
Chapter 2
Data and methodology

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2.1. Introduction

Winds, waves and bathymetry are the major oceanographic parameters required for wave modelling / wave research. These can be obtained from sources such as visual observations, wave arrays, wave buoys and remote sensing sensors. Nowadays, directional wave rider buoys and moored data buoys are the main sources of direct wave measurements. They provide spectral information at a pre-defined location. Significant wave height and wind speed are obtained from the satellite altimeters and wind vectors are obtained from scatterometers. Spectral wave data can also be obtained from the Synthetic Aperture Radar (SAR), with a prior request. Wind and sea state information can be extracted from the altimeter measurements directly without prior knowledge of the local sea state or wind field, whereas a reliable interpretation of scatterometer and SAR data requires first-guess wind data and wave spectra, respectively as input for inverse modelling techniques (Komen et al., 1994).

Locally, we can obtain reliable wind data from Autonomous Weather Station (AWS), which is a point source. On global scale, altimeters and scatterometers provide wind data with reasonable spatial resolutions. Since, temporal resolutions of such data are very coarse, it may not be adequate for a proper time series analysis. However, gridded products of scatterometer data such as QuickScat are useful to obtain relatively fine resolution wind vectors. The re-analysis winds available at NCEP (National Centres for Environmental Prediction, USA), ECMWF (European Centre for Medium-Range Weather Forecasts) and blended winds available at IFREMER (French Research Institute for Exploitation of the Sea) are widely used for global wind analysis and used as the input for numerical wave modelling.

In the present study, wave data obtained from directional wave rider buoys, moored data buoys and Jason-1 altimeter and wind data obtained from AWS, Scatterometers, re-analysis and blended winds have been used for analysis. Cyclone track data obtained from JTWC (Joint Typhoon Warning Centre, USA) and pressure level data from IDWR (Indian Daily Weather Report) (IMD, 1996) have also been used for the extreme weather event analysis.

Numerical modelling has been carried out utilising the wind data obtained from the above sources.

2.2. Data used

Based on availability, accuracy and regional/seasonal interest, various wind data have been used for the analysis and in numerical wave simulations. Each wind data (re-analysed/remotes sensing/simulated) has its own merits and demerits in terms of accuracy and temporal/spatial resolutions. An intercomparison between various winds has been made and described in Sec. 2.2.12.

Wave simulations have been carried out using winds from different sources, and the accuracy of the predictions has been tested (Sec. 3.3.3). NCEP re-analysis winds are reliable and used in the present study for analysis and wave modelling, though there are limitations in the spatial resolutions (Sudheesh et al., 2004; Vethamony et al., 2006; Aboobacker et al., 2009 and Vethamony et al., 2009). QuickSCAT data are used for wave simulations in the Indian Ocean, however, the temporal resolution is very coarse (Raj Kumar et al., 2009; Bhowmick et al., 2009). QuickSCAT data is very useful to analyse sea breeze distribution along the west coast of India during pre-monsoon season (Aparna et al., 2005). IFREMER/CERSAT provides blended winds with relatively fine spatial resolution, which is adequate to analyse localised/regional characteristics of winds to some extent, and thus incorporated in the wave simulations. NCMRWF wind data was also used to simulate waves in the north Indian Ocean, and provided reasonably good results (Sudheesh et al., 2004). However, fine resolution wind data are required for the analysis and modelling of waves in coastal regions. Therefore, as a particular case study, coastal winds off Goa have been simulated using MM5 and used in the numerical wave model.

The following sections describe about the wind and wave data used in the present study.

2.2.1. Directional wave rider buoy

Directional wave rider buoy (Figure 2-1) developed by Datawell b.v., the Netherlands are used for wave measurements (Datawell BV, 2006). It consists of a spherical steel shell of 90 cm diameter, designed to float on the sea surface. It has three accelerometers housed inside it and these accelerometers measure the vertical, north and west accelerations of the buoy. All these accelerations are then digitally integrated twice to get displacements (elevations) and filtered to a high frequency cut-off at 0.6 Hz. The vertical accelerometer

yields the measurement of wave height. Wave direction is determined by measurement of the horizontal motion of the buoy and correlating this motion with the vertical motion of the buoy.

The directional wave rider buoy transmits buoy motion time history, reduced data as spectral density, wave direction etc. in cyclic messages to a shore based receiving/recording station, with the help of 2 m long antenna mounted on top of the buoy. The signals from the directional wave rider buoy are received onshore by Wave Direction Receiver (WAREC) and record the data on a Personal Computer. The processor in the receiver also checks for transmission errors. The personal computer interfaced with the WAREC communicates and controls the WAREC system. The wave rider buoys were calibrated in the laboratory by giving known wave heights and periods and recorded by using WAREC and PC. The buoy can function within -20 to +20 m of wave height with an accuracy of 3% within the wave period 1.6 - 30 s. The direction accuracy is within $0.5 - 2^\circ$ depending on the latitude.

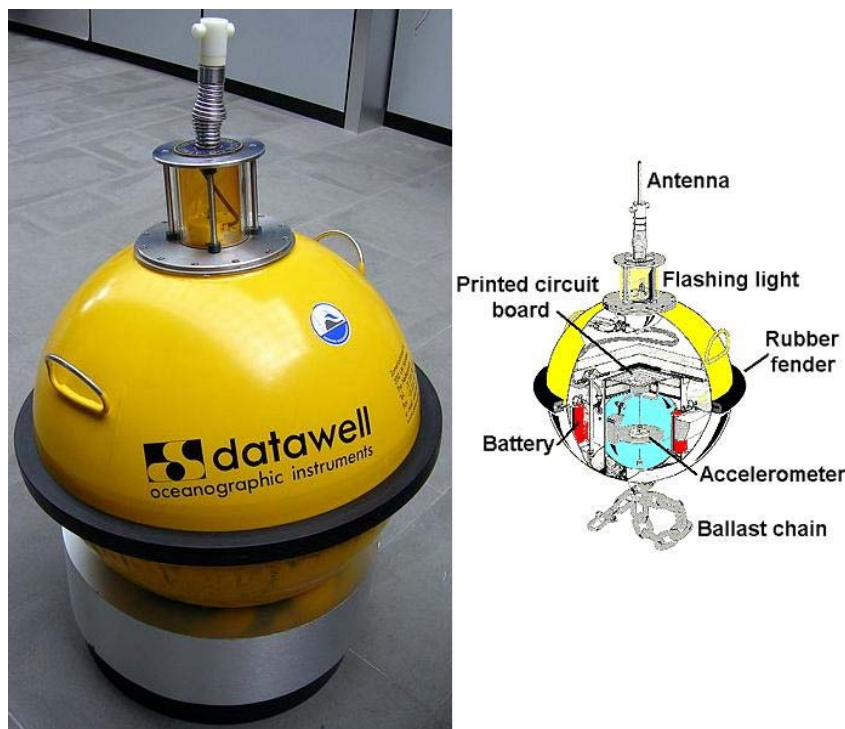


Figure 2-1. Datawell wave rider buoy and associated parts (www.datawell.nl).

Wave data collected using Datawell Directional Wave Rider Buoys (WRB) at different locations along the Indian coast during various periods have been analysed. The details of

the locations and measurement periods are listed in Table 2-1. Locations of wave measurements conducted by wave rider buoys (B1 to B10) are marked in Figure 2-2. The sampling duration is 20-minutes, and the spectra are calculated using Fast Fourier Transform (FFT) (Datawell, 2001).

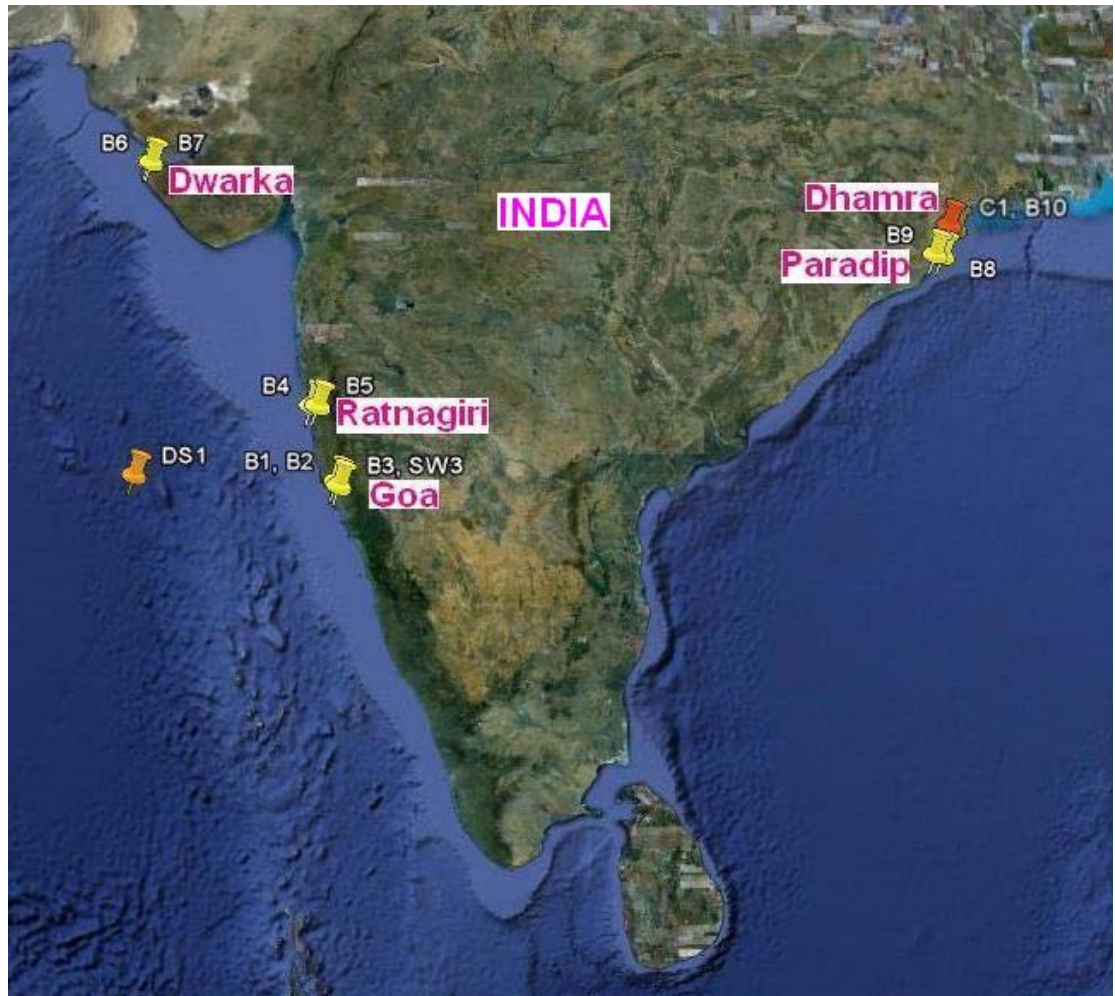


Figure 2-2. Wave measurement locations using wave rider buoys (B1 to B10), moored buoys (DS1 and SW3) and non-directional wave recorder (N1). Image courtesy: Google Earth.

Table 2-1. Details of wave measurement locations, water depth, measurement duration and data interval (directional wave rider buoys).

Region	Location	Water depth (m)	Duration	Data interval (h)
Goa	15.465° N 73.683° E (B1)	23	Feb 1996 - May 1997	3.0
	15.488° N 73.700° E (B2)	25	01 - 21 May 2005	1.0
	15.423° N 73.749° E (B3)	15	06 - 21 May 2005	0.5
Ratnagiri	17.004° N 73.120° E (B4)	35	24 Jan - 25 Feb 2008	0.5
	17.007° N 73.250° E (B5)	15	24 Jan - 25 Feb 2008	0.5
Dwarka	22.088° N 69.040° E (B6)	30	05 Dec 2007 - 05 Jan 2008	0.5
	22.088° N 69.090° E (B7)	15	05 Dec 2007 - 05 Jan 2008	0.5
Paradip	20.143° N 86.745° E (B8)	30	May 1996 - Jan 1997	3.0
	20.165° N 86.581° E (B9)	16	06 Sep - 05 Nov 2005	3.0
Dhamra	20.720° N 87.100° E (B10)	12	14 Jul - 14 Aug 2005	1.0

2.2.2. Moored buoys

The moored data buoys are floating platforms, which carry sensors to measure wind speed and direction, atmospheric pressure, air temperature, humidity, conductivity, sea surface temperature, current speed and direction and wave parameters. National Data Buoy Program (NDBP) of the National Institute of Ocean Technology (NIOT), Chennai, India deployed a number of such moored buoys at different locations around the Indian Ocean. The buoys are equipped with global positioning system, beacon light and satellite transceiver. These buoys are operable from 20m water depths to full ocean depth. It measures the full spectrum of the waves for 17 min. duration. It has an accuracy ± 10 cm for wave height upto 20 m and $\pm 5^\circ$ for wave direction. The wind data measured at these buoys has an accuracy of $\pm 1.5\%$ for wind speed at the range 0 – 60 m/s and $\pm 3.6^\circ$ for wind direction.

In the present study, wave data measured at a deepwater location off Goa (DS1) during January – September 2001 has been used for validation of wave model results. The winds and waves at the deepwater location, DS1 during July - November 1999, May - July 2000, January 2001 and May - September 2001 and at shallow water location off Goa (SW3) during May - September 2001 and October 2004 - March 2005 are utilised for the case study described in Chapter 5. Apart from these, SW3 data during Feb – May 2004 is also used to analyse the nearshore wave characteristics off Goa during pre-monsoon season. The locations of DS1 and SW3 are marked in Figure 2-2. The details of deployment locations, water depth and data duration are listed in Table 2-2.

2.2.3. Non-directional wave recorder

The Non-directional Wave Recorder (Aanderaa WTR9) data collected 6 m at water depth off Dhamra Port is also used for the study of wave transformation. The data were sampled for every 30 min during 12 Jul – 14 Aug 2005. Table 2-3 describes the details on location, depth, duration and data intervals for the non-directional wave measurement. The location of wave measurement using non-directional wave recorder (C1) is marked in Figure 2-2.

The instrument records data internally in a removable and reusable solid state Data Storage Unit (DSU) 2990. It has a pressure sensor, which is based on a high precision quartz crystal oscillator. The pressure is measured every 0.5 s and 1024 samples are taken (512 s) and stored in an internal RAM for wave analysis. The parameters/ channels are transmitted as Aanderaa standard PDC-4 from the electronic control board to the removable DSU. The

instrument is housed in a pressure case that is closed by two C-clamps. By use of the Deck Unit 3127 interface, the output signals can be read by a PC via the same terminal and converted into engineering units. A mode switch, with a test and serial communication setting, a depth-setting switch and a recording interval switch is built into this board. The quartz pressure sensor is also attached to the board by a shock-absorbing bracket. A specially designed bottom mounting frame was used for installing the instrument on the seabed. The sensor is of quartz pressure type based on a pressure-controlled oscillator having frequency of 30 – 45 kHz. It has a range of 0-690 kPa, with an accuracy of 210 Pa and a resolution of 7 Pa.

Table 2-2. Details of wave measurement locations, water depth, measurement duration and data interval (NIOT moored buoys).

Region	Location	Depth (m)	Duration	Data interval (h)
off Goa Deep water (DS1)	15.500° N, 69.283° E	3700	July - Nov 1999	3
			May - Jul 2000	
			Jan - Sep 2001	
			May 2005	
off Goa Shallow water (SW3)	15.406° N, 73.755° E	20	May -September 2001	3
			October 2004 - March 2005	

Table 2-3. Details of wave measurement locations, water depth, measurement duration and data interval (non-directional wave recorder).

Region	Location	Depth (m)	Duration	Data interval (h)
Off Dhamra Port	86.970° E, 20.800° N (C1)	6	12 Jul - 14 Aug 2005	0.5

2.2.4. Autonomous Weather Station (AWS)

A state-of-art Autonomous Weather Station (AWS) has been designed for meteorological measurements on land and at sea by NIO, Goa. The weather station comprises of a suite of meteorological sensors such as wind speed and direction, air temperature, relative humidity and pressure, and has a flexibility to interface additional sensors. The accuracy in wind speed is 0.2 m/s for the range 0-60 m/s and the accuracy in wind direction is 3°.

The AWS was set at a height of 10 m at Dwarka and Ratnagiri coastal stations and at a height of 43.5 m at Dona Paula (Goa) coastal station. The details are listed in Table 2-4.

AWS winds at 43.5 m height were reduced to 10 m height using logarithmic wind profile (Roland, 1988) as follows:

$$U(z) = \frac{U_*}{\kappa} \ln (z/z_0) \dots\dots\dots (2.1)$$

where, $U(z)$ is the wind speed measured at a height, z ($=43.5\text{m}$), U_* the surface friction velocity, Z_0 ($=0.22\text{m}$) the aerodynamic roughness length and κ ($=0.4$) is the von Karman constant. As $U(z)$, κ and z_0 are known at $z=43.5\text{m}$, the surface friction velocity U_* has been calculated using Eqn. 2.1. Further, wind speed at 10m height, $U(z = 10)$ has been estimated. The reduced wind is used for further analysis.

Table 2-4. Details of AWS wind measurement locations, measurement height, measurement duration and data interval.

Region	Location	Height (m)	Duration	Data interval (min.)
Goa	73.800° E, 15.455° N	43.5	Feb 1996 - May 1997	10
Dwarka	68.970° E, 22.240° N	10.0	05 Dec 2007 - 05 Jan 2008	10
Ratnagiri	73.280° E, 16.890° N	10.0	24 Jan - 25 Feb 2008	10

2.2.5. NCEP re-analysis winds

NCEP provide reanalysis wind vectors (U and V components) globally on six-hourly interval for every $2.5^\circ \times 2.5^\circ$ grid resolutions (Kalney et al., 1996). NCEP data are widely

used for applying in numerical models to generate waves on global scale. Tolman (1998) had validated NCEP re-analysed winds and used in offshore wave prediction models. Aboobacker et al. (2009) and Vethamony et al. (2009) used NCEP winds to simulate waves around the Indian Ocean.

NCEP reanalysis wind vectors in the Indian Ocean (65°S to 30° N and 20°E to 120°E) have been downloaded (<http://www.esrl.noaa.gov/psd/data/reanalysis>). The wind data from various locations during different seasons along the Indian coast has been analysed and used as the input parameter in wave modelling for the Indian Ocean. Following wind data has been used in the present study:

- Feb 1996 – May 1997
- May – Aug 2000
- May 2004 – Dec 2005
- Dec 2007 – Feb 2008

Wherever possible, NCEP winds were compared with measured wind data, as the accuracy of wave model results depends on the winds to a larger extent.

2.2.6. *IFREMER/CERSAT Blended winds*

To enhance the spatial and temporal resolutions of surface wind, the remotely sensed retrievals from QuikScat are blended to the operational ECMWF wind analyses over the global oceans by IFREMER/CERSAT (Bentamy et al., 2006 and Bentamy et al., 2009). The spatial resolution of the resulting wind fields is 0.25° in longitude and latitude and the data is available for every 6 hours. Ebuchi et al. (2002) analysed the quality of the blended winds by comparing with buoy winds and found a good correlation between them.

Since, the spatial resolution of blended winds is relatively fine, it can be used for the analysis of wind patterns near the coast. In the present study, blended winds during Jan. – Dec. 2005 and Dec. 2007 – Feb. 2008 have been utilised for the analysis of wind patterns around the Indian Ocean and Indian coastal regions. The accuracy of wave predictions using blended winds has been tested.

2.2.7. *NCMRWF winds*

NCMRWF (National Centre for Medium Range Weather Forecasting, India) wind data has been utilised to predict waves in the north Indian Ocean, as a part of the case study

described in Chapter 5. These winds are available in $1.5^\circ \times 1.5^\circ$ grid size for every six hour interval in the form of U and V components. The data available during July - August 1999, May - July 2000 and May - September 2001 have been used in the present study. Vethamony et al. (2003) and Sudheesh et al. (2004) used NCMRWF winds to generate offshore waves in the north Indian Ocean using MIKE 21 Offshore Spectral Wave model (OSW).

2.2.8. QuikSCAT winds

QuikSCAT vector winds with $0.5^\circ \times 0.5^\circ$ resolution available twice daily (Tang and Liu, 1996) have been downloaded for the Indian Ocean to study offshore as well as coastal wind variations. The QuikSCAT wind data during January – December 2005 and December 2007 – February 2008 have been used in this study.

To study the sea breeze characteristics during pre-monsoon season, QuikSCAT winds (u and v components) available for 06 h and 18 h (local time) were extracted along a section off Goa upto 200 km from the coast during May 2005.

2.2.9. MM5 winds

MM5, a Mesoscale Model developed by Pennsylvania State University / National Centre for Atmospheric Research (PSU/NCAR), is a three dimensional, limited area, non-hydrostatic model designed to simulate atmospheric circulation (Grell et al., 1994). Dhanya et al (2010) simulated the coastal winds along the central west coast of India using MM5 and studied the coastal atmospheric circulation over the region. In the present study, coastal winds off Goa, west coast of India have been simulated using MM5 during May 2005 to analyse the coastal wind patterns, especially sea breeze-land breeze systems. For this purpose, nested model domains were selected in the Arabian Sea covering Goa region with spatial resolutions of 27 km, 9 km and 3 km. The model simulates wind vectors for every 1 hour interval. These winds are further used to simulate wind seas off Goa during May 2005 (pre-monsoon season).

2.2.10. Jason-1 Altimeter

Gridded ($1^\circ \times 1^\circ$ resolution) significant wave heights from Jason-1, a mini-satellite developed by NASA and CNES designed for oceanographic and meteorological purposes are also utilized in the present study to explain the significant wave height distribution in the open ocean areas. The data is available in alternate 3 and 4 days time scale. These data

have also been used to validate the wave model results of deep waters, where the buoy measurements are not available. The significant wave heights off Goa in various grids during May 2005 have been downloaded and used in the present study.

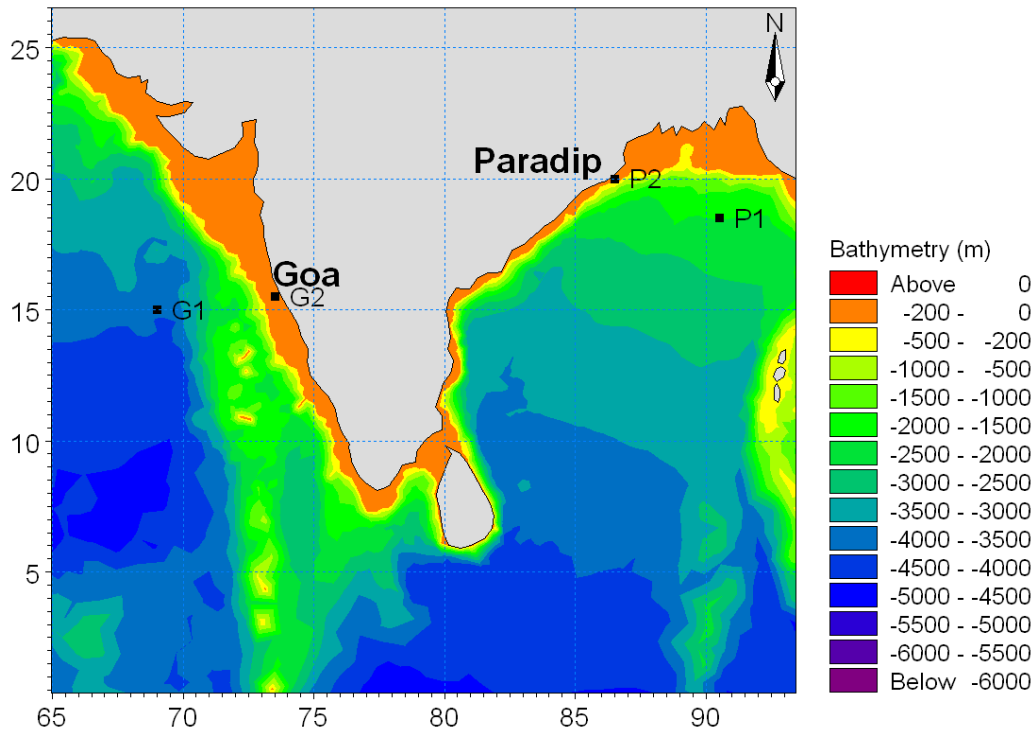


Figure 2-3. Jason-1 data extraction locations off Goa and Paradip.

2.2.11. JTWC and IDWR

A few cyclone track data obtained from JTWC (Joint Typhoon Warning Center, USA) were used to analyse characteristics of waves associated with these events in the Arabian Sea and Bay of Bengal. For example, the two tropical storms (15 -25 June 1996 and 14 Oct. – 2 Nov. 1996) occurred in the Arabian Sea and the two storms occurred in the Bay of Bengal during 11-18 June 1996 and 14 Oct – 2 Nov 1996. Cyclone tracks were obtained from Unisys Weather site (<http://weather.unisys.com>).

Indian Daily Weather Report (IMD, 1996) provides pressure level and wind speed of coastal stations twice daily. These data are useful to analyse atmospheric pressure fluctuations during extreme events. In the present study, the IDWR data has been used to identify the evolution of storms and depressions occurred during 1996 in the Paradip and

Goa regions. Pressure level data obtained from Cyclone Detection Radar Centre (CDRC) located at Paradip were also used.

2.2.12. Comparison of analysed winds with measured winds

Analysed winds (NCEP, Blended and QuikSCAT) are compared with measured buoy winds at location SW3 (Figure 2-1) during January – March 2005 (Figure 2-4). The wind speed and direction show good match for NCEP and Blended winds with buoy winds, however, the match is fair for QuikSCAT winds. Figure 2-5 shows the scatter between buoy wind speed and analysed (NCEP, Blended and QuikSCAT) wind speeds. Limitations in temporal and spatial resolution of analysed winds are reflected in the statistical parameters, correlation coefficient, bias, r.m.s. error and scatter index (Figure 2-5). The correlation is good for NCEP (0.49) and Blended (0.69) winds, and poor for QuikSCAT winds (0.39). Biases are minimum for NCEP (0.14 m/s) and Blended (-0.39 m/s) winds, and maximum for QuikSCAT winds (-1.58 m/s).

NCMRWF winds have been used specifically for the case study mentioned in Chapter 5. Accuracy of these winds has been tested earlier by Sudheesh et al. (2004). For instance, a comparison between buoy winds and NCMRWF winds during July 1999 at location DS1 (Figure 2-1) is shown in Figure 2-6. NCMRWF winds show very good match with buoy winds.

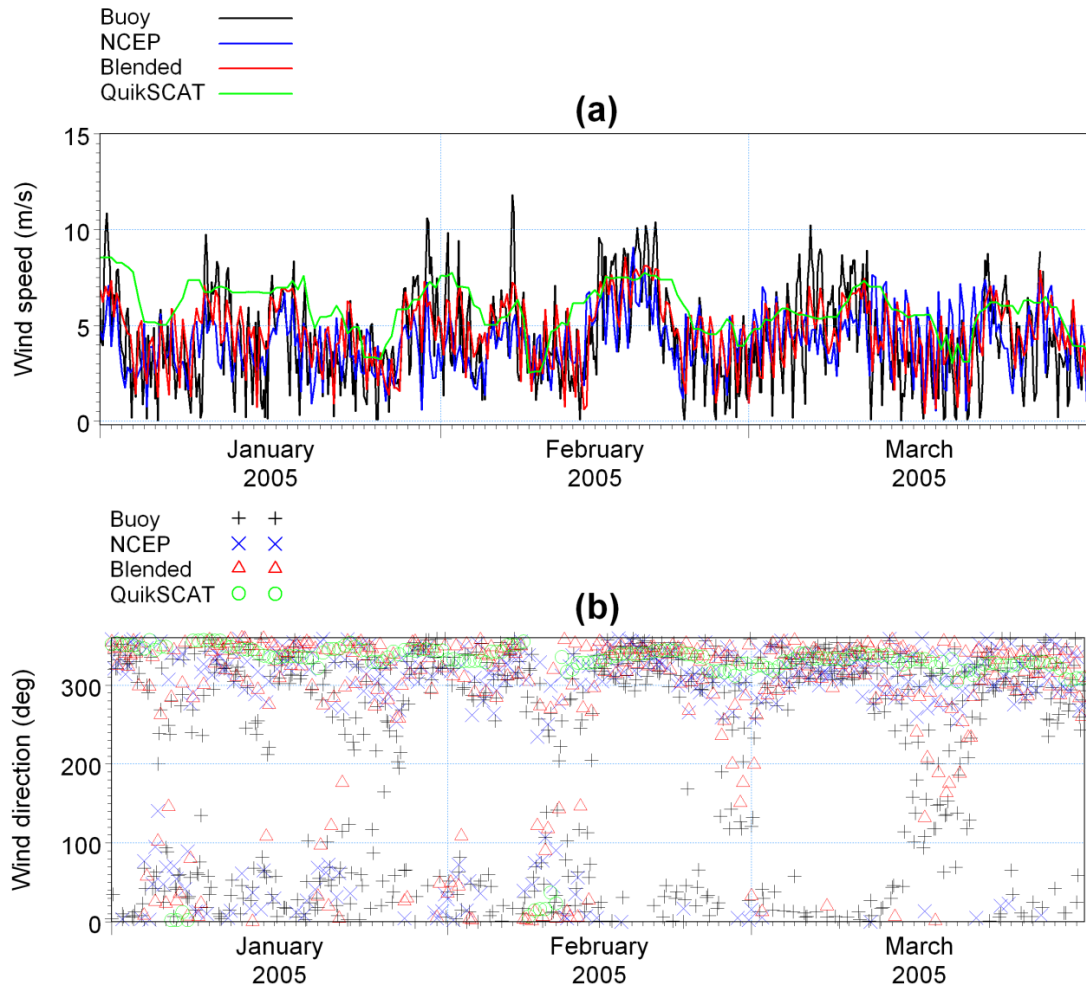


Figure 2-4. Comparison between measured (buoy) and analysed (NCEP, Blended and QuikSCAT) winds: (a) wind speed and (b) wind direction.

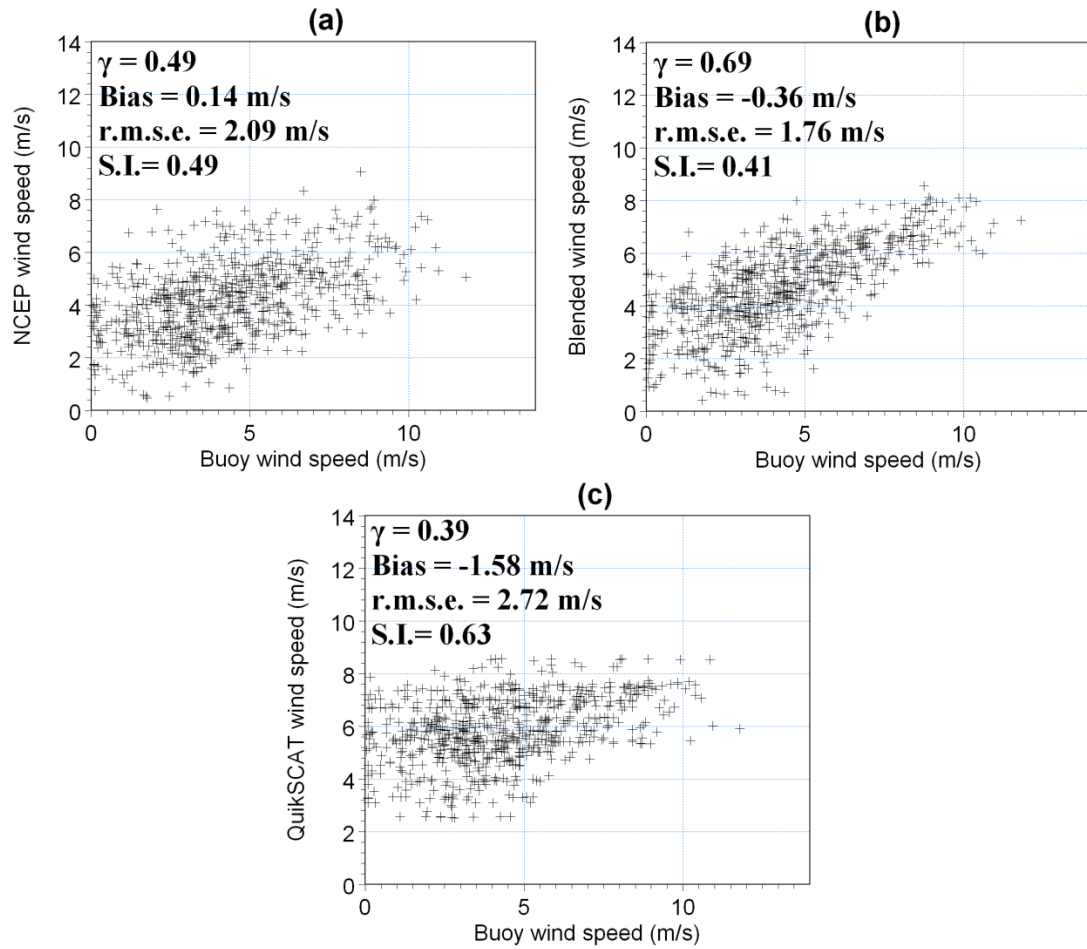


Figure 2-5. Scatter between measured wind speed and: (a) NCEP, (b) Blended and (c) QuikSCAT wind speeds.

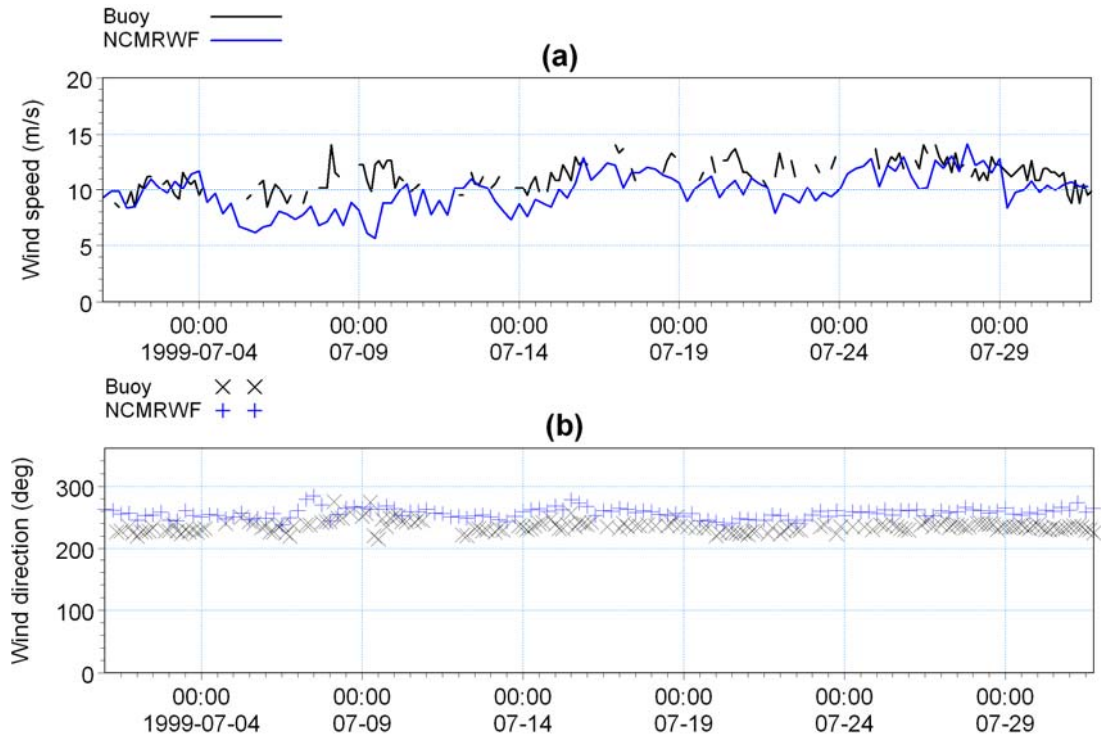


Figure 2-6. Comparison between measured and NCMRWF wind speed and direction.

2.3. Methodology

The methodologies used in the present study are described in the following sections. Sec. 2.3.1 describes the calculation of wind sea and swell parameters from the measured wave energy spectra. Sec. 2.3.2 introduces numerical modelling. Sec. 2.3.3 explains the analysis of extreme events and Sec. 2.3.4, the analysis of local effects on the wave characteristics along the Indian coasts. Sec. 2.3.5 describes the methodology of wave transformation.

2.3.1. Separation of wind sea and swell

Wind sea and swell parameters have been separated from the wave energy spectra utilizing the methodology provided by Gilhousen and Hervey (2001). The algorithm is based on wave steepness parameter from which the separation frequency has been derived.

The general definition of the steepness function is the ratio of wave height to wavelength. The wave steepness parameter, ζ , at all frequencies f , can be written as,

$$\xi(f) = \frac{2\pi H_s(f)}{gT_m^2(f)} \dots\dots\dots (2.2)$$

where, H_s (the significant wave height) and T_m (the mean wave period) are functions of a given frequency f . When wave spectrum components are expressed in terms of moments of the distribution, $\xi(f)$ for all frequencies f_i can be rewritten as,

$$\xi(f) = \frac{8\pi \int_{f_l}^{f_u} f^2 E(f) df}{g \sqrt{\int_{f_l}^{f_u} E(f) df}} \dots\dots\dots (2.3)$$

where, f_u (=0.58 hz) and f_l (= 0.03, 0.04, ..., 0.58 hz) are the upper and lower frequency limits of measured wave spectra. Using Eqn.(2.3), $\xi(f)$ has been calculated for all frequencies from the measured data (f_u is fixed for all calculations and f_l varies in such a way that $f_l = f_1, f_2, \dots, f_u$). The frequency f_x (peak frequency) corresponds to the maximum steepness parameter ($\xi(f)$) has been used to calculate the separation frequency f_s , as follows:

$$f_s = C f_x \dots\dots\dots (2.4)$$

where, $C = 0.75$, is an empirically determined constant (Gilhousen and Hervey, 2001).

The methodology proposed by Wang and Hwang (2001) has been applied to study the sensitivity of the results obtained from separation frequency method of Gilhousen and Hervey (2001). Figure 2-7 shows the comparison of separation frequencies obtained from both the methods, and there is an excellent agreement between them.

The wave spectra have been divided into two parts (swell region and wind sea region) after the separation using f_s . Each wind sea and swell spectrum has been used to calculate significant wave height (H_s), mean wave period (T_m) and mean wave direction (θ) separately for wind sea and swell. There are cases, where the multiple peaks are observed within the separated wind sea and swell spectra. Such cases were treated as a part of single wind sea or swell system. H_s and T_m are calculated as follows:

$$H_s = 4\sqrt{m_0} \dots\dots\dots (2.5a), \quad T_m = \sqrt{\frac{m_0(f)}{m_2(f)}} \dots\dots\dots (2.5b)$$

where,
$$m_n = \int_{f_l}^{f_u} f^n E(f) df \dots\dots\dots (2.6)$$

f_l and f_u are the lower and upper frequencies, respectively for each wind sea and swell spectra. The directions correspond to the peak energy of the wind sea and swell spectra has been taken as the mean wave direction (θ) of wind sea and swell. Significant wave heights of wind sea, swell and resultant wave follow the relation given below:

$$H_s = \sqrt{H_{s\text{swell}}^2 + H_{s\text{sea}}^2} \dots\dots\dots (2.7)$$

In general, resultant wave (or simply ‘wave’) is the combination of wind sea and swell energies, and from this energy the resultant wave parameters (such as wave height and wave period) are derived.

In the present study, wave data measured during February 1996 to May 1997 (16 months) at a nearshore location off Goa has been analysed to study the dominance of wind seas and swells during different seasons, including extreme events using the separation frequency method.

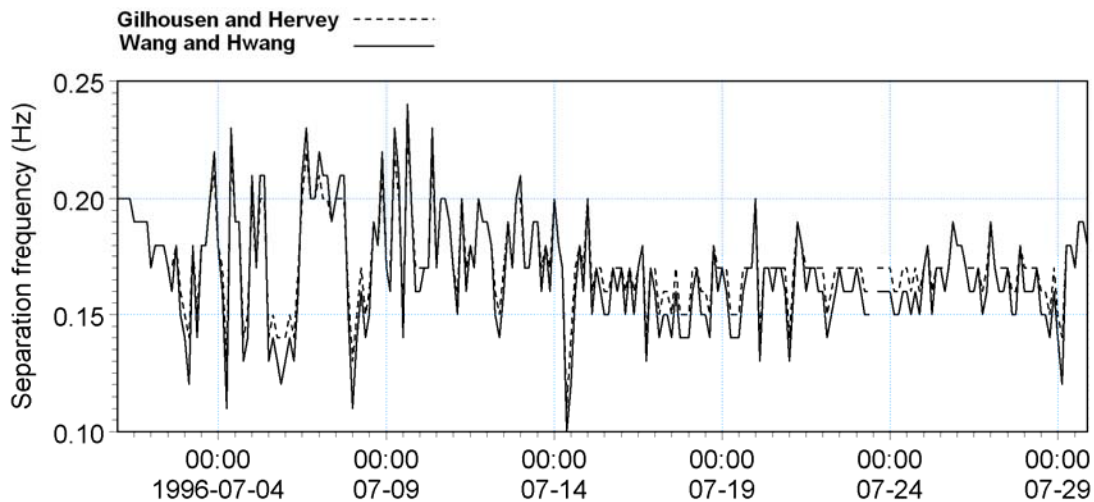


Figure 2-7. Comparison of separation frequencies obtained from ‘Gilhousen and Harvey’ and ‘Wang and Hwang’ methods.

2.3.2. Validation of MM5 winds

MM5 winds simulated during May 2005 have been validated to utilise in the numerical wave simulations. Winds measured using AWS at Dona Paula coastal station during May 2005 has been used for the validation purpose. Figure 2-8 shows the comparison between measured and modelled wind vectors (u and v components) at Dona Paula coastal station

during May 2005. There is good agreement between measured and simulated wind vectors Table 2-5. The correlation coefficient for the zonal component is 0.86, whereas it is 0.59 for the meridional component. Since the zonal component is due to sea breeze, a well predicted sea breeze distribution off Goa is obtained from the MM5 simulation results. The low correlation of meridional component is mainly due to irregular topographic features of the region. Recently, Dhanya et al. (2010) simulated the coastal winds along the central west coast of India and found a good match between measured and MM5 winds.

The MM5 winds have been further utilised to simulate wind seas off Goa during May 2005, and to study wind sea characteristics due to sea breeze along the west coast of India during pre-monsoon season.

Table 2-5. Correlation coefficient, bias and r.m.s. error between measured and simulated winds off Goa (May 2005).

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

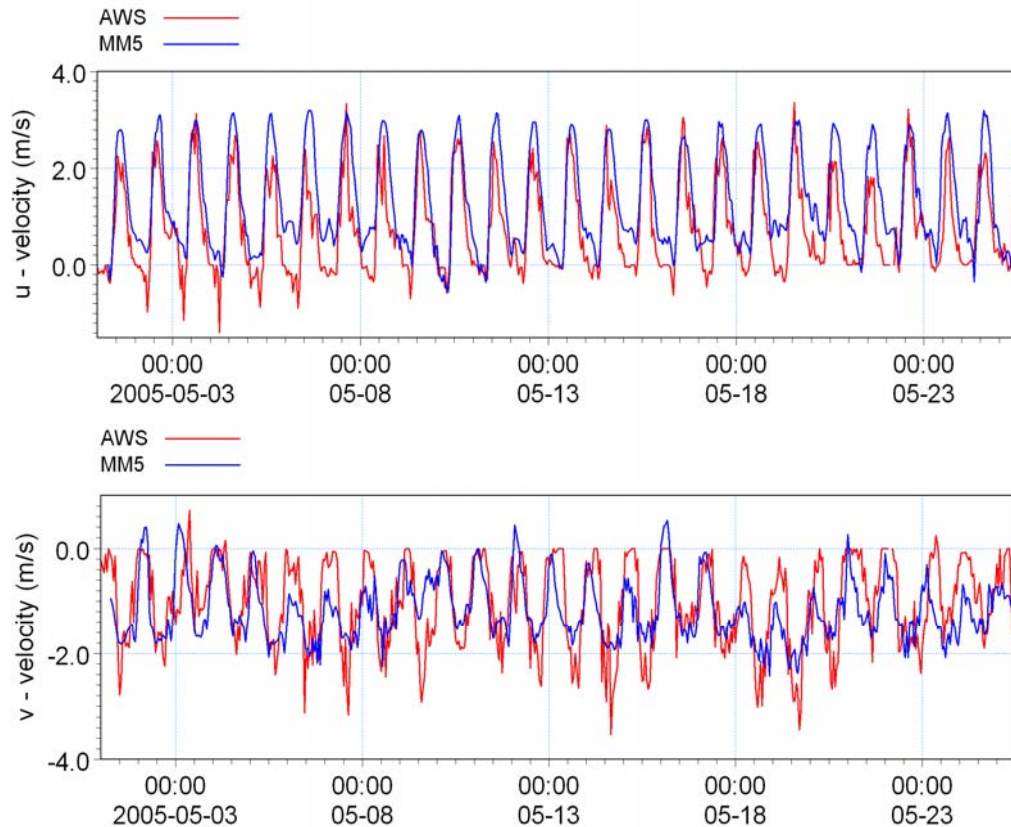


Figure 2-8. Comparison between measured and modelled wind vectors at Dona Paula coastal station (May 2005).

2.3.3. Wave modelling

State-of-the-art numerical models have been utilised to predict waves in the Indian Ocean and shallow waters along the coastal regions. The applied numerical models are MIKE 21 OSW (Offshore Spectral Wave), MIKE 21 NSW (Nearshore Spectral Wave) and MIKE 21 SW (Spectral Wave). Wave parameters and spectra obtained from the simulations are analysed to understand (i) seasonal wave characteristics, (ii) waves during extreme weather events and (iii) wave transformation at nearshore regions. A brief description of the above models is described in the following sections. Details of model setup, calibration and validation are described in Chapter 3.

2.3.3.1. MIKE 21 OSW

MIKE 21 OSW is a fully spectral wind-wave model developed by DHI Water & Environment, Denmark, which describes the propagation, growth, decay and

transformation of wind generated waves of short period and short crested waves in offshore as well as in coastal areas (DHI, 2001). It is a time dependent discrete spectral wind-wave model formulated in terms of the energy density spectrum with discrete resolution of frequencies and directions. The energy is calculated in discrete points of a rectangular grid for a number of discrete frequencies and directions. The model includes two different descriptions of physical processes governing the wind-wave generation and decay: state-of-the-art third generation formulation and second generation formulation. The third generation model is based on the internationally developed WAM Cycle 4 model originally developed for deep-water application on global and regional scales. The model is based on the numerical integration of the spectral energy (F) balance equation formulated in Cartesian co-ordinates.

$$\frac{DF}{Dt} = S_{wind} + S_{non-linear} + S_{bottom\ dissipation} + S_{whitecapping} + S_{wave\ breaking} \dots\dots\dots (2.8)$$

The left-hand side describes the wave propagation in time and space using linear wave theory. The right-hand side represents the superposition of source functions describing various physical phenomena. Wave-wave interaction, refraction and dissipation due to breaking are included in this model. The basic input parameters to the model are bathymetry and wind fields. The model domain is divided into different grids and input parameters are provided at each grid point. Time step corresponding to the Courant Number is chosen, keeping the minimum wave period present.

The output from the model consists of wave energy spectra and integral wave parameters including the significant wave height, peak wave period, average wave period, peak wave direction and mean wave direction. For detailed analysis of the wave climate in coastal and shallow waters, the MIKE 21 OSW model is used in combination with MIKE 21 NSW.

In the present study, MIKE 21 OSW is applied to simulate waves in the Indian Ocean during May – Dec 1996. Wave characteristics during monsoons and extreme events are discussed in Chapter 4. OSW is also applied to simulate waves during July – Aug 1999, May – July 2000, May – Sep 2001 and May 2004 – June 2005, and the results are discussed in Chapter 5.

2.3.3.2. *MIKE 21 NSW*

MIKE 21 NSW is a stationary and directionally de-coupled parametric wind-wave model, which describes the growth, decay and transformation of wind-generated waves and swells

in nearshore areas (DHI, 2001). The model takes into account the effects of refraction and shoaling due to varying depth, local wind generation and energy dissipation due to bottom friction and wave breaking and wave-current interaction. The basic equations are solved using an Eulerian finite difference technique. The zeroth and the first moment of the action spectrum are calculated on a rectangular grid for a number of discrete directions. A once-through marching procedure is applied in the predominant direction of wave propagation.

The high resolution nearshore model requires wave conditions along the offshore model boundary. Hence, the wave parameters at offshore boundaries are extracted from the OSW model results to use as the boundary conditions for the NSW model. The basic output from the NSW model is integral wave parameters such as significant wave height, mean wave period, mean wave direction, directional standard deviation and radiation stresses.

2.3.3.3. *MIKE 21 SW*

MIKE 21 SW is a spectral wind-wave model based on unstructured meshes, which simulates the growth, decay and transformation of wind generated waves and swell in offshore and in coastal areas. The spectral formulation is based on the wave action conservation equation as described in Komen et al. (1994) and Young (1999), where, the directional-frequency wave action spectrum is the dependent variable. The basic conservation equations are formulated in Cartesian polar spherical co-ordinates. The discretization of the governing equation in geographical and spectral space is performed using cell-centered finite volume method. In the geographical domain, an unstructured mesh technique is used. The time integration is performed using a fractional step approach, where a multi-sequence explicit method is applied for the propagation of wave action.

The energy source term, $S (=DF/Dt)$, represents the superposition of source functions as given in Eqn. 2.10. The model includes the following physical phenomena: (i) wave growth by action of wind, (ii) non-linear wave-wave interaction, (iii) dissipation due to white-capping, (iv) dissipation due to bottom friction, (v) dissipation due to depth-induced wave breaking, (vi) refraction and shoaling due to depth variations, (vii) diffraction, (viii) wave-current interaction and (ix) effect of time varying water depth.

Numerical simulations of waves in the deep waters as well as shallow waters have been carried out using MIKE 21 OSW, MIKE 21 NSW and MIKE 21 SW models.
