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

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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.

Keywords: Ocean State Forecast system, spectral wave model, tropical cyclone, wave fields.

OPERATIONAL wave forecasting during tropical cyclones is of paramount importance as the associated extreme waves impact safe navigation and operations at sea and also greatly affect the coastal communities at the time of landfall. Tropical cyclones generate severe and complex ocean wave fields which can propagate for thousands of kilometres away from the eye of the cyclone. While propagating, these wave fields undergo dramatic variations in space and time, and thus predicting cyclone-generated wave fields is a challenge for marine forecasters[1]. When they approach the coast, cyclones threaten lives and property because of their high winds, associated high waves, storm surges, excessive rainfall and flooding.

To ensure safe navigation and operations at sea, and to forewarn the users such as the fishermen community, Oil and Shipping industry, Ports and Harbours, Navy and Coast Guard on hazardous oceanic situations, Indian National Centre for Ocean Information Services (INCOIS) started the Ocean State Forecast (OSF) service in 2005 by issuing forecasts of vital ocean parameters like significant wave heights, remotely generated waves (swells) and ocean surface winds, seven days in advance and at three hourly intervals, with daily updates. Most of the users utilize these forecasts as a guidance for their daily operational activities and to ensure safe navigation. Though international agencies such as National Centres for Environmental Prediction (NCEP), USA and European Centre for Medium-Range Weather Forecasts (ECMWF), UK issue sea state forecasts based on models such as WAVEWATCH III and WAM, these forecasts are for the open ocean. The INCOIS model set-up is refined to provide accurate location-specific forecast by setting up high-resolution models in the coastal waters using best available bathymetry data of that location, and tuning them using observed wave measurements. Real-time and on-line validation of the forecast products is given in the INCOIS website to boost the confidence of the user community. Being the only operational OSF agency for the northern Indian Ocean, INCOIS has initiated a forecast service for Maldives recently and intends to extend similar service for other Indian Ocean rim countries. The forecast wave parameters have been validated with *in situ* Wave Rider Buoy observations as well as satellite (altimeter) data.

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Subsequently, to warn the fishermen and other users, INCOIS initiated a specific service called 'High Wave Alert'. It is aimed at providing location-wise 'watch' when the significant wave height is between 2.5 and 3.0 m and 'alert' when the wave height exceeds more than 3.0 m, due to disturbed conditions (because of local winds or propagation of high swells from far away regions). These alerts are also intimated to the user communities such as fishermen (through NGOs), Navy, Coast Guard, Port Offices, Coastal Police, etc. INCOIS advisories provide detailed information on the wave environment giving the exact locations along the coastline which are likely to experience the maximum possible wave heights, timings of the same, along with the forecast images. The advisories are issued in multi-lingual mode. These early warnings are validated on-line using the real-time automated observation systems such as wave rider buoys deployed at sea. India Meteorological Department (IMD), on the other hand, issues warnings qualitatively like rough sea, very rough sea, etc. based on the prevailing wind over the sea surface.

We report here the reliability of the system and the accuracy of the warning/forecasts during tropical cyclone *Thane*, which made landfall on the southeast coast of India. During the last five years, among the cyclones that affected the Puducherry coast, *Thane* cyclone was the most intense followed by *Nilam* cyclone. *Thane* cyclone (25–31 December 2011) caused more serious damage to the Puducherry coast, with maximum significant wave heights of 5.6 m, much more than the *Nilam* cyclone that struck the same coast during 28 October–1 November 2012 with maximum significant wave heights of 3.3 m. Hence, the performance of the OSF system during *Thane* cyclone is evaluated here[2,3]. We used spectral wave (SW) model for forecasting the wave fields such as significant wave height, wave period and direction generated by the cyclone.

Significant wave height is the average of the highest one-third of waves measured during a period of time. The significant wave height was intended to mathematically express the height visually estimated by a 'trained observer' at sea. Maximum wave height likely to be experienced is double the significant wave height. Wave period is the time taken for two successive wave crests to pass a given point (Figure 1). Swells are long-period (>8 s) remotely generated waves, and travel in groups. Each group consists of waves having similar characteristics. These 'swell trains' do not dissipate their energy significantly even though they originate thousands of kilometres away, and can cause damage to the shore, ports and harbours and disturb the operations of oil and offshore industries. The period corresponding to the wave with maximum energy is called the peak wave period and the direction from which it is approaching is the peak wave direction. The distribution of wave energies over different frequencies is represented by the frequency spectrum and is commonly referred to as one-dimensional spectrum.

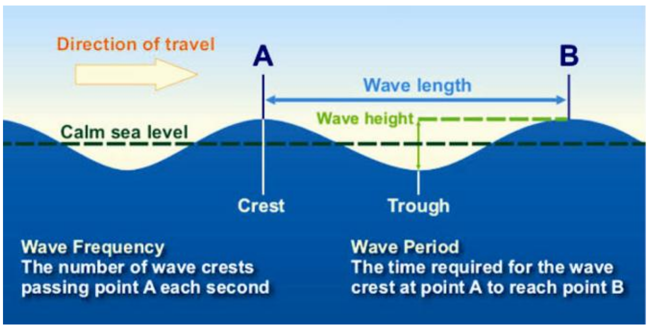

Figure 1. Schematic diagram showing the important ocean wave parameters.

Thane cyclone

A low pressure area that formed over the southeastern Bay of Bengal on 25 December 2011 developed into a deep depression on 26 December 2011 (ref. 2). This turned into a cyclonic storm (*Thane*) on 27 December 2011 and further intensified as a severe cyclonic storm (28 December 2011) and very severe cyclonic storm (29 December 2011) with 3 min sustained wind speeds of 140 km/h. The track of cyclone *Thane* is presented in Figure 2. The cyclone made landfall on 30 December 2011 on the north Tamil Nadu coast between Cuddalore and Puducherry.

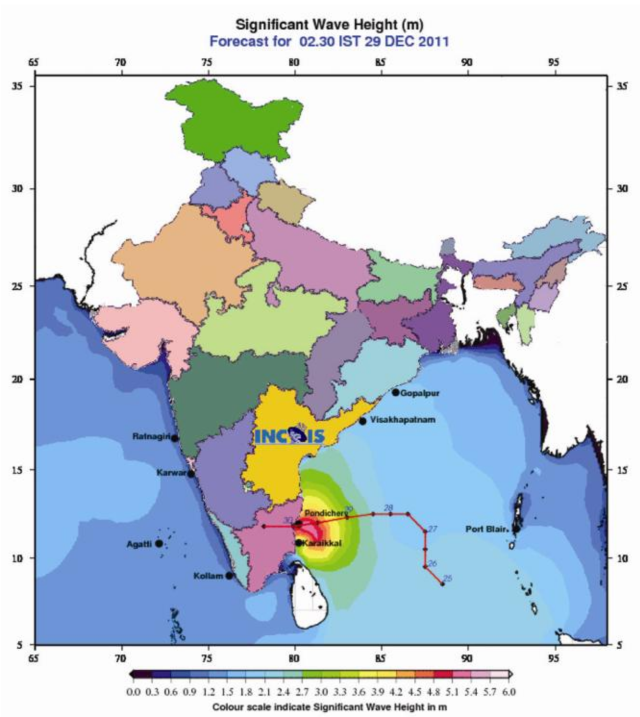

Figure 2. Image showing Ocean State Forecast product (significant wave height) issued from Indian National Centre for Ocean Information Services (INCOIS) during tropical cyclone *Thane*. The locations of INCOIS wave rider buoy network (black dots around the coasts) and cyclone track (red line) are overlaid.

Wave observation

INCOIS has established a wave rider buoy network at eight different locations along the Indian coast, including the Andaman and Nicobar Islands and the Lakshadweep Islands (Figure 2). In this article, data collected from Datawell Directional Wave Rider Buoys[4] deployed off Puducherry (11.87°N, 79.84°E) at 15 m water depth and Visakhapatnam (17.63°N, 83.26°E) at 20 m water depth are used for delayed mode and real-time validations of the forecast. The directional buoy measures horizontal (roll and pitch) and vertical (heave) accelerations using two accelerometers and an on-board compass to give the directional displacements in two horizontal axes. With this information, displacement in the north-south and east-west directions is calculated. The displacements are converted to wave parameters using in-built software in the buoy. The data are received real-time at INCOIS through the Indian National Satellite System (INSAT)/ Global System for Mobile Communications (GSM) modes.

Forecast generation

MIKE21 SW is a third-generation spectral wind–wave model[5] based on unstructured meshes, which takes into account all the important phenomena like wave growth by influence of wind, nonlinear wave–wave interaction, dissipation of wave energy due to white-capping, bottom friction and depth-induced wave breaking, refraction and shoaling due to depth variations and wave current interaction[6]. Remya *et al.*[7] evaluated SW model for the Indian Ocean and found it to be suitable for the region. The operational model domain set up at INCOIS extends from 60°S to 30°N and 30°E to 120°E. The southern boundary of the model domain is extended up to 60°S in order to capture the swells from the Southern Ocean. Since offshore areas are not very sensitive to bathymetry effects compared to coastal areas, coarse spatial resolution grid is used in the offshore parts of the Arabian Sea and the Bay of Bengal. The inputs required for running the model are the forcing winds and bathymetry. The first day forecast winds from ECMWF is used for forcing the wave model. The bathymetry used is the modified ETOPO2 (http://www.nio.org/index/option/com_subcategory/task/show/title/Sea-floor%20Data/tid/2/sid/18/thid/113). The SW model forecasts are sensitive to initial conditions such as wind data. The model is run in 'hot start' mode, in which the realistic ocean state from a previous model run is given as the initial condition.

The forecast products and dissemination

INCOIS issued 'High Wave Alert' for the coasts of Tamil Nadu (TN) and southern Andhra Pradesh (AP) for the period from 25 to 30 December 2011 on a daily basis. The forecasts and alerts about the prevailing rough sea conditions were disseminated through various modes such as INCOIS website (the primary mode: http://www.incois.gov.in), IMD website (OSF link in http://www.imd.gov.in/section/nhac/dynamic/cyclone1.htm), television, telephone, radio, village information centres, e-mail and SMS in local languages. The forecasts and alerts were disseminated daily in local languages through 40 specially designed electronic display boards (EDBs) installed in the fishing harbours along the TN and AP coasts. The wave forecasts were also provided in image form in English (http://www.incois.gov.in/Incois/indofos_alert.jsp) and Tamil (www.incois.gov.in/Incois/indofos_alert_tamilnadu.jsp). The results were validated in real-time using the data from the wave rider buoys deployed off Puducherry and Visakhapatnam and posted in the INCOIS website (http://www.incois.gov.in/Incois/wrbimage.jsp). INCOIS collaborates with NGOs such as M.S. Swaminathan Research Foundation (MSSRF), Chennai, Pondicherry Multipurpose Social Service Society (PMSSS), Puducherry, fishermen associations, district administration, coastal police, Indian Navy, Indian Coast Guard and port authorities to disseminate this information to the coastal population. Feedback from the above users suggests that timely dissemination of high wave alerts resulted in people, particularly fishermen, not venturing into the sea during the cyclone period. On account of this, the loss of human life/missing person cases at sea along the coast of Puducherry and Visakhapatnam was reported to be minimal (see Box 1).

Reliability of the forecast

Wave parameters

INCOIS carries out real-time validation of the forecast products using the automated observational systems such as wave rider buoys (integrated with INSAT) and these images are available at the INCOIS website. Figure 3

Box 1. 'The Tsunami of December 26, 2004 instilled in the minds of artisanal fishermen a sense of fear and uncertainty concerning the behaviour of the ocean. The technology developed by the Ocean State Forecast Division of INCOIS has however changed this scenario and has made the fishermen confident of the wave heights at different distances from the shore line. They now go with great joy and courage into the sea and they also now know where approximately the fish shoals are. This has enabled them to complete their work within a couple of hours as compared to over 8 to 10 hours in the past. Thus, INCOIS has helped to transform the lives and livelihoods of small scale fisher families.'

M. S. Swaminathan, MSSRF, Chennai

Figure 3. ***a***, The forecast image issued during tropical cyclone *Thane* for Puducherry and Tamil Nadu. ***b***, High wave alerts displayed through electronic display boards. ***c***. On-line and real-time validation posted at the INCOIS website.

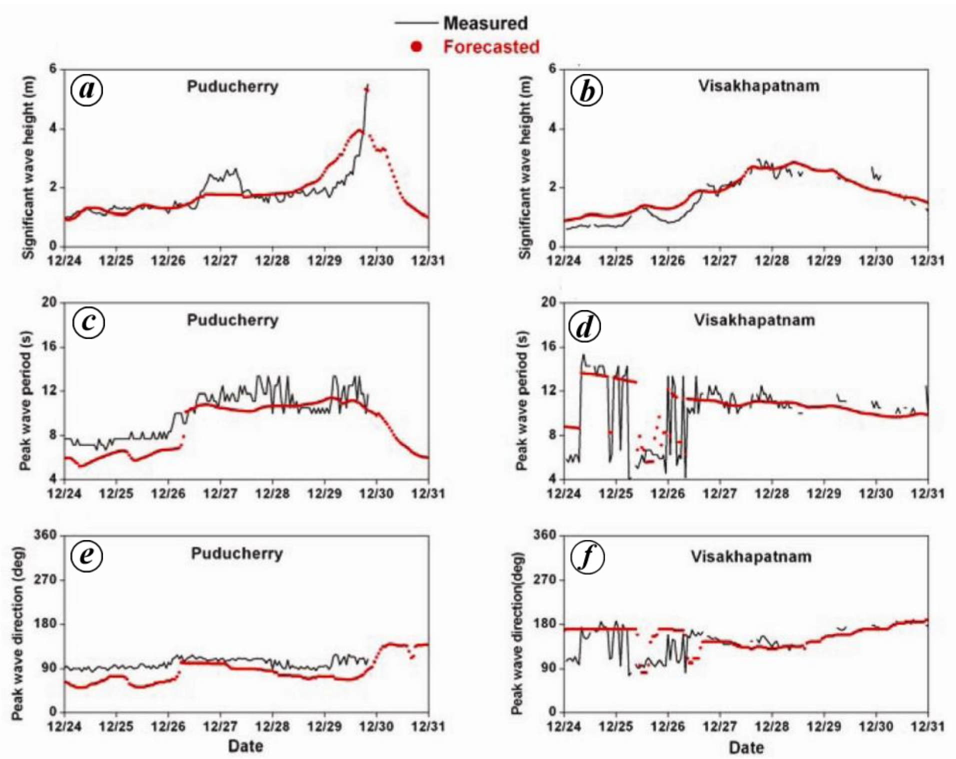

Figure 4. Comparison of forecasted and measured significant wave height at (***a***) Puducherry and (***b***) Visakhapatnam. Peak wave period at (***c***) Puducherry and (***d***) Visakhapatnam. Peak wave direction at (***e***) Puducherry and (***f***) Visakhapatnam.

shows the forecast image issued during cyclone *Thane* for Puducherry and Tamil Nadu, High wave alerts displayed through EDBs and the on-line, real-time validation posted at the INCOIS website.

Forecasted significant wave height, peak wave period and direction are compared with measured values at Puducherry and Visakhapatnam (Figure 4). The comparison shows that forecasted significant wave height, peak wave period and peak wave direction agree well with the measured values. On 29 December 2011, forecasted significant wave height reached a maximum value of 5.3 m, whereas the measured value is 5.6 m, at Puducherry (Figure 4 *a*).

The error quantification of forecast products is represented by statistical terms such as bias, root mean square (RMS) error, scatter index (SI) and correlation coefficient (Table 1). Bias is the average of the difference between

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

	Puducherry (n = 141)		Visakhapatnam (n = 142)	
Error statistics	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

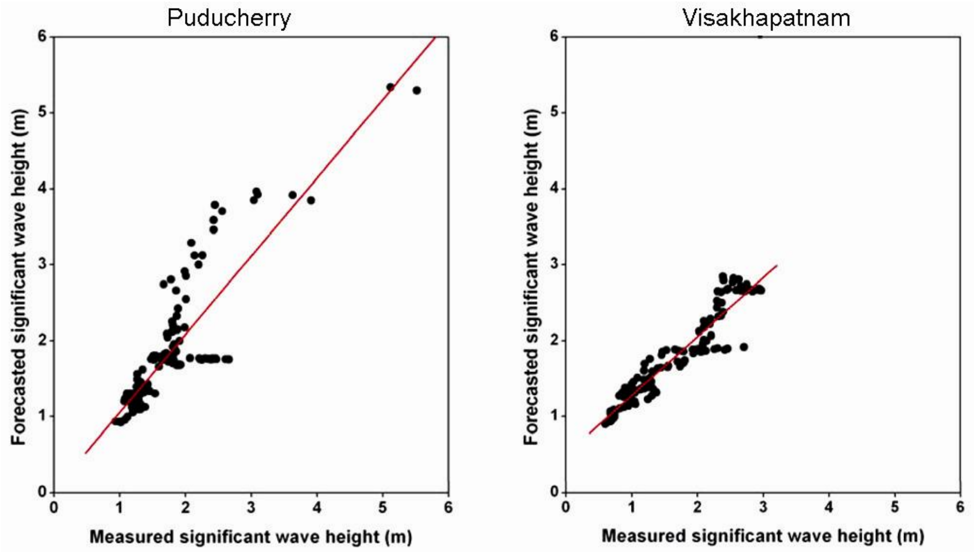

Figure 5. Scatter plots of forecasted and measured significant wave heights at Puducherry and Visakhapatnam.

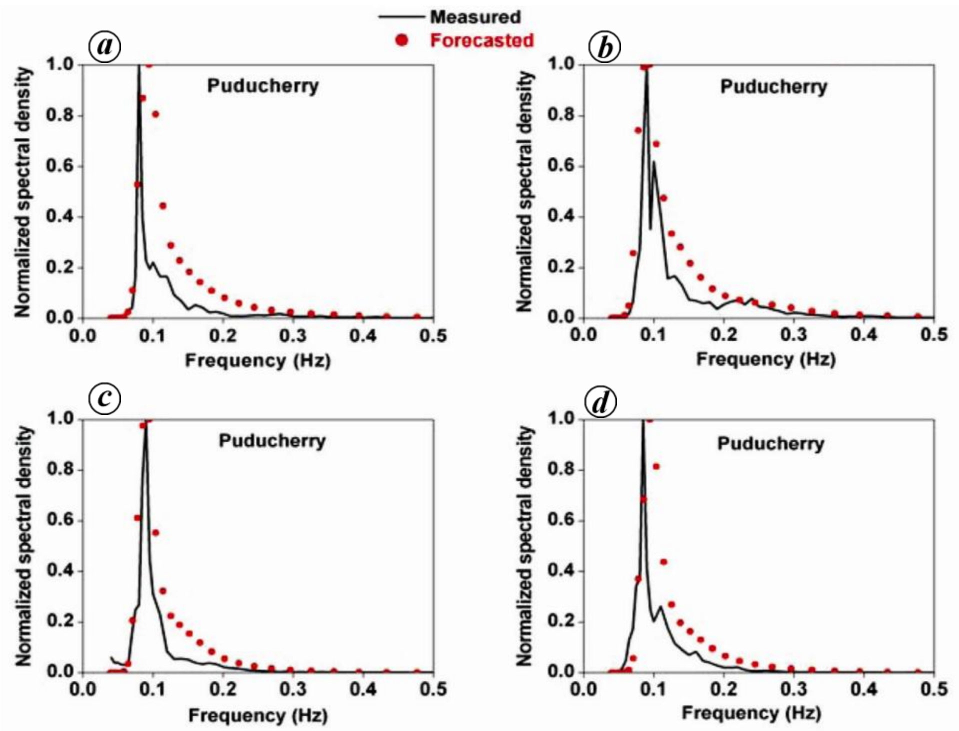

Figure 6. Comparison of measured and forecasted one-dimensional wave spectra at Puducherry during (***a***) 27 December 2011, 20 h; (***b***) 28 December 2011, 19 h; (***c***) 29 December 2011, 20 h; (***d***) 30 December 2011, 00 h.

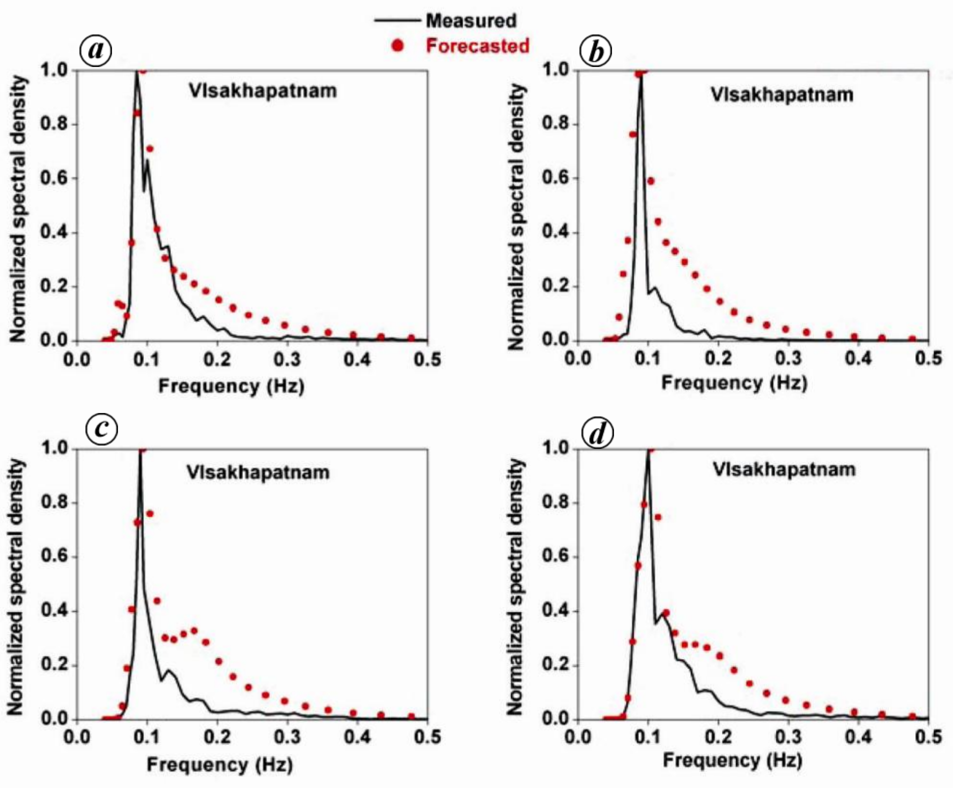

Figure 7. Comparison of measured and forecasted one-dimensional wave spectra at Visakhapatnam during (***a***) 27 December 2011, 06 h; (***b***) 28 December 2011, 00 h; (***c***) 29 December 2011, 09 h; (***d***) 30 December 2011, 11 h.

forecasted and observed parameters. RMS error is defined as the square root of the mean of the squares of the difference between forecasted and observed parameters. SI is defined as the RMS error normalized by mean of the observed wave parameters and correlation coefficient is a measure that determines the degree to which forecasted and measured parameters are associated.

The results indicate that the forecast of significant wave height and peak wave period both for Puducherry and Visakhapatnam is reliable as bias, RMS error and SI are low along with high correlation coefficients. The bias in significant wave height as well as peak wave period at Puducherry and Visakhapatnam is small. The results also show that the forecast error (SI) in significant wave height is less than 25% with RMS error of 0.44 m at Puducherry, whereas at Visakhapatnam SI is less than 20% with RMS error of 0.28 m. The wave parameters (significant wave height and peak wave period) are well correlated with correlation coefficient values 0.85 and 0.89 respectively, at Puducherry, whereas they are well correlated with correlation coefficient values 0.95 and 0.71 respectively, at Visakhapatnam. The results show that the forecast error (SI) in wave period is 15% with RMS error of 1.5 s at Puducherry and 20% with RMS error of 2.0 s at Visakhapatnam. The forecast wave parameter with SI of less than 30% is widely accepted by the user community for operational planning[8].

Scatter plots of forecasted and measured significant wave heights at Puducherry and Visakhapatnam are presented in Figure 5. It is clear from the figure that the forecasting of extreme wave heights above 5 m also agreed well with observations.

Wave energy spectra

Figure 6 shows the comparison between forecasted and measured one-dimensional frequency spectra at Puducherry. The comparison shows agreement, especially in simulating low frequencies. The forecasted spectra are single peaked due to the extreme event that prevailed in the region. Figure 7 shows the comparison between forecasted and measured one-dimensional frequency spectra at Visakhapatnam. Similar to the case of Puducherry, the agreement between the forecasted and measured spectra is generally good at Visakhapatnam.

Conclusion

Performance of the operational OSF system at INCOIS during tropical cyclone *Thane* that affected TN and AP coasts is evaluated in this article. High wave alerts were provided by INCOIS for the benefit of the user community, well in advance of the landfall through various dissemination modes. Feedback from the user community indicates that the high wave alert is a useful service. Because of the timely dissemination of this reliable information, people particularly fishermen, did not venture into the sea during the cyclone period. During the high wave alert period, loss of life/missing person cases at sea along the coast off Puducherry and Visakhapatnam was reported to be minimal.

In the near future, it is intended to operationalize the multigrid WAVEWATCH III model for the open ocean and Simulating WAves Nearshore (SWAN) model for the nearshore region on high performance computers. The wave rider buoy network as well as the ship-mounted real-time wave observation network will be further expanded to improve the quality of the forecasts, as these data will also be assimilated into the models.

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