

# Simulated wave climate and variability over the North Indian Ocean

Basanta Kumar Jena\*, J. Rajkumar, Aruna Kumar Avula, K. Jossia Joseph and M. V. Ramana Murthy

National Institute of Ocean Technology, Ministry of Earth Sciences, Chennai 600 100, India

**The wave parameters and long-term statistics of wave height are important parameters required for coastal/offshore engineering design and analysis. The 20-year wave simulation has been carried out using MIKE-21 spectral wave model developed by the Danish Hydraulic Institute. The model was forced with the wind data from ECMWF operational archive wind data from 1998 to 2017. The MIKE C-MAP bathymetry data for less than 250 m depth in the North Indian Ocean and ETOPO1 for above 250 m depth were utilized for model bathymetry. The wave measurements available at various depths in the North Indian Ocean were utilized to validate model result. Wave parameters extracted at 27 locations at an interval of 1 degree at 25 m water depth were used for showing monthly variability of significant wave height, average wave period and mean wave direction. The extreme value analysis of significant wave height was carried out using Weibull analysis for 2, 5, 20 and 50 years return period. The maximum wave height of 5.7 m near Odisha coast in 50 years return period was calculated from the extreme value analysis.**

**Keywords:** Extreme value analysis, numerical model, wave direction, wave height, wave period.

## Introduction

ACCURATE wave information is vital to many coastal and offshore activities and describes ocean-state in general. Waves play an important role in design criteria of coastal and offshore structures. The characteristics and variability of waves require long-term observations with sufficient spatial and temporal resolutions. In general, the availability of measured wave data is sparse and may not cover the various meteorological conditions (seasonal and inter-annual variability, cyclones, etc.) and is limited to specific locations.

The location-specific wave climate is a significant input in coastal and offshore developmental activities and it is difficult to obtain at the preliminary stage of a project for planning. The absence of readily available information on wave demands site-specific measurements of

wave and the numerical modelling studies need to be carried out which is time consuming task. The wave climatologies have been prepared using voluntary ship observations<sup>1</sup>, simulated data<sup>2-4</sup>, satellite altimetry<sup>5</sup>, wave measurements, etc. WORLDWAVES, a Matlab toolbox, simplifies and speeds up the estimation of wave conditions at coastal sites worldwide<sup>6</sup>. Charts of monthly mean wind speed and significant wave height for the world oceans on a  $4^\circ \times 4^\circ$  grid are derived from GEOSAT altimeter data from November 1986 to January 1990 (ref. 7). However, many of these data sets do not cover the Indian seas or wave parameters in  $4^\circ \times 4^\circ$  grid resolution along the Indian coast. The wave atlas of the North Indian Ocean<sup>1</sup> was prepared using voluntary ship observations and measured data by the National Institute of Oceanography (NIO), Goa. NIO Wave Atlas lacks uniform data set and the reliability is limited due to visual observation. GEOSAT (GEOdetic SATellite) altimeter data for the period 1986–1989 have been utilized to derive wave climatology for the Indian Ocean region<sup>8</sup> and may not be suitable for the studies which require long-term statistics. The wave information along the Indian coast with sufficient spatio-temporal resolution and duration can help in the planning stage of many coastal activities.

Considering the wide gap in readily available-wave information for planning purposes of coastal developmental activities, the National Institute of Ocean Technology (NIOT), MoES initiated the project towards developing a ready reference for wave as part of the project ‘Technical Criteria Atlas’. The uniform space–time coverage of numerical model results for sufficiently long period is essential for preparing the wave atlas. This study was carried out with 20-year wave data simulated (1998–2017) using MIKE21 spectral wave model developed by the Danish Hydraulic Institute (DHI), Denmark covering the North Indian Ocean (Figure 1). The model wind forcing was provided using European Centre for Medium-Range Weather Forecasting (ECMWF) operational archive wind data for the period 1998–2017. The first version of wave atlas covering wave simulation from 1998 to 2012 (15 years) was published in September 2014 (ref. 9). The annual and monthly data statistics were computed at 27 locations at one-degree interval at 25 m water depth along the coastal belt of the Indian mainland. The computation of long-term averaging of significant wave

\*For correspondence. (e-mail: bkjena.niot@gov.in)

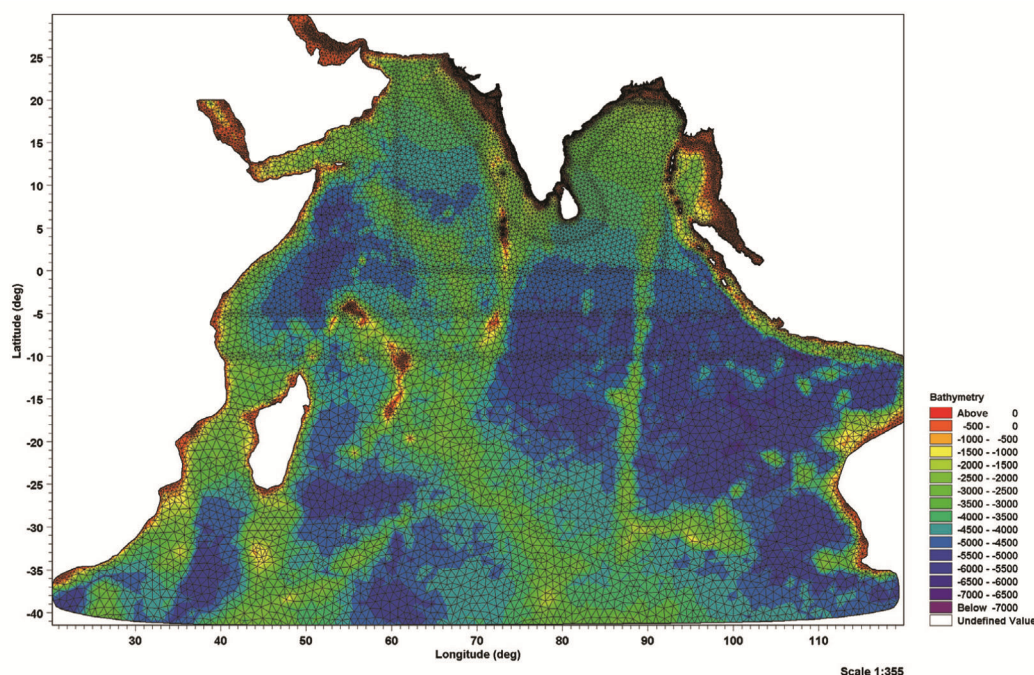


Figure 1. Model domain for North Indian Ocean.

Table 1. Resolution of ECMWF wind data used for the present study

Spatial resolution	Temporal resolution	Period
0.5 × 0.5 deg	6 hourly	1 January 1998 to 31 January 2006
0.25 × 0.25 deg	6 hourly	1 February 2006 to 30 June 2012
0.125 × 0.125 deg	6 hourly	1 July 2012 to 31 December 2017

height was carried out using the method of Weibull analysis. From the 20-year wave simulations, extreme value analysis of significant wave height was carried out for 2, 5, 20 and 50-year return period. The 100-year wave height estimation required minimum 33 years wave simulations.

**Material and methods**

*Wind data*

The ECMWF analysed wind data set from operational archive was available with a variable grid at every six hour interval since August 1982. These data sets are produced at ECMWF as part of various global analyses and forecasts and archived in MARS (Meteorological Archival and Retrieval System). The resolution and internal representation of the archive vary according to changes in data assimilation and forecast systems in operational use at ECMWF. The ECMWF wind data during January 1998 to December 2017 (Table 1) was used as wind input for wave hindcasting and validated with field observations.

*In-situ buoy observations*

The moored buoy network established by the NIOT under the Ministry of Earth Sciences provided major source of the *in-situ* observations for validating the input wind and the simulated wave data. The buoy data are available at specific locations in the North Indian Ocean since 1998. Apart from the moored buoy observations, the wave data measured using Directional Wave Recorder (DWR) buoys by NIOT as part of various other projects was also utilized in this project. The wave observational network of the Indian National Center for Ocean Information Services (INCOIS) started in 2007 and presently operates a network of 10 wave rider buoys. The DWR-buoy measurements carried out by the INCOIS during the reporting period were obtained and utilized to validate the model results. Combining all available data, more than 25 buoy locations in coastal and deep waters were utilized to validate the model results (Figure 2).

*Numerical methods*

The wave model used for this study is MIKE 21 Spectral Wave Model (MIKE21-SW) developed by DHI. It is a third generation spectral wind-wave model based on unstructured meshes. The model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas. The model includes wave growth by action of wind, nonlinear wave-wave interaction, wave-current interaction, refraction and shoaling. The dissipation due to white-capping, bottom

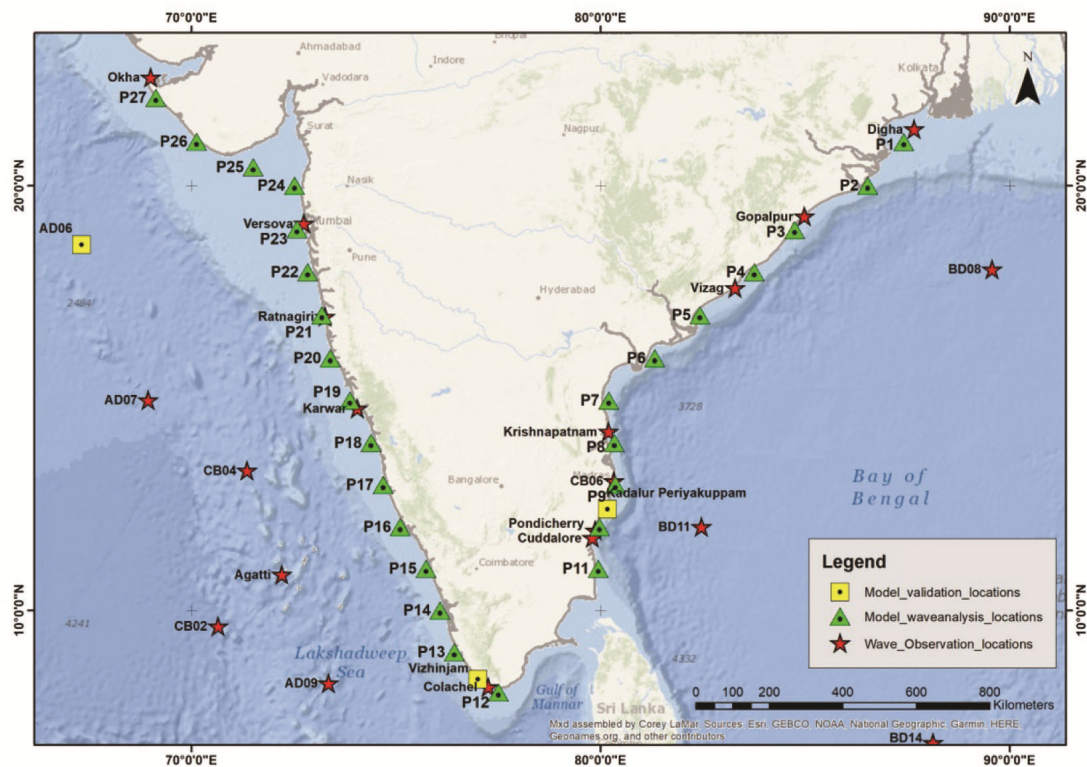


Figure 2. Location map of the buoy network used for validation of model results.

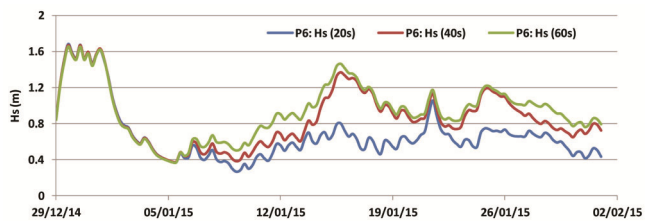


Figure 3. Significant wave height variation from sensitive analysis.

friction and depth-induced wave breaking is also included. The model is based on the wave action balance equation where the wave field is represented by the wave action density spectrum. The details of the model equations and methods of solution are explained elsewhere<sup>10</sup>.

### Bathymetry and model domain

The primary bathymetry data set used for the present project was Earth Topography1-Minute (ETOPO1) gridded elevation (land) and bathymetry (seafloor) data set. However, the sensitivity analysis indicated better agreement when the coastal bathymetry was replaced with MIKE Sea Chart in Digital Format (CMAP) data. Consequently combinations of these data sets with CMAP data for water depth less than 250 m in North Indian Ocean

and ETOPO1 elsewhere were used to prepare the model bathymetry of the study area (Figure 1). The coastline was prepared using the coastline extractor from the National Oceanic and Atmospheric Administration (NOAA)/National Geophysical Data Center (NGDC).

The wave model simulates growth, decay and transformation of wind-generated waves and swells. The sensitivity analysis of spatio-temporal resolution and model domain was carried out to identify the optimum resolution and extent of model domain. These factors influence the model performance and time consumption. Hence, the model domain was closed in the Malacca Strait. However, the Red Sea and the Persian Gulf were included in the domain. The south-eastern boundary was closed at 120°E with Australia. The swells are long period wave generated far away from shore. In order to study the swells, the sensitivity analysis with three southern boundary (extend up to 20°S, 40°S and 60°S) was simulated. The  $H_s$  variation from sensitivity simulation (boundary 20°S, 40°S and 60°S) at the Machilipatnam Coast (Andhra Pradesh) is presented in Figure 3. Based on the comparison of results with observed wave data, the southern boundary was fixed at 40°S.

The bathymetry was setup with varying grid sizes which covers 40°S to 30°N over a longitudinal extent of 20°E to 120°E. Bathymetry contours at 200 m, 100 m and 50 m along the coastal belt with a fine resolution of 0.04, 0.02 and 0.01 deg<sup>2</sup> element area were utilized.



*Model calibration parameters*

The calibration parameters available with MIKE21-SW are spectral resolution, bottom friction, wave breaking parameters and white capping parameters<sup>10</sup>. The model direction was resolved with 16 directions resulting in a resolution of 22.5°. The logarithmic distribution of frequency is selected with a frequency factor of 1.1 with 27 frequencies. The wave period ranged from 2.1 to 25.0 sec (i.e. frequencies from 0.48 to 0.04 Hz).

The calibration of the remaining model parameters is carried out with the corresponding values varying between permissible ranges to minimize the difference with the measured data. The selection of a large model domain and the availability of non-homogenous validation points made it difficult to arrive at a uniform coefficient applicable for the entire domain. Hence the default values are utilized for the wave hindcasting.

*Computation of long-term average of significant wave height*

The computation of long-term average of significant wave height was carried out using the method of ‘Weibul’ analysis. The formula of the three parameter distribution is given below

$$P = 1 - e^{-(H - \gamma/\beta)^\alpha}, \tag{1}$$

where  $P$  is the probability of non-exceedance ( $P = 1 - Q$ ),  $\alpha$  the shape parameter,  $\gamma$  the location parameter and  $\beta$  is the scale parameter. After taking the logarithm on both sides the equation becomes

$$[\ln(1/Q)]^{1/\alpha} = (1/\beta)H - (\gamma/\beta), \tag{2}$$

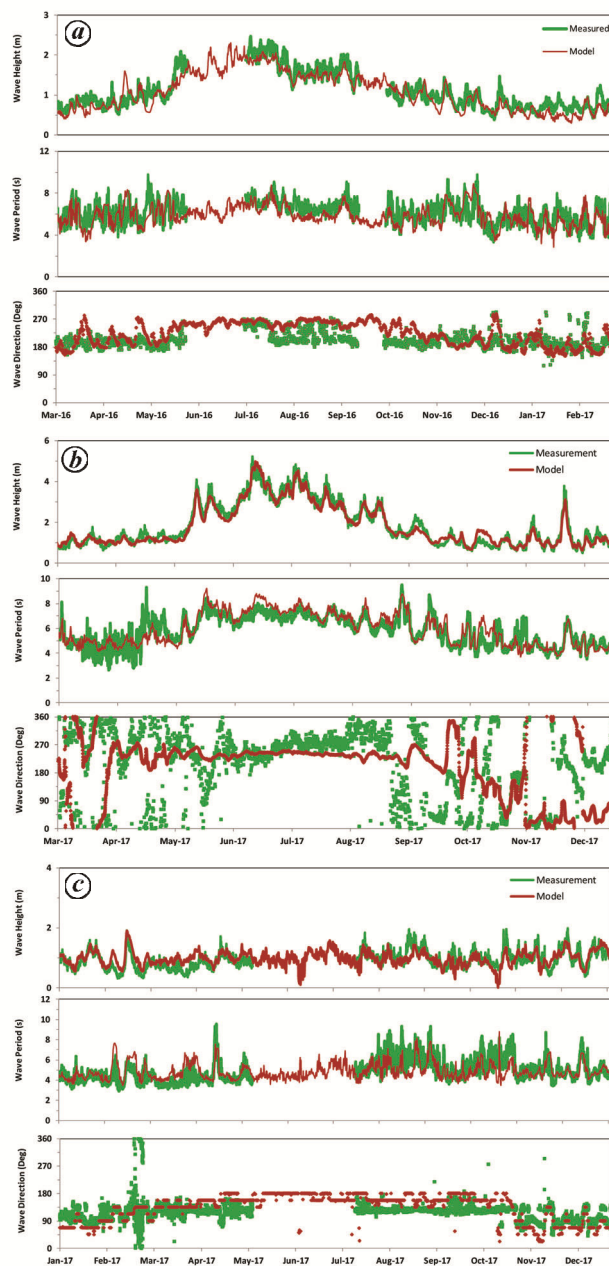
where the  $[\ln(1/Q)]^{1/\alpha}$  is called the reduced variate of Weibull distribution. A best line fit was drawn using the least square method and the values of  $\beta$  and  $\gamma$  are obtained from the slope and intercept of the best line fit. The shape parameter is a kind of numerical parameter of probability distributions. This parameter affects the shape of a distribution rather than simply shifting it (as a location parameter) or stretching/shrinking it (as scale parameter). Shape parameter can be estimated in terms of the higher moments, method of moments, skewness or kurtosis. Weibull shape parameter is known as Weibull slope, which varies between 0.8 and 1.3 with an increment of 0.05 is selected from the best line fit which gives the highest value of correlation coefficient.

**Results and discussion**

The wave simulations were carried out for 20-year period between 1998 and 2017. The simulated wave characteris-

tics using MIKE21-SW were validated using moored buoy data to assess the quality and reliability of the model. The comparison was carried out in deep as well as in shallow waters in the Arabian Sea and the Bay of Bengal.

One-year data measured off Vizhinjam, deep water location on the west coast (AD06) and off Kadalur Periyakuppam at 15 m water depth during 2016–17 is presented as a case study for locations (Figure 4). The seasonal variability and high frequency fluctuations are well captured in this location as well. It is also observed that the model results are slightly over estimated for  $H_s$  less



**Figure 4.** Validation of wave parameters (a) off Vizhinjam, Kerala, (b) at deep water west coast (AD06), (c) off Kadalur Periyakuppam, Tamil Nadu.

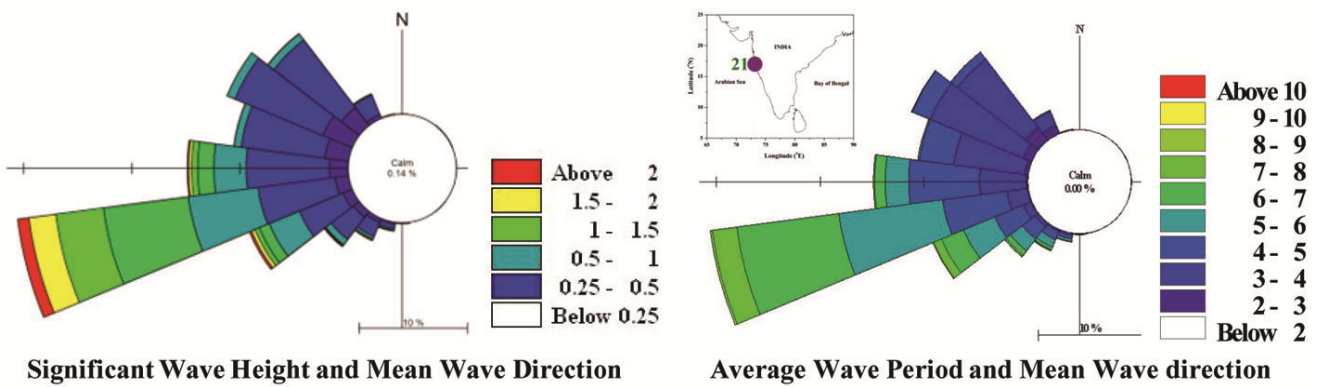


Figure 5. Rose plot of annual significant wave height off Vijaydurg (West coast of India).

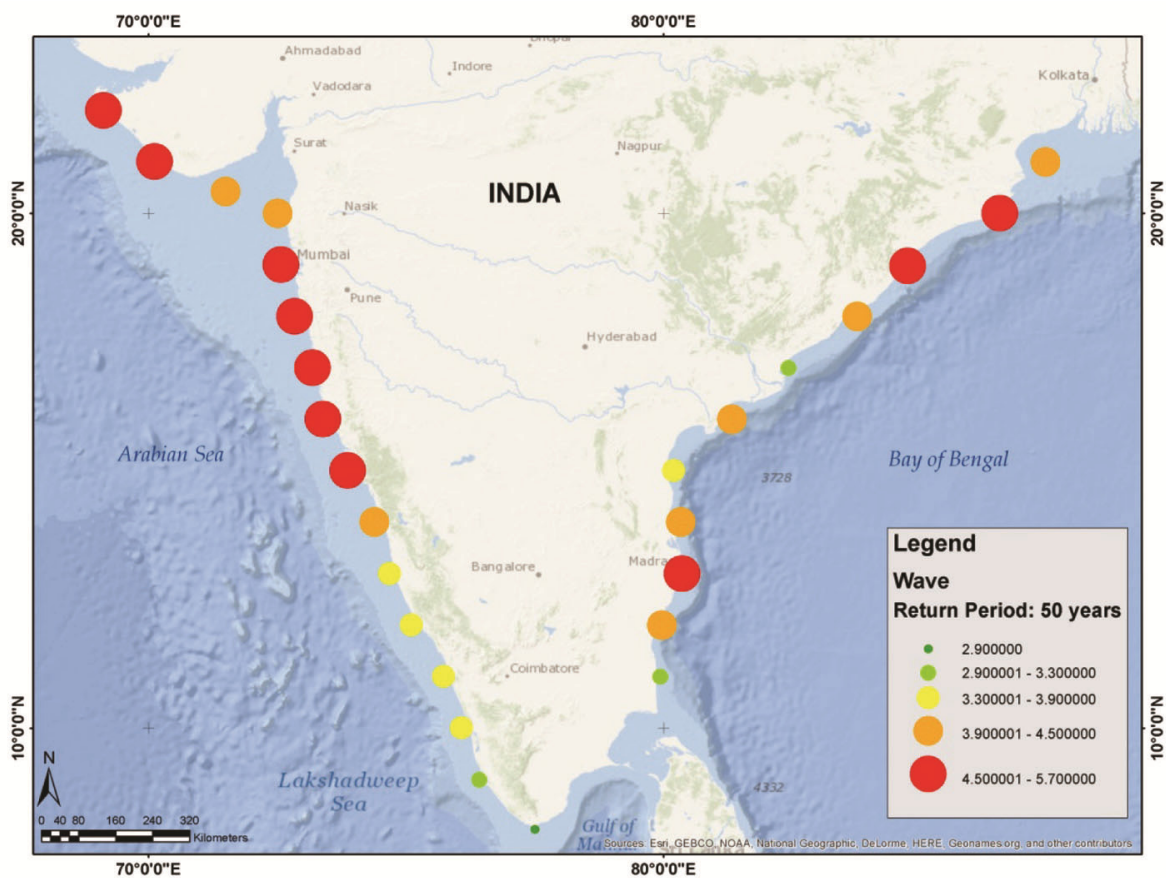


Figure 6. One in 50 years significant wave height along North Indian Ocean from hind cast model.

Table 2. Correlation coefficient between observed and model

Location	Parameter	Correlation
Vizhinjam (KL)	Significant wave height ( $H_s$ )	0.92
	Mean zero up-crossing period ( $T_z$ )	0.60
Deep water in the west coast (AD06)	Significant wave height ( $H_s$ )	0.98
	Mean zero up-crossing period ( $T_z$ )	0.86
Kadalar Periyakuppam (TN)	Significant wave height ( $H_s$ )	0.64
	Mean zero up-crossing period ( $T_z$ )	0.59

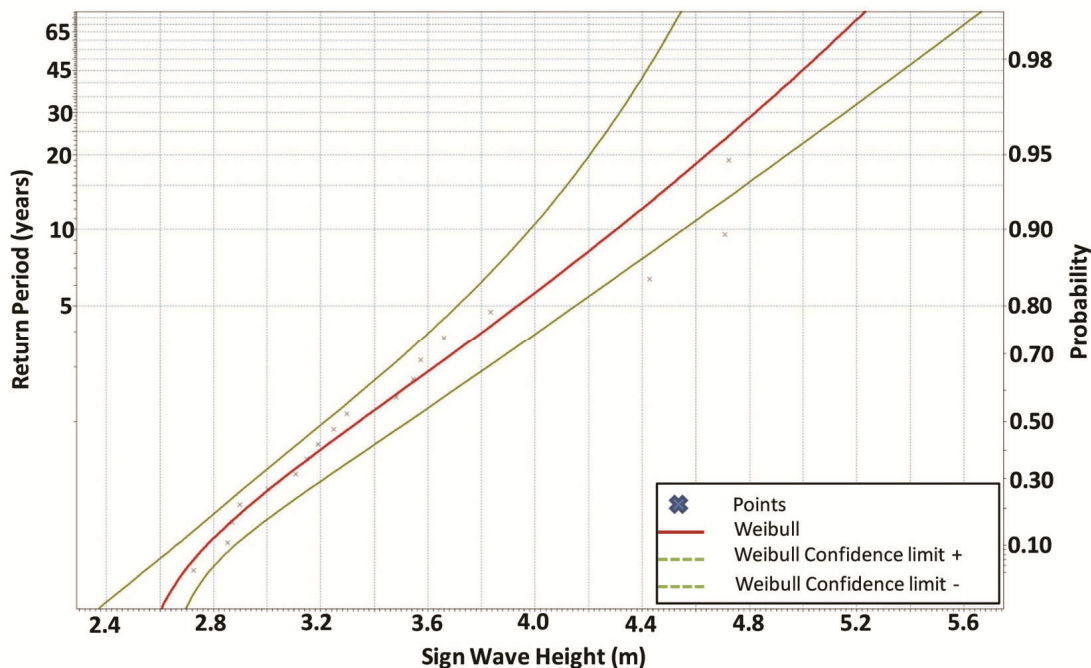


Figure 7. Probability plot of significant wave height return period from wave simulation.

than 1 m and underestimated the stronger waves. The  $T_z$  agreed well with the observations except for the underestimation corresponding to the period of overestimation of  $H_s$ . The  $M_{dir}$  is in good agreement with the observations and the seasonal variability has been well captured.

It was observed that the  $H_s$  exhibits good agreement with the observations with a correlation coefficient of more than 0.75 in most of the locations. The detailed analysis revealed that the  $H_s$  is in better agreement for lesser wave height than that of strong sea conditions. In Vizhinjam, the correlation coefficient is about 0.92 (Table 2) and  $R^2 = 0.83$  (linear regression).

The simulated  $T_z$  well exhibits the spatial and temporal variability in the Indian seas. However, it is observed that the simulated period is slightly underestimated at all shallow water locations of validation. The annual, monthly, single parameter and joint distribution statistics are computed at 27 locations at one degree interval at 25 m water depth along the Indian mainland (Figure 2). The annual variation of significant wave height and average wave period from model results at location 21 are presented in Figure 5. Similarly the statistical estimation of simulated wave parameters has been carried out for 20 years simulation.

The extreme value analysis module from MIKE 21 tool was utilized for 20 years wave simulated data. The wave data extracted at 25 m water depth along the Indian coastline was used for long-term analysis with annual maximum series (AMS) method. The return period of significant wave height in 2, 5, 20 and 50 years was calculated using Weibull distribution and the result is presented in Figure 6. From the figure, it is observed that the

estimated 50 year return period significant wave height is higher off coasts of Odisha, Chennai, Goa and Maharashtra. The probability plot is presented in Figure 7.

### Summary

The Wave Atlas was prepared utilizing 20-year simulated wave data. Great care has been taken in calibrating the model and validation of model results. In general, the model outputs could simulate the intra-annual variability as well as the spatial variability of wave parameters in the North Indian Ocean. The general trend in the observed data is well exhibited in the simulated data. In general, the simulated wave height is in good agreement for low wave heights and is underestimated during high seas at all validation points. The average wave period is slightly underestimated whereas the mean wave direction is in good agreement at all wave conditions. The return period for long-average of  $H_s$  is solely based on simulated data in which tropical cyclones are not resolved and consequently exhibits underestimated values. The wave atlas exhibits the detailed wave statistics at 27 locations selected at 25 m water depth along the east and west coast of India.

It is proposed to bring out the next level of Wave Atlas with more information utilizing an extended period of simulated data with including Islands and high resolution ECMWF wind data (0.125 deg). It is also planned to calculate long-term wave climate during extreme events like storm/cyclone.

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