistics shows very good agreement with buoy data especially in the case of Hs with a low RMSE of 0.29 m, high correlation of 0.91, and a very small bias of −0.04 m.

Apart from the tables, we have also shown in figure 3, the scatter plots showing the overall comparison between model wave heights and buoy wave heights as well as between the model wave periods

Table 2. *Statistics of the comparison of model wave parameters with buoy wave parameters in the Arabian Sea.*

Parameters	RMSE	R	Bias	SI
Domain 60S				
U_{10} (m/s)	2.06	0.79	0.07	0.39
Hs (m)	0.37	0.95	−0.15	0.23
Hss (m)	0.52	0.93	−0.41	0.55
Hsw (m)	0.37	0.93	0.17	0.29
Tm (s)	1.05	0.84	−0.73	0.18
Domain 10S				
U_{10} (m/s)	2.09	0.79	0.07	0.39
Hs (m)	0.33	0.97	−0.09	0.20
Hss (m)	0.50	0.92	−0.41	0.53
Hsw (m)	0.31	0.95	−0.06	0.24
Tm (s)	1.12	0.74	−0.37	0.20

Table 3. *Statistics of the comparison of model wave parameters with buoy wave parameters in the Bay of Bengal.*

Parameters	RMSE	R	Bias	SI
Domain 60S				
U_{10} (m/s)	1.61	0.85	−0.30	0.29
Hs (m)	0.29	0.91	−0.04	0.20
Hss (m)	0.36	0.72	−0.16	0.49
Hsw (m)	0.31	0.90	0.05	0.27
Tm (s)	0.94	0.77	0.10	0.16
Domain 10S				
U_{10} (m/s)	1.61	0.85	−0.30	0.29
Hs (m)	0.40	0.88	−0.54	0.28
Hss (m)	0.57	0.33	−0.53	0.77
Hsw (m)	0.30	0.91	−0.39	0.24
Tm (s)	1.94	0.22	0.88	0.34

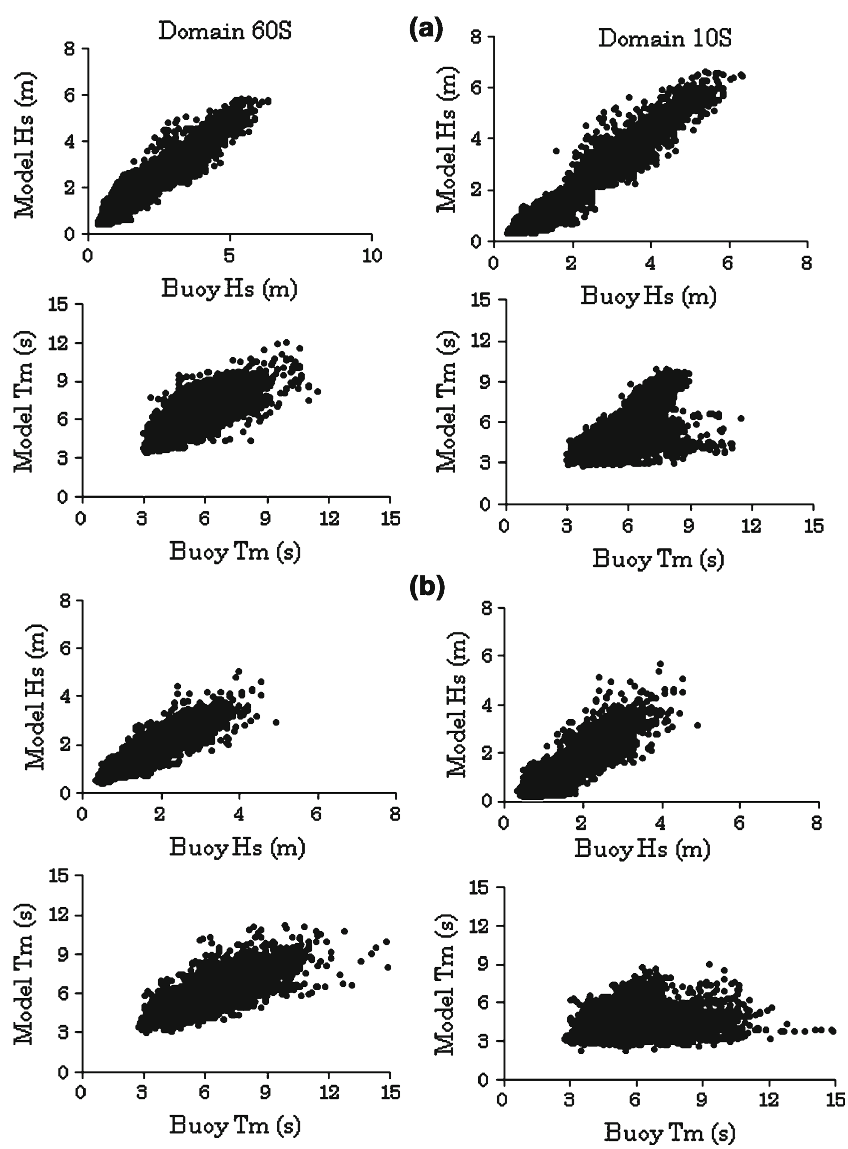

Figure 3. Scatter plot of Hs and Tm for Domain 60S and Domain 10S. (**a**) Arabian Sea and (**b**) Bay of Bengal.

Table 4. *Statistics of the comparison of Hs, Tz and U_{10} with similar altimeter parameters.*

Parameters	Bias	RMSE	SI	R
Domain 60S				
U_{10}	−0.56	1.35	0.21	0.89
Hs	−0.03	0.4	0.19	0.91
Tz	−0.17	0.83	0.13	0.81
N-IO(5°N–25°N)				
U_{10}	−0.38	1.32	0.21	0.89
Hs	−0.17	0.4	0.24	0.92
Tz	−0.23	0.9	0.15	0.73
S-IO(5°S–30°S)				
U_{10}	−0.63	1.36	0.2	0.88
Hs	0.08	0.41	0.17	0.88
Tz	−0.07	0.77	0.11	0.76
Eq-IO(−5°S–5°N)				
U_{10}	−0.63	1.37	0.26	0.81
Hs	−0.18	0.37	0.21	0.85
Tz	−0.42	0.9	0.14	0.73

and buoy wave periods. Figure 3(a) is for the Arabian Sea, while figure 3(b) is for the Bay of Bengal. All the six buoys have been taken into account for the individual basins.

The buoy data used for comparison was not continuous (table 1). Because of the sparse and discontinuous occurrence of buoy data we resorted to the alternative of using wave height derived by altimeter with dense coverage. Once again the Domain 60S simulation results have been used. Although the model extends up to 60°S, for comparison we have considered the region 30°S–25°N and 40°–100°E. In other words, the region below 30°S has been treated as sponge layer, where the model results are not supposed to be very accurate. Model-estimated wave data and altimeter derived wave data have been collocated and this collocation resulted in more than 0.736 million data pairs. The selected wind speed range for the comparison was 2–20 m/s. The maximum wave height in this range was around 8 m. Although altimeter does not provide direct measurement, there are algorithms to estimate this parameter from altimeter observations. We have used the recently developed algorithm by Govindan *et al* (2011). The zero crossing surface wave period is computed as:

$$\mathrm{Tzalt} = (((\xi - 5.78))/(\xi + (\mathrm{U}_{10}/(\mathrm{Hs}^*((\mathrm{U}_{10}/\mathrm{Hs}) + \mathrm{Hs}))))) + (\mathrm{Hs} + (5.70))) \quad (5)$$

where ξ is the wave age, $\xi = 3.25\left(\mathrm{Hs}^2\mathrm{g}^2/\mathrm{U}_{10}^4\right)^{0.31}$.

Neither Hss nor Hsw can be estimated from altimeter data. So the comparison is limited to Hs and Tz. Table 4 provides the statistics for the comparison of model derived wave height and wave period with corresponding data from altimeter. From the analysis of this statistics, it is quite clear that the model derived wave height and wave period are in good agreement with similar quantities from altimeter in the southern as well as in the northern Indian Oceans. The study also clearly shows that MIKE 21 SW model is capable of providing good quality simulation of wind generated waves and swells in the offshore and coastal areas.

5. Summary

In this study, an attempt has been made to carry out hindcasts of wave parameters in the Indian Ocean using MIKE 21 SW model. Such hindcasts are important in ocean engineering and coastal infrastructure development and management. A variable resolution has been used for the proper representation of deep water waves and coastal waves. In order to evaluate the effect of southern ocean swells, two different model domains have been chosen, with the boundary of one being shifted far south. It has been found that there is indeed a significant impact of these swells on the model simulation in the Bay of Bengal basin. As far as the Arabian Sea is concerned, the impact of these swells is partly nullified by other oceanic phenomena like sea breeze and Shamal swells. Further experiments have been made with the larger domain model to take into account these swells. The model has been evaluated by comparing the simulation results with available altimeter observations. Apart from the parameter directly observed by an altimeter, which is the wave height, we have also used another auxiliary parameter like wave period, which has been estimated by a recently formulated novel algorithm. All the validation results point to the fact that the performance of the model is quite satisfactory. Hence it can be concluded with reasonable confidence that the model with this particular configuration can serve the purpose of reliable wave hindcasts in the Indian Ocean region.

Acknowledgements

The authors wish to thank the Director, Space Applications Centre, the Deputy Director, Earth, Ocean, Atmosphere, Planetary Sciences and Applications Area and the Group Director, Atmospheric and Oceanic Sciences Group, for the motivation and encouragement. They are also indebted to two anonymous reviewers for their valuable comments.

References

Aboobacker V M, Vethamony P and Rashmi R 2011 'Shamal' swells in the Arabian Sea and their influence along the west coast of India; *Geophys. Res. Lett.* **38(3)** 7p, doi: 10.1029/2010GL045736.

Battjes J A and Janssen J P F M 1978 Energy loss and set-up due to wave breaking of random waves; *Proc. 16th International Conference on Costal Engineering, ASCE*, pp. 569–587.

Bentamy A, Ayina H L, Queffeulou P and Croize-Fillon D 2006 Improved near real time surface wind resolution over the Mediterranean Sea; *Ocean Science Discussion* **3** 435–470.

Bentamy A, Ayina H L, Queffeulou P, Croize-Fillon D and Kerbaol V 2007 Improved near real time surface wind resolution over the Mediterranean Sea; *Ocean Science* **3** 259–271.

DHI 2005 *Mike 21 spectral wave module, Scientific documentation*; Danish Hydraulic Institute (DHI).

Govindan R, Kumar R, Basu S and Sarkar A 2011 Altimeter derived ocean wave period using genetic algorithm; *IEEE Geosci. Rem. Sens. Lett.* **8** 354–358.

IOC 2003 *Centenary Edition of the GEBCO Digital Atlas*, published on CD-ROM on behalf of the Intergovernmental Oceanographic Commission and the International Hydrographic Centre, Organization as part of the General Bathymetric Chart of the Oceans; British Oceanographic Data Liverpool.

Neetu S, Shetye S and Chandramohan P 2006 Impact of sea-breeze on wind-seas off Goa, west coast of India; *J. Earth Syst. Sci.* **115** 229–234.

Sørensen O R, Kofed-Hansen H, Rugbjerg M and Sørensen L S 2004 A third generation spectral wave model using an unstructured finite volume technique; *Proc. 29th International Conference on Coastal Engineering*, Lisbon, Portugal.

Sverdrup H U and Munk W H 1947 Wind, sea, and swell: Theory of relations for forecasting; US Navy Department, Hydrographic Office Publication no 601, pp. 1–44.

MS received 30 May 2011; revised 11 October 2011; accepted 13 October 2011