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Estimation of wave heights during cyclonic conditions using wave propagation model

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Abstract Data from satellites are invaluable for applications including long-term climate studies and engineering design. Most present applications of wind-wave research for coastal engineering and environmental purposes involve the use of numerical models that simulate the evolution of directional wave energy spectra in time or space or both which can be used to forecast climate change, currents, and waves. Using NCEP winds, the wave climate over the offshore region was simulated from January 2004 to December 2005 using MIKE 21 offshore spectral wave module (OSW). Three cyclones Baaz, Fanoos and 7B occurred in 27 November–3 December (2005), 5–12 December (2005) and 15–24 December (2005), respectively, happen to fall during the period of study. Hence, the applicability of this model in the prediction of wave conditions during cyclones was carried out. The significant wave heights in the North Indian Ocean are in the range of 1.0–1.5 m increasing to a maximum of 3.3 m during cyclonic conditions. The results have proved the suitability of OSW Model in the prediction of the offshore wave climate during extreme conditions.

Keywords OSW model · Significant wave height · Cyclone tracks · NCEP reanalyzes

1 Introduction

The demand for reliable information on oceanic wave conditions is increasing as a result of the utilization of offshore region greater than before for navigation, fishing, and due to

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climatic importance. The damages from landfalling cyclones are mainly due to three factors: rain, strong winds, and storm surges. Death and destruction arise directly from the intense winds that are characteristic of tropical cyclones blowing over a large surface of water which is bounded by a shallow basin. As a result of these winds, the massive piling up of the sea water occurs at the coast leading to the sudden inundation and flooding of coastal regions (Dube et al. 2009; Sindhu and Unnikrishnan 2011). The Bay of Bengal is potentially energetic for the development of cyclonic storms and accounts for about 7 % of the global annual total number of storms (Dube et al. 1997). Storm surges are an extremely serious hazard along the east coast of India, Bangladesh, Myanmar, and Sri Lanka. Some of the earlier investigations on storm surges in the Bay of Bengal are Ali (1979), Rao (1982), Roy (1984), Murty (1984), Murty et al. (1986), Das 1994a, b, Gonnert et al. (2001), Dube et al. 1997, 2000a, Chittibabu (1999). Storm surges occur during monsoon along the east coast of India or Bangladesh. Timely and reasonably accurate prediction of these storms can reduce the loss of human lives and damage to properties. Dube et al. 1994, 1997, 2000a, 2004, 2005, 2006), Rao et al. (1997), Chittibabu (1999), Chittibabu et al. 2000, 2002, and Jain et al. 2006a, b have discussed about operational numerical storm surge prediction models which have been successfully applied in the Bay of Bengal and the Arabian Sea. A large number of location-specific high-resolution models have been developed and successfully applied to the regions covering maritime states along the east coast of India for Tamil Nadu (Chittibabu et al. 2002), Andhra Pradesh (Dube et al. 2000a, b), and Orissa (Sinha et al. 2008). Mohanty and Mandal (2005) had studied the performance of the mesoscale model for the prediction of intensity of storms using National Center for Environmental Prediction/National Center of Atmospheric Research (NCEP/NCAR) reanalyzes winds (Kalnay et al. 1996) between 1995 and 1999. The track of the storms simulated by the model and forecast errors indicate a good accuracy with the observed track of Indian Meteorological Department with few exceptions. The present study focus on the prediction of wave climate along cyclone tracks.

The third-generation model used for the present study is based on the WAM cycle 4 model (Komen et al. 1994). It includes refined description of the physical processes governing the wind-wave generation and decay. For the calculation of transport of wave energy from one time step to the next, a Lagrangian transport was used because the domain had open boundary. MIKE 21 offshore spectral wind wave (OSW) is a fully spectral wind-wave model, which describes the propagation, growth, and decays of wind-generated waves in offshore as well as in the coastal areas (DHI Software 2009). MIKE 21 OSW model is basically a discrete spectral model, i.e., the energy is calculated in a number of discrete points of a rectangular Eulerian grid for a number of discrete frequencies and directions. However, a parametric model was used to describe the high-frequency energy i.e., the energy for frequencies above the highest discrete energy. This energy is “fed” into the discrete model as the sea grows. The discrete model thus covers the main frequency range using the parametric model as a trigger function. MIKE 21 OSW model is used for a number of applications like assessment of wave loads as part of the design of offshore construction, establishment of design wave conditions for offshore wind farms and marine pipelines in coastal areas, wave forecast etc. In the present study, the application of OSW model in predicting the significant wave heights during cyclonic conditions was attempted.

Vethamony et al. (2006) used MIKE 21 OSW model for wave modeling the North Indian Ocean using National Centre for Medium-Range Weather Forecast winds. Spectral analysis was carried out in the west coast of India for fixing the Inland Vessel limit for the port of Mormugao (Vethamony et al. 2009). This study has been further extended for the analysis of wind and wave data for superimposition of wind sea on pre-existing swells off Goa coast (Vethamony et al. 2011).

2 Simulation of offshore wave climate

Database for climate researches has been substantially improved through the collection of comprehensive global data sets such as NCEP/NCAR and ERA-15 (European Reanalysis project from European Centre for Medium-Range Weather Forecasts, ECMWF, for the period 1979–1994) reanalyzes. NCEP has been receiving the real-time "fast delivery" scatterometer wind data from the European Space Agency for operational use since 1992. The NCEP/NCAR reanalyzes, currently available back to 1948, contain several meteorological parameters in a global spatial resolution of 2.5° × 2.5° (latitude × longitude). The NCEP winds for North Indian Ocean (5° South to 22° North latitudes and 50° to 98° East longitudes) at 6-h interval were downloaded from the website (www.cdc.noaa.gov) from January 2004 to December 2005. The downloaded wind field had a resolution of ~275 km × 275 km. For analysis, the data were interpolated for a grid size of 77 km × 77 km (Fig. 1) and were compared with OB8 buoy data (off Cuddalore) located at 81.460° East and 11.509° North (Fig. 2). Wind speeds of NCEP are higher than the buoy data, whereas wind direction matches well with each other. To reduce the wind speed, the NCEP winds are multiplied with factors such as 0.75, 0.85, and 0.92. For winds with factor 0.92, the accuracy of wind speed measurements is 1.5 % of full scale (0–60 m/s), i.e., 0.9 m/s; hence, 0.92 is fixed as a constant factor.

From Etopo2 (www.ngdc.noaa.gov), bathymetry was prepared for the same areal extent (as that of wind field) with a grid size of 77 km × 77 km. For stability reasons, courant number, the convergence criteria for explicit time-marching simulations to avoid blowup during simulations was given <1. The wave heights simulated after multiplying the winds with the factor 0.92 give reasonable comparison with the buoy data at OB8-Off Cuddalore (Fig. 3). The OSW model was run several times and fine tuned with model parameters viz., white capping and bottom friction for normal marine conditions (Figs. 4, 5). The results of offshore wave model were validated with waves observed by OB8 buoy data. The accuracy of MIKE 21 OSW model results is closely related to the accuracy of wind-field specifications. It is inferred that the model values are slightly higher wherever peaks occur. Not surprisingly, the comparison between model outputs and buoy data shows an average correlation coefficient of 0.84 (Fig. 6).

Monthly wave climate for North Indian Ocean was simulated between January 2004 and December 2005; using NCEP data and the seasonal changes i.e., post-monsoon (April), southwest (September) and northeast (November) in wave climate are shown in Fig. 7. The wave height during the post-monsoon shows a uniform distribution ranging around 0.75–0.9 m. The significant wave height during southwest monsoon is from 1.4 to 1.6 m. The significant wave heights are noticed in the southwest part of North Indian Ocean, as it is the monsoon period indicating the progress of the monsoon in the Arabian sea (Sanil Kumar et al. 2004). During northeast monsoon (November), the waves are high (above 1.5 m) in the deeper parts of the Bay of Bengal and in the southeast part of North Indian Ocean. The significant wave height in the offshore of North Indian Ocean is in the range of 1.0–1.5 m (Suresh et al. 2010; Aboobacker et al. 2009). As OSW model is applicable only for deeper regions, the underestimation of wave heights in the coastal regions are not considered in the present study.

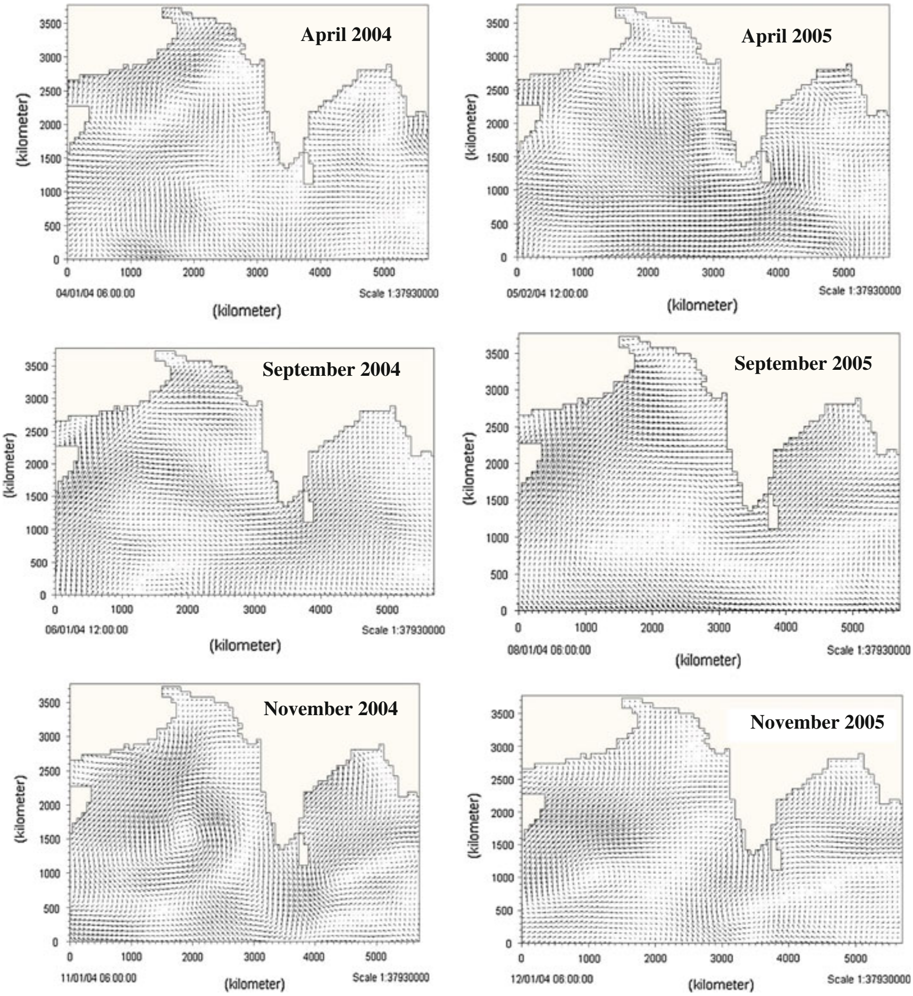

Fig. 1 NCEP winds during different seasons

3 Simulation of wave climate during cyclones

Three tropical cyclones were witnessed in the Bay of Bengal (IMD report 2006; ATCR 2005) in less than 3 weeks during 2005 as shown in Tables 1 and 2.

3.1 Cyclonic storm: Baaz

A system formed from a well-marked low pressure area was seen over south Andaman Sea and adjoining southeast Bay of Bengal on the morning of November 27, 2005. It concentrated into a depression on the morning of 28. Moving in a westerly direction, it intensified into a cyclonic storm "BAAZ" around midnight of November 28, 2005; thereafter, it moved swiftly in a northwesterly direction till the same evening. Then "BAAZ" became sluggish in its movement and hovered around the area till the morning of

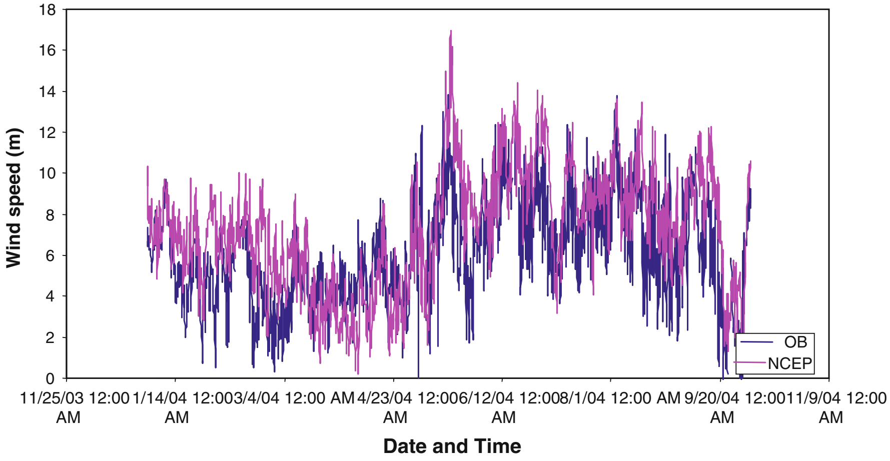

Fig. 2 Comparison between Buoy and NCEP wind speed

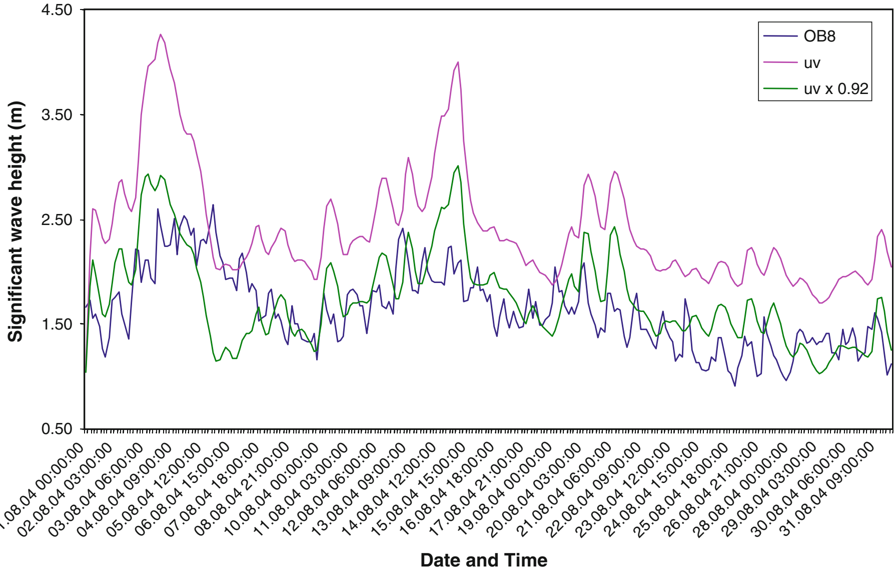

Fig. 3 Comparison between simulated SWH with/without factor and buoy data

December 1, 2005. Thereafter, the system was moving in a northwesterly direction, gradually weakened, and dissipated over sea itself on the morning of December 2. Fairly widespread, with isolated heavy rainfall occurred in north coastal Tamil Nadu and Andhra Pradesh on December 3 and 4, 2005. According to press reports, heavy rain caused floods in Nellore, Chittoor, and Cuddapah districts of Andhra Pradesh, with 11 deaths and breaching of 27 tanks. Many villages were reported to be marooned in the above districts.

Fig. 4 Comparison between simulated SWH with/without white capping and buoy data

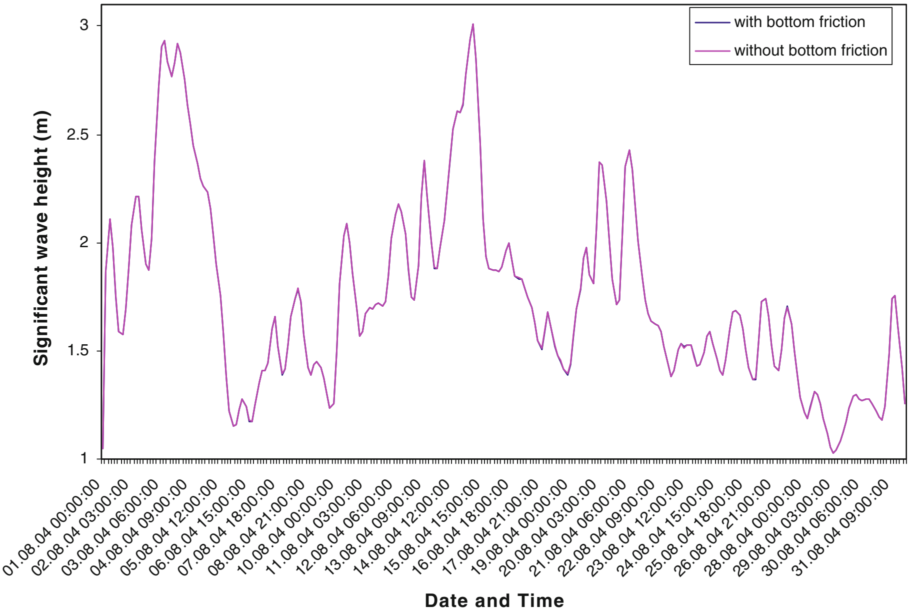

Fig. 5 Comparison of simulated SWH with/without bottom friction

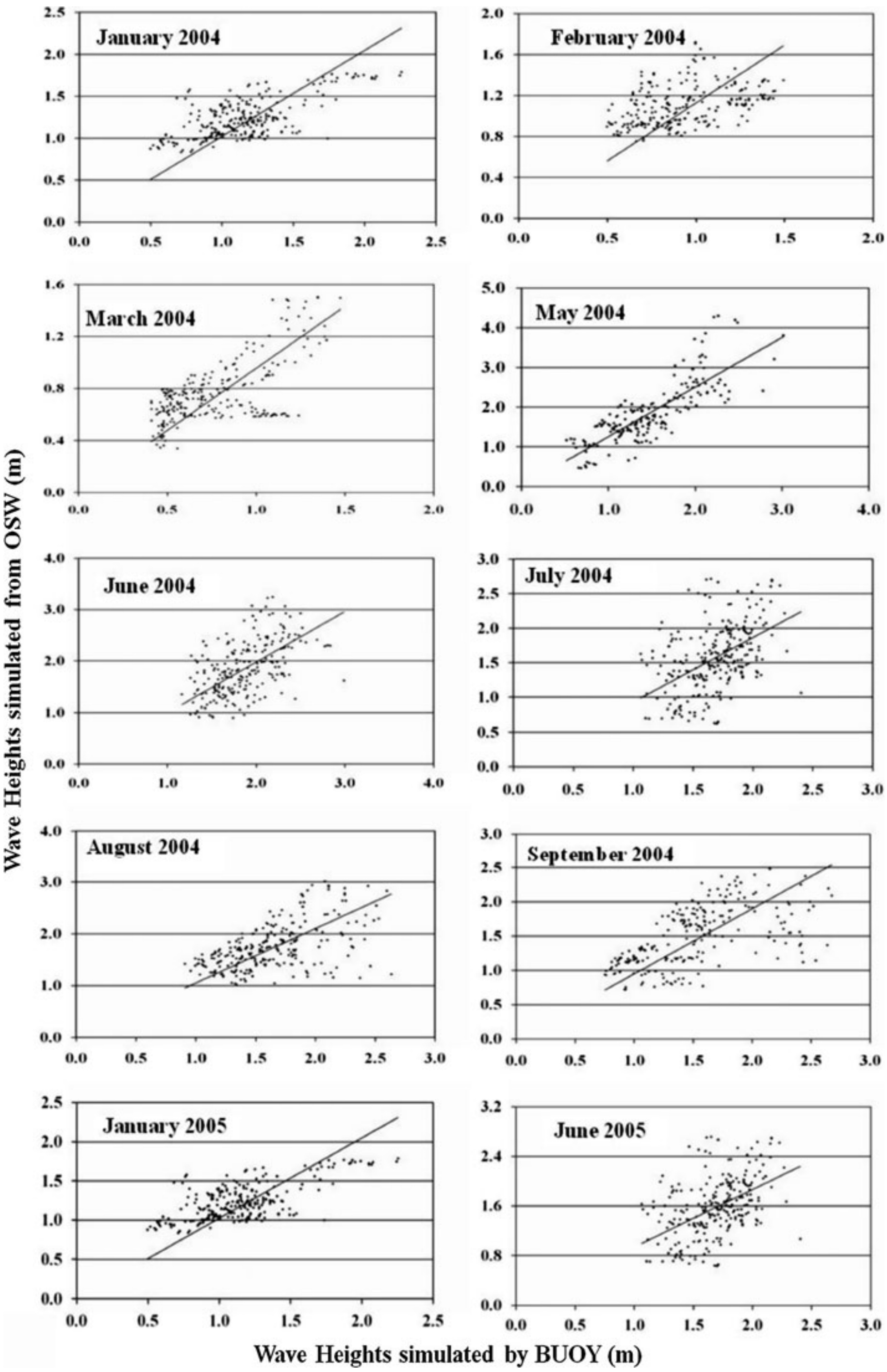

Fig. 6 Scatter plot between simulated and buoy wave heights

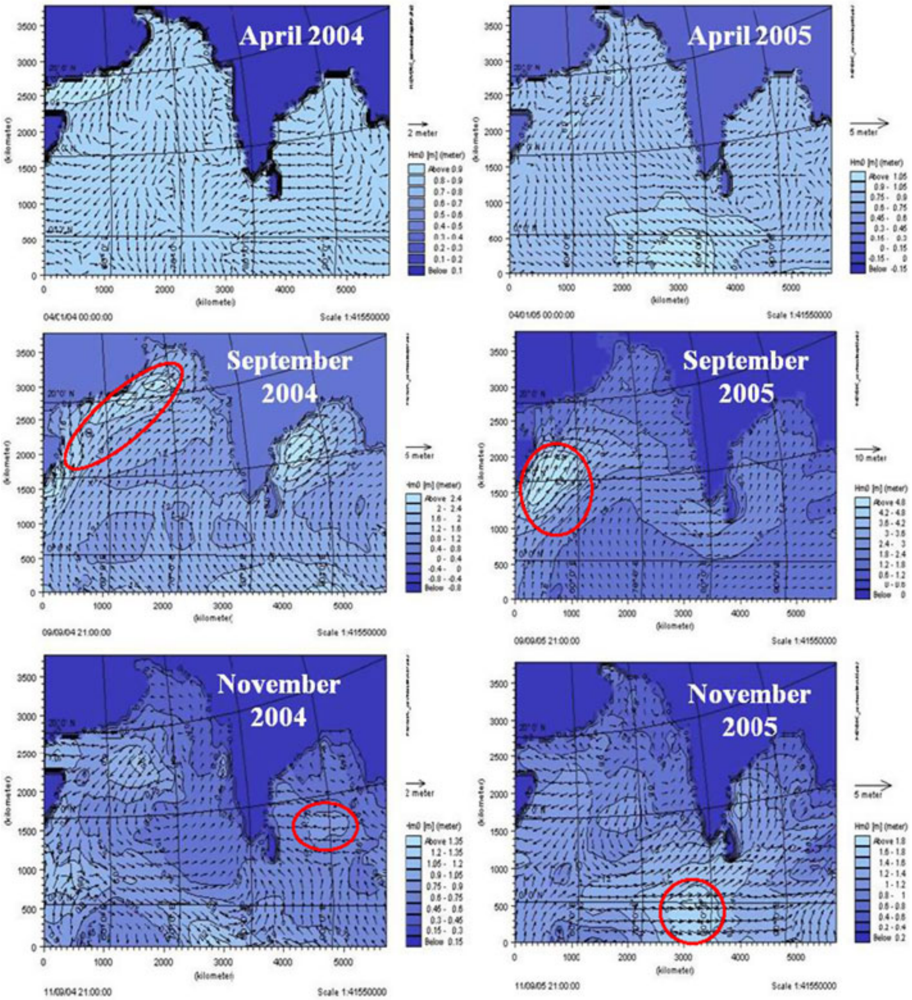

Fig. 7 Simulated offshore waves

3.2 Cyclonic storm: Fanoos

The cyclonic storm Fanoos developed from a low pressure area over south Andaman Sea. It intensified into a depression and laid over southeast Bay of Bengal in the morning of December 6, 2005. Moving in a northwesterly direction, it further intensified into a deep depression in the same afternoon. Thereafter, it took a steady westerly direction and intensified into a cyclonic storm in the morning of 7 December. It had southwestward movement till the morning of 8 December; thereafter, it moved westwards till morning of 10 December. On morning of 10 December, due to the proximity to land, it weakened into a deep depression and crossed north Tamil Nadu coast, south of Nagapattinam (close to Vedaranyam) around 0530 UTC. After landfall, it rapidly weakened into a depression at 0600 UTC of the same day. Moving in a westerly direction, it weakened further into a low

Table 1 Details of cyclones

Tropical cyclone	Name	Period	Date, time (UTC) and Lat N/long. E of genesis	Date, time (UTC) place of landfall/dissipation	Warnings issued	Surface wind speed (km/hr)	Mean sea level pressure (MB)	Maximum T. No. attained
05B	Baaz	27 November–3 December 2005	November 28, 0300 UTC near 10.5°N/90.5°E	Weakened over southwest and adjoining west central Bay of Bengal on December 02 around noon	10	65–83	991	T3.0
06B	Fanoos	06–10 December 2005	December 06, 0300 UTC near 10.5°N/89.5°E	Crossed Tamil Nadu coast close to Vedaranyam south of Karaikal the forenoon of December 10	11	111–139	980	T3.0
07B	07B	17–22 December 2005	December 15, 1200 UTC near 8°N/87°E	Weakened over southwest and adjoining central Bay of Bengal on December 22 forenoon	12	83–102	992	T2.0

Table 2 Development of cyclones

	Grade
Baaz	
28.11.2005	Depression developing to deep depression
29.11.2005	Cyclonic storm
30.11.2005	Cyclonic storm
1.12.2005	Cyclonic storm turned to deep depression
2.12.2005	Depression
Fanoos	
6.12.2005	Depression developing to deep depression
7.12.2005	Deep depression converted to cyclonic storm
8.12.2005	Cyclonic storm
9.12.2005	Cyclonic storm
10.12.2005	Deep depression turned to depression
7B	
15.12.2005	Depression
16.12.2005	Depression
17.12.2005	Deep converted to deep depression
18.12.2005	Deep depression
19.12.2005	Deep depression
20.12.2005	Deep depression turned to depression
21.12.2005	Depression
22.12.2005	Depression

pressure area in the morning of 11 December. Northeast monsoon rainfall activity was significantly enhanced by this system, and Tamil Nadu received widespread rainfall with scattered heavy to very heavy falls on December 11 and 12, 2005. No damage was reported in India due to this system.

3.3 Deep depression: 07B

A low pressure area formed over south Andaman Sea on 14 December. It concentrated into a depression over southeast Bay of Bengal and lay centered at 1,200 UTC near latitude 8°N and longitude 87°E on 15 December. It moved westwards and concentrated into a deep depression and lay centered at 0300 UTC of 17 December over southwest Bay near 8°N/84°E. The system moved northwestwards till 19 December 1,200 UTC and then took a northeasterly movement. Moving in a northeasterly direction, the system weakened into a depression and lay centered on 20 December at 0600 UTC near 11.5°N/84°E. Continuing its northeasterly direction, it further weakened into a well-marked low pressure area and lay over southwest and adjoining central Bay of Bengal at 22 December, 0300 UTC. Scattered rainfall was realized on 18 and 19 December over Tamil Nadu. The system did not cause any damage in India.

3.4 Discussion

The tracks of these cyclones were obtained from www.tropicalcyclone2005.com. The study area and model setup were the same as that simulated for normal conditions. After

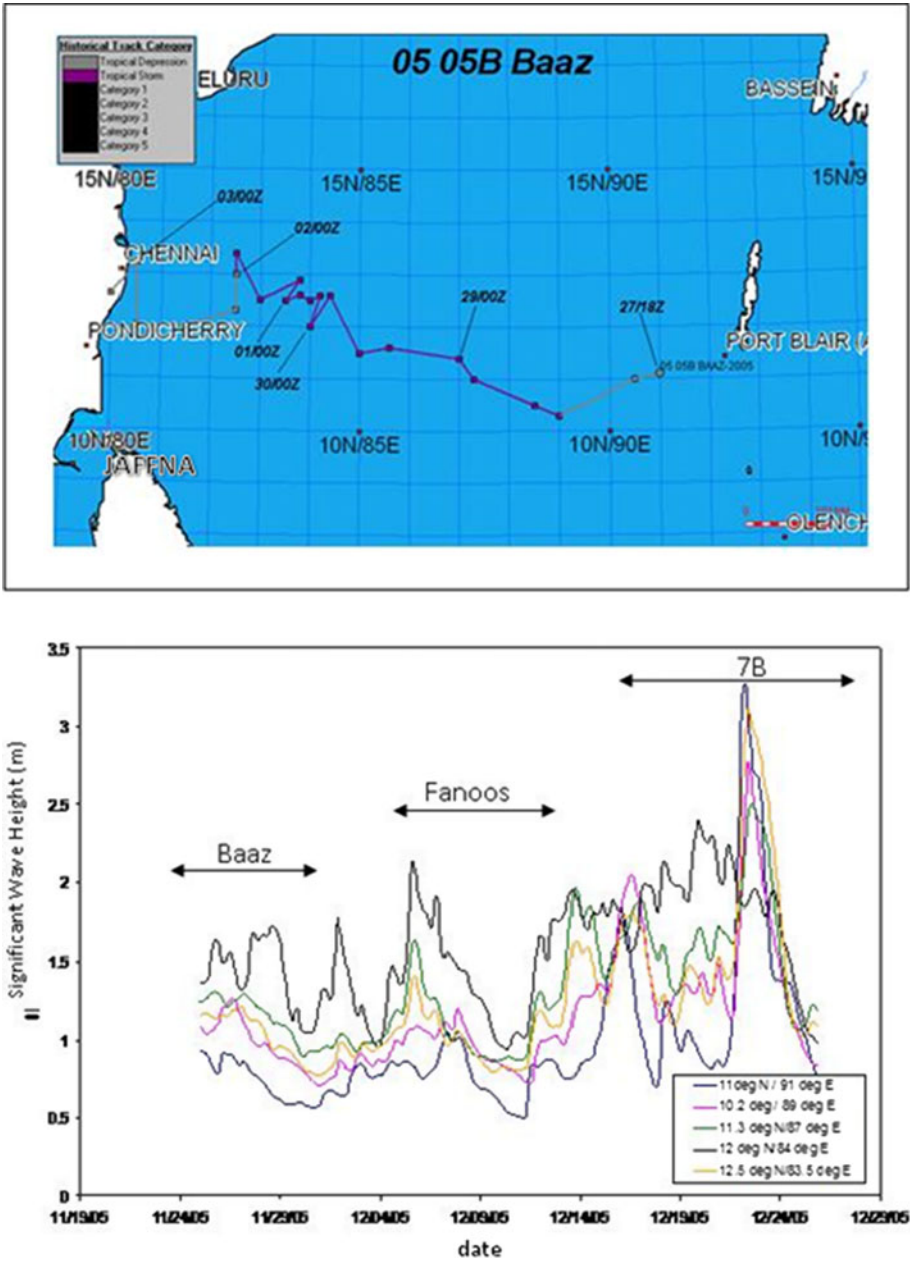

Fig. 8 Significant wave heights along the track of Baaz cyclone

simulation, the wave heights were extracted from selected points on the respective cyclone tracks. Among the three cyclones, Baaz and Fanoos lasted for about seven to 8 days whereas 7B lasted for 10 days. The cyclone tracks and simulated significant wave heights are shown in Figs. 8, 9 and 10 with arrows indicating the periods of each cyclone and the significant wave heights occurred during these periods are given in Table 3.

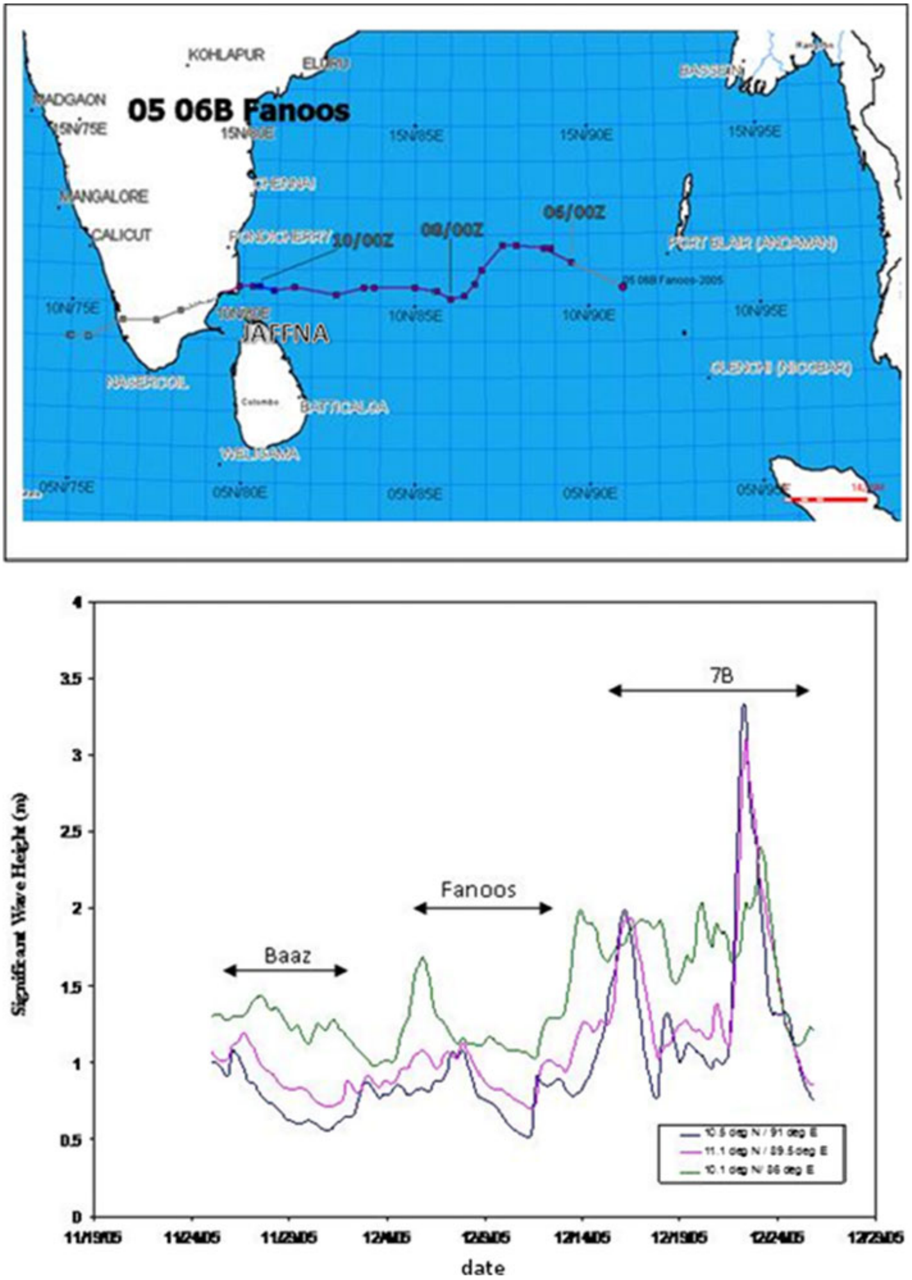

Fig. 9 Significant wave heights along the track of Fanoos cyclone

A closer look at the SWH observed during Baaz confirms that the wave height is the lowest at 11°N/91°E; as this point is lying on the east of the cyclone, this is not disturbed by the cyclone (Fig. 8). When Baaz changes to “deep depression” on November 28, 2005, an increase of about 0.3 m in wave height is observed at 10.2°N/89°E which increases

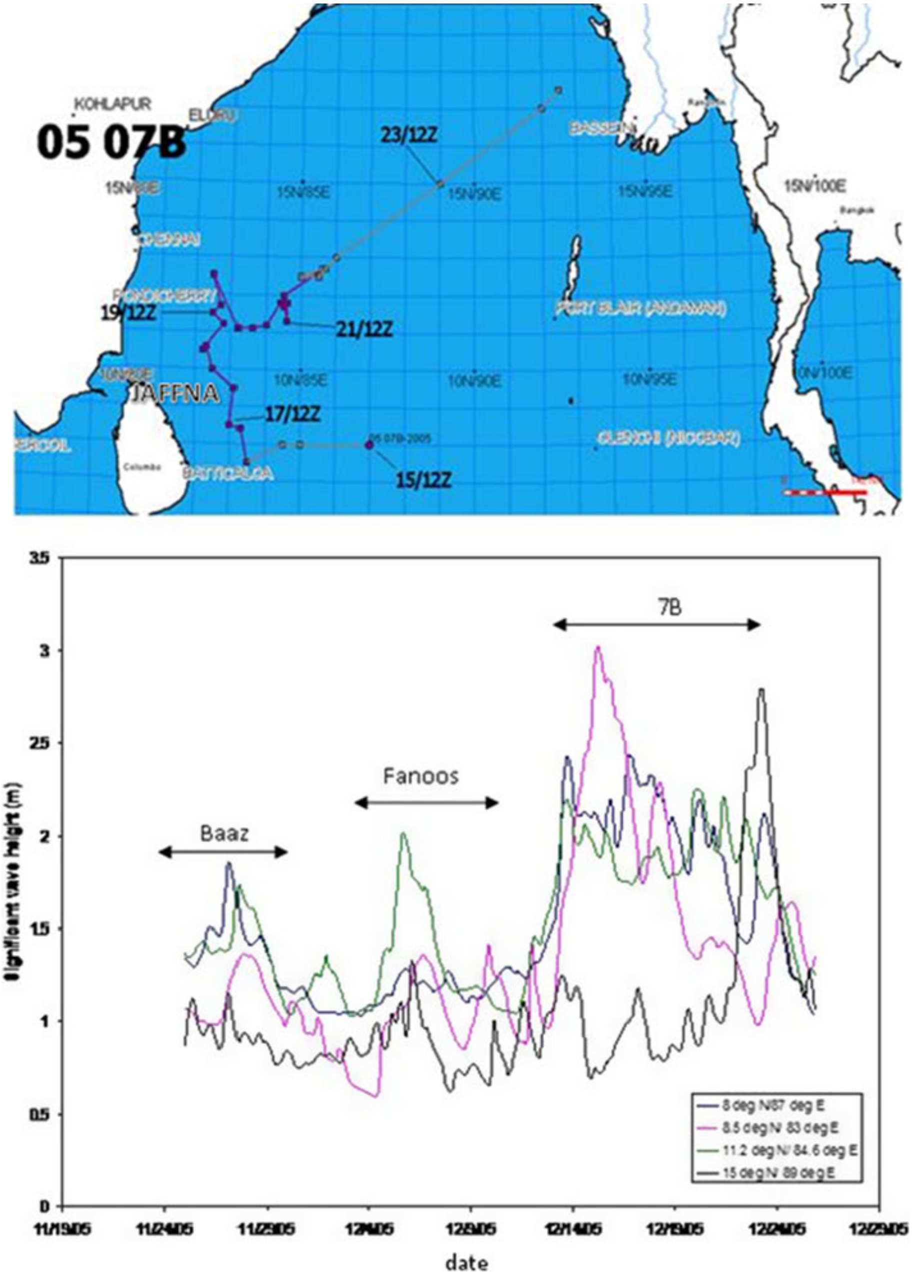

Fig. 10 Significant wave heights along the track of 7B cyclone

further (~0.25 m) when the "deep depression" changes to "cyclonic storm" on November 29, 2005 at 11.3°N/87°E. When the "cyclonic storm" condition persist for the next day, extreme waves up to 1.78 m are identified at 12°N/84°E and after the climatic conditions were improved by reducing to "depression", a decrease in wave heights are noticed on December 1 and 2, 2005. Track of Fanoos lies below that of Baaz, and the locations

Table 3 Significant wave heights in the cyclone tracks

Cyclones	Significant wave height (m)		
	Maximum	Minimum	Average
Baaz	1.78	0.94	1.34
Fanoos	1.69	1.03	1.22
7B	3.01	1.33	1.93

Table 4 Significant wave heights in the tracks of Baaz and Fanoos during 7B cyclone

Impact of 7B cyclone in	Significant wave height (m)		
	Maximum	Minimum	Average
Baaz track	3.26	1.06	1.89
Fanoos track	3.34	1.11	1.73

11.3°N/87°E, 12°N/84°E and 12.5°N/83.5°E are located on the west of this track; hence, when Fanoos occurs between December 6–10, 2005, an amplification in the wave heights observed at these sites on 6 and 7 December ("cyclonic storm") could be due to the propagation of swell waves. Similar explanation holds good for the highest waves (3.26 m) identified on December 23, 2005 at these locations after the occurrence of 7B cyclone. In addition, though the wave heights are higher during the rest of the period, comparatively less SWH occur at 12°N/84°E, as this point lies in the 7B cyclone track itself.

SWH is the lowest at 10.5°N/91°E, as it is not falling in the track of Fanoos (Fig. 9). The location 11.1°N/89.5°E is closer to the origination of Fanoos while 10.1°N/86°E lies within the track explains the comparatively lower wave heights in the former than the latter. Further, high waves are observed during "cyclonic storm" grade on December 7, 2005. These three locations are situated closer to Baaz track but, on the east of 7B cyclone track; hence, not much increase in wave heights is noticed during Baaz, whereas SWH raises up to 3.34 m due to the domination of swell waves which is evidenced from the amplification of wave heights with the increase in distance.

The path of 7B cyclone is completely different from the tracks of other cyclones; hence, the SWH are comparatively lower during period of occurrence of Baaz and Fanoos cyclones (Fig. 10). From the SWH values, it can be inferred that the locations 8.5°N/83°E and 15°N/89°E are not situated in the direction of propagation of swell waves. Relatively higher wave heights observed at 8°N/87°E and 11.2°N/84.6°E during Baaz and only at 11.2°N/84.6°E during Fanoos confirm the domination of swells, as these are closer to the respective cyclones. The locations 8.5°N/83°E and 11.2°N/84.6°E lie in the track of 7B cyclone record higher waves, but the "deep depression" conditions prevailing in the former position causes further increase in wave heights up to 3 m.

Of the three cyclones, the simulated wave heights are the lowest for Fanoos. Baaz and Fanoos cyclones exhibit the significant wave height on November 29 and December 7, 2005, respectively, when the cyclones reaches the "cyclonic storm" condition. The wave heights in the tracks of Baaz and Fanoos during 7B cyclone are given in Table 4. The significant wave heights observed during the cyclone 7B when compared with others, with the highly disturbed wave conditions may be attributed to the orientation of its track which supports the possibility of travel of swell waves in different directions causing an increase in the significant wave heights in the entire region. Due to the absence of the measured wave data during cyclonic conditions, the simulated significant wave heights could not be validated. Considering the accuracy of the predicted SWH under normal conditions and also the SWH simulated during the cyclonic conditions harmonize with the grades of the extreme events, it is confirmed that NCEP winds and OSW model can be effectively used to estimate wave heights during cyclones.

4 Conclusion

The sea state during the extreme climatic conditions is well derived using MIKE 21 OSW model. Under normal conditions, the comparison between model outputs and buoy data show an average correlation coefficient of 0.84 and the significant wave height in the offshore of North Indian Ocean is in the range of 1–1.5 m. Model-predicted significant wave heights during the three cyclones fit very well with the variations of cyclone grades such as depression, deep depression, and cyclonic storm, as well as the propagation of swell waves from its origin. Though the validation of wave heights predicted from the model could not be carried out, its accuracy under normal wave conditions has proved the effective use of the models in predicting the wave climate over the oceans. MIKE 21 OSW can play a vital role in the ship routing and in the assessment of the nature of offshore wave climate during cyclones and storms.

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