
# Ocean Wave Modeling and Forecasting System

*Training Workshop on*
*'Ocean Information Services for Cyclone forecasters'*
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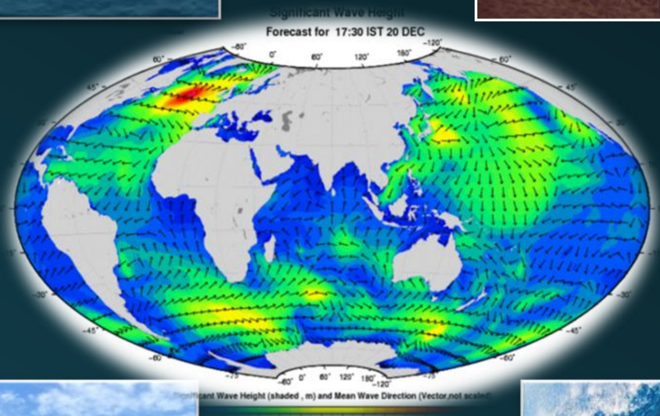
Sandhya K G
Scientist, ISG
INCOIS

# Numerical Modeling of Ocean Waves

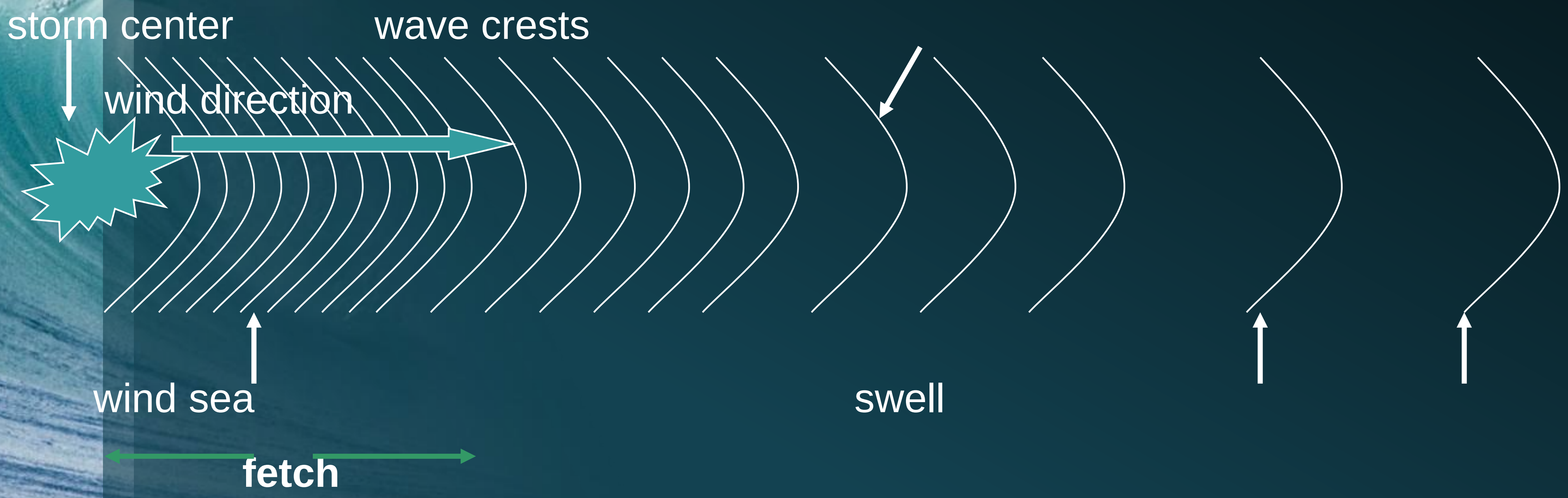
## Why model ocean waves ?

- Safe navigation
- Public safety
- Design of offshore and coastal infrastructures
- Recreation


# Wind seas and Swells

Sea state is a combination of wind seas and swells.




Fetch is the distance over which wind blows over the water surface

# Chaotic Sea exhibiting complex surface wave forms

SWELL WAVES

## ○ What does a wave model predict ?

➢ Only wind generated waves.

➢ How waves evolve as changing wind fields act on the surface of the ocean.

➢The outputs from a wave model are wave parameters such as significant wave height, swell height, mean & peak wave periods, .... and optionally wave energy spectrum (1D and 2D).

# Wave groups and group velocity

- Individual waves in a group travel at the velocities corresponding to their wave lengths, but the wave group as a coherent unit travels at its own velocity - the group velocity

- Group velocity is the velocity with which the wave energy is propagated

- Group velocity can be written as

$$C_g = d\omega/dk$$

- Deep water group velocity is

$$C_g = C/2$$

=> The wave group travels slower than the fastest wave in the group.

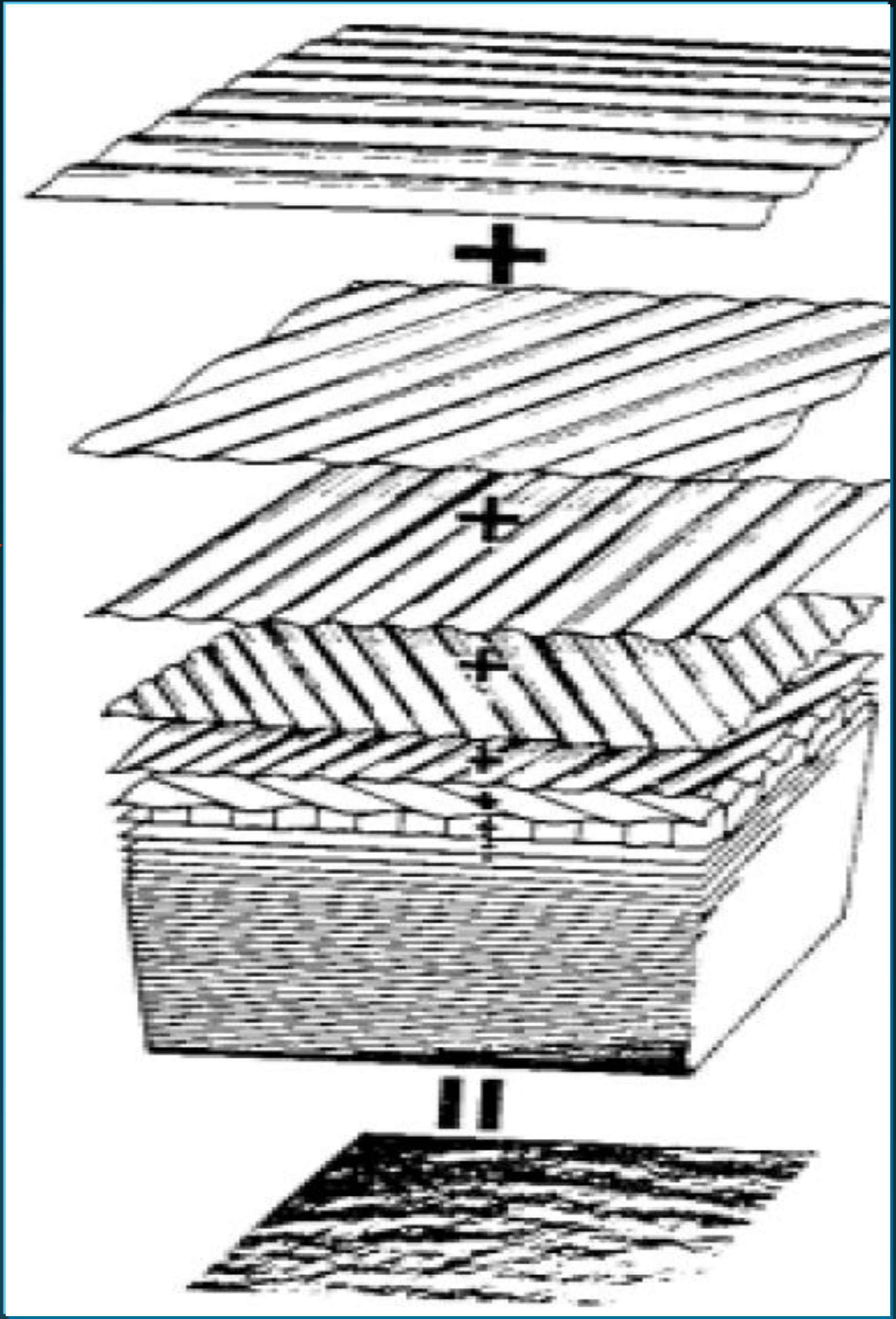
- Shallow water group velocity is

$$C_g = C$$

This is since the shallow water waves are non dispersive.

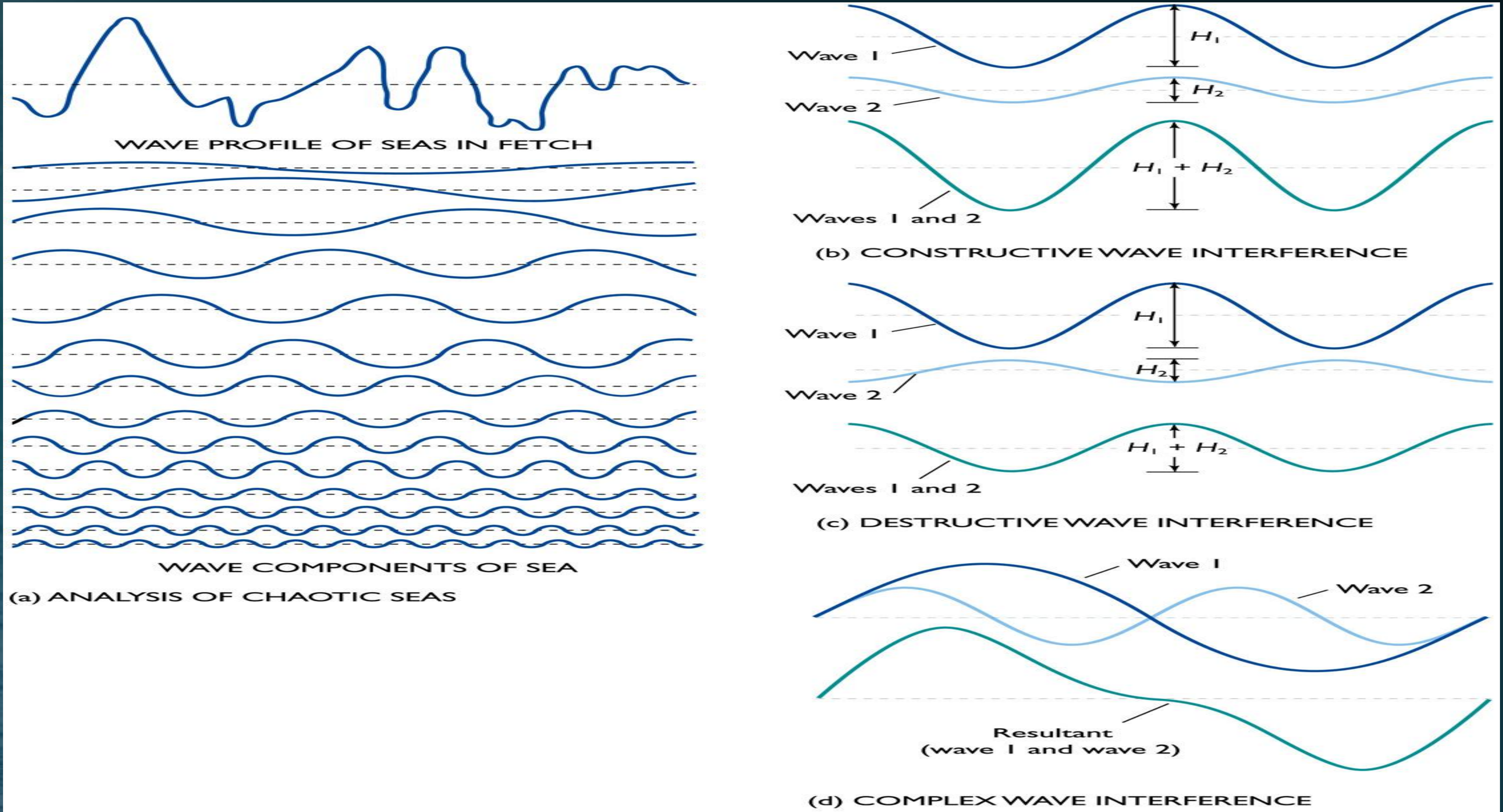
# Wave fields on the ocean – a composition of simple waves

The sea surface obtained from the sum of many sinusoidal waves



Any observed wave pattern in the ocean could be shown to comprise a number of simple waves, which differ from each other in height, wavelength and direction.

# How a complex wave pattern could be analyzed???



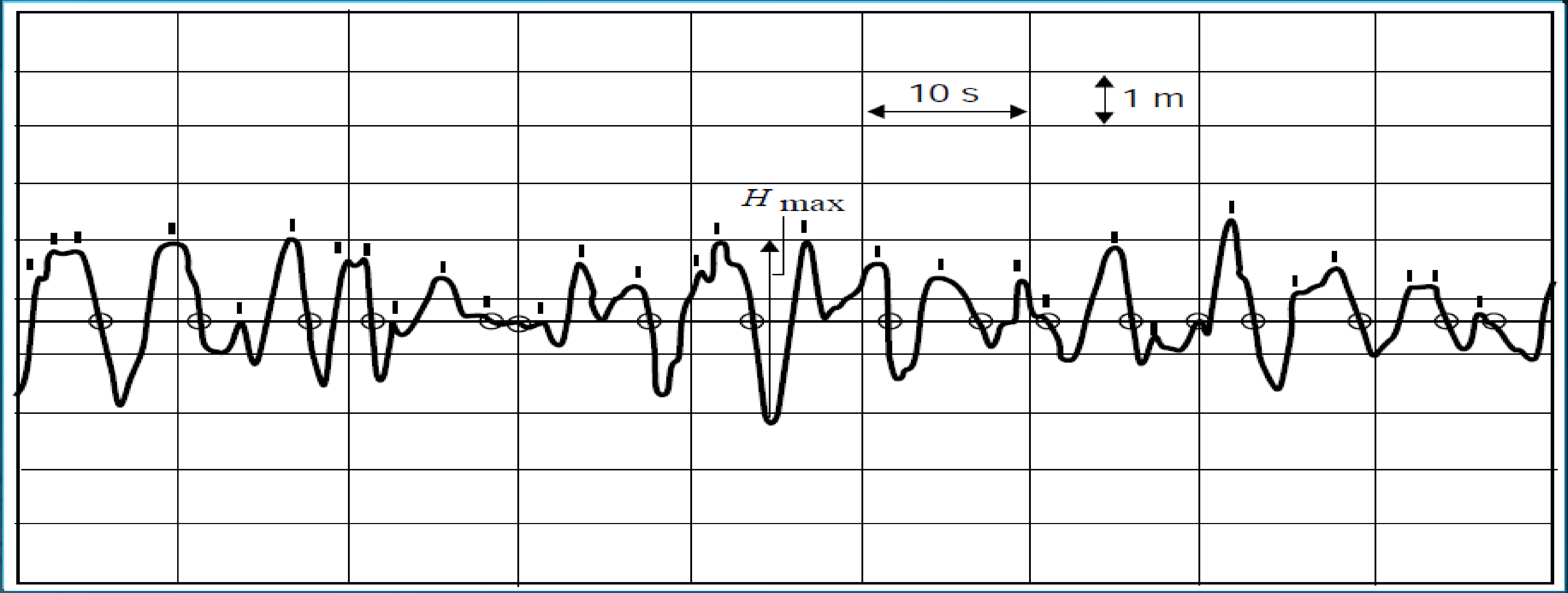
# *In-situ* wave measurement - Waverider buoys

- Small & light, deployable from small vessels

- The non-directional wave buoy measures its own vertical acceleration on a gravity stabilised platform. This is double integrated to get the vertical displacement of the buoy. Applying FFT to this wave record gives you the power spectral density.

- The directional wave rider buoys measures tilt (pitch and roll) in addition to vertical acceleration and gives the directional information of waves, in addition to the vertical displacement.

# Wave record - the motion of water surface at a fixed point

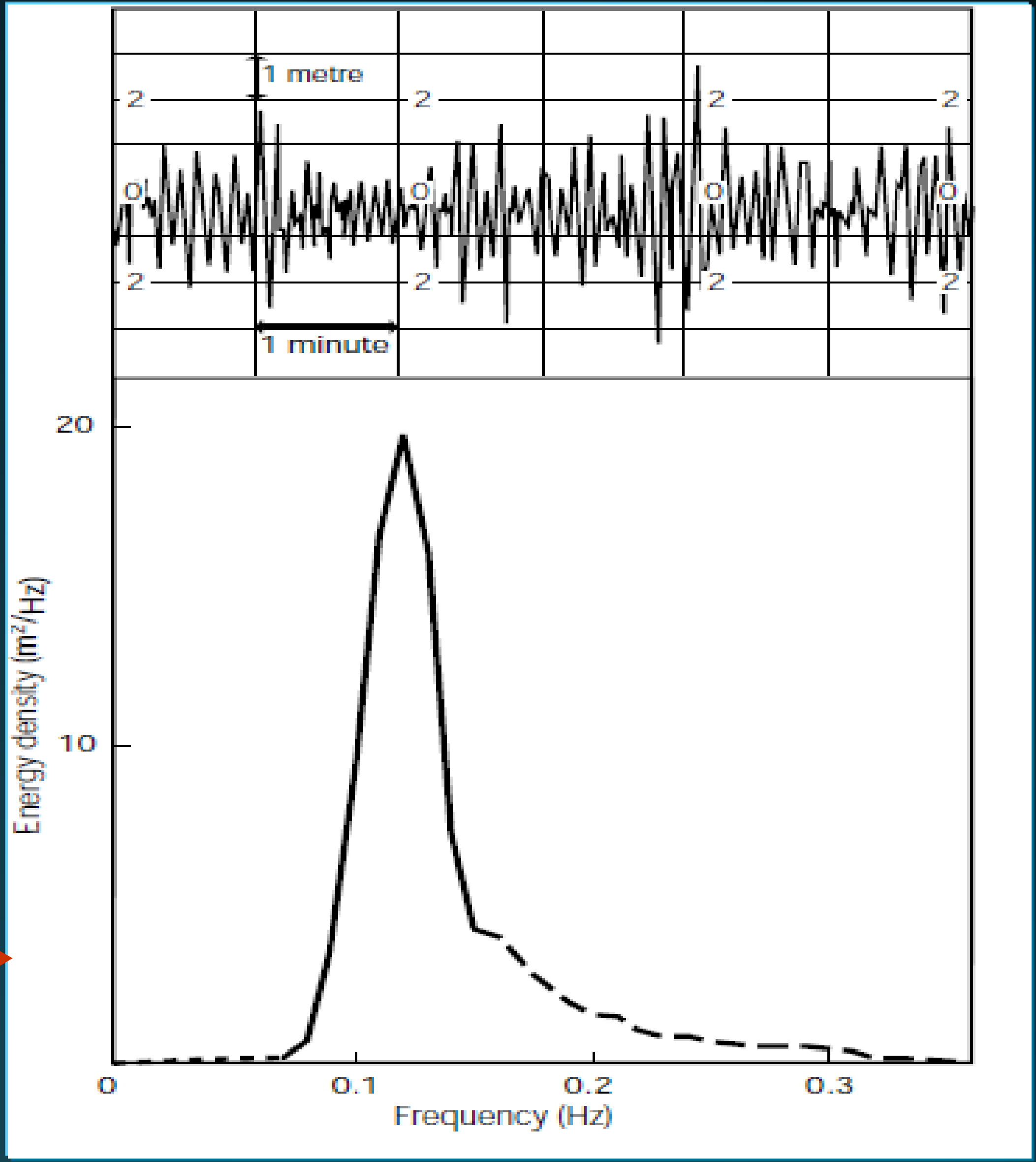


# Wave spectrum - Concept

Wave spectrum is the distribution of wave energy over various frequencies (or directions). It is obtained by the FFT of the wave record.

The concept of wave spectrum is used in modelling the sea state.

Example of a wave spectrum with corresponding wave record.



# Wave parameters derived from the spectrum

- Wave parameters are usually expressed in terms of the moments of the spectrum. The $n^{th}$ order moment of the spectrum is given by

$$m_n = \int_0^\infty f^n E(f)\,df$$

where $E(f)df$ represents the variance $a_i^2/2$ contained in the $i^{th}$ interval between $f$ and $f+df$ and $a_i$ is the amplitude of the $i^{th}$ component in a wave record.

- Zeroth moment $m_0$ is the area under the spectral curve. It could be derived that the significant wave height $H_{m0}$ (average (1/3)rd of the highest waves) is

$$H_{m0} = 4\sqrt{m_0}$$

# Wave parameters derived from the spectrum

- Peak wave frequency $f_p$ is the wave frequency corresponding to the peak of the spectrum.

- Peak wave period $T_p$ is the period corresponding to $f_p$ ,

$$T_p = 1/f_p$$

- Mean wave period

$$T_{m02} = \sqrt{\frac{m_0}{m_2}}$$

○ **What are the processes affecting the energy of ocean waves ?**

- Gain from the external environment (Source)
- Advection (rate of energy propagated into and away from the location)
- Losses due to dissipation (Sink)

# Concepts of Spectral Wave model

- In wave modelling, the sea surface elevation at a point is represented by the sum of several spectral components:

  $$ή(t) = \sum a(i) \cos(\sigma i\ t + \theta i)$$

  where a(i) is the amplitude of the ith wave component and σi is the relative frequency of the ith wave component, θi is the phase of the ith wave component

- The total energy of the waves per unit surface area is related to the variance of the sea surface elevation

- The total wave energy at a particular point evolves in geographic space (x,y) and spectral space (σ,θ) and in time. This evolution is modelled in the current generation wave models. Hence they are categorized as **Spectral Wave models.**

# Concepts of Spectral Wave model…

The basic equation describing a Spectral Wave model is called the spectral action balance equation

$$\partial N/\partial t + \partial(C_x N)/\partial x + \partial(C_y N)/\partial y + \partial(C_\sigma N)/\partial \sigma + \partial(C_\theta N)/\partial \theta = S/\sigma,$$

where N is the wave action density and

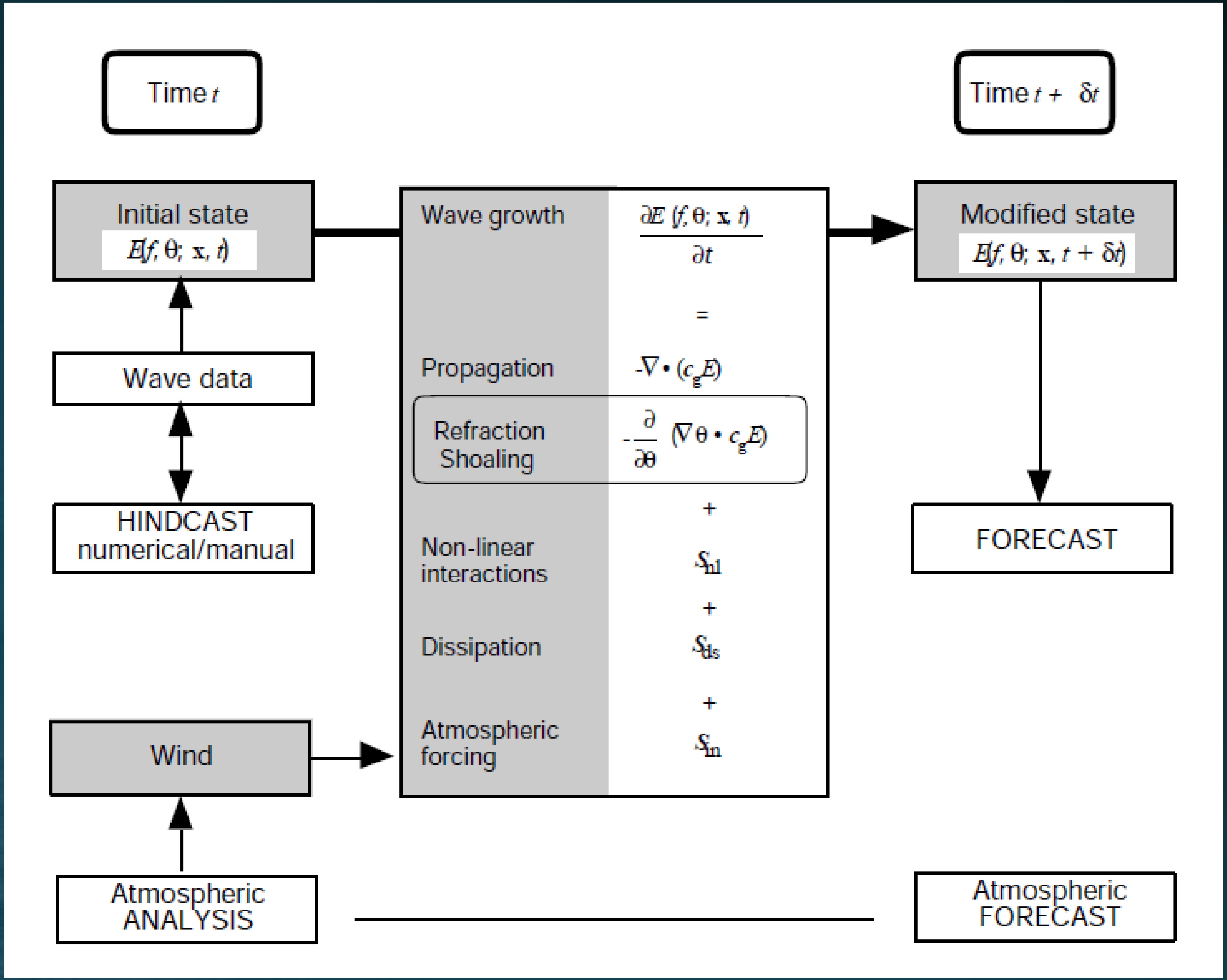
$$S = S_{in} + S_{nl} + S_{wc} + S_{bot} + S_{db}$$

In the above equation,

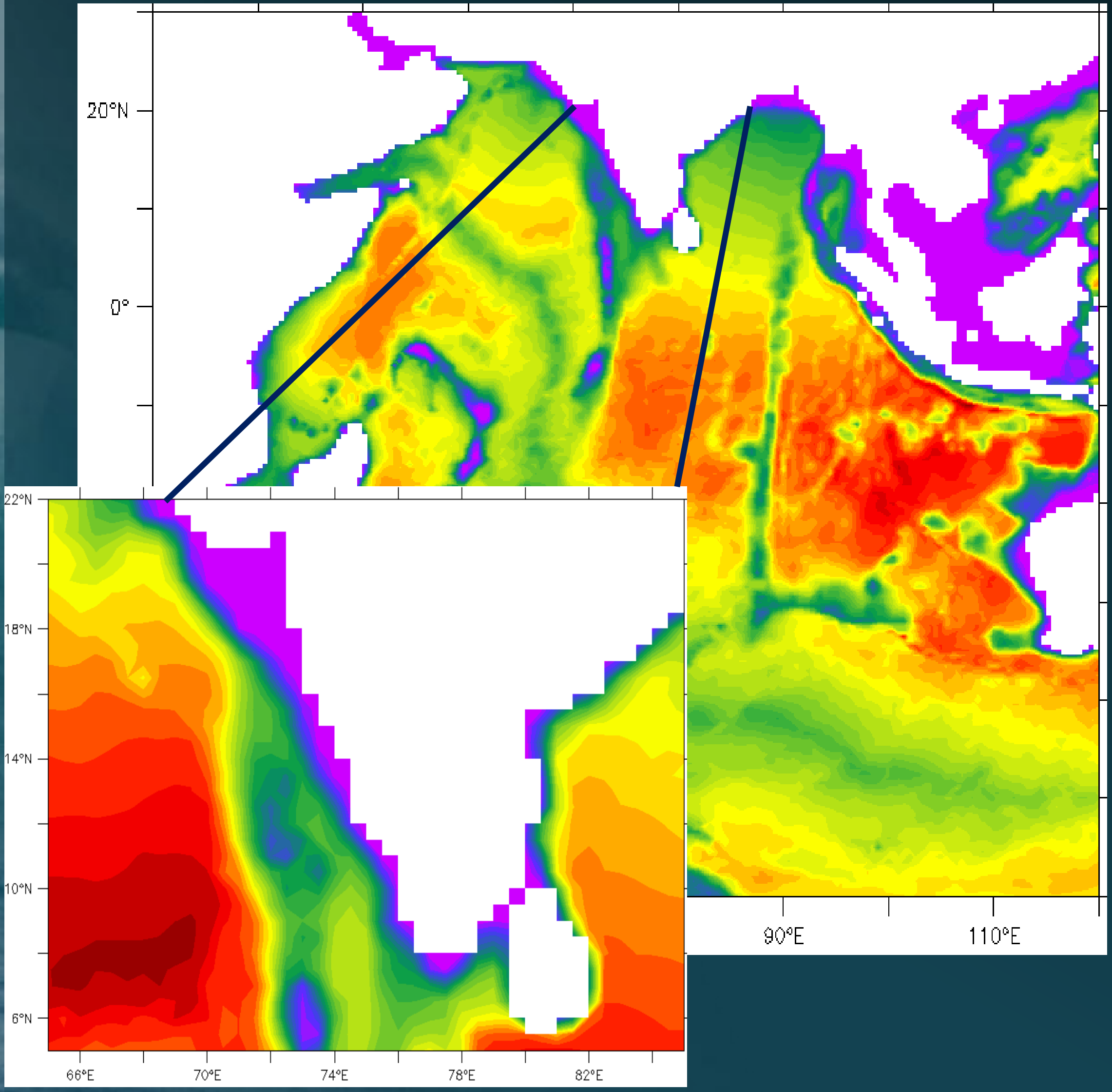
- $S_{in}$ takes care of the wave growth by the action of wind
- $S_{nl}$ accounts for the non-linear wave-wave interactions
- $S_{wc}$ sink term for dissipation due to white-capping
- $S_{bot}$ sink term for dissipation due to bottom friction
- $S_{db}$ sink term for dissipation due to depth-induced wave breaking

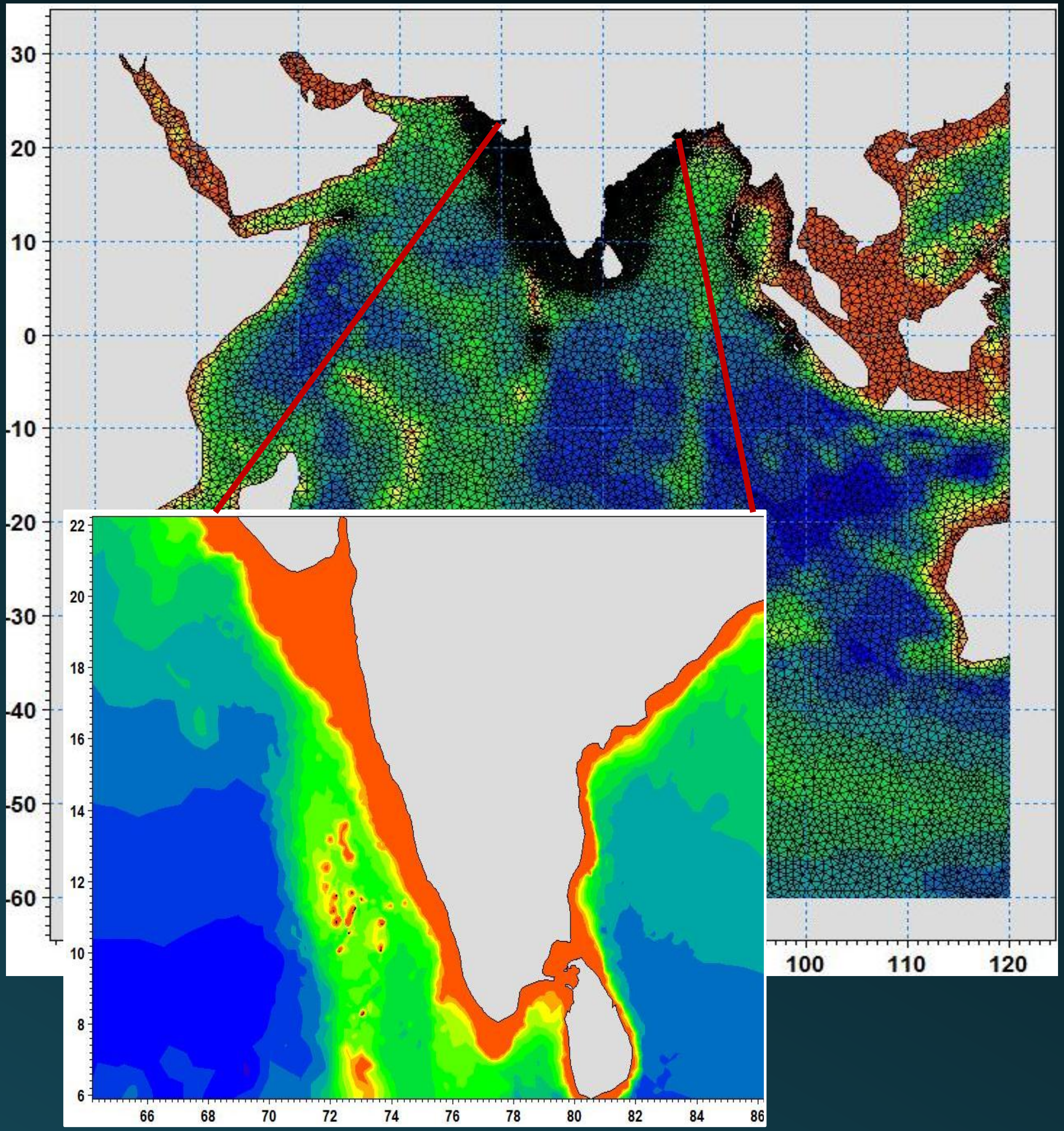
The model also considers refraction and shoaling due to depth variations.

# Elements of wave modelling



# Model grids – Structured vs Unstructured

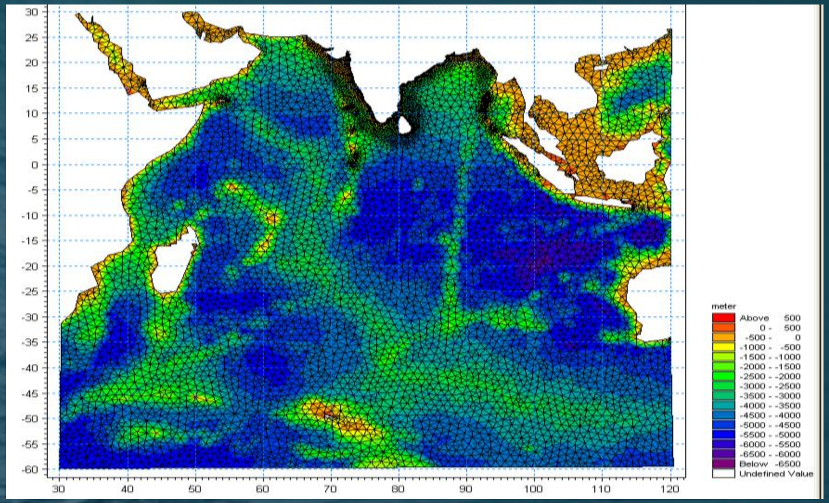


# MIKE 21 SW model (operational)

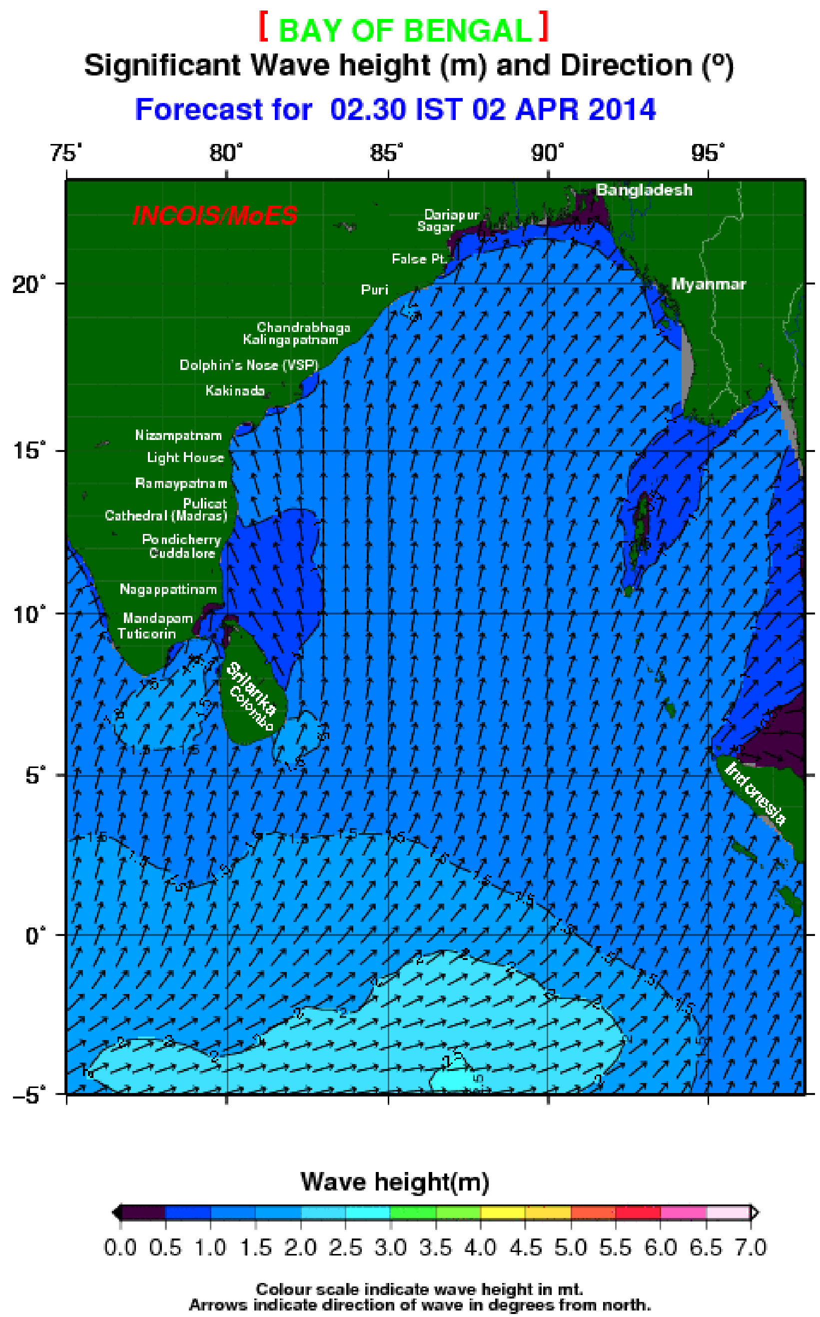
- Spectral Waves (SW) is a module in the MIKE 21 software
- SW simulates the wind-generated waves and swells in open ocean and coastal waters
- The model uses unstructured grid, with varying resolution
- Wind, Bathymetry and optionally current are the inputs to the model
- Model grid is from 60 S to 30 N and from 30 E to 120 E
- Wind from ECMWF with 0.25 resolution is used as forcing
- Bathymetry from ETPO2, NHO and CMAP are used

**A sample bathymetry file used in the model**




Spatial resolution:
•150 km in the southern Indian ocean
• 55 km in the Arabian sea and BOB
• 8-15 km along the Indian coast

Temporal resolution: 3 hrs

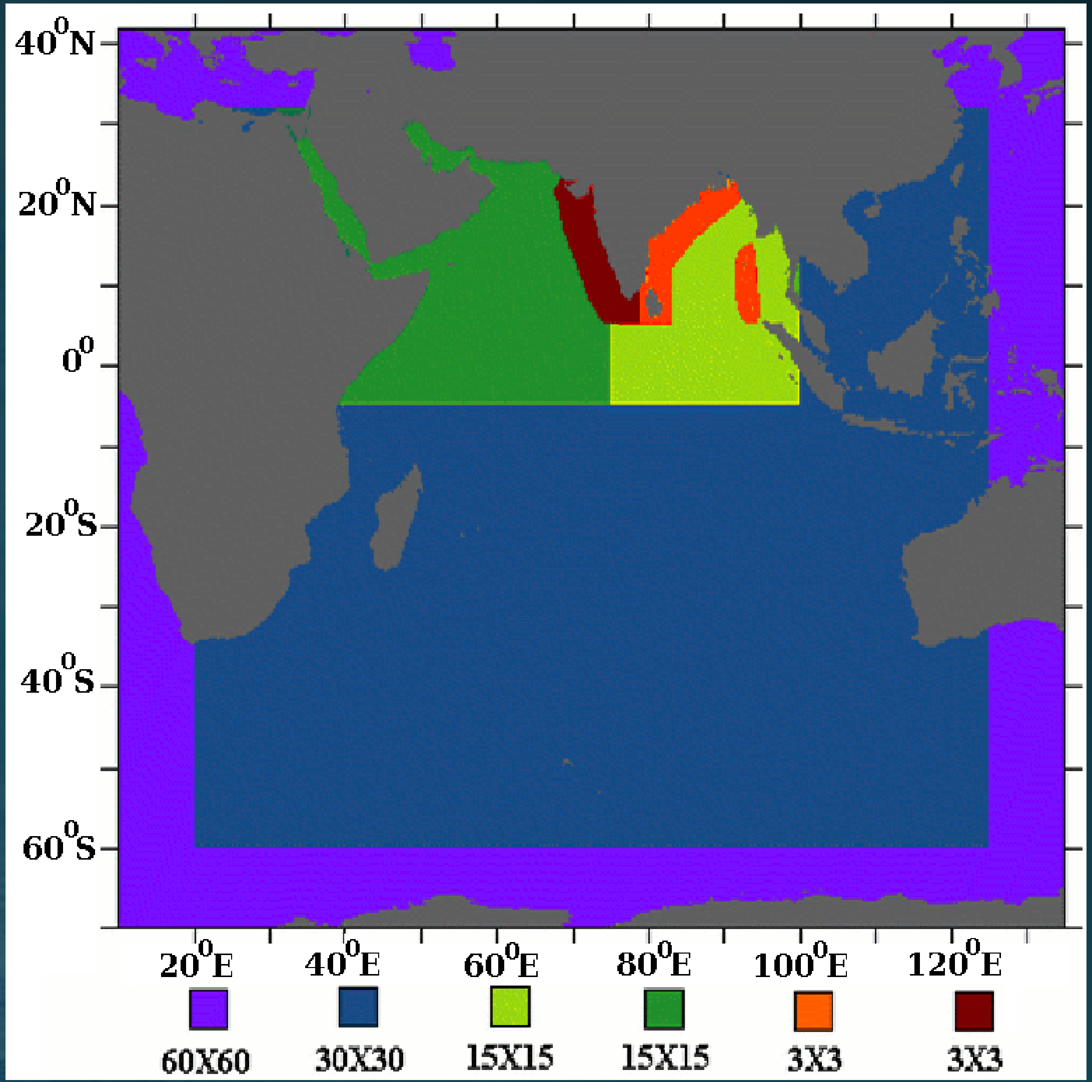

[ BAY OF BENGAL ]
Significant Wave height (m) and Direction (°)
Forecast for 02.30 IST 02 APR 2014
75° 80° 85° 90° 95°
20° 15° 10° 5° 0° -5°
INCOIS/MoES
Bangladesh
Dariapur
Sagar
False Pt.
Puri
Myanmar
Chandrabhaga
Kalingapatnam
Dolphin's Nose (VSP)
Kakinada
Nizampatnam
Light House
Ramaypatnam
Pulicat
Cathedral (Madras)
Pondicherry
Cuddalore
Nagappattinam
Mandapam
Tuticorin
Srilanka
Colombo
Indonesia
Wave height(m)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0
Colour scale indicate wave height in mt.
Arrows indicate direction of wave in degrees from north.

# WAVEWATCH III (operational)



- Simulates wind-generated waves and swells
- Third generation wave model using regular grids
- Wind from NCMRWF at 1x1 degree resolution, in 6 hourly interval for 5 days is the forcing
- Bathymetry is also to be given as input to the model
- Has the option for multigrid – rectangular grids having variable resolution in the computational domain
- Can simulate waves on a global scale
- Gives spectral output(1D and 2D) as well as spectral parameters
- **Can generate boundary conditions for a small scale model**
- Code is parallelized
- Currently installed in HPC at INCOIS

# Multi-Grid WAVEWATCH III setup at INCOIS




1 deg Southern Hemisphere grid
0.5 deg Indian Ocean grid
0.25 deg Arabian Sea grid
0.25 deg Bay of Bengal grid
0.05 deg West Coast grid
0.05 deg East Coast grid

# Indian Ocean Forecast System (INDOFOS)

## Global

Global

Arabian Sea
Bay of Bengal
Northern Indian Ocean
Southern Indian Ocean
Red Sea
Persian Gulf
South China Sea

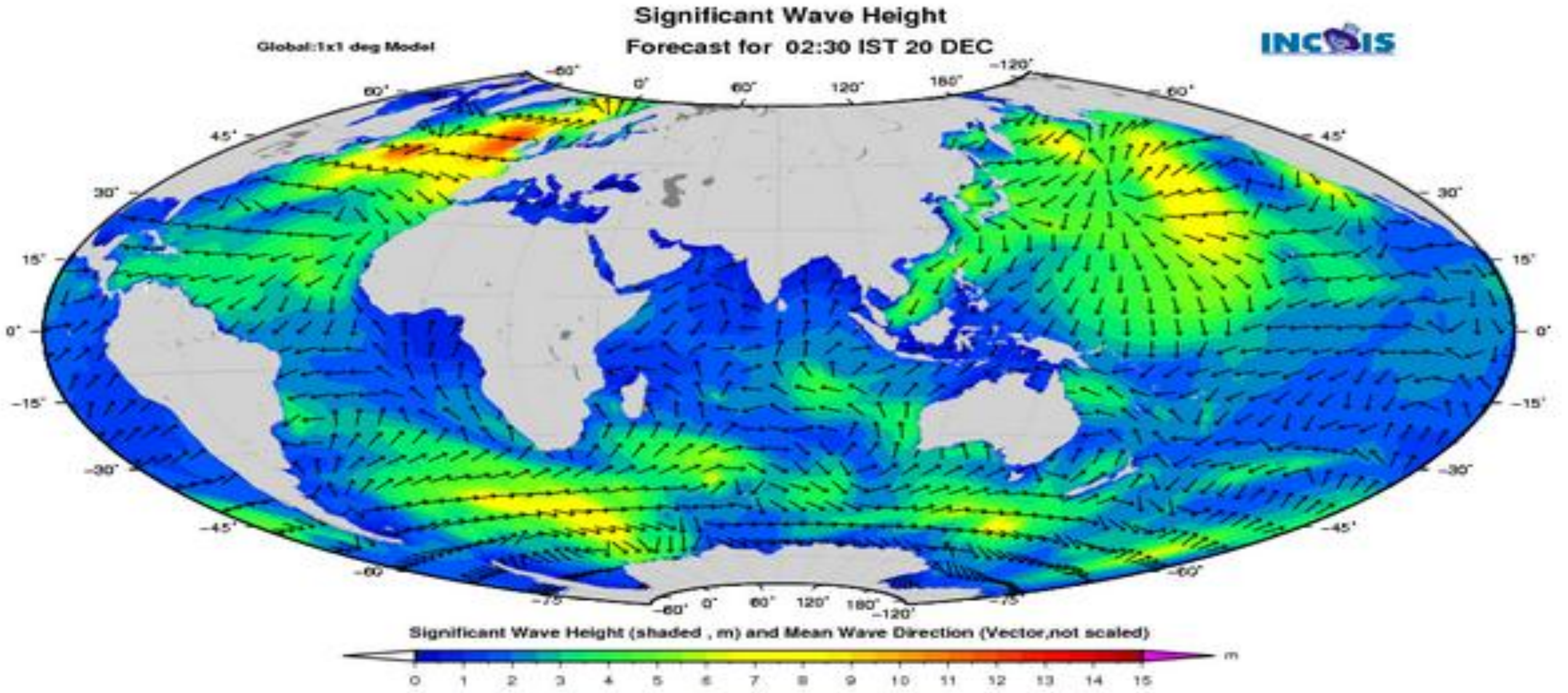
Select Parameter

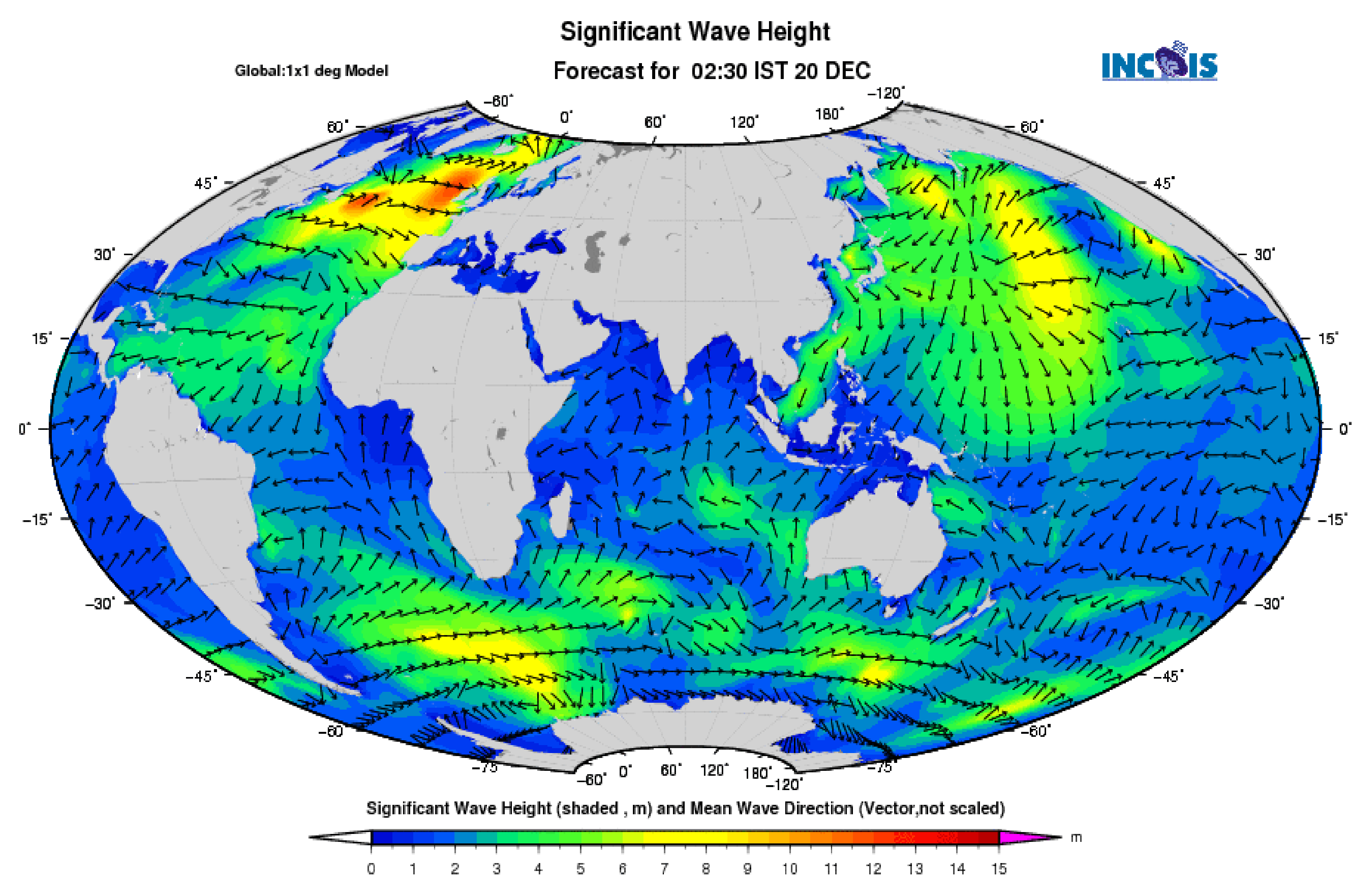
Select Parameter
Wave Height and Direction
Swell Height and Direction
Wave Period
Swell Period

20-12-2013--0230

Submit

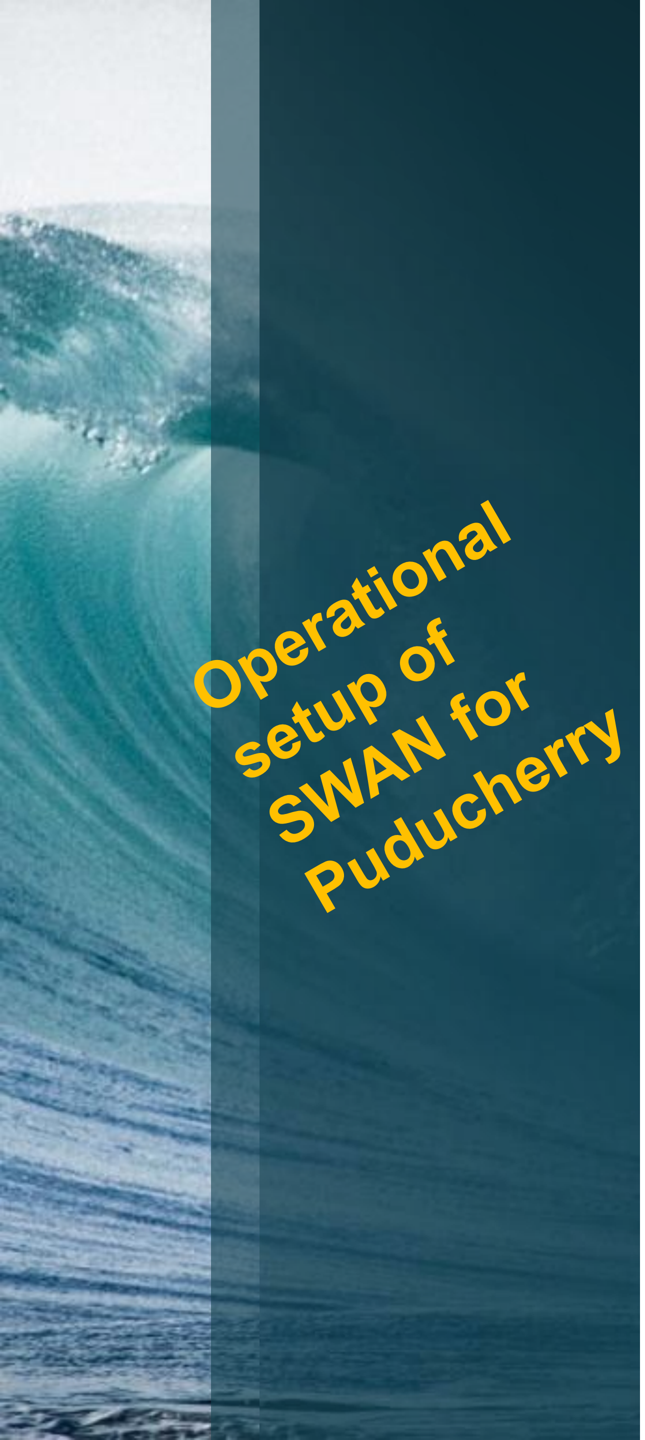
Click here for animation




Significant Wave Height
Global:1x1 deg Model
Forecast for 02:30 IST 20 DEC
INCOIS
Significant Wave Height (shaded , m) and Mean Wave Direction (Vector,not scaled)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
m

# SWAN (Simulating WAves Nearshore) model (offline)

- Simulates wave parameters in coastal areas and lakes from given wind, bottom and current conditions
- Third generation wave model which uses regular grids and optionally unstructured grids
- Could be nested in WW3
- Gets boundary conditions from WW3
- Valid for water depths up to 5m
- Used for wave parameter simulation in regional scales or at specific locations
- Code is parallelized
- Presently installed in INCOIS HPC with a spatial resolution of 250 m and a temporal resolution of 3 hrs

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# Wave forecasting system for operational use and its validation at coastal Puducherry, east coast of India

K.G. Sandhya [a], T.M. Balakrishnan Nair [a], Prasad K. Bhaskaran [b,*], L. Sabique [a], N. Arun [a], K. Jeykumar [a]

[a] *Information Services and Ocean Sciences Group, Indian National Centre for Ocean Information Services, Ministry of Earth Sciences, Hyderabad, India*
[b] *Department of Ocean Engineering and Naval Architecture, Indian Institute of Technology Kharagpur, Kharagpur-721 302, West Bengal, India*

A R T I C L E I N F O

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SWAN
Nesting
Wave rider buoy
Validation

A B S T R A C T

An incredible demand for coastal sea-state forecast in recent years has led to development and implementation of wave forecasting system in operational centers, having wide practical applications relevant to marine industry. The wave forecasting system takes advantage of parametric techniques, by nesting global ocean wave models to coastal and near-shore high-resolution wave models. The Indian National Centre for Ocean Information Services (INCOIS) at Hyderabad has a mandate for operational marine weather forecast services that envisages integration and coupling state-of-the-art weather models for operational oceanographic needs. In the present study, two state-of-art wave models viz; WAVEWATCH III (WW3) and Simulating WAves Nearshore (SWAN) are nested and forced with French Research Institute for Exploitation of the Sea/Laboratory of Oceanography From Space (IFREMER/CERSAT) blended surface winds. The objective is to investigate wave evolution at a coastal location off Puducherry in the east coast of India. To evaluate model performance, a detailed validation study is performed by comparing model-simulated wave parameters and wave spectra with corresponding in-situ wave rider buoy observations for four prominent seasons viz; northeast monsoon, southwest monsoon, pre- and post-monsoon. The study signifies applicability of nested wave model for operational use during normal weather condition at coastal Puducherry.

# Operational setup of SWAN for Puducherry

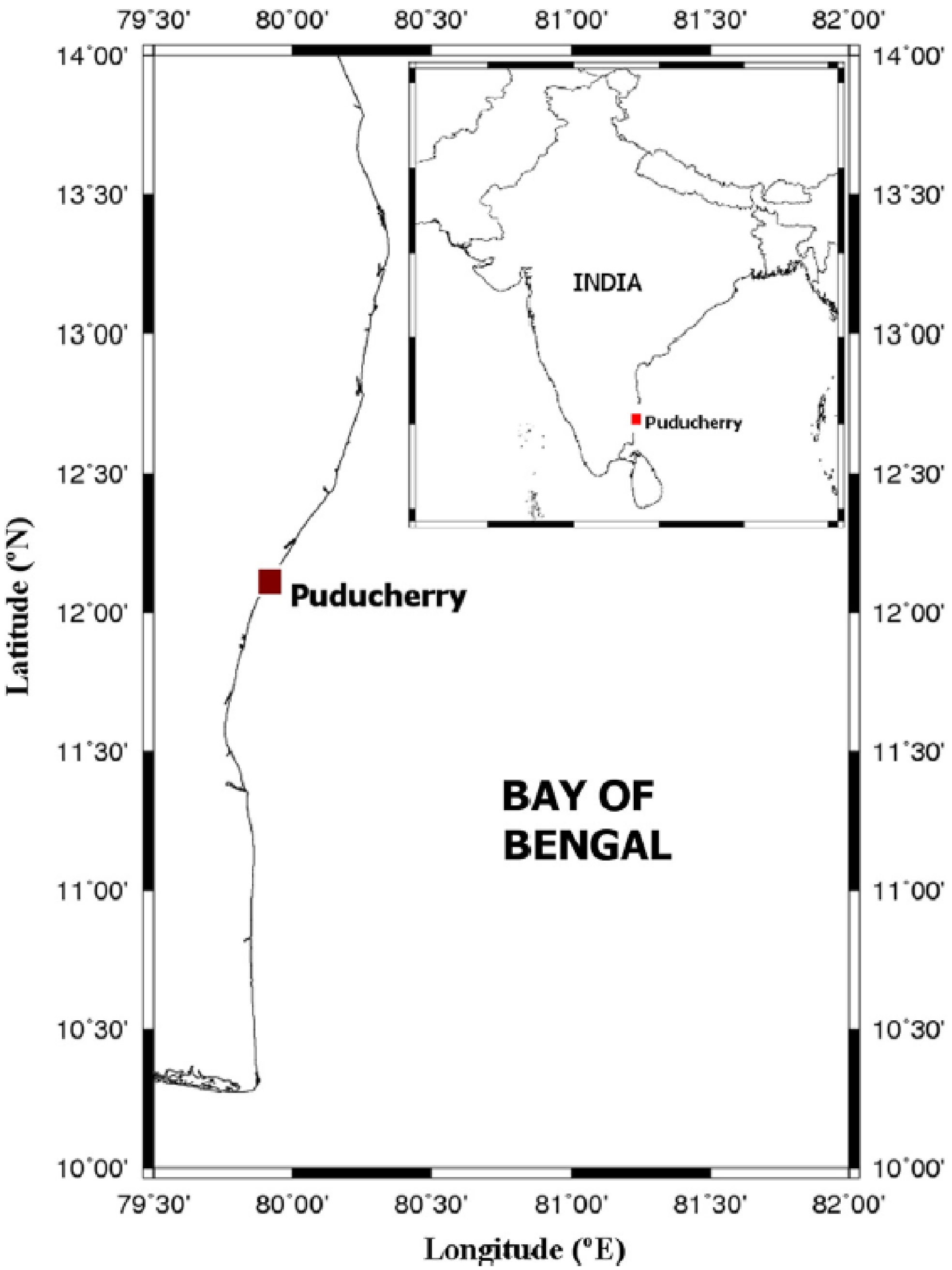



**Fig. 1.** Study region with location of Puducherry and the nested domain of SWAN.

# Importance of boundary conditions

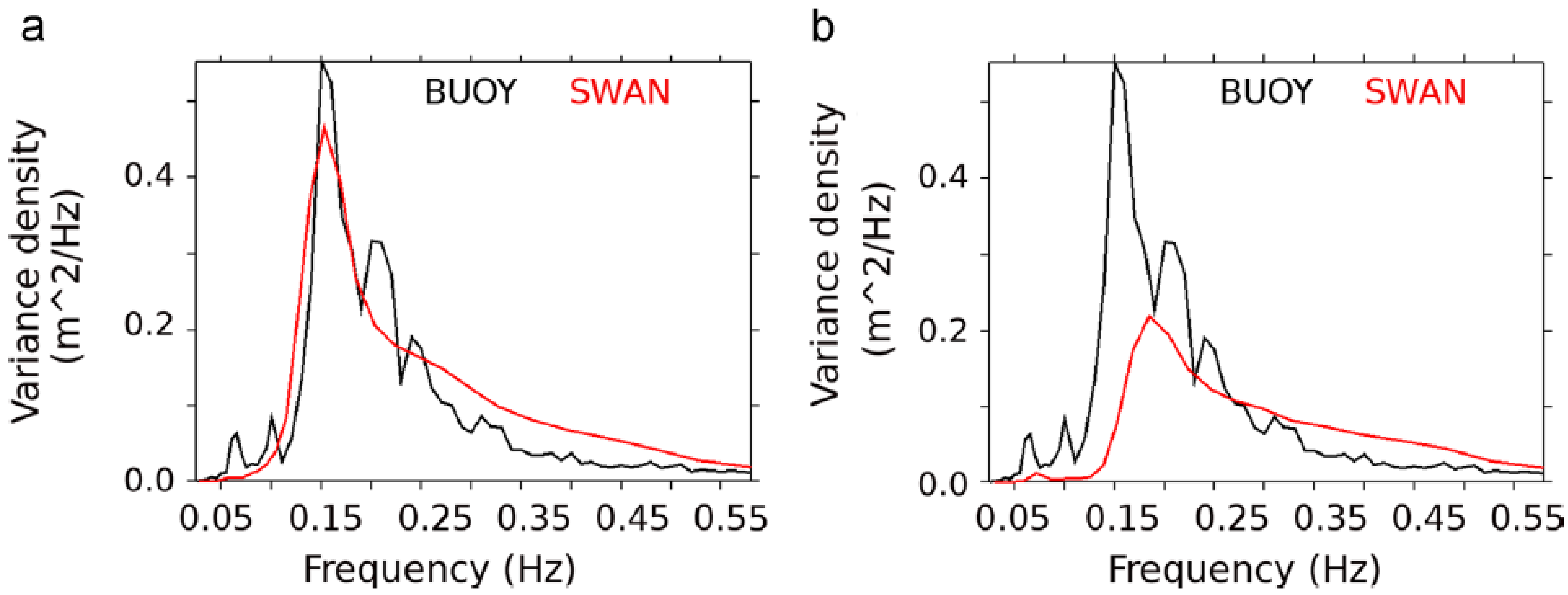



**Fig. 8.** Comparison of one-dimensional wave energy spectra (m2/Hz) between model and buoy observation during 02 January 2008 (21Z) (a) with nesting in WW3, and (b) without nesting.

# Validation of Hs at Puducherry for 2007-2009

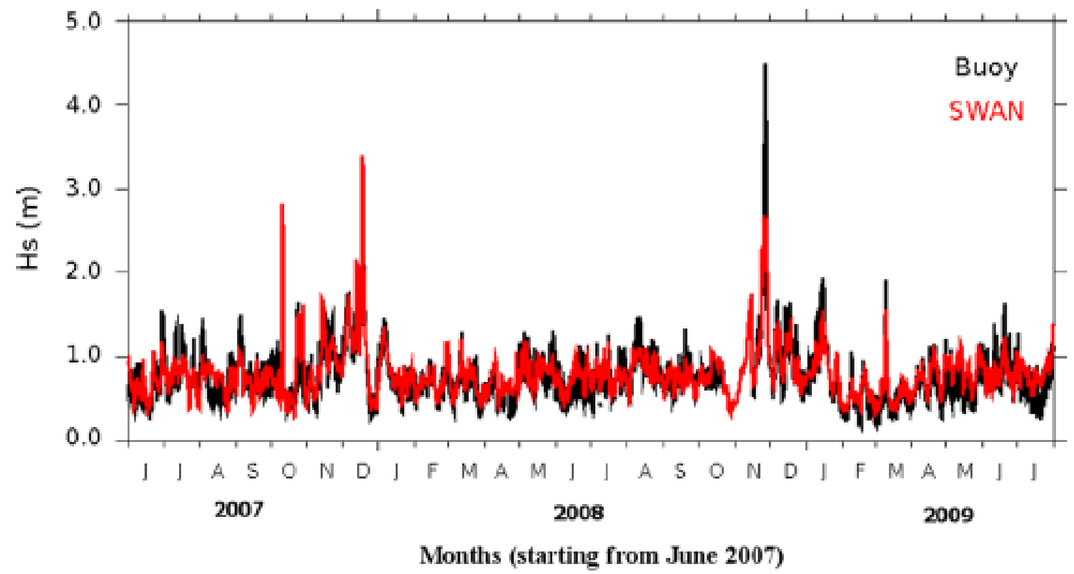



Fig. 3. Validation of Significant wave height (in m) at coastal Puducherry for the period 2007–2009.

# Error statistics for Hs at Puducherry

**Table 1**
Validation statistics between model and buoy observations for different seasons

| Season | Bias (m) | RMSE (m) | SI (%) | R | Buoy average (m) | Model average (m) | SD of buoy (m) | SD of model (m) | No. of points |
|---|---|---|---|---|---|---|---|---|---|
| Pre-monsoon | 0.15 | 0.18 | 35.25 | 0.79 | 0.52 | 0.68 | 0.14 | 0.13 | 903 |
| SWM | 0.03 | 0.17 | 22.5 | 0.68 | 0.76 | 0.78 | 0.2 | 0.12 | 1971 |
| Post-monsoon | −0.05 | 0.24 | 29.08 | 0.87 | 0.83 | 0.78 | 0.24 | 0.24 | 727 |
| NEM | −0.003 | 0.15 | 18.83 | 0.93 | 0.79 | 0.79 | 0.29 | 0.26 | 1785 |
| Pre-excluded | 0.1 | 0.18 | 27.12 | 0.7 | 0.68 | 0.78 | 0.21 | 0.17 | 791 |
| Post-excluded | 0.009 | 0.15 | 18.17 | 0.89 | 0.85 | 0.82 | 0.35 | 0.32 | 602 |

# Wave forecasting and monitoring during very severe cyclone *Phailin* in the Bay of Bengal

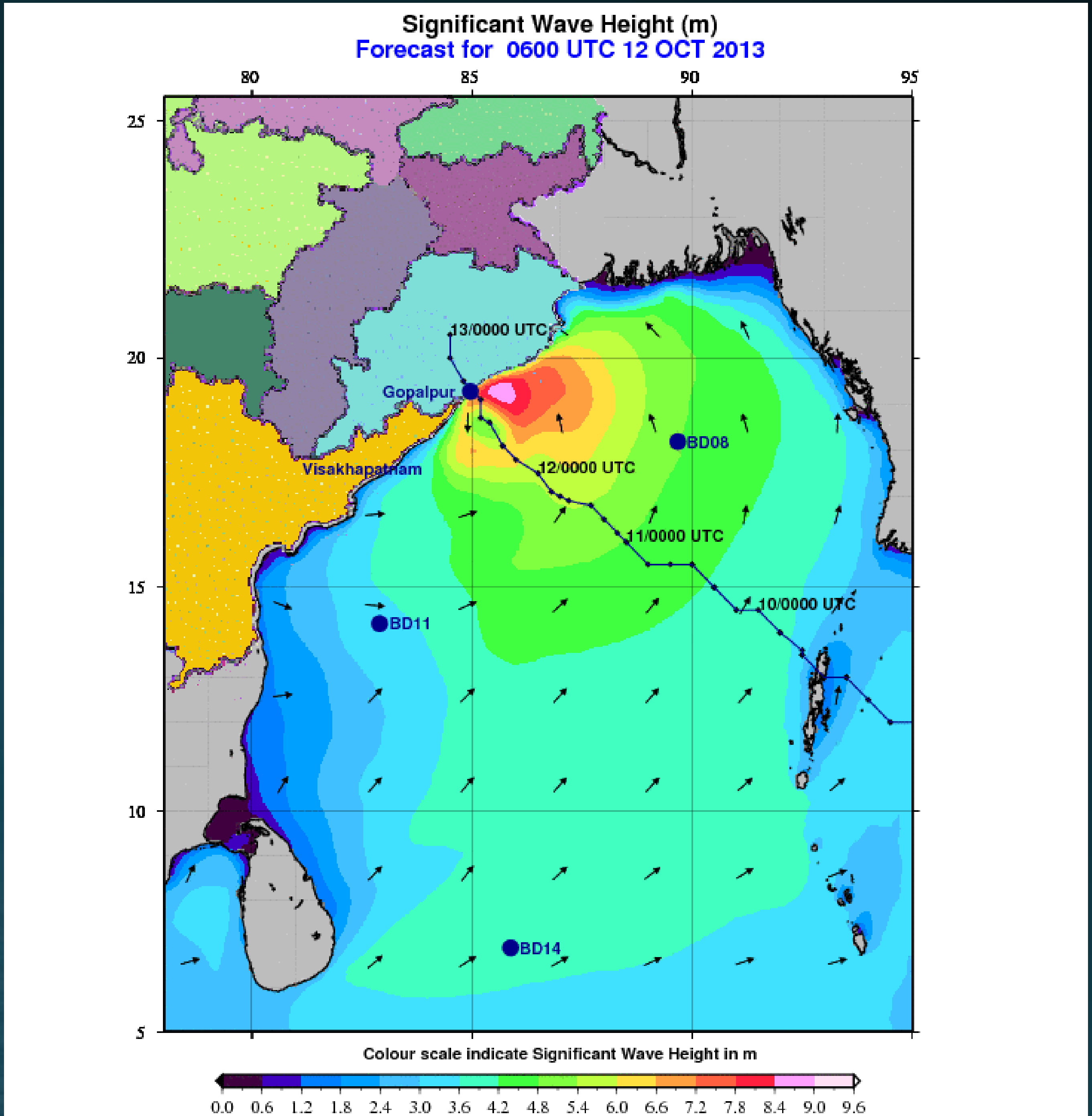
**T. M. Balakrishnan Nair[1,*], P. G. Remya[1], R. Harikumar[1], K. G. Sandhya[1], P. Sirisha[1], K. Srinivas[1], C. Nagarju[1], Arun Nherakkol[1], B. Krishna Prasad[1], C. Jeyakumar[1], K. Kaviyazhahu[1], N. K. Hithin[1], Rakhi Kumari[1], V. Sanil Kumar[2], M. Ramesh Kumar[1], S. S. C. Shenoi[1] and Shailesh Nayak[3]**

[1]Information Services and Ocean Sciences Group, Indian National Centre for Ocean Information Services, 'Ocean Valley', Pragathi Nagar (BO), Nizampet (SO), Hyderabad 500 090, India

6 days from 8 to 14 October 2013 and it made landfall on 12 October at 1700 UTC in Gopalpur, Odisha (Figure 1). During the Odisha super cyclone of 1999, no quantitative OSF system was in place for forewarning the coastal communities, but for *Phailin*, the warnings were issued five days in advance. This helped the maritime authorities and users to take maximum precautions well in advance and save lives and properties. *Phailin* also provided a unique opportunity to study instrumentally recorded extreme wave data and evaluate the forecast.

Monitoring of extreme wave fields and evaluation of its forecast (issued from ESSO–INCOIS) have been done using data from the directional wave rider buoy[3,4] (DWRB) network of ESSO–INCOIS, including off Gopalpur (19.28°N, 84.97°E at 12 m water depth), the landfall location of *Phailin*. Wave data obtained from deep-sea moored buoys BD08 (18.14°N, 89.67°E), BD11

Track and Hs for Phailin



## Real-time validation of Hs for Phailin

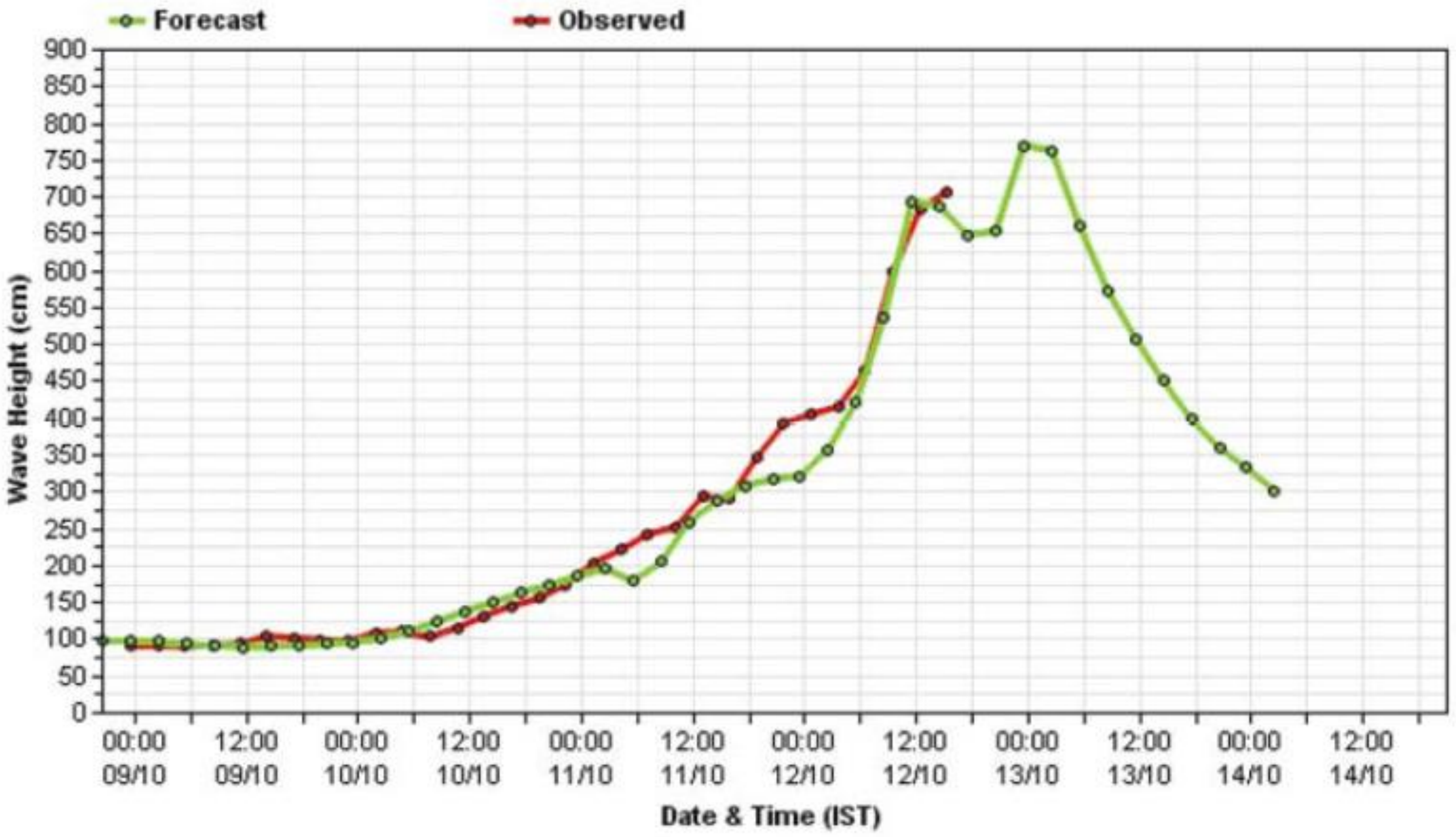



**Figure 2.** Real-time comparison between the forecast and observed significant wave heights at Gopalpur, during very severe cyclonic storm *Phailin*.

Model-computed 2D spectra for Phailin

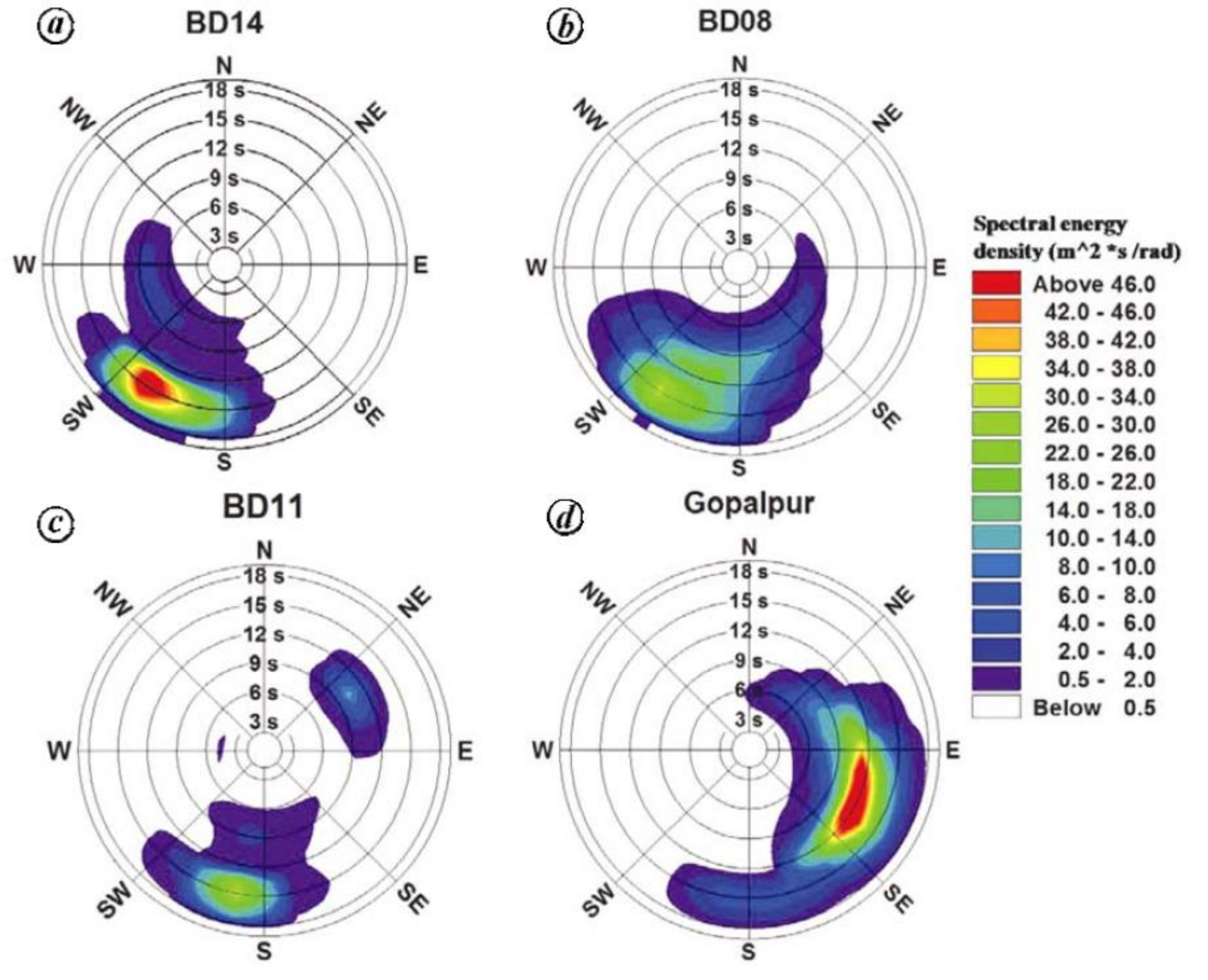



**Figure 5.** Model-derived two-dimensional wave energy spectra at (*a*) BD14 on 10 October 2013 at 1500 UTC, (*b*) BD08 on 11 October 2013 at 1800 UTC, (*c*) BD11 on 11 October 2013 at 1800 UTC and (*d*) Gopalpur on 12 October 2013 at 0600 UTC. The time steps are chosen in such a way that the southern swells and cyclone-generated waves are easily discernible.

Error statistics of Hs for Phailin

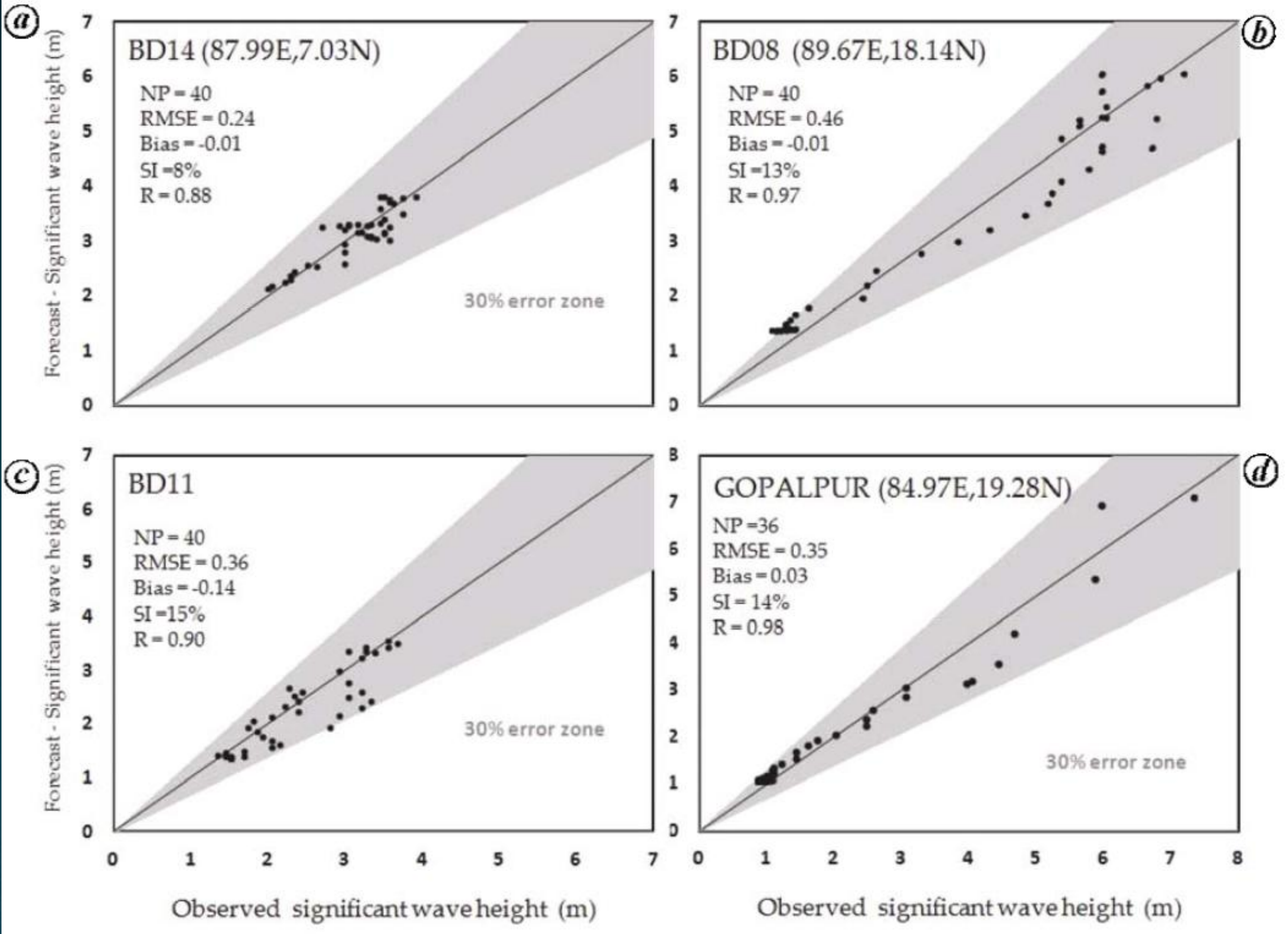



**Figure 6.** *a–d*, Comparison of observed and forecast $H_s$ for the selected buoys. Shadows indicate 30 % error zone, the acceptable error limit for operational wave forecasting. NP, Number of points.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GENERAL ARTICLE

# Performance of the Ocean State Forecast system at Indian National Centre for Ocean Information Services

*T. M. Balakrishnan Nair*, P. Sirisha, K. G. Sandhya, K. Srinivas, V. Sanil Kumar, L. Sabique, Arun Nherakkol, B. Krishna Prasad, Rakhi Kumari, C. Jeyakumar, K. Kaviyazhahu, M. Ramesh Kumar, R. Harikumar, S. S. C. Shenoi and Shailesh Nayak*

*The reliability of the operational Ocean State Forecast system at the Indian National Centre for Ocean Information Services (INCOIS) during tropical cyclones that affect the coastline of India is described in this article. The performance of this system during cyclone Thane that severely affected the southeast coast of India during the last week of December 2011 is reported here. Spectral wave model is used for forecasting the wave fields generated by the tropical cyclone and validation of the same is done using real-time automated observation systems. The validation results indicate that the forecasted wave parameters agree well with the measurements. The feedback from the user community indicates that the forecast was reliable and highly useful. Alerts based on this operational ocean state forecast system are thus useful for protecting the property and lives of the coastal communities along the coastline of India. INCOIS is extending this service for the benefit of the other countries along the Indian Ocean rim.*

# Track and Hs for Thane

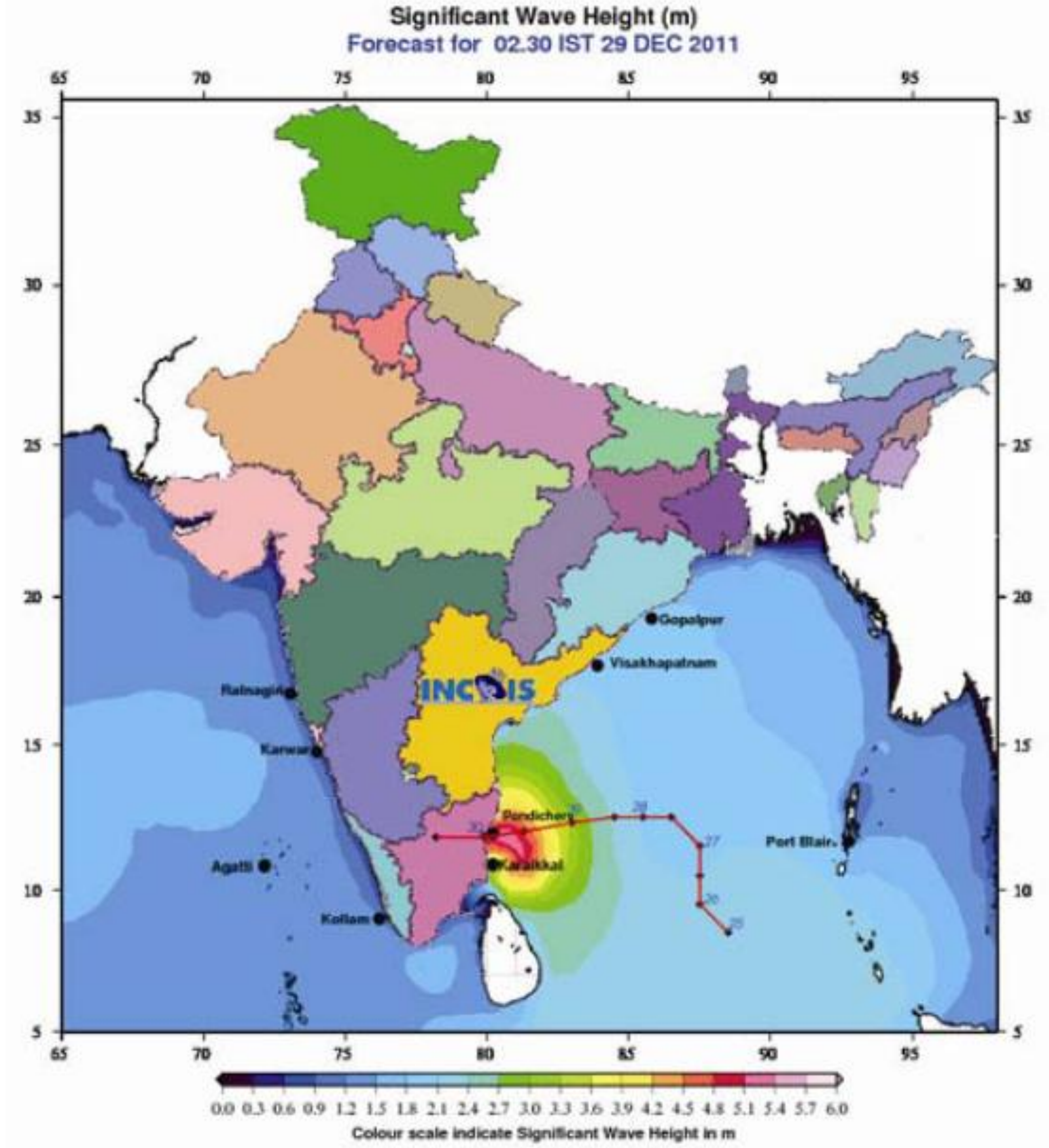



**Figure 2.** Image showing Ocean State Forecast product (significant wave height) issued from Indian National Centre for Ocean Information Services (INCOIS) during tropical cyclone *Thane*. The locations of INCOIS wave rider buoy network (black dots around the coasts) and cyclone track (red line) are overlaid.

# Validation of wave parameters for Thane

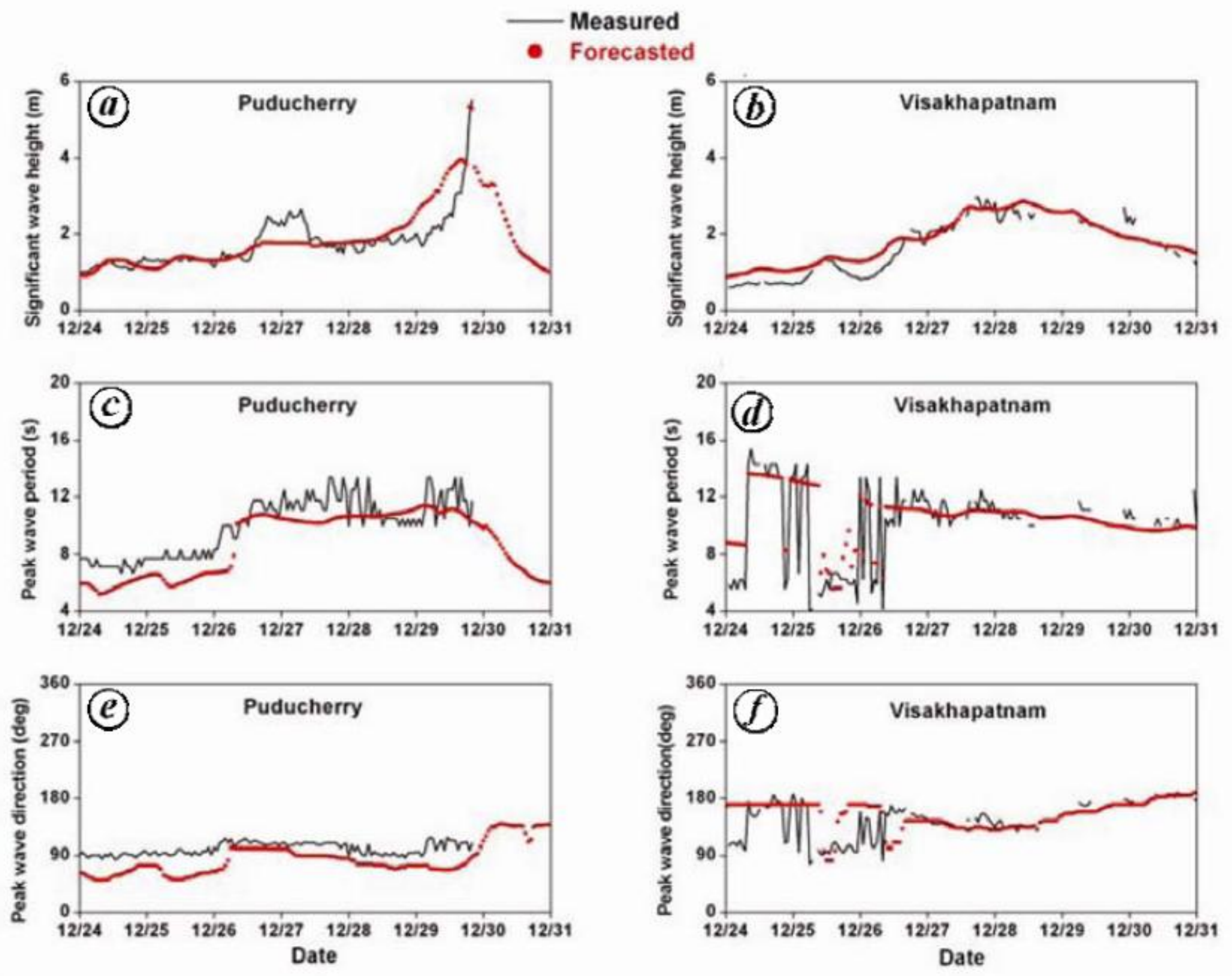
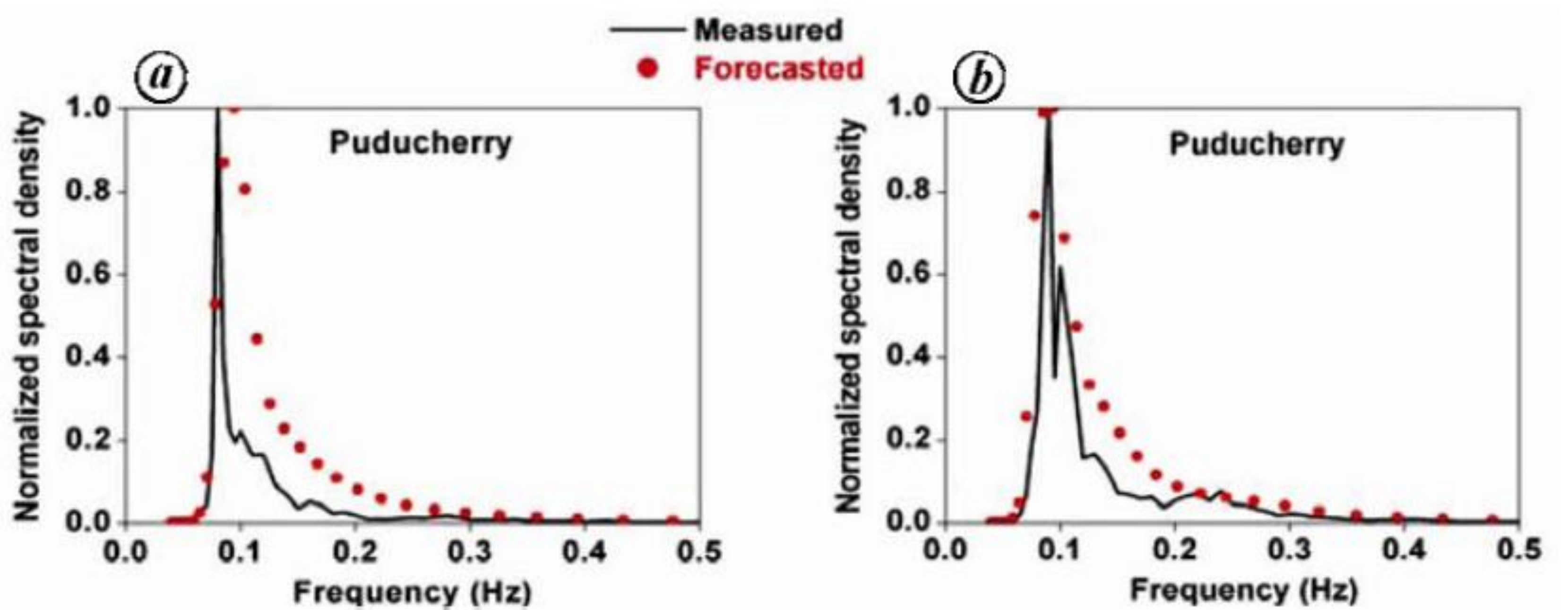



**Figure 4.** Comparison of forecasted and measured significant wave height at (*a*) Puducherry and (*b*) Visakhapatnam. Peak wave period at (*c*) Puducherry and (*d*) Visakhapatnam. Peak wave direction at (*e*) Puducherry and (*f*) Visakhapatnam.

**Table 1.** Error statistics estimated based on the comparison of forecasted and measured wave parameters

| Error statistics | Puducherry ($n$ = 141) | | Visakhapatnam ($n$ = 142) | |
|---|---|---|---|---|
| | Significant wave height (m) | Wave period (s) | Significant wave height (m) | Wave period (s) |
| Bias | 0.06 | –1.0 | 0.16 | 0.4 |
| RMS error | 0.44 | 1.5 | 0.28 | 2.0 |
| SI (%) | 25 | 15 | 19 | 20 |
| CC | 0.85 | 0.89 | 0.95 | 0.71 |

Comparison of measured and modelled wave energy spectra for Thane



*Thank you for your kind attention !!!*