CHAPTER 3

WAVE GENERATION AND TRANSFORMATION
IN DEEP WATERS

3.1 GENERAL

The demand for reliable information on wave conditions, in offshore region is increasing as a result of the increased utilization of offshore region for navigation, fishing and due to meteorological importance. In the absence of long term wave data collected at offshore, the calculation of wave statistics requires various data sets such as buoy data, float measurements, observation from ship, satellite data etc. to be assembled at offshore sites. Further, a suitable wave model is required, capable of predicting the offshore and nearshore wave climates. One such modelling software is MIKE 21 which is capable of handling wave action and momentum concept models.

3.2 WAVE GENERATION AND ITS GROWTH

Ocean waves are undulations of the water surface resulting from the transfer of energy. The disturbance is propagated by the interactions of disturbing (eg. wind) and restoring (eg. gravity) forces. Most ocean waves are created by tangential drag exerted on the surface of the ocean by winds of speeds in excess of 1m s\(^{-1}\). Waves grow in size depending on wind speed, their upper limit is set by gravity and surface tension. The tide is large wave, driven by the gravity of moon and the sun. As the wind starts blowing over the initially calm water body, generates ripples. With the continuous wind
blow, these ripples grow to a full fledged wave and their maximum height is
limited either by the length of the fetch or restricted by the duration of wind
flow. The waves, which leave the generation area are called as swell and
propagate towards the coastline without major change in their characteristics
until they reach shallow waters.

In the area where waves are generated, the sea surface becomes
very choppy as individual waves are shaped into sharp angular crests with
smaller wavelets and ripples superimposed on them. The height of the wind
waves that are generated depends on wind speed, fetch, (distance over which
wind is affecting the sea surface) and the duration of the wind event. When
fetch length is sufficient or the storm has been blowing for sufficient duration,
the choppiness reaches a state of art that is called a fully arisen (or fully
developed) sea. At this point, energy is dissipated by waves at the same rate
as they receive energy from the wind, and after this state is reached the size
and characteristics of the waves do not change. The wave characteristics
briefly overshoot the equilibrium state, but they rapidly return to it (Barnett
and Sutherland 1968).

Wave length and period are maintained as a wave group travels
beyond the area of wave generation, but wave height can decrease slightly as
waves travel. The waves disperse radially from the storm area, with about
90% of the wave energy contained within the angle of 45° from the direction
of travel. In deep water, the speed of travel of the wave group (group velocity)
is half the speed of the individual waves (phase velocity). The first wave in
the group acts to initiate movement of the surface of the water and it
disappears from the front of the group and a new wave forms at the rear.
Therefore, as the individual waves advance twice the length of a wave, the
group only advances one length. Individual waves travel through the group,
starting at the back, moving through to the front where they lost.
Measurements of waves in the open sea suggest that waves of almost incredible heights do occur. Although no relationship exists between wave height and wavelength, the ratio between these two variables is an important one, it is known as the wave steepness ($\varepsilon$).

$$\varepsilon = \frac{H}{L} \quad (3.1)$$

In theory, waves whose steepness exceeds 0.14 (1/7) become unstable and collapse; in practice waves with steepness greater than 0.1 are rarely encountered while at the other extreme few waves are less steep than 0.056 i.e (1/18).

Waves of a particular frequency may lose or gain energy as a result of nonlinear resonant interactions with other waves, and their propagation may be affected by interaction with currents. As the wave form moves across the sea surface, the water particles beneath also move but since they rotate around closed orbits there is no net forward displacement of the water. Water theories predict that the diameter of these closed orbits will be directly related to wave height:

$$S = H^* e^n \quad (3.2)$$

$$N = (2\pi/L)Z_0 \quad (3.3)$$

where $e$ - base of natural log
H - wave height
L - wave length
S - orbital diameter
$Z_0$ - water depth beneath the orbit’s center
The above expression applies only to deep water conditions, predicts that the orbital diameter of the water particles will decrease with depth beneath the surface. The velocity of these orbiting water particles is directly related to their orbital diameter (Figure 3.1).

\[ u_z \propto \frac{\pi S}{T} \]  

where \( u_z \) - orbital velocity at depth \( z \)

This relationship predicts a rapid drop in orbital velocity beneath the surface so that at depths greater than one wavelength, the orbital velocities are less than 1% of those at the surface and may be considered negligible.

### 3.3 OFFSHORE SPECTRAL WIND WAVE MODULE

MIKE 21 OSW is a fully spectral wind-wave model, which describes the propagation, growth and decay of wind generated waves in
offshore as well as in the coastal areas. MIKE 21 OSW is a time dependent discrete wind wave model formulated in terms of the energy density spectrum with a discrete resolution of frequencies and directions. The model includes two different descriptions of physical processes governing the wind wave generation and decay. The model comprises of the phenomenon wind induced wave growth, non linear wave - wave interaction, wave breaking, bottom friction and shoaling, and refraction. MIKE 21 OSW 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 windfarms and marine pipelines in coastal areas, wave forecast etc.

The basic equation states that a component of the direction frequency spectrum moves by its group velocity, being subjected to an increase or decrease in energy depending on the bathymetry, wind speed/direction and spectral shape.

\[
\frac{\partial E}{\partial t} + \cos \theta/c \left( \frac{\partial (Ec_g)}{\partial x} \right) + \sin \theta/c \left( \frac{\partial (Ec_g)}{\partial y} \right) + \frac{c_g}{c} \left( \sin \theta \left( \frac{\partial c}{\partial x} \right) - \cos \theta \left( \frac{\partial c}{\partial y} \right) \right) \frac{\partial E}{\partial \theta} = S \quad (3.5)
\]

\( E(t,x,y,f, \theta) \) - Directional wave Energy spectrum
\( t \) - time
\( x, y \) - cartesian coordinates
\( f \) - frequency
\( \theta \) - direction of wave propagation
\( c_g \) - group velocity
\( c \) - wave celerity
\( S \) - net source term
The left hand side of the basic equation (3.5) takes into account the effects of refraction and shoaling. These effects are introduced because the energy $E(f, \theta)$ is not a conserved quality along the characteristic curves in the general case with non-horizontal bathymetry. In this case $E(f, \theta) c_c$ is conserved along wave orthogonals. The net source term includes the effects of energy loss due to dissipation, energy input from the wind and wave-interactions.

By means of partial differentiation equation (3.5) can be rewritten as

$$\frac{\partial E}{\partial t} + \cos \theta c_c \frac{\partial E}{\partial x} + \sin \theta c_c \frac{\partial E}{\partial y} + \frac{c_g}{c} (\sin \theta \frac{\partial c}{\partial x} - \cos \theta \frac{\partial c}{\partial y}) \frac{\partial E}{\partial \theta} = S - \left[ \cos \theta (\frac{\partial c}{\partial x}) + \frac{c_g}{c} (\frac{\partial c}{\partial x}) + \sin \theta (\frac{\partial c}{\partial y}) + \frac{c_g}{c} (\frac{\partial c}{\partial y}) \right] E \quad (3.6)$$

This introduces on the right hand side an additional source term, which accounts for the effects of refraction. The basic equation (3.6) was solved in two alternating steps. At each time step, the homogenous transport equation including refraction, was first considered

$$\frac{\partial E}{\partial t} + \cos \theta c_c \frac{\partial E}{\partial x} + \sin \theta c_c \frac{\partial E}{\partial y} + \frac{c_g}{c} (\sin \theta \frac{\partial c}{\partial x} - \cos \theta \frac{\partial c}{\partial y}) \frac{\partial E}{\partial \theta} = 0 \quad (3.7)$$

Thereafter the source terms were included.

MIKE 21 OSW 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.

### 3.3.1 Solution Technique for the Homogeneous Transport Equation

A numerical solution technique for the homogeneous transport equation has to make use of higher order difference schemes. Otherwise unacceptable numerical dispersion arises. In MIKE 21 OSW, a semi-Lagrangian explicit higher order scheme has been formulated. The energy spectrum $E(f,\theta)$ is calculated in the mesh point of a fixed Eulerian grid using a Lagrangian approach. The energy of a component $E(x_0,y_0,f_0,\theta_0)$ which, at a time step $n+1$, has the direction of propagation $\theta_0$ and arrives at a grid point $(x_0,y_0)$, has at time step $n$, a direction of propagation $\theta$ and is placed at a grid point $(x,y)$. Hence

$$E^*_{n+1}(x_0,y_0,f_0,\theta_0) = E_n(x,y,f_0,\theta) \quad (3.8)$$

The notation indicates that $E^*_{n+1}$ is a first estimate of the energy at time step $n+1$, the source terms have not yet been included. The direction of propagation, $\theta$, at point $(x,y)$ generally differs from the direction of propagation, $\theta_0$, at point $(x_0,y_0)$.

- **Calculation of $E_n(x,y,f_0,\theta)$**

  For wave direction $\theta$ the energy is found by linear interpolation between the nearest two discrete directions. The energy at point $(x,y)$ is then calculated from known energies at 12 surrounding grid points, to which a polynomium reaching fourth order in $\Delta x$ and $\Delta y$ is fitted. For water points
close to land a more simple 4-point scheme is applied and in all land points the energy is zero.

- **Shoaling effects**

The shoaling effects are defined from equation (3.6) as

\[
(\partial E/\partial t)_{\text{shoaling}} = [\cos \theta (\partial c_g/\partial x) + (c_g/c \partial c/\partial x) + \sin \theta (\partial c_g/\partial y) + (c_g/c \partial c/\partial y)]E
\]

(3.9)

Hence, a new estimate \(E_{n+1}^\star\) of \(E_{n+1}\) is given by

\[
E_{n+1}^\star(x_0,y_0,f_0,\theta_0) = E_{n+1}^*(x_0,y_0,f_0,\theta_0) [1 + (\cos \theta_0 (\partial c_g/\partial x) + c_g/c \partial c/\partial x) + \sin \theta_0 (\partial c_g/\partial y) + c_g/c \partial c/\partial y)]
\]

(3.10)

- **Source terms for wave growth/decay and wave – wave interaction**

The total energy source term \(S\) is defined as:

\[
S = S_{\text{wind}} + S_{\text{nl}} + S_{\text{diss}}
\]

(3.11)

where

- \(S_{\text{wind}}\) - is the input from the atmosphere (wind)
- \(S_{\text{nl}}\) - is the source term due to wave-wave interaction
- \(S_{\text{diss}}\) - is the energy loss due to dissipation

The energy \(E_{n+1}\) is then given by

\[
E_{n+1}(x_0,y_0,f_0,\theta_0) = E_{n+1}^\star(x_0,y_0,f_0,\theta_0) (1 + S_{\text{wind}} + S_{\text{nl}} + S_{\text{diss}})
\]

(3.12)
• **Time step interval**

The time step of 3600sec was selected to provide adequate resolution of the time variation of the wave and wind field and to satisfy the stability criterion for the numerical scheme. The numerical scheme is stable if the following criterion is satisfied:

\[
C_r = \frac{c_g \Delta t}{\Delta x} < 1 \text{ or } \Delta t < \Delta x \frac{c_r}{c_g}
\]  

(3.13) 

(3.14)

where \(C_r\) is the courant number, \(\Delta x\) the grid spacing, \(\Delta t\) the time step and \(c_g\) the group velocity defined as

\[
c_g = \frac{g}{2\pi f_{\text{min}}}
\]  

(3.15)

with \(f_{\text{min}}\) being the minimum frequency specified for inclusion in the simulation and \(g\) gravity. The limiting time step as a rule of thumb can be calculated as

\[
\Delta t < 1.068 \Delta x f_{\text{min}}
\]  

(3.16)

• **Energy dissipation from wave breaking (depth limited wave breaking)**

Wave breaking is the process by which waves loose (dissipate) energy when the waves are too high to be supported by the water depth (i.e. reach a limiting \(H/d\)). The formulation in MIKE 21 OSW of wave breaking due to limiting water depth is based on the formulation of Battjes
and Janssen (1978). The model was run with and without wave breaking. When included friction coefficient \( \gamma \) of 0.183 and \( \alpha \) of 1 was given.

They introduced the following expression for the rate at which the energy is dissipated due to wave breaking

\[
\frac{dE}{dt} = -\alpha / 8\pi Q_b \omega H_{m}^2
\]

(3.17)

where

\[
1 - \frac{Q_b}{\ln{(Q_b)}} = -\left(\frac{H_{rms}}{H_{m}}\right)^2
\]

(3.18)

Here \( E \) is the total energy, \( \omega \) is the frequency, \( H_{rms} \) is the rms value of the wave height, \( H_m \) is a maximum allowable wave height, \( Q_b \) is the fraction of breaking waves and \( \alpha \) is an adjustable constant. \( Q_b \) controls the rate of dissipation, and the maximum wave height is calculated by

\[
H_{m} = k^{-1} \tanh (kd)
\]

(3.19)

where \( k \) is the wave number, \( d \) is the water depth and \( \Upsilon \) is a wave breaking parameter.

Battjes and Janssen used the following values for the wave breaking parameters

\[
\alpha = 1.0 \text{ and } \Upsilon = 0.8
\]

(3.20)

\( \Upsilon \) was calibrated from dissipation model against measurements and obtained as
\[ Y = 0.5 + 0.4 \tanh (33 - S_0) \]  

(3.21)

where \( S_0 \) is the deep water wave steepness calculated as \( \frac{H_{rms,0}}{L_{op}} \). \( H_{rms,0} \) is the deep water root mean square wave height and \( L_{op} \) is the deep water wave length based on peak frequency.

### 3.4 METHODOLOGY

#### 3.4.1 NCEP Data Analysis

- The NCEP winds for North Indian Ocean (5° South to 22° North latitudes and 50° to 98° East longitudes) was downloaded from the website (www.cdc.noaa.gov) for the period January 2004 to December 2005. Even though the focus of the study was to predict the wave climate of Bay of Bengal, entire North Indian Ocean was selected as study area because of its influence in determining the wave climate of Bay of Bengal.

- The downloaded u and v components of wind had a resolution of ~ 275km x 275km. For analysis, the data was interpolated for a grid size of 77km x 77km.

- The NCEP winds were validated with OB8 buoy data (off Cuddalore) located at 81.460° East and 11.509° North.

- Bathymetry, which is a prerequisite for any wave transformation model was prepared for the same areal extent as that of wind from Etope2 (www.ngdc.noaa.gov) at a grid size of 77km x 77km.
The OSW model was run several times and fine tuned with model parameters for normal marine conditions.

The results of offshore wave model were validated with waves observed by OB8 buoy data.

### 3.4.2 QuikSCAT Data Analysis

- A small stretch of eastern coast of India, from 9° to 15° 05’ N latitudes and 79° to 91° E longitudes was selected as study area to simulate offshore waves. The study area covers 1334 km in the x direction and 723 km in the y direction in Bay of Bengal.

- Wind speed and direction obtained from QuikSCAT had a resolution of 0.5° (54 km), for better results the data was interpolated for 0.25° i.e. 27 km, and was validated with DS3 Buoy data (12.162° North latitude and 90.754° East longitude).

- Bathymetry to run QuikSCAT winds was prepared from Naval Hydrographic chart for a grid size of 27 km x 27 km so as to fit the grid size of wind data.

- OSW model was run for the same setup files as that used to run NCEP winds.

- The results obtained from OSW simulation using QuikSCAT data was validated with available DS3 buoy data.
3.4.3 Synthesis of Offshore Wave Climate

- Inter comparison of simulated offshore wave climate between NCEP and QuikSCAT was made
- Monthly wave climate for North Indian Ocean were simulated between January 2004 and December 2005 using NCEP data
- The wave heights along the cyclone tracks of Baaz, Fanoos and 7B were extracted to assess the capability of NCEP winds in estimating cyclonic wave conditions.

3.5 SATELLITE DATA UTILIZED

3.5.1 NCEP

Latter 1990s the data base for climate researches has been substantially improved through the collection of comprehensive global data sets such as NCEP/NCAR (National Center for Environmental Prediction/National Center of Atmospheric Research) reanalyses and ERA-15 (European Reanalysis project from European Centre for Medium-Range Weather Forecasts, ECMWF, for the period 1979-1994) reanalyses. NCEP has been receiving the real-time "fast delivery" scatterometer wind data from the European Space Agency (ESA) for operational use since 1992. There are two primary requirements for the use of these data; subjectively, by operational marine meteorologists to improve ocean surface weather analyses, and objectively by the global data assimilation system to improve initial conditions for numerical weather prediction models. The NCEP/NCAR reanalyses, are currently available back to 1948, contains several meteorological parameters in a global spatial resolution of 2.5° x 2.5° (latitude x longitude). They are a composite of different data sources such as:
land station and ship observations, upper air rawinsonde measurements, satellite observations and numerical weather forecasts, which are assimilated in an Atmospheric Global Circulation Model (AGCM) and reanalyzed by means of a "frozen" state of an AGCM back to 1948.

3.5.2 **QuikSCAT**

The microwave scatterometer SeaWinds was launched on the QuikBird satellite in June 1999. The primary mission of these SeaWinds scatterometers is to measure winds near the ocean surface. They are also useful for some land and sea ice applications. The SeaWinds instruments are the third in a series of National Aeronautics and Space Administration scatterometers that operate at Ku band (a frequency near 14 GHz). SeaWinds scatterometers are essentially radars that transmit microwave pulses down to the Earth's surface and then measure the power that is scattered back to the instrument. This "backscattered" power is related to surface roughness. QuikSCAT wind retrievals are done on a 25 km x 25 km spatial scale. For water surfaces, the surface roughness is highly correlated with the near-surface wind speed and direction. Hence, wind speed and direction at a height of 10m over the ocean surface are retrieved from measurements of the scatterometer's backscattered power.

3.6 **SIMULATION OF OFFSHORE WAVE CLIMATE**

3.6.1 **Study area**

In the present study MIKE 21 OSW was used to generate offshore waves using NCEP wind data. North Indian Ocean was selected as offshore model study area (Figure 3.2). The OSW study area extends from 5° South to 22° North latitudes and 50° East to 98° East longitudes. Surface hydrology of the Northern Indian Ocean is basically determined by the monsoon winds,
hence a broader area was selected to simulate the offshore waves of Bay of Bengal. North Indian oceans have two broad monsoonal wave climates i.e the northeast monsoon from November to February and southwest monsoon from March to October. To be specific, summer or the southwest monsoon is considered from June to September, winter or northeast monsoon is observed from November to December. April, May (non monsoon) and October are normally transitional months but at times the summer and winter monsoon sets prior to June and November. The simulation was run for normal conditions. Predicted waves were validated with OB8 – Off Cuddalore wave rider buoy data.

Figure 3.2 Study area – Offshore wave model with validation point
3.6.2 Bathymetry

Setting up the bathymetry includes the appropriate selection of the area to be modeled, the selection of grid spacing in addition to specifying the water depth in each grid point. In the present study, the bathymetry required for the study area was extracted from Etopo2. Etopo2 bathymetry are seafloor data at 2’ interval, derived from satellite altimetry observations combined with carefully, quality–assured shipboard echo-sounding measurements. Thus extracted bathymetry was interpolated for 77 km along x and y directions, which comprises of 75 grids in the x direction and 50 grids in the y direction (Figure 3.3). In addition to the area of interest, a much larger surrounding area was also added in order to have the proper computation of fetch limited wave growth. The depth of the study area increases from north to south. Maximum depth of about 5600m is inferred to the east of Sri Lanka.

In deep waters, the stability was attained by avoiding large gradients in bathymetry. In a continental shelf region wave frequency of 0.04hz corresponding to a maximum wave period of 25 sec was considered as the waves will not feel the bottom if the water depth is more than 0.5L₀, where L₀ is the deep water wave length.

\[ L₀ = \frac{gT²}{2 \pi} = 976 \text{m} \]  

(3.5)

which means that water depths larger than 488 m do not affect the calculations. Hence the offshore boundary towards the coast was fixed at a depth of 500 m from where the nearshore boundary will start. Though OSW predicts the waves for coastal regions also, it is not accurate due to the coarse resolution of the data, the absence of detailed bathymetry and the information about the wave breaking.
3.6.3 Wind

NCEP reanalysed winds from January 2004 to December 2005 were downloaded as u and v components. A seasonal representation of NCEP wind during 2004 and 2005 are shown in Figure 3.4 to 3.9. The data had a resolution of 2.5° x 2.5° at 6 hour interval. u and v components of this data were imported into grid series files. To improve the resolution, the wind data was interpolated to 77 km x 77 km grid size. The wind speed and direction were computed from the u and v components of NCEP winds. From the wind vector, it is observed that from November to February winds are in northeast direction, while from March to October it is in southwest direction. This is in good agreement with the normal monsoonal direction of North Indian Ocean. The NCEP wind speeds were validated with wind data obtained from OB8 – Off Cuddalore wave rider buoy.
Figure 3.4 NCEP winds during non monsoon season (April 2004)
Figure 3.5 NCEP winds during southwest monsoon season (September 2004)
Figure 3.6  NCEP winds during northeast monsoon season (November 2004)
Figure 3.7  NCEP winds during non monsoonal season (April 2005)
Figure 3.8  NCEP winds during southwest monsoon season (September 2005)
Figure 3.9  NCEP winds during northeast monsoon season (November 2005)
3.6.4 Model Inputs

Inputs to run OSW are summarized in Table 3.1

Table 3.1 Input parameters for OSW

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bathymetry</td>
<td>The bathymetry prepared from Etopo2 was given as input to the model</td>
</tr>
<tr>
<td>Bathymetry parameter</td>
<td>The land value was specified as 10m</td>
</tr>
<tr>
<td>Numerical scheme</td>
<td>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. For stability reasons, courant number was given &lt;1 at the same time not too close to 1.</td>
</tr>
<tr>
<td>Simulation period</td>
<td>Quasi stationary</td>
</tr>
<tr>
<td>No. of time steps</td>
<td>Time steps depends on the number of days in a month and data availability for which simulation has to be done which in turn depends on time step interval eg: 735</td>
</tr>
<tr>
<td>Time step interval</td>
<td>1 hour</td>
</tr>
<tr>
<td>Source time step per sec</td>
<td>2</td>
</tr>
<tr>
<td>Simulation start time</td>
<td>The simulation was carried on monthly basis for 2004 and 2005. The date, month, year and time depends on simulation month eg. 4/1/2004 12.00.00 am.</td>
</tr>
<tr>
<td>Solution parameter</td>
<td>Logarithmic</td>
</tr>
</tbody>
</table>
Table 3.1 (continued)

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Description</th>
</tr>
</thead>
</table>
| Spectrum Discretion               | The frequency range should cover wave frequencies expected to be found in the model area.  
                                      No. of frequencies – 18  
                                      Minimum frequency – 0.1 hz  
                                      Frequency ratio – 1.1 hz |
| Directional Discretization        | The number of directions into which a 360° compass rose is divided should be large enough to resolve the directional variation of the waves. Also the number of directions must be a multiple of 4.  
                                      No. of directions = 16  
                                      Interpolation - Both 4 and 12 points interpolation  
                                      Water depth 0.5 m |
| Initial condition                 | The third generation model requires a “hot” start and hence JONSWAP spectrum (fp) was selected.  
                                      Fetch length = $2e^{0.004}$  
                                      $\alpha$ (phillips constant) – 0.0081  
                                      Maximum peak frequency = 0.245  
                                      Shape parameters, $\sigma_a = 0.07$  
                                      Shape parameters, $\sigma_b = 0.09$  
                                      Peakedness parameters, $\gamma = 3.3$ |
| Wind conditions                   | Wind was included as u and v component varying in space and time. |
| Water level condition             | Constant – 0 |
| Boundary conditions               | Program detected boundary was selected and specified as open or symmetrical |
| Model Parameters                  | Wind input  
                                      NCEP winds were given as u and v components.  
                                      White capping  
                                      Included as Dissipation coefficient $C_{diss} = 1.8$,  
                                      Dissipation coefficient $\Delta_{diss} = 0.8$. |
Table 3.1 (continued)

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom dissipation</td>
<td>JONSWAP spectrum, was selected.</td>
</tr>
<tr>
<td>Breaking parameter</td>
<td>Dissipation coefficient, $C_f = 0.183$</td>
</tr>
<tr>
<td>Wave breaking</td>
<td>Friction coefficients: $\gamma = 0.55$, $\alpha = 1$</td>
</tr>
</tbody>
</table>

**Model outputs**

Following 9 integral wave parameters are the output of the simulation:

- Significant wave height, $H_{m0}$
- Peak wave period, $T_p$
- Average wave period, $T_{01}$
- Zero-crossing period, $T_{02}$
- Wave energy period, $T_{10}$
- Peak wave direction, $\theta_p$
- Mean wave direction, $\theta_m$
- Directional standard deviation, $\sigma$
- $H_{m0}$ in x and y directions (for plotting purpose)

### 3.7 MODEL CALIBRATION

The purpose of calibration is to tune the model in order to reproduce known/measured conditions for a particular circumstance. The situation selected for calibration and verification of the model covers the range of criteria needed to be investigated in the production runs. However, the OB8 buoy data used for calibration covered January to March 2004, May to September 2004 and January, June 2005 against which calibration and validation was done.

#### 3.7.1 Wind input

The wind speeds of OB8 buoy data and NCEP data were compared to check their accuracy. Initial comparison of NCEP wind speed with OB8
buoy data show good trend but the wind speeds of NCEP are clearly higher than the buoy data. To reduce the wind speed, the NCEP winds are multiplied with factors such as 0.75, 0.85, and 0.92. Winds with factor 0.92 had good comparison with the buoy data. Hence, 0.92 is fixed as a constant factor (Figure 3.10). The maximum, minimum and average wind speeds obtained from NCEP data are given in Table 3.2. Test runs made with and without constant factor are given in Figure 3.11. The wave heights are over estimated when winds without factors are used for simulations whereas the wave heights simulated after multiplying the winds with the factor 0.92 give reasonable comparison with the buoy data at OB8-Off Cuddalore. For example, the correlation coefficient between measured Vs obtained from the simulation for August 2004 with and without the factor 0.92 is 0.63 and 0.55 respectively (Figure 3.11). The accuracy of MIKE 21 OSW results is closely related to the accuracy of wind field specifications.
Figure 3.11 Comparison of simulated SWH with/without factor and buoy data

Table 3.2 Wind speeds for 2004 and 2005

<table>
<thead>
<tr>
<th>Months</th>
<th>Wind speed (m/sec)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Minimum</td>
<td>Average</td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>10.29</td>
<td>2.80</td>
<td>7.02</td>
<td></td>
</tr>
<tr>
<td>February</td>
<td>10.03</td>
<td>2.04</td>
<td>6.66</td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>8.95</td>
<td>0.72</td>
<td>4.37</td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>8.50</td>
<td>0.21</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>16.89</td>
<td>1.68</td>
<td>8.4</td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>14.38</td>
<td>4.99</td>
<td>10.01</td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>13.08</td>
<td>3.20</td>
<td>8.75</td>
<td></td>
</tr>
<tr>
<td>August</td>
<td>13.60</td>
<td>4.49</td>
<td>8.90</td>
<td></td>
</tr>
<tr>
<td>September</td>
<td>12.25</td>
<td>0.28</td>
<td>7.09</td>
<td></td>
</tr>
<tr>
<td>October</td>
<td>10.81</td>
<td>0.56</td>
<td>5.52</td>
<td></td>
</tr>
<tr>
<td>November</td>
<td>9.52</td>
<td>1.27</td>
<td>6.08</td>
<td></td>
</tr>
<tr>
<td>December</td>
<td>10.85</td>
<td>1.03</td>
<td>6.92</td>
<td></td>
</tr>
</tbody>
</table>
3.7.2 White capping

The white capping dissipation source term represents the process by which wave energy is lost through deep water wave breaking. It is primarily controlled by the steepness of the waves and is perhaps the least understood mechanism in deep water (Ris 1997). The MIKE 21 OSW model was run with Komen (1994) wind input option, with and without the white capping turned on. For wind-wave modelling in the north Indian Ocean very good results have been obtained using the following slightly modified values for $C_{\text{diss}} = 1.8$, and $\Delta_{\text{diss}} = 0.8$. The simulation with white capping showed better agreement between measured and predicted wave parameters (Figure 3.12). The result without white capping showed increased wave height and peak period with bias of $-1.74$ and RMS error of $1.83$, while simulation with white capping showed a bias of $-0.11$ and RMS error of $0.41$. This clearly demonstrates that white capping play a major role in determining the wave climate.

3.7.3 Bottom friction

The bottom friction was provided as constant JONSWAP’s dissipation coefficient, $C_f$. The model was run with and without bottom friction. An increase of bottom friction coefficients in shallow water depths leads to increased energy dissipation and thus decreased wave heights and increased wave periods. In deep water, the effect of bottom friction is negligible, since the waves do not feel the bottom.

When waves propagate from deep water to waters of finite depth, shoaling leads to an increase in wave height. If the wave height to water depth ratio becomes too large, the waves start to break and wave energy is rapidly dissipated by depth-induced wave breaking (Ris, 1997). The breaking wave
parameters can also be used as calibration factors in some cases. The parameter $\alpha$ controls the rate of energy dissipation after breaking while $\gamma$ controls the amount of depth related breaking. An increase in $\alpha$ increases the rate of energy dissipation. Increase in $\gamma$ reduces the amount of depth related wave breaking. The model was run with and without the bottom friction and wave breaking parameters. The results are not affected in either way (Figure 3.13).

![Graph showing simulated SWH with/without white capping and buoy data](image)

**Figure 3.12** Comparison of simulated SWH with/without white capping and buoy data
Figure 3.13 Comparison of simulated SWH with/without bottom friction

3.8 QUIKSCAT DATA ANALYSIS

Monthly winds from QuikSCAT for 2000 and 2001 were given as input to the OSW with same setup used for NCEP wave simulation. The bathymetry for the study area, a portion of Bay of Bengal was prepared from National Hydrographic chart. Due to high resolution wind data, both the bathymetry and wind data were interpolated at a grid size of 27 km. QuikSCAT u and v wind components had a resolution of $0.5^\circ$ which was higher than the NCEP data, but the data is available on daily basis. Offshore wave heights were simulated with the same set up used for NCEP from January 2000 to December 2001. Thus simulated Significant wave heights were compared with available data (December 2000, May and August 2001) of DS3 – off Chennai wave rider buoy (Figure 3.14) and the model efficiency is given as bias and RMS in Table 3.3. The waves simulated using QuikSCAT
Figure 3.14 Significant wave heights from QuikSCAT
wind is in good agreement with the DS3 buoy data regarding direction and height. The wave heights obtained from the simulation of QuikSCAT winds are given in Table 3.4, the variation in wave height between 2000 and 2001 are less than 4%. Give the location of DS3 and DS1 in a map and refer that here.

Table 3.3 Comparison of simulated wave height with buoy data

<table>
<thead>
<tr>
<th>Period</th>
<th>Bias</th>
<th>RMS error</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 2000</td>
<td>-0.119</td>
<td>0.215</td>
</tr>
<tr>
<td>May 2001</td>
<td>-0.212</td>
<td>0.174</td>
</tr>
<tr>
<td>August 2001</td>
<td>-0.172</td>
<td>0.385</td>
</tr>
</tbody>
</table>

Table 3.4 Wave heights for 2000 and 2001 from QuikSCAT

<table>
<thead>
<tr>
<th>Months</th>
<th>Wave height (m)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Minimum</td>
<td>Average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>2.05</td>
<td>2.13</td>
<td>0.70</td>
<td>0.75</td>
<td>1.38</td>
</tr>
<tr>
<td>February</td>
<td>1.86</td>
<td>1.84</td>
<td>0.62</td>
<td>0.68</td>
<td>0.94</td>
</tr>
<tr>
<td>March</td>
<td>1.81</td>
<td>1.79</td>
<td>0.74</td>
<td>0.76</td>
<td>1.18</td>
</tr>
<tr>
<td>April</td>
<td>1.98</td>
<td>1.94</td>
<td>0.76</td>
<td>0.79</td>
<td>1.15</td>
</tr>
<tr>
<td>May</td>
<td>3.21</td>
<td>3.46</td>
<td>0.78</td>
<td>0.78</td>
<td>2.02</td>
</tr>
<tr>
<td>June</td>
<td>3.61</td>
<td>3.63</td>
<td>1.37</td>
<td>1.42</td>
<td>2.46</td>
</tr>
<tr>
<td>July</td>
<td>4.14</td>
<td>4.0</td>
<td>1.18</td>
<td>1.10</td>
<td>2.38</td>
</tr>
<tr>
<td>August</td>
<td>3.98</td>
<td>3.92</td>
<td>1.79</td>
<td>1.79</td>
<td>2.70</td>
</tr>
<tr>
<td>September</td>
<td>2.87</td>
<td>2.93</td>
<td>1.19</td>
<td>1.19</td>
<td>1.89</td>
</tr>
<tr>
<td>October</td>
<td>2.95</td>
<td>2.91</td>
<td>0.71</td>
<td>0.65</td>
<td>1.94</td>
</tr>
<tr>
<td>November</td>
<td>2.91</td>
<td>2.86</td>
<td>0.92</td>
<td>0.89</td>
<td>1.62</td>
</tr>
<tr>
<td>December</td>
<td>2.81</td>
<td>2.74</td>
<td>0.86</td>
<td>0.84</td>
<td>1.35</td>
</tr>
</tbody>
</table>
3.9  MODEL VALIDATION

3.9.1  Buoy data

The performance of MIKE 21 OSW computation was statistically analysed. The computed Significant wave height, average peak period and mean wave directions were compared with values measured at OB8 buoy location and the Bias and Root-Mean Square (RMS) error were calculated as follows (Table 3.5):

\[
\text{Bias} = \frac{\sum (P_{\text{measured}} - P_{\text{simulated}})}{n} \quad (3.10)
\]

\[
\text{RMS Error} = \sqrt{\frac{\sum (P_{\text{measured}} - P_{\text{simulated}})^2}{n}} \quad (3.11)
\]

where

- \( P_{\text{measured}} \) - Mean wave parameter (buoy)
- \( P_{\text{simulated}} \) - Modelled wave parameter (OSW)
- \( n \) - Number of values

Positive and negative biases represent underestimation and overestimation by the model. Prediction of significant wave height is better than wave period and direction. The comparison of simulated results with OB8 buoy data are given in the Figures 3.15 to 3.19. It is inferred that the model values are slightly higher wherever peaks occur. Not surprisingly, the comparisons between model outputs and buoy data have lesser scatter (Figure 3.20).
<table>
<thead>
<tr>
<th>Period</th>
<th>Significant wave height (m)</th>
<th>Average wave period (sec)</th>
<th>Mean wave direction (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bias (m)</td>
<td>RMS error (%)</td>
<td>Bias (m)</td>
</tr>
<tr>
<td>January 04</td>
<td>-0.08</td>
<td>0.26</td>
<td>-0.58</td>
</tr>
<tr>
<td>February 04</td>
<td>-0.17</td>
<td>0.30</td>
<td>-0.15</td>
</tr>
<tr>
<td>March 04</td>
<td>0.00</td>
<td>0.21</td>
<td>-0.46</td>
</tr>
<tr>
<td>May 04</td>
<td>-0.16</td>
<td>0.36</td>
<td>-0.68</td>
</tr>
<tr>
<td>June 04</td>
<td>0.01</td>
<td>0.44</td>
<td>-0.27</td>
</tr>
<tr>
<td>July 04</td>
<td>0.11</td>
<td>0.44</td>
<td>-0.01</td>
</tr>
<tr>
<td>August 04</td>
<td>-0.11</td>
<td>0.41</td>
<td>-0.61</td>
</tr>
<tr>
<td>September 04</td>
<td>0.02</td>
<td>0.40</td>
<td>0.04</td>
</tr>
<tr>
<td>January 05</td>
<td>0.01</td>
<td>0.25</td>
<td>-0.62</td>
</tr>
<tr>
<td>June 05</td>
<td>-0.08</td>
<td>0.32</td>
<td>0.67</td>
</tr>
</tbody>
</table>
Figure 3.15  Comparison of wave climate for January and February 2004
Figure 3.16 Comparison of wave climate for March and May 2004
Figure 3.17  Comparison of wave climate for June and July 2004
Figure 3.18  Comparison of wave climate for August and September 2004
Figure 3.19  Comparison of wave climate for January and June 2005
Figure 3.20  Scatter plot between simulated results and buoy data
3.8.2 QuikSCAT data

The predicted monthly offshore significant wave heights from NCEP and QuikSCAT for 2000-2001 and 2004-2005 respectively are given in Table 3.6. About 2% deviation is observed between NCEP and QuikSCAT wave heights. There is no overlap between the satellite data, hence the present result indicate that there has been no measurable change in the wave field over the period of time spanned by the satellite missions. The accurate wave predictions not only for normal conditions, even during monsoon season encourage the coupling of satellite data and numerical model in hindcasting the wave climate.

Table 3.6 Significant wave height from QuikSCAT and NSEP

<table>
<thead>
<tr>
<th>Months</th>
<th>Significant wave Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2000</td>
</tr>
<tr>
<td>January</td>
<td>1.38</td>
</tr>
<tr>
<td>February</td>
<td>0.94</td>
</tr>
<tr>
<td>March</td>
<td>1.18</td>
</tr>
<tr>
<td>April</td>
<td>1.15</td>
</tr>
<tr>
<td>May</td>
<td>2.02</td>
</tr>
<tr>
<td>June</td>
<td>2.46</td>
</tr>
<tr>
<td>July</td>
<td>2.38</td>
</tr>
<tr>
<td>August</td>
<td>2.70</td>
</tr>
<tr>
<td>September</td>
<td>1.89</td>
</tr>
<tr>
<td>October</td>
<td>1.94</td>
</tr>
<tr>
<td>November</td>
<td>1.62</td>
</tr>
<tr>
<td>December</td>
<td>1.35</td>
</tr>
</tbody>
</table>
3.9.3 Earlier Works on Validations

3.9.3.1 Using ENVISAT

Johnsen et al (2005) used Advanced Synthetic Aperture Radar (ASAR) and Radar Altimeter (RA2) Instruments onboard ENVISAT for assimilation with original ESA ENVISAT products to derive wave height of North Indian ocean using WAM model. The model had been run with and without assimilation of RA2 and ASAR. In both the cases the assimilation procedure strongly increased the linear correlation between the satellite and model outputs. The results were compared with DS3 and DS1 buoy data as given in the Table 3.7. All the three cases showed clear improvement of the deviation measurements, better linear correlation and reduced mean error between the satellite data and the assimilated results, because a swell dominated area leads to an increased assimilation impact.

**Table 3.7 Statistical analysis of model with and without assimilation**

<table>
<thead>
<tr>
<th>Assimilation</th>
<th>DS3</th>
<th>DS1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bias (m)</td>
<td>RMS</td>
</tr>
<tr>
<td>No Assimilation Vs Buoy</td>
<td>0.44</td>
<td>1.14</td>
</tr>
<tr>
<td>Assimilation RA2 Vs Buoy</td>
<td>0.15</td>
<td>0.30</td>
</tr>
<tr>
<td>Assimilation ASAR Vs Buoy</td>
<td>0.26</td>
<td>0.34</td>
</tr>
</tbody>
</table>
3.9.3.2 Using TOPEX/Poseidon

Barstow et al (2003) had done an intercomparison of WAM, TOPEX/POSEIDON and buoy data for two locations (DS 1 and DS 3) in Indian Ocean. The input for their model was from ECMWF. Their results are summed up in Table 3.8.

Table 3.8 Inter comparison of WAM, Topex/Poseidon and buoy data

<table>
<thead>
<tr>
<th></th>
<th>WAM Vs TOPEX</th>
<th>WAM Vs Buoy</th>
<th>TOPEX Vs Buoy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Residual Scatter Index (%)</td>
<td>Bias (cm)</td>
<td>Residual Scatter Index (%)</td>
</tr>
<tr>
<td>DS1</td>
<td>11.2</td>
<td>0.8</td>
<td>15.4</td>
</tr>
<tr>
<td>DS3</td>
<td>13.6</td>
<td>-10.1</td>
<td>13.4</td>
</tr>
</tbody>
</table>

When the bias and RMS errors of present study and earlier works are compared, errors are minimized when reanalyzed winds are used rather than using single assimilation like altimeter data. This is because of the utilization of reanalyzed winds from various sources viz, land station and ship observations, upper air rawinsonde measurements, satellite observations and numerical weather forecasts.

3.10 OFFSHORE WAVE CLIMATE

3.10.1 Model outputs from NCEP winds

The model was run for each month of 2004 and 2005. Validation of the results was done using OB8 wave rider buoy data. Simulated wave
climate from January 2004 to December 2005 are given as roseplot in Figures 3.21 and 3.22. During northeast monsoon the waves are high (above 1.5 m) in the deeper parts of Bay of Bengal (South Bay of Bengal) and in the southeast part of North Indian Ocean. The average waves in the offshores of North Indian ocean are in the range of 1 – 1.5m. The model is applicable only for deeper regions, as the results of coastal regions are underestimated. The average wave height during southwest monsoon is from 1.4 to 1.6 m. The maximum wave heights are noticed in the southwest part of North Indian ocean as it is the monsoon period. The simulated results of offshore wave climates for northeast, southwest and non monsoon seasons for 2004 and 2005 are given in Figures 3.23 and 3.24.
Figure 3.21  Offshore wave climate – Significant wave height Vs Mean Wave direction
Figure 3.22 Offshore wave climate – Peak wave period Vs Mean wave direction
Figure 3.23 Simulated offshore waves in 2004
Figure 3.24  Simulated offshore waves in 2005
The highest waves are observed in summer monsoon during May to September than winter monsoon which agrees with Barstow et al (2003) due to the longer fetches for the westerly wind seas and in addition the location is exposed to long periodic swells from south caused by the southern hemisphere extra-tropical storms. Since the wind sea is much lower, swells more often dominate the wave spectrum and the wave direction switches frequently between northeast wind sea and southerly swell. The average wind speed in May and June are 8.4 m/sec and 10.01 m/sec respectively with southwest direction shows good comparison between measured and predicted waves, which is due to the developed sea condition along Bay of Bengal. February show poor correlation because of the frequent change in wind direction, which cannot be incorporated in the reanalysis of the winds. The derived wave climates for Off Chennai area for 2004 and 2005 and given in Table 3.9. Significant wave height simulated between 2004 and 2005 show less variations than the other parameters.

Table 3.9 Average wave climate of 2004 and 2005 from model results

<table>
<thead>
<tr>
<th>Months</th>
<th>Significant wave Height (m)</th>
<th>Average wave period (s)</th>
<th>Mean wave direction (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1.23</td>
<td>1.41</td>
<td>6.09</td>
</tr>
<tr>
<td>February</td>
<td>1.10</td>
<td>1.03</td>
<td>6.20</td>
</tr>
<tr>
<td>March</td>
<td>0.77</td>
<td>0.81</td>
<td>6.48</td>
</tr>
<tr>
<td>April</td>
<td>0.70</td>
<td>0.66</td>
<td>6.30</td>
</tr>
<tr>
<td>May</td>
<td>1.63</td>
<td>1.00</td>
<td>6.45</td>
</tr>
<tr>
<td>June</td>
<td>1.89</td>
<td>1.80</td>
<td>6.45</td>
</tr>
<tr>
<td>July</td>
<td>1.57</td>
<td>2.26</td>
<td>6.25</td>
</tr>
<tr>
<td>August</td>
<td>1.75</td>
<td>1.69</td>
<td>7.44</td>
</tr>
<tr>
<td>September</td>
<td>1.47</td>
<td>1.77</td>
<td>6.99</td>
</tr>
<tr>
<td>October</td>
<td>1.16</td>
<td>1.05</td>
<td>6.96</td>
</tr>
<tr>
<td>November</td>
<td>1.08</td>
<td>1.08</td>
<td>6.11</td>
</tr>
<tr>
<td>December</td>
<td>1.32</td>
<td>1.32</td>
<td>6.54</td>
</tr>
</tbody>
</table>
3.10.2 Inter Comparison of NCEP and QuikSCAT waves

Seasonal wave pattern for a portion of Bay of Bengal simulated from Bay of Bengal are given in Figure 3.25. As QuikSCAT has a good resolution of 27km, approximately 3 grids together form a single grid in NCEP, hence minor variations in the wave pattern can also be clearly identified. The agreement in the wave distribution between NCEP and QuikSCAT adds confidence that the use of satellite data together with a numerical model yields reliable results. The circulation pattern in November in Figure 3.25 is due to the specific climatic conditions due to northeast monsoon prevailed in 2001. These results extend and refine previous comparison between the satellite data sets and buoy data. This provides the basis for the development of long-term data series of both wind speed and wave height from satellite missions.

3.11 OFFSHORE WAVE CLIMATE DURING CYCLONES

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. These storms, the post monsoon cyclones that cross east coast of India or Bangladesh are highly devastating. Timely and reasonably accurate prediction of these storms can reduce the loss of human lives and damage to properties.
Figure 3.25 Simulation of offshore waves from QuikSCAT
Mohanty and Mandal (2005) had studied the performance of the mesoscale model using NCEP for the period 1995 - 1999. The performance of the model was evaluated towards prediction and intensity of the storms. The track of the storms simulated by the model and forecast errors indicate good accuracy with the observed track of Indian Meteorological Department (IMD) with few exceptions. The forecast of the cyclone track and intensity from similar studies can be used to predict the wave climate along cyclone tracks. One such attempt is given below.

Three tropical cyclones were witnessed in the Bay of Bengal in less than three weeks during 2005 as follows

- **Baaz** – 27 November to 3 December (2005)
- **Fanoos** – 5 -12 December (2005)

The tracks of these cyclones were obtained from www.tropicalcyclone2005.com. The study area and model setup are the same as that simulated for normal conditions. After simulation, the wave heights were extracted from selected points of the respective cyclone tracks.

Among the three cyclones Baaz and Fanoos lasted for about seven to eight days whereas 7B lasted for 10 days. Winds of 55 and 65 kts were recorded during cyclones. The intensity of the cyclone can be explained from the wave climate derived during cyclones. Of the three cyclones, the simulated wave heights are the lowest for Fanoos, as its intensity is less when compared to Baaz and 7B. Fanoos and Baaz cyclones had maximum wave height on 29.11.2005 and 8.12.2005 when the cyclone was at its peak. 7B was the most destructive one, as it persisted for about 10 days and the wave...
heights are the highest when compared with other two cyclones. The wave heights are not only high on the tracks of 7B but also in the tracks of other two cyclones indicating the generated disturbance of the 7B cyclone for a wide region.

The cyclone tracks and simulated significant wave height are given in the Figures 3.26 to 3.28 with arrows indicating the period of cyclone. The results of significant wave height are summarized in Table 3.10. Since, the wave heights during 7B cyclone was high, the wave heights in the tracks of Baaaz and Fanoos during 7B cyclone is given in Table 3.11. From the simulation results, NCEP winds and OSW model can be effectively used to estimate wave heights during cyclones.
Figure 3.26 Significant wave heights along the track of Baaz cyclone
Figure 3.27 Significant wave heights along the track of Fanoos cyclone
Figure 3.28 Significant wave heights along the track of 7B cyclone
Table 3.10  Significant wave heights in the cyclone tracks

<table>
<thead>
<tr>
<th>Cyclones</th>
<th>Significant Wave height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
</tr>
<tr>
<td>Baaz</td>
<td>1.78</td>
</tr>
<tr>
<td>Fanoos</td>
<td>1.69</td>
</tr>
<tr>
<td>7B</td>
<td>3.01</td>
</tr>
</tbody>
</table>

Table 3.11  Significant wave heights in the tracks of Baaz and Fanoos during 7B cyclone

<table>
<thead>
<tr>
<th>Impact of 7B cyclone in</th>
<th>Significant Wave height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
</tr>
<tr>
<td>Baaz track</td>
<td>3.26</td>
</tr>
<tr>
<td>Fanoos track</td>
<td>3.34</td>
</tr>
</tbody>
</table>