

Spectral characteristics of the nearshore waves off Paradip, India during monsoon and extreme events

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Abstract

Spectral and statistical wave parameters obtained from the measured time series wave data off Paradip, east coast of India during May 1996–January 1997 were analysed along with MIKE 21 spectral wave model (SW) results. Statistical wave parameters and directional wave energy spectra distinctly separate out the wave conditions that prevailed off Paradip in the monsoon, fair weather and extreme weather events during the above period. Frequency-energy spectra during extreme events are single peaked, and the maximum energy distribution is in a narrow frequency band with an average directional spreading of 20°. Spectra for other seasons are multi-peaked, and energy is distributed over a wide range of frequencies and directions. The NCEP re-analysis winds were used in the model, and the results clearly bring out the wave features during depressions. The simulated wave parameters reasonably show good match with the measurements. For example, the correlation coefficient between the measured and modelled significant wave height is 0.87 and the bias -0.25.

Keywords: Directional wave spectra, depressions, wave measurements, MIKE21, wave modelling, Paradip coast

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1. Introduction

Wave is the dominant forcing parameter for most of the nearshore processes. Design of coastal structures to a large extent depends on waves than any other environmental factors. When waves generated by storms leave the zone of generation, they couple with locally generated waves, and create complex characteristics in the nearshore region. The east coast of India is characterized by narrow continental shelf width compared to the west coast. The sudden decrease in water depth causes the waves to surge further during extreme events, creating severe coastal hazards. As an example, Sanil Kumar et al (2004) demonstrated the wave characteristics along the Visakhapatnam coast (east coast of India) during an extreme event. The present study is important because Paradip region houses Paradip Port and several major industries, and this region is vulnerable to cyclones frequently.

Deepwater waves can be well modelled with third-generation wave models which are driven by predicted wind fields [e.g., WAMDI Group 1988; Komen et al. 1994], and based on physical processes rather than empirical formulations. However, as temporal and spatial resolutions of most of the wind models are coarse, some of the major features such as wind information near the eye of cyclones cannot be incorporated accurately. Also, the impact of locally generated winds on nearshore waves cannot be predicted with coarse resolution wind fields.

The Bay of Bengal (north Indian Ocean) experiences three different weather conditions – fair, southwest monsoon and northeast monsoon. During fair weather season, the sea surface is usually calm and the coastal region is dominated by swells and to a smaller extent by locally generated waves. Extreme weather events are common during southwest monsoon (June-September) as well as northeast monsoon (October – December) seasons.

We have observed that in the Bay of Bengal, in general, the wave spectra are double or multi-peaked. The double-peaked spectra are mainly due to the existence of wind seas along with the ‘young’ swells. Multi-peaked spectra are due to complex sea state where the separation of wind seas and swells is complicated. The single-peaked spectra are observed during extreme events, wherein all the energies are concentrated in the low frequency region.

Low frequency waves (swells) can propagate faster than the generating wind fields and reach areas not influenced by this wind field or at least before the area is influenced directly by it. This swell component will add to the locally generated wind sea and create double (or multiple) peaked spectra.

For wind dominated sea, a secondary system (swell) containing extra energy will be present. For swell dominated sea, if the local wind decays, the waves will loose energy for high frequencies. This swell (“old” wind sea) can represent the highest spectral peak if no new local wind seas are generated with sufficient spectral peak density. For wind dominated sea, the secondary system represents an average of swell sea for the area, whereas for swell dominated sea, the secondary sea system represents local wind sea.

In this study, MIKE 21 two dimensional Offshore Spectral Wave model (OSW) developed by the Danish Hydraulic Institute (DHI), Denmark (Anonymous 2001) has been utilized to simulate offshore waves off Paradip. This model has been earlier used for comparing waves derived from MSMR winds and NCEP reanalysis winds with measured waves of north Indian Ocean (Sudheesh et al. 2004 and Vethamony et al. 2006). MIKE 21 Spectral Wave model (SW) has been used to simulate nearshore wave characteristics, taking into account the results of OSW.

2. Data and Methods

2.1 Data

Wave measurements were carried out off Paradip (Fig.1) during May 1996 - January 1997 using a Datawell directional wave rider buoy deployed at the location $20^{\circ} 08.57'$ N and $86^{\circ} 44.67'$ E, where the water depth is 30 m. A few data loss are found on those days when the buoy was retrieved for safety during extreme events or maintenance. Wave characteristics as well as directional spectra of the region are discussed for different seasons – premonsoon (May), southwest monsoon (June-September) and northeast monsoon (November- January) and extreme events.

Indian Daily Weather Report (Anonymous 1996) reveals the presence of 4 storms / depressions in the Bay of Bengal during the study period. The pressure level data from the Cyclone Detection Radar Centre at Paradip indicates that pressure dropped from 1003.1 to 996.9 mb during 26-30 May 1996, from 1008.0 to 994.2 mb during 10-21 June 1996 and from 1003.0 to 991.2 mb during 18-26 July 1996 (Fig. 2), leading to extreme wave conditions. The fourth depression could not intensify, though the pressure level decreased from 1012.3 to 1000.4 mb during 24-28 October 1996.

Reanalysed NCEP winds available in the form of **U** and **V** components for $2.5^{\circ} \times 2.5^{\circ}$ grids and six hourly intervals have been interpolated into $0.75^{\circ} \times 0.75^{\circ}$ grid size by linear interpolation. The Etopo-5 bathymetry data (National Geophysical Data Centre, USA) available in $5' \times 5'$ grid is extracted for every $0.75^{\circ} \times 0.75^{\circ}$ grid as OSW requires only coarse resolution. The bathymetry data for the nearshore flexible mesh model is taken from MIKE-CMAP of DHI - digitized data of hydrographic charts.

2.2 Offshore Spectral Wave model (OSW)

OSW consists of second generation and third generation models, WAM 2G and WAM 3G. The second generation model WAM 2G is utilized in the present study. It is a spectral wind - wave model describing the propagation, growth and decay of short period waves in the offshore areas. The model takes care of the effects of wave generation due to winds, refraction, shoaling due to varying depths and frictional resistance. It also includes the effect of interaction between waves with different frequencies. The model is based on the numerical integration of the spectral energy balance equation

formulated in Cartesian co-ordinates. For the calculation of transport of wave energy from one time step to the next a Lagrangian transport scheme is applied.

The model domain for the MIKE21 OSW ranges from 5° S to 25° N and from 50° E to 95° E, and is divided into 40×60 grids in longitude and latitude respectively, with a grid spacing of $0.75^{\circ} \times 0.75^{\circ}$. The boundary along 5° S latitude is considered as open boundary, and all other boundaries are closed. The model starts with zero energy in all grid points, that means the model performed a 'cold' start so that it will take a few time steps to perform the actual simulations. In order to provide an accurate description of the transport of energy the time steps with 1 hour intervals are selected so that the Courant number based on the group velocity is less than unity. Simulations are carried out for the year 1996 and 3 hourly wave parameters are extracted.

2.3 Flexible mesh model

Nearshore wave simulations are carried out using the MIKE 21 flexible mesh Spectral Wave model (SW). The offshore and alongshore extensions are 150 km and 100 km, respectively from the origin (Fig. 3). The region including measurement location is triangulated with a maximum area of 5 km x 5 km and the shallowest region with a maximum area of 1.5 Km x 1.5 Km. The water points are interpolated in the entire mesh by Natural Neighborhood method so that output parameters from any desired point can be extracted.

There are three open boundaries - north, east and south, out of which north boundary is considered as lateral boundary. The boundary conditions are extracted from the output of MIKE21 OSW, and applied to the east and south boundaries. The SW output parameters at the buoy location are compared with the measurements.

3 Results and discussion

In May 1996 (pre-monsoon season), the predominant wave direction was between SSW and SSE with significant wave heights varying between 0.9 and 2.7 m (Fig. 4). The depression during 26-30 May 1996 caused the waves to grow and the significant wave height reached upto 2.7 m on 28 May in the SSW direction. On 29 May, the wave direction shifted to S and also the height reduced. The predominant wave direction during southwest monsoon season (June – September) was between S and SSE, and the significant wave height reached a maximum value of 3.8 m and 4.2m on 16 June and 25 July, respectively. This includes waves during the two depression periods. In northeast monsoon (November - January), the predominant wave direction was between SE and NE, and the maximum significant wave height observed was 2.1 m (SE direction) on 28 October due to the depression occurred in the Bay of Bengal (24 - 29 October 1996). Even though the pressure level decreased from 1012.3 to 1000.4 mb, the depression could not intensify further, and generate high waves. In the rest of the year, the waves were below 0.8 m in height, and varied between S and SSE direction.

An analysis of several years of wave data from the Bay of Bengal shows that wave parameters such as significant wave height, wave period and mean wave direction are significantly different for various weather events. In general, during fair weather season off Paradip significant wave heights are below 1.0 m, during monsoon below 3.5m and during extreme weather events of the order of 5.0 to 7.0 m.

Frequency - energy spectra during extreme events are single peaked, and the maximum energy distribution is in a narrow frequency band (Fig. 5a) with an average directional spreading of 20° . Spectra for other seasons are multi-peaked, and energy is distributed over a wide range of frequencies (Figs. 5 b&c) in different directions. The type of spectra shown in Figs. 5 b&c represent the seasonal variation of wave conditions in the Bay of Bengal in the absence of extreme events. Wave spectra of extreme events are distinctly different from that of monsoon or fair weather season. In general, wave spectra along the Indian coast are multi-peaked, often with two peaks (Harish and Baba 1986; Vethamony and Sastry 1986; Rao and Baba 1996). Greenslade (2001) found that when energy shifts from one portion of the spectrum to another, the spectral peak suddenly jumps to a different frequency. Sanil Kumar et al (2004) found that wave spectra during extreme sea states are mainly single-peaked, and the percentage occurrence of double-peaked spectra is higher for low sea states. In the present case also, the spectra are single-peaked, and the maximum energy is centered in a narrow frequency band. The maximum spectral energy during the two depressions are $30.33 \text{ m}^2/\text{hz}$ (15 June) and $31.25 \text{ m}^2/\text{hz}$ (26 July), which are very high compared to the energy during normal monsoon months [eg. $7.63 \text{ m}^2/\text{hz}$ (13 June) and $5.68 \text{ m}^2/\text{hz}$ (28 July)]. It is evident from the spectra that wave energy is higher during southwest monsoon season than the northeast monsoon. Typical measured directional energy spectra representing SW and NE monsoon seasons are shown in Figs. 6 a & 7 a, respectively. Corresponding wind directions during the period is also shown in Figs. 6 b & 7 b.

Bathymetry contours off Paradip are parallel to the coast, and the slope is very gentle. In general, winds are either southwesterlies or northeasterlies. Sufficient fetch is available for both the wind directions. Therefore, changes in the spectral peakedness are negligible.

During extreme events, long waves with higher amplitudes are generated and most of the energy is concentrated in the low frequency region. So, typically the spectra will be single-peaked. When swells reach the region where the locally generated waves are present, the spectra show double or multi-peaks. Normally during fair weather season, the sea states are swell dominated. Hence, the primary peak will be in the low frequency region and secondary peak will be in the high frequency region depending on the locally generated wind seas.

During monsoons, the sea state is usually wind sea dominated. Distant swells from various directions will also propagate to the region and forms complex sea state. Hence, the peak energy will shift from

low frequency to the high frequency region depending on the strength of the prevailing winds on the region.

The criterion for the single-peakedness is $T_p = T_{pf}$, where T_{pf} is the spectral peak period (period of the highest spectral density) for fully developed sea at the actual location and T_p is the peak wave period (Torsethaugen, K., Haver, S. 2004). Hence all the energy will be concentrated into a narrow banded low frequency region. If $T_p < T_{pf}$, ie the sea state is wind sea dominated, the spectral peak will be in the high frequency region and there may be double or multiple peaks in the spectra. The case $T_p > T_{pf}$, is swell dominated usually occurs during fair weather season, where the spectral peak will be in the low frequency region.

Modelled directional energy spectra during 26 July are shown in Fig. 8. The spectra shows the single-peakedness as in the measured spectra for most of the time steps due to the extreme event prevailed in the region.

Modelled wave heights, wave periods and wave directions agree closely with the measured values (Figs. 9, 10 & 11). For example, the correlation coefficient between the measured and modelled significant wave height is 0.87 and the bias -0.25. The modelled wave heights are underestimated mainly due to deficiency in spatial and temporal resolution of wind parameters as the local wind effect inside the model domain is not incorporated in the simulation and the winds used at the boundaries have coarse resolution. The modelled wave directions are between SSW and SSE from May to September and between N and NW in November and December. Mean wave period ranges from 4 to 10 s during SW monsoon and from 2 to 8 s during NE monsoon. The highest measured significant wave height is 4.2 m, whereas the corresponding modelled value is 3.4 m (22 July 1996), corresponding to an extreme event prevailed in the region.

4. Conclusions

The analysed time series wave data covering all seasons off a typical east coast of India distinctly show the response of coastal waves to the seasons. The accuracy of model results could be improved when fine spatial resolution winds are used. The results of this study are very useful for the design of proposed SPM at the wave measurement location and other coastal activities planned in this region.

Acknowledgments

We thank Dr SR Shetye, Director, National Institute of Oceanography (NIO), Goa for providing necessary facilities and the Indian Oil Corporation Ltd (IOCL), New Delhi for funding the project. We acknowledge all the project participants for their help during wave data collection.

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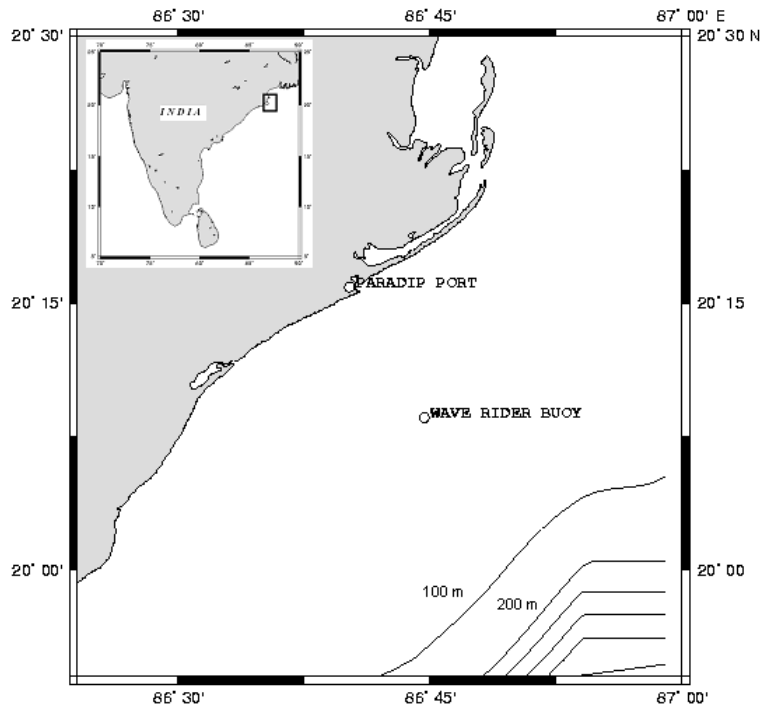


Fig.1. Study area showing the wave measurement location

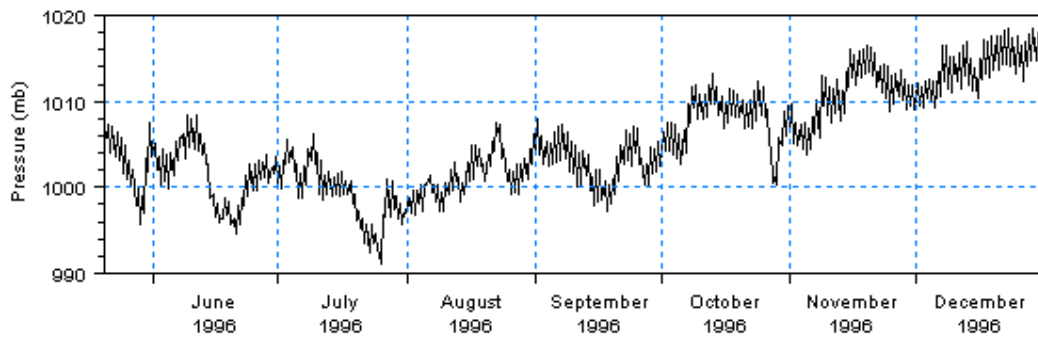


Fig. 2. Pressure levels during May 1996 – December 1996

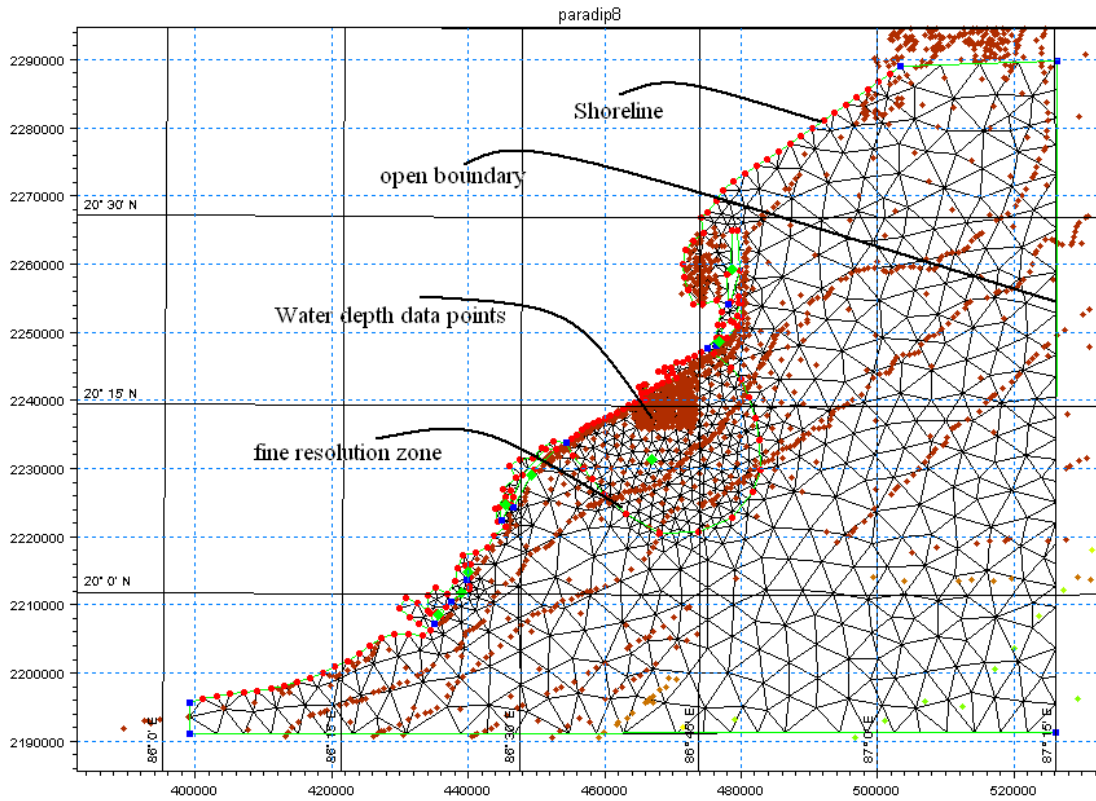


Fig. 3. Triangulated flexible mesh and model domain for nearshore wave prediction using Spectral Wave model

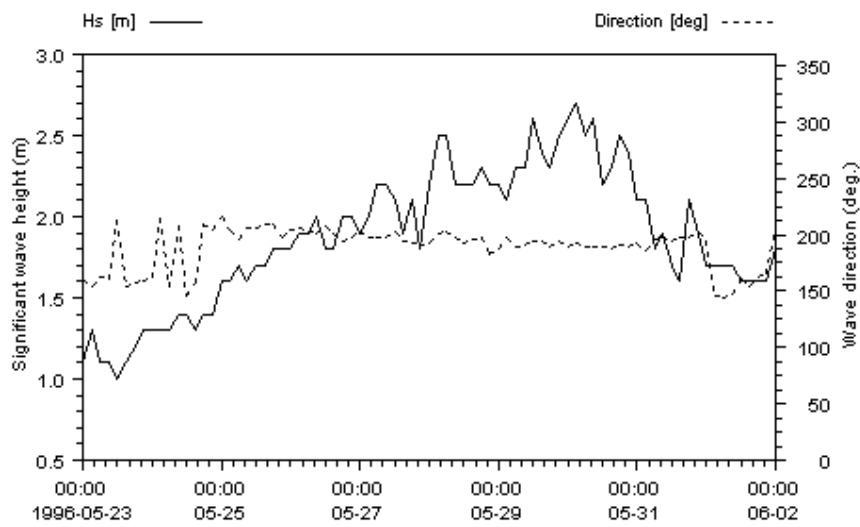


Fig. 4. Significant wave height pattern during an extreme event (23 May - 02 June 1996) indicating wave growth and decay

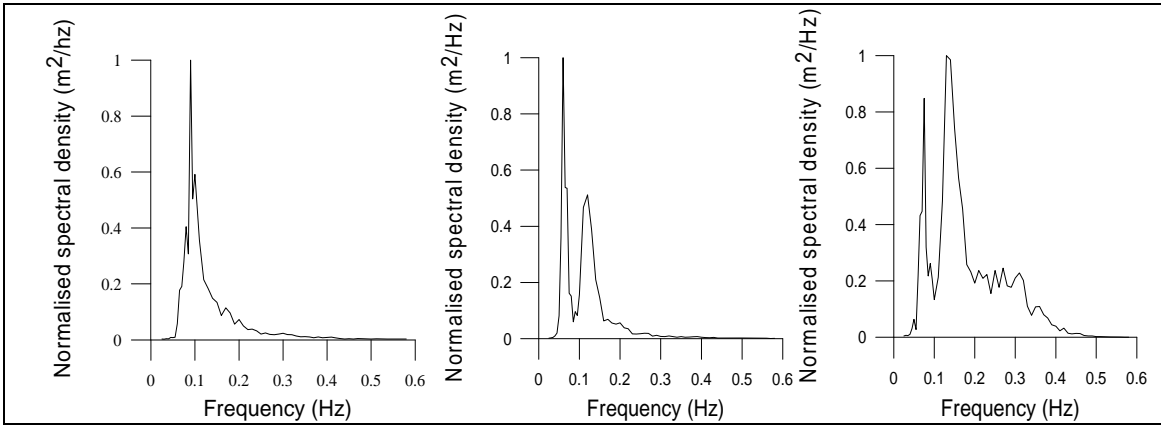


Fig. 5. Typical wave spectra during (a) 26 July at 09 h, (b) 3 Aug 1996 at 09 h and (c) 3 July 09 h

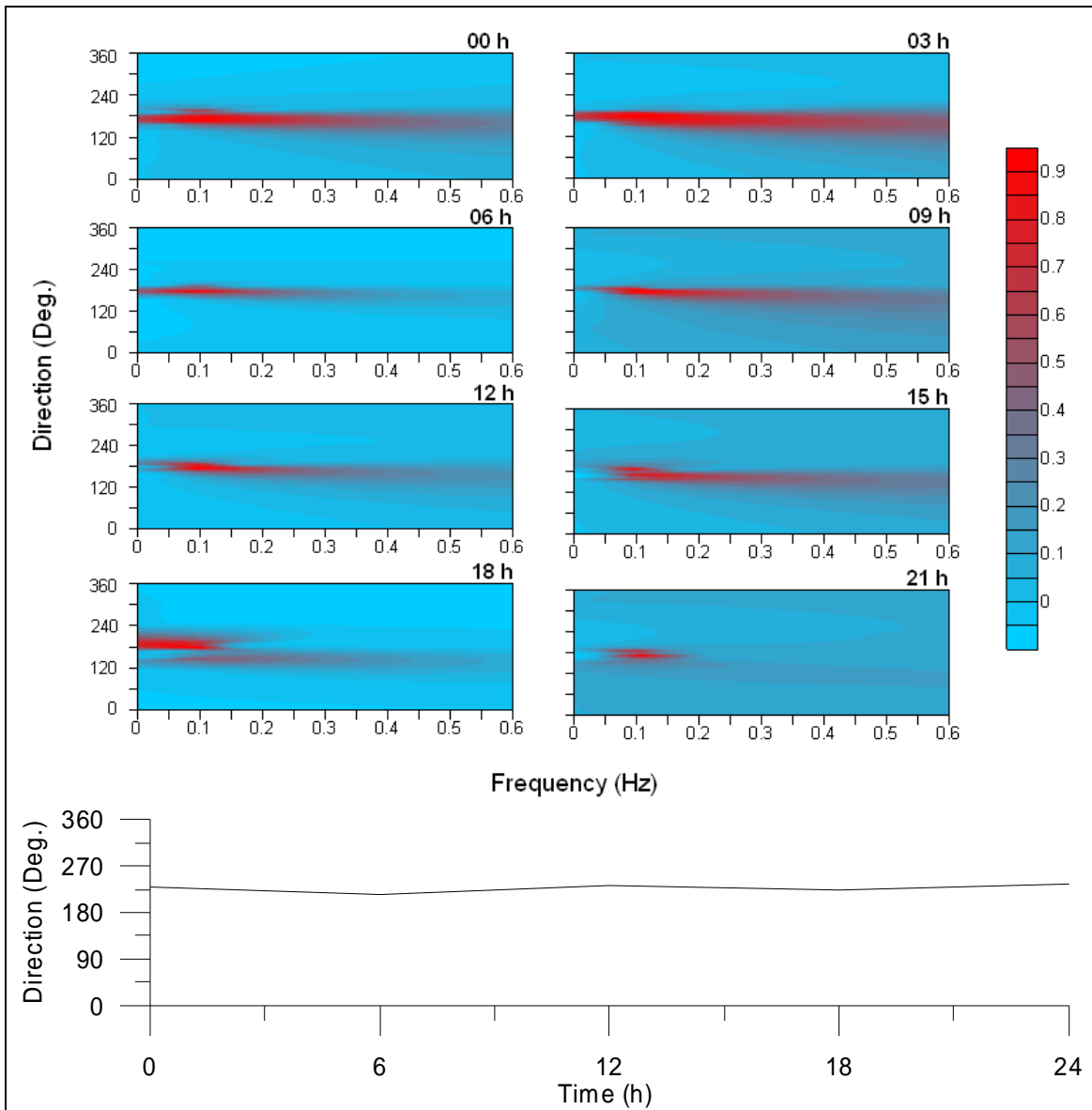


Fig. 6 (a) Measured directional energy spectra from 00 h to 21 h (for every 3 h) and (b) NCEP wind (6-hourly) at offshore location near to the study region on 26 July 1996.

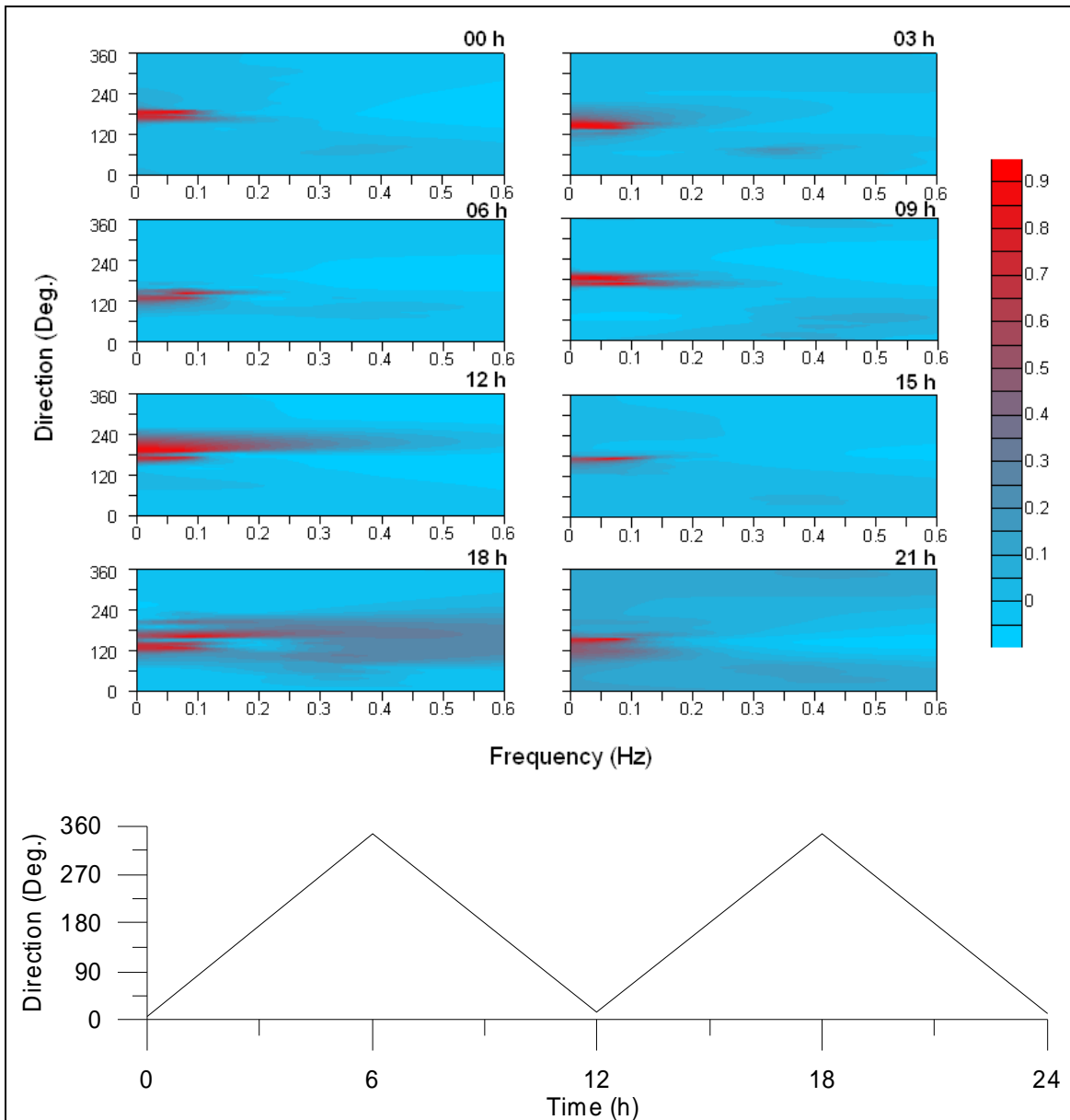


Fig. 7 (a) Measured directional energy spectra from 00 h to 21 h (for every 3 h) and (b) NCEP wind (6-hourly) at offshore location near to the study region on 15 November 1996.

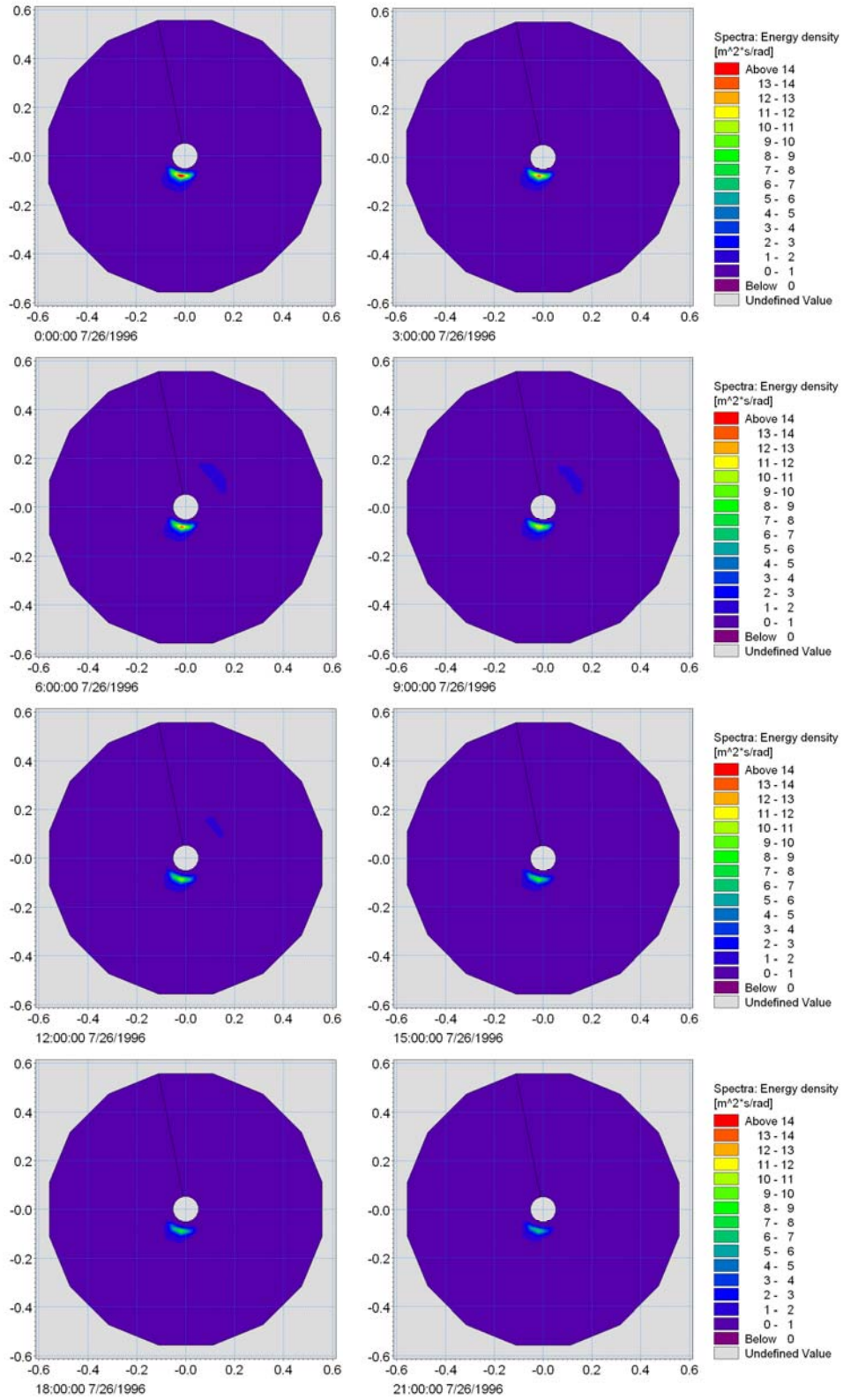


Fig. 8. Modelled directional energy spectra during 26 July for every 3h simulations (00 h to 21 h).

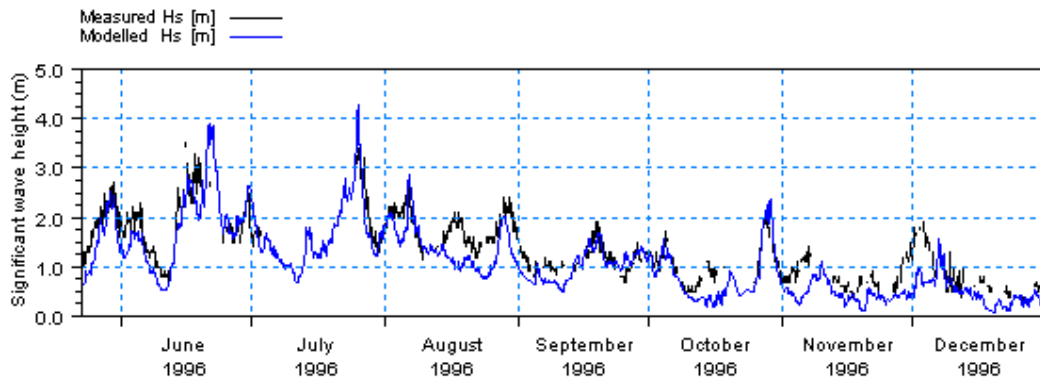


Fig. 9 Measured and modelled significant wave heights (May- December 1996)

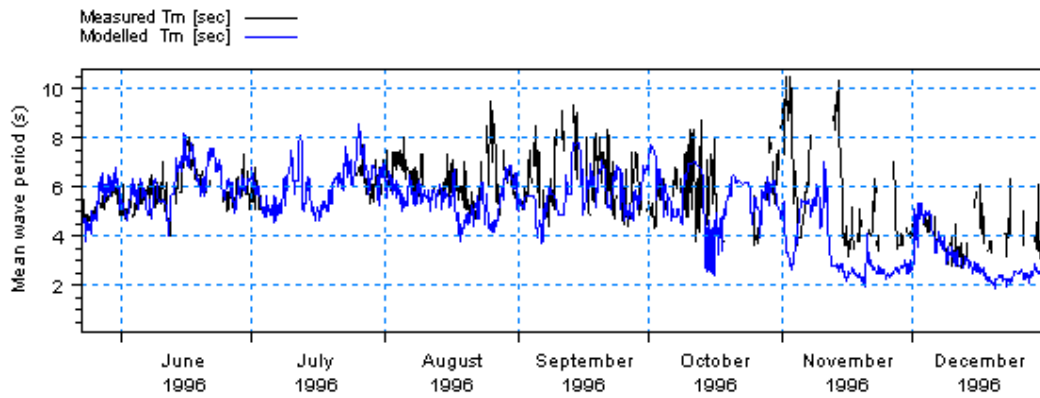


Fig. 10. Measured and modelled mean wave periods (May - December 1996)

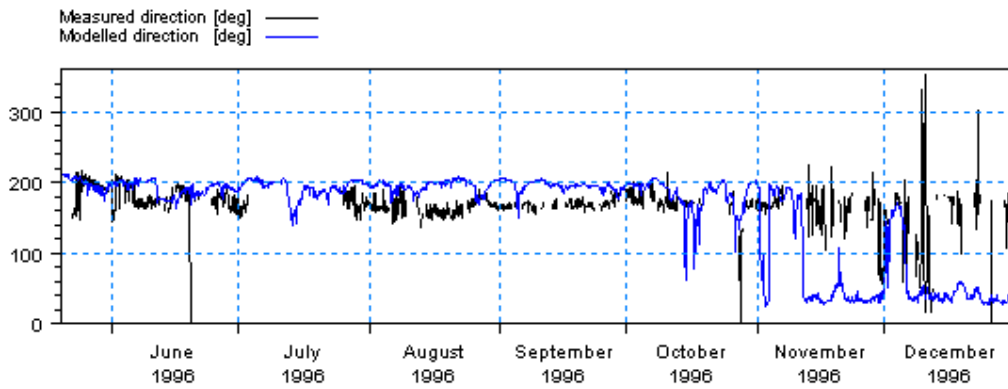


Fig. 11. Measured and modelled mean wave directions (May - December 1996)