

## Wave modelling for the north Indian Ocean using MSMR analysed winds

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### **Abstract:**

NCMRWF (National Centre for Medium Range Weather Forecast) winds assimilated with MSMR (Multi-channel Scanning Microwave Radiometer) winds are used as input to MIKE21 Offshore Spectral Wave model (OSW) which takes into account wind induced wave growth, non-linear wave-wave interaction, wave breaking, bottom friction and wave refraction. The model domain covers the north Indian Ocean, bounded by Equator to 30°N and 50° to 100° E. An experiment has been conducted to find out improvement in wave prediction when NCMRWF winds blended with MSMR winds are utilised in the wave model. A comparison between buoy and TOPEX wave heights of May 2000 at 4 buoy locations provides a good match, showing the merit of using altimeter data, wherever it is difficult to obtain measured data for comparison with model wave heights. This is further confirmed when model wave heights for January 2001 in the entire model domain was compared with TOPEX altimeter data - a good match for the full range of wave heights considered. Model wave heights, periods and directions have been compared with the data of deep and shallow water buoys. The correlation coefficients between model and measured wave heights are in the range of 0.85 to 0.91. The model slightly over-predicts wave periods, but match is reasonably good. In general, model wave periods are of the order of 6-9 s during June-July 2001 and 4-8 s during May, August and September 2001. The wave periods clearly indicate that waves during June - September are generated by monsoon wind forcing, and dominated by 'wind waves'.

**Keywords:** NCMWRF winds assimilated with MSMR winds; wave modelling; MIKE 21 OSW model; TOPEX altimeter; north Indian Ocean

## 1. Introduction

Winds and waves are the two important driving forces, which generate several oceanic phenomena in the coastal and open ocean. Waves are very essential for activities such as exploitation of natural resources, ship-routing, design of harbors, breakwaters and jetties, loading and unloading of ship's cargo and estimation of sediment transport. Adequate reliable wind and wave data has long been recognized as a major limiting factor to such activities in the North Indian Ocean (NIO), comprising of the Arabian Sea and the Bay of Bengal.

For evaluation of wave climatology or design criteria, there is often a need for merging data obtained from different sources into unified data sets (Krogstad et al., 1999). There are several ways of obtaining wind and wave information. Each source has got its own inherent limitations. For example, *in situ* measurements provide point data. But are very expensive; remote sensing provides good coverage, but good algorithms are required to derive wind and wave information; models give predicted wind and wave parameters, but they should be provided with accurate input data and boundary conditions. In this context, the space-borne measurements along with numerical modelling offer an effective way to supplement the conventional synoptic network, and contributing with substantial information on marine environmental parameters.

The SWAMP group (1985) carried out extensive intercomparison experiments with various wind-wave prediction models and concluded that none of the models is suitable for all kinds of wind fields and extreme situations. The third generation wave model WAM, developed by the WAMDI group (1988), is based on physical processes rather than empirical relations and can be used in a global as well as in a regional domain. Khandekar (1989) compiled the state-of-the-art in wave prediction and their utility for real time operations and applications.

Francis and Stratton (1990) used altimeter wind speed to provide information on the distribution of energy within the wave spectrum. Lionello et al. (1992) assimilated altimeter wave data in a third generation wave model. Vethamony et al. (2000) used ECMWF (European Centre for Medium-Range Weather Forecast) winds in a second generation wave model to hindcast waves of NIO. The model results have been compared with GEOSAT altimeter and with visually observed wave parameters. There was striking difference between the three sets of results, basically due to limitation of the model in shallow water and inaccuracy in the visually observed wave data. However, in the present study, we have used reliable wave buoy data for comparison.

Several studies have been undertaken on how best to utilise the wealth of data available from satellite observing system in wave models (Greenslade, 2001). Swain et al. (2003) carried out performance evaluation study of the WAM in the Indian Ocean region using MSMR analysed winds. Bhatt et al. (2004) used MSMR winds in the WAM model and compared the results with buoy and altimeter observations in the Indian Ocean and showed that ingestion of MSMR winds in the forecast model improves surface wind analysis and wave prediction.

The Arabian Sea is under the influence of southwest monsoon from June to September and it is practically calm with long swells in the rest of the year. On the other hand, the Bay of Bengal gets rough seas during southwest and northeast monsoon (October-December) seasons. For several coastal and offshore activities, the information on waves during monsoon is of prime importance. As *in situ* measurements are difficult to get during monsoons, a good model can provide the required wave information for any practical application, subject to the accuracy of winds.

In the present study, we have used the available NCMRWF (National Centre for Medium Range Weather Forecast, India) predicted winds, assimilated with Multi-frequency Scanning Microwave Radiometer (MSMR) winds, as input to MIKE21 Offshore Spectral Wave model - OSW (User Guide 2001). The objectives of the study are: (i) to evaluate improvements in wave prediction with MSMR analysed winds; (ii) to compare wave modelling results with measured and TOPEX altimeter waves; and (iii) to build confidence in using deep water waves obtained from model as design parameters for the currently expanding deep water activities in the NIO.

## **2. Data and methodology**

### **2.1. IRS-P4 satellite and MSMR payload specifications**

India launched its first ocean remote sensing satellite IRS-P4 (Oceansat-1) on May 26, 1999. Oceansat-1 is a polar sun-synchronous satellite covering the global oceans in two days with equatorial crossing time at 1200 h (descending). It carried a MSMR and an Ocean Colour Monitor (OCM).

The brightness temperature of the ocean surface is a function of surface roughness, and this in turn is a function of wind speed. The MSMR provides global microwave brightness temperature measurements at 6.6, 10.65, 18 and 21 GHz frequencies with dual polarization having spatial resolutions of about 120 to 40 km, respectively. In order to assess and eliminate the contribution by atmospheric constituents, the above four frequencies with

vertical and horizontal polarization have been chosen (Users' Handbook, 1999). The brightness temperature accuracy for eight MSMR channels has been evaluated based on simulation of brightness temperature, and minimizing the difference from MSMR data for the Indian Ocean region between 30° latitude belt and equator. The 6.6 and 10.65 GHz bands (useful for surface winds and SST) were not available in any other satellite during 1999-2001, and IRS P4 thus offers a unique opportunity to get such observations during that period.

## **2.2. NCMRWF analysed winds (assimilated with MSMR winds)**

The MSMR data received at the earth station complex in Hyderabad, India, have been processed and distributed by the National Remote Sensing Agency, Hyderabad. Forward simulations for brightness temperature at appropriate frequency channels and polarization have been carried out using a radiative transfer model developed for this purpose. When applied to MSMR winds, the model had an accuracy of 1.5 m/s for the range 2-24 m/s. The MSMR winds have been validated with measured in situ winds in the NIO (Muraleedharan, 2003). In order to generate wind fields, MSMR derived global surface wind speeds (along with other global meteorological data) are assimilated in the NCMRWF Global Data Assimilation System (GDAS). The 6-hour analysed wind vectors generated by GDAS are used in the present study to run the wave model.

## **2.3. Model set up**

MIKE21 OSW model developed by the Danish Hydraulic Institute, Denmark, is a fully spectral wind-wave model, which describes growth, decay and transformation of wind-generated waves in offshore as well as coastal areas. The model takes into account the following phenomena: wind induced wave growth, non-linear wave-wave interaction, wave breaking, bottom friction and wave refraction. It is a time-dependent spectral model formulated in terms of energy density spectrum with a discrete resolution of frequencies and directions. The model is based on numerical integration of energy balance equation formulated in Cartesian co-ordinates.

$$\frac{DE}{Dt} = S_{\text{wind}} + S_{\text{nonlinear}} + S_{\text{bottom-dissipation}} + S_{\text{white-capping}} + S_{\text{wave-breaking}}$$

The LHS describes the wave spectral energy (E) propagation in space and time and the RHS represents the superposition of source functions describing various physical phenomena. Directional wave spectra and other parameters such as significant wave height

(SWH), peak wave period, average wave period, peak wave direction and mean wave direction can be obtained from the model.

The details of MSMR and NCMRWF analysed winds, moored buoy data and TOPEX altimeter data used for wave modelling and comparison are given in table 1. The model domain covers the region between Equator to 30°N and 50° to 100° E. The model domain as well as the locations of shallow and deep water data buoys in the Arabian Sea and the Bay of Bengal is given in figure 1 and table 2. NCMRWF winds are available in 1.5° X 1.5° grid size for every 6 h interval, in the form of U and V components. These winds are further converted into resultant winds in 0.75° X 0.75° grid size as we used ETOPO5 - 5 minute gridded bathymetry data. Wave parameters are generated for 1h interval.

### **3. Results and discussion**

#### ***3.1. Improvement in wave prediction with MSMR winds***

An experiment has been conducted to find out improvement in wave prediction when NCMRWF winds blended with MSMR winds are utilised in the wave model (Vethamony et al., 2003). As a first step, time series of analysed winds (with and without MSMR winds) has been compared with buoy wind speeds (Fig. 2). Also, wave model runs have been carried out using NCMRWF winds, with and without MSMR blended winds. Both the cases have been compared with the corresponding time series of moored buoy wave heights. This experiment indicates that the inclusion of satellite MSMR winds with NCMRWF, especially the higher winds of NCMRWF brings the model wave heights closer to measured SWH (Fig. 3).

Comparison of model SWH utilising NCMRWF winds with and without MSMR at all locations shows that the waves predicted with MSMR winds are slightly higher than those predicted without MSMR winds, except off Paradip and Chennai (Fig. 3). Though there is only marginal difference between the model SWH of both the cases, the ranges of model SWH have changed from 1.0 - 4.0 m (NCMRWF winds without MSMR) to 0.7 - 4.5 m (NCMRWF winds with MSMR) - closer to the measured SWH (1.7 to 5.0 m).

A comparison between collinear points of buoy and TOPEX wave heights at 3 buoy locations for May-August 2000 provides a good match (Fig. 4). The calculated correlation coefficient (0.955) exceeds the critical value (0.456) at 0.05 % significant level for 17 degrees of freedom. This shows the merit of using altimeter data for comparison with measured or model results, especially to validate the model results in deep waters, where it is difficult to get measured data. In an another exercise, we have compared the gridded model SWH

(obtained from NCMRWF with MSMR winds) of May-August 2000 in the entire NIO with TOPEX data, for each month (Fig. 5). There is a wide spread scatter in the distribution of wave height values, but the range of model and altimeter wave heights for the entire domain matches good ( $\approx 1.0 - 6.0$  m).

Thus, we find that with all limitations in MSMR winds, the comparison still sounds good, and this gives the confidence to use model results for NIO offshore activities, where there is a huge expansion of deep-water activities for oil and gas.

### **3.2 Wave modelling for monsoon winds**

Waves during May-September over the NIO are generated by monsoon winds. Wave heights, periods and directions obtained from the model for May-August 2000 MSMR data sets have been compared with the data of deep water buoys off Goa, Kochi and Chennai, and typical results for the above parameters are presented in Figs. 6, 7 and 8, respectively. Similar comparison is carried out for modelling results of May - September 2001 MSMR data sets and data of deep water buoys (off Goa, Kochi and Chennai) as well as shallow water buoys (Gulf of Khambhat, off Goa and Kochi). The match is very good. Comparison between model and measured wave heights is presented as scatter plots (Fig. 9).

The correlation coefficients ( $\gamma$ ) for model and measured wave heights (Table 3) are in the range of 0.85 to 0.91 at all locations in the NIO, except for Chennai ( $\gamma = 0.68$ ). The discrepancies can be attributed to limitations in MSMR winds or shallow water wave modelling. Wyatt et al. (2003) compared model results of significant wave heights with wave measurements conducted during EuroROSE experiments and obtained correlation coefficients between 0.932 and 0.937 with rms difference between 0.55 and 0.58m. The model wave periods slightly over-predict the buoy wave periods, but in general, match is reasonably good ( $\gamma = 0.72$ ). Wave periods are of the order of 6-9 s at all locations during June and July 2001 and of the order of 4-8 s during May, August and September 2001. Wave characteristics clearly indicate that waves during June - September are dominated by 'wind waves'. Greenslade (2001) assimilated ERS-2 altimeter significant wave heights into a wave model AUSWAM and found that the bias was reduced to  $\sim 10\%$  and rms error by  $\sim 8\%$ . However, in this work, measured and remote sensing SWH are not assimilated into the model, and this can be attempted in the future.

A typical representation of wave conditions (height, period and direction) during monsoon season for the entire NIO is shown in Fig. 10. As monsoon winds pick up in May, we find that wave heights in NIO are generally high, of the order of 2 to 4 m.

#### **4. Conclusions**

The comparison of wave model results with buoy and altimeter data shows that model results can be used where there is no observation (example: deep water regions identified for oil and gas exploration in the NIO). The model results clearly bring out monsoon wave pattern over the NIO. It is planned to prepare a wave atlas for the NIO, making use of the hindcast waves along with measured and remote sensing wave parameters. Assimilation of measured and remote sensing wave parameters will further improve the model performance as the NIO experiences variable winds during southwest and northeast monsoons.

#### **Acknowledgements**

We thank the Directors of NIO, Goa and SAC, Ahmedabad for providing facilities. The MSMR analysed winds and part of buoy data have been provided by Space Applications Centre, Ahmedabad under the project "IRS-P4: MSMR Data Utilisation". TOPEX altimeter data have been downloaded from the site <http://podaac.jpl.nasa.gov> maintained by the NASA, Physical Oceanography Distributed Active Archive Center (PO.DAAC), at the NASA Jet Propulsion Laboratory, Pasadena, CA, USA. This is NIO contribution No. 4094.

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**Table 1: Data source used for wave modelling and comparison**

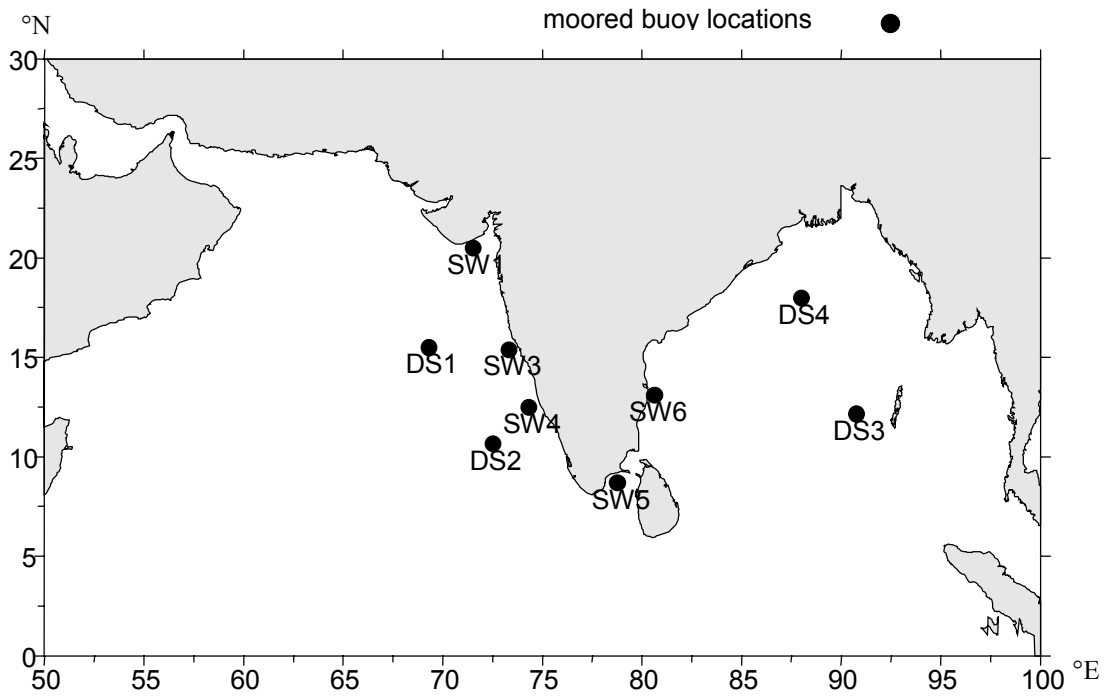
Sensor	Data source and duration													
	July '99	Aug '99	Oct '99	Nov '99	Jan '00	May '00	Jun '00	Jul '00	Jan '01	May '01	Jun '01	Jul '01	Aug '01	Sep '01
NCMRWF (with MSMR)	√	√				√	√	√		√	√	√	√	√
NCMRWF (without MSMR)	√			√	√				√					
Moored Buoy	√	√	√	√		√	√	√	√	√	√	√	√	√
TOPEX ALT	√	√				√	√	√	√					

**Table 2: Details of buoy data used for comparison**

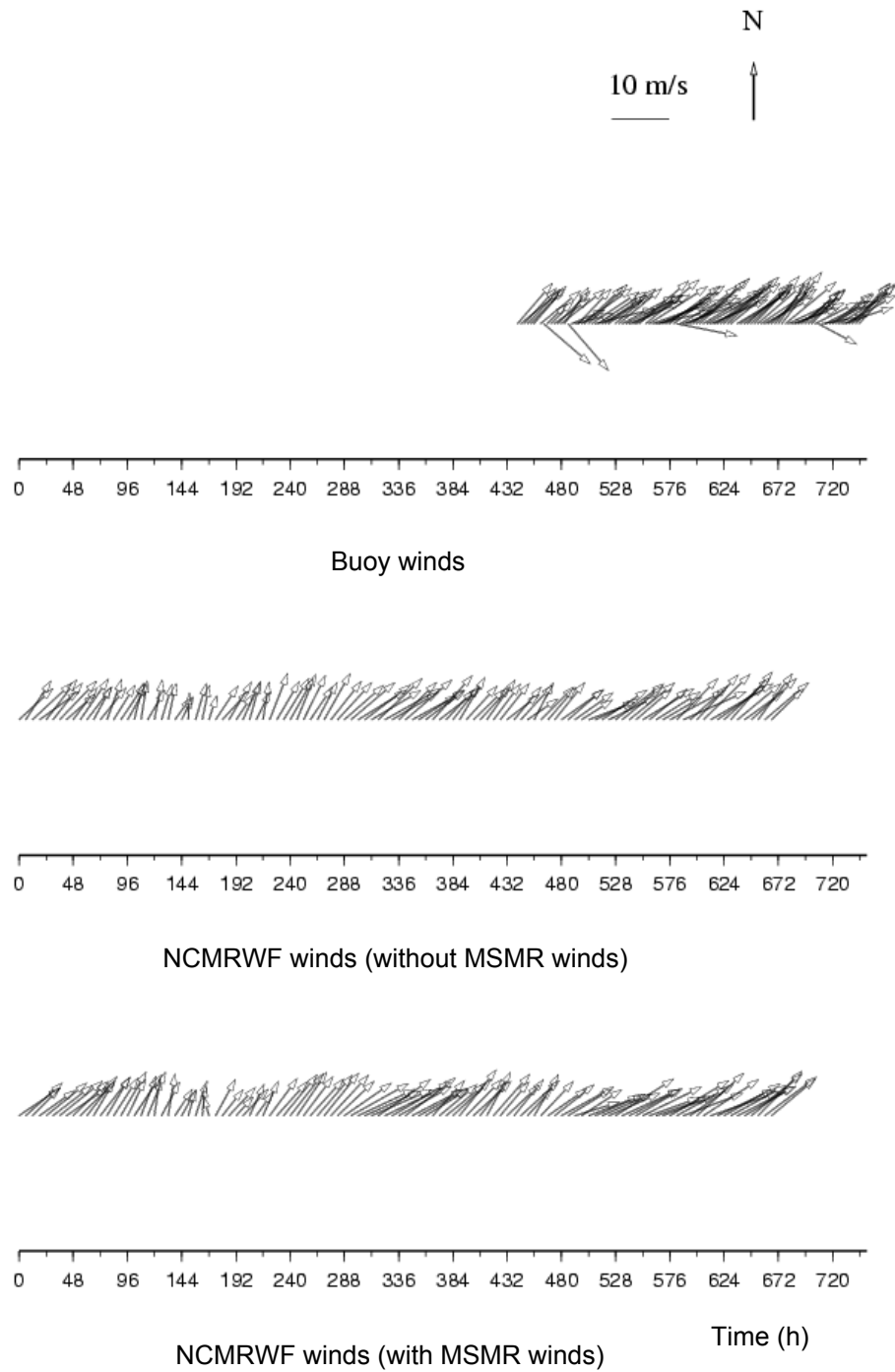
Buoy ID	Buoy position		Region
	Latitude	Longitude	
<b><i>Deep water buoys</i></b>			
DS1	15°30'	69°17'	off Goa
DS2	10°37'	72°30'	off Kochi
DS3	12°30'	87°30'	off Chennai
DS4	18°00'	88°00'	off Paradip
<b><i>Shallow water buoys</i></b>			
SW1	20°53'	71°30'	Gulf of Khambhat
SW3	15°24'	73°48'	off Goa
SW4	12°30'	75°00'	off Kochi
SW5	08°42'	78°21'	off Tuticorin
SW6	12°30'	77°30'	off Chennai

**Table 3: Correlation (significant at 0.05 level) of SWH and wave periods between model and measured values at moored buoy locations (May - Sept 2001)**

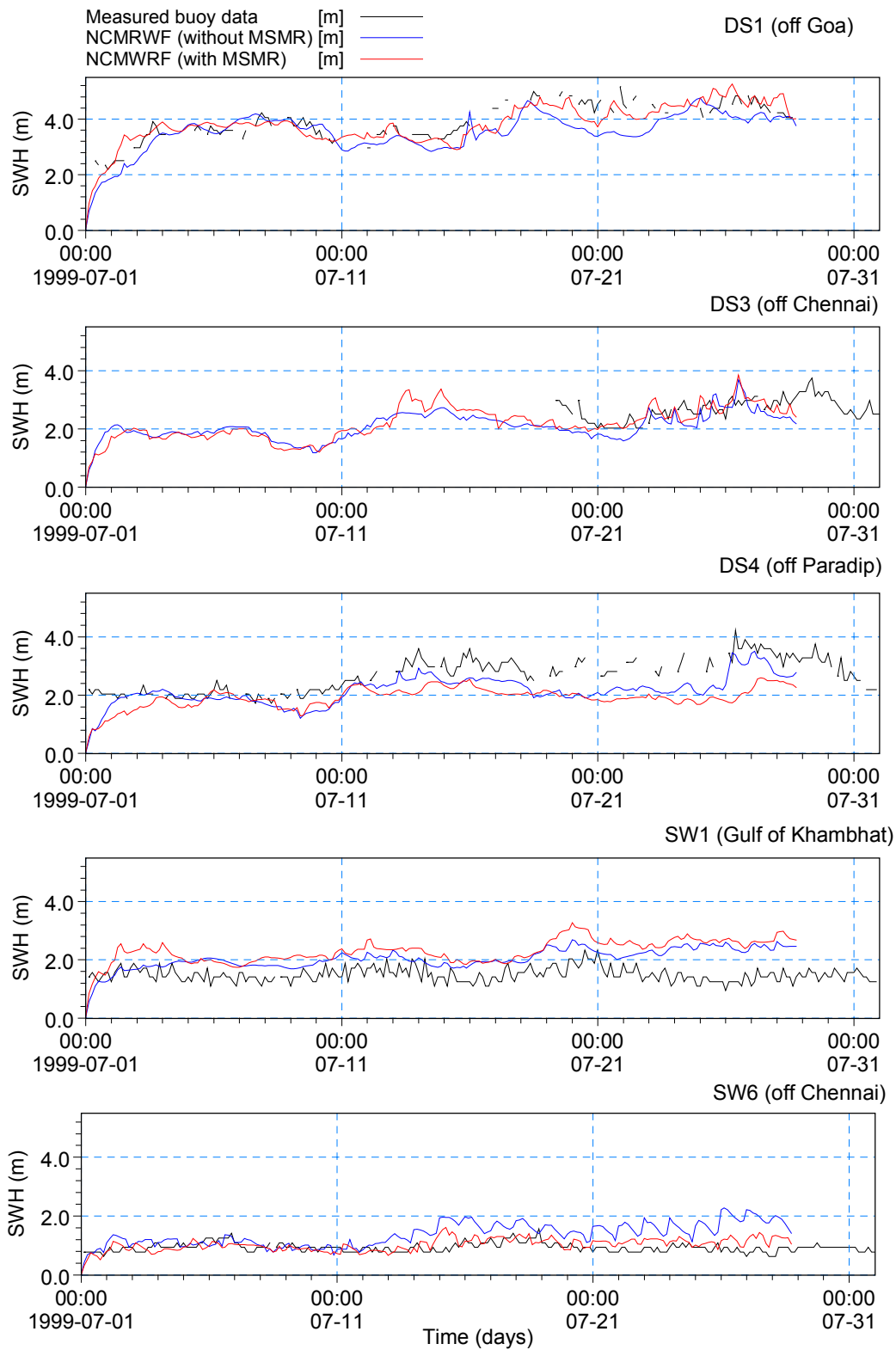
Location	SWH			Period		
	Correlation coefficient $\gamma$	Bias (m)	rms (m)	Correlation coefficient $\gamma$	Bias (m)	rms (m)
DS1 (off Goa)	0.91	0.07	0.57	0.72	0.16	0.86
DS2 (off Kochi)	0.89	0.23	0.43	0.33	-0.01	1.09
DS3 (off Chennai)	0.68	-0.38	0.57	0.68	-0.47	1.04
SW1 (off Khambhat)	0.85	0.61	0.75	0.72	0.61	1.43
SW3 (off Goa)	0.87	0.26	0.48	0.77	0.62	0.96
SW4 (off Kochi)	0.91	-0.01	0.30	0.71	0.51	0.95



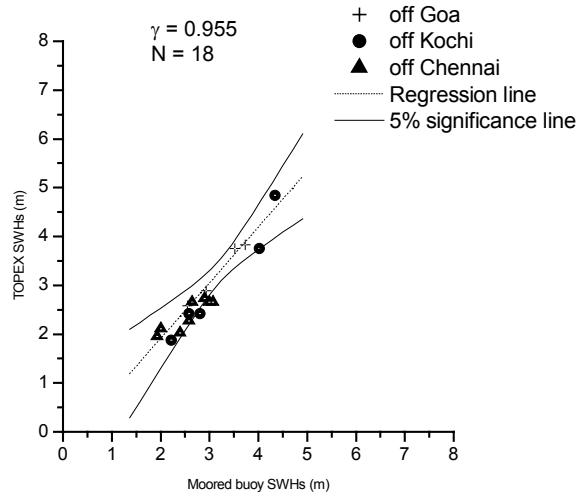
**Fig. 1. Region of study including buoy locations**



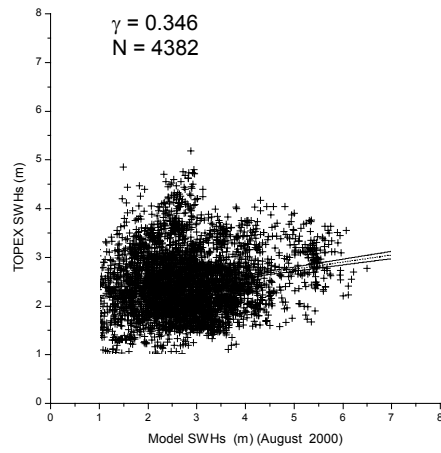
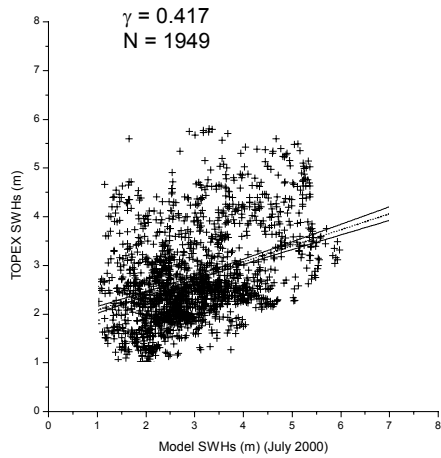
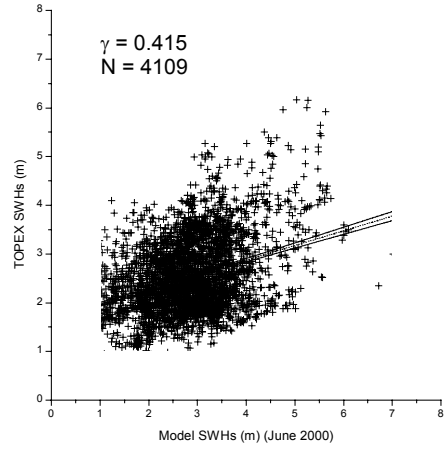
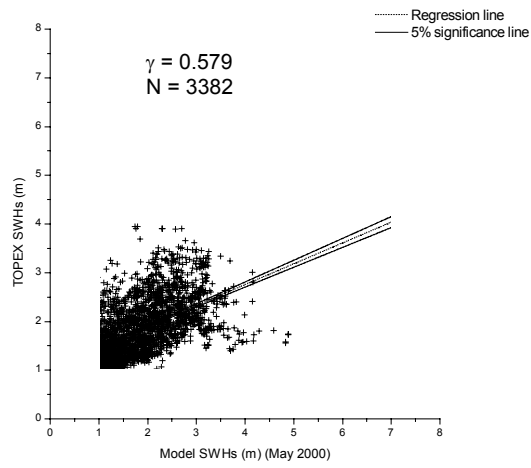
**Fig. 2. Typical analysed winds (with and without MSMR winds) and buoy winds off Chennai for July 1999**



**Fig. 3. Improvements in wave prediction with MSMR assimilated winds**

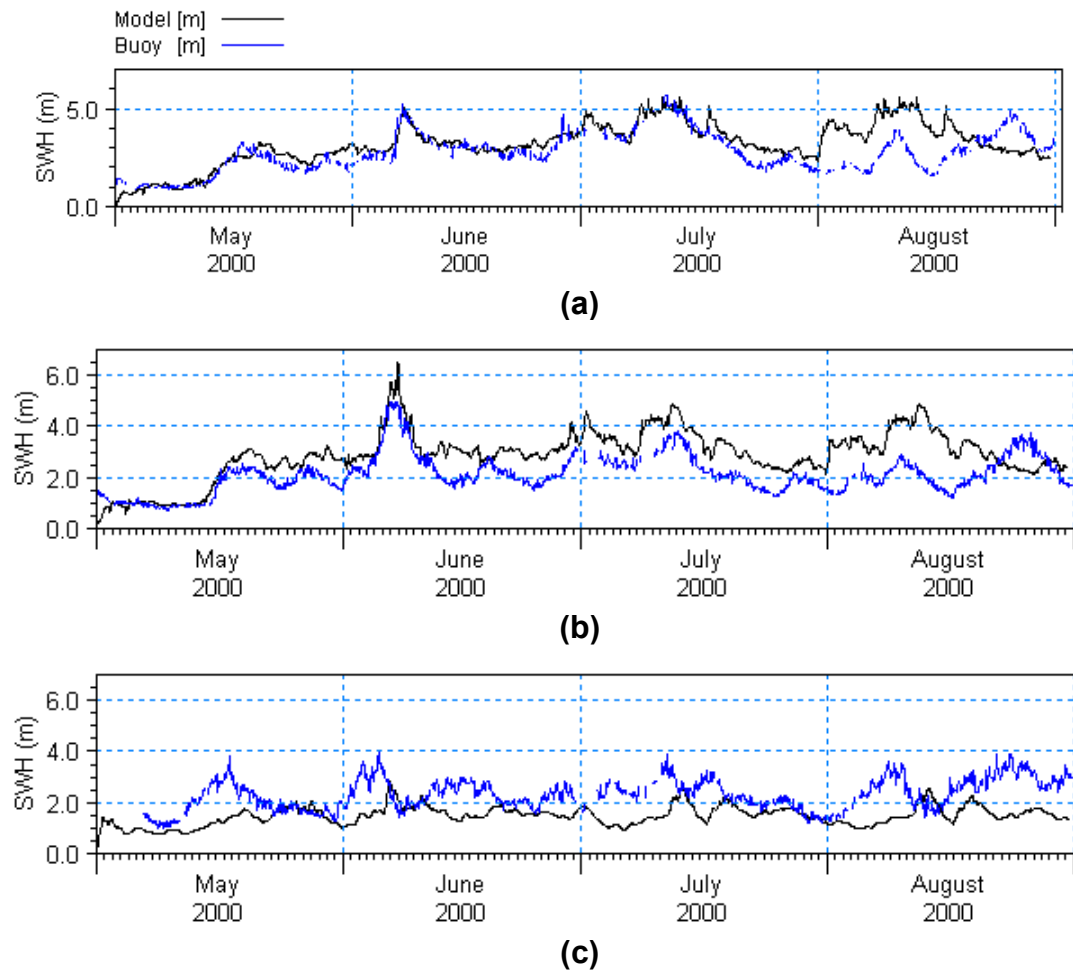


**Fig. 4. Comparison of SWH between moored buoy and TOPEX altimeter (collinear points) for May - August 2000**

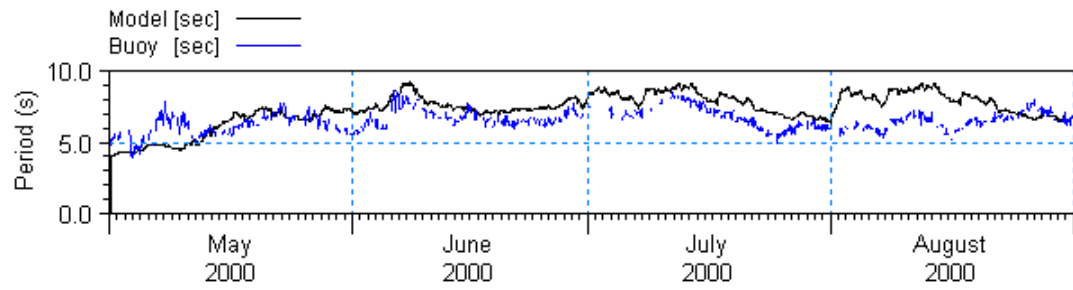


**Fig. 5. Comparison of monthwise model SWH (May - August 2000) with TOPEX altimeter SWH at grid points in the entire North Indian Ocean**

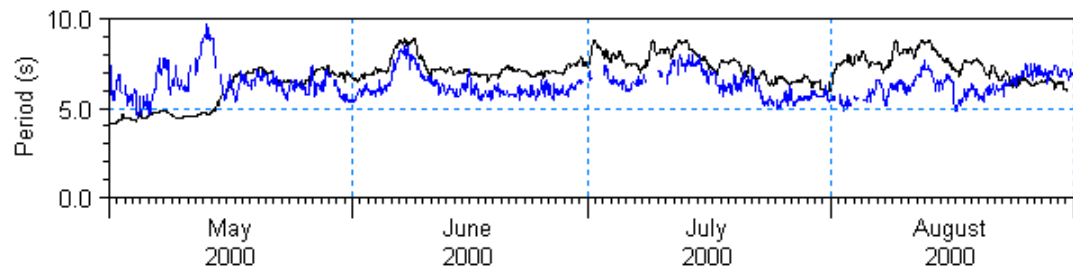




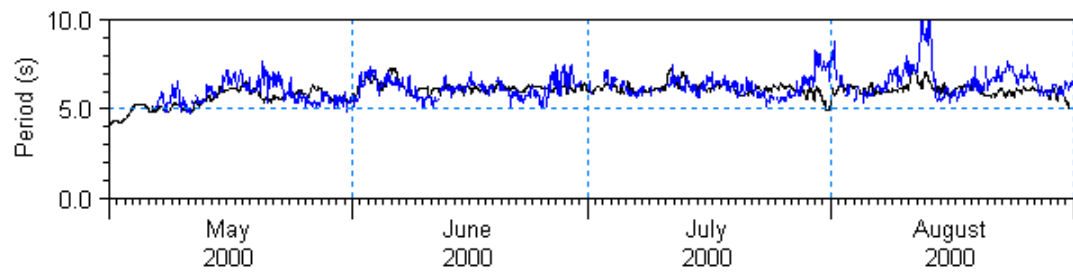
**Fig. 6. Comparison of SWH between model and buoy (deep water) for May - August 2000: (a) off Goa, (b) off Kochi and (c) off Chennai**



(a)

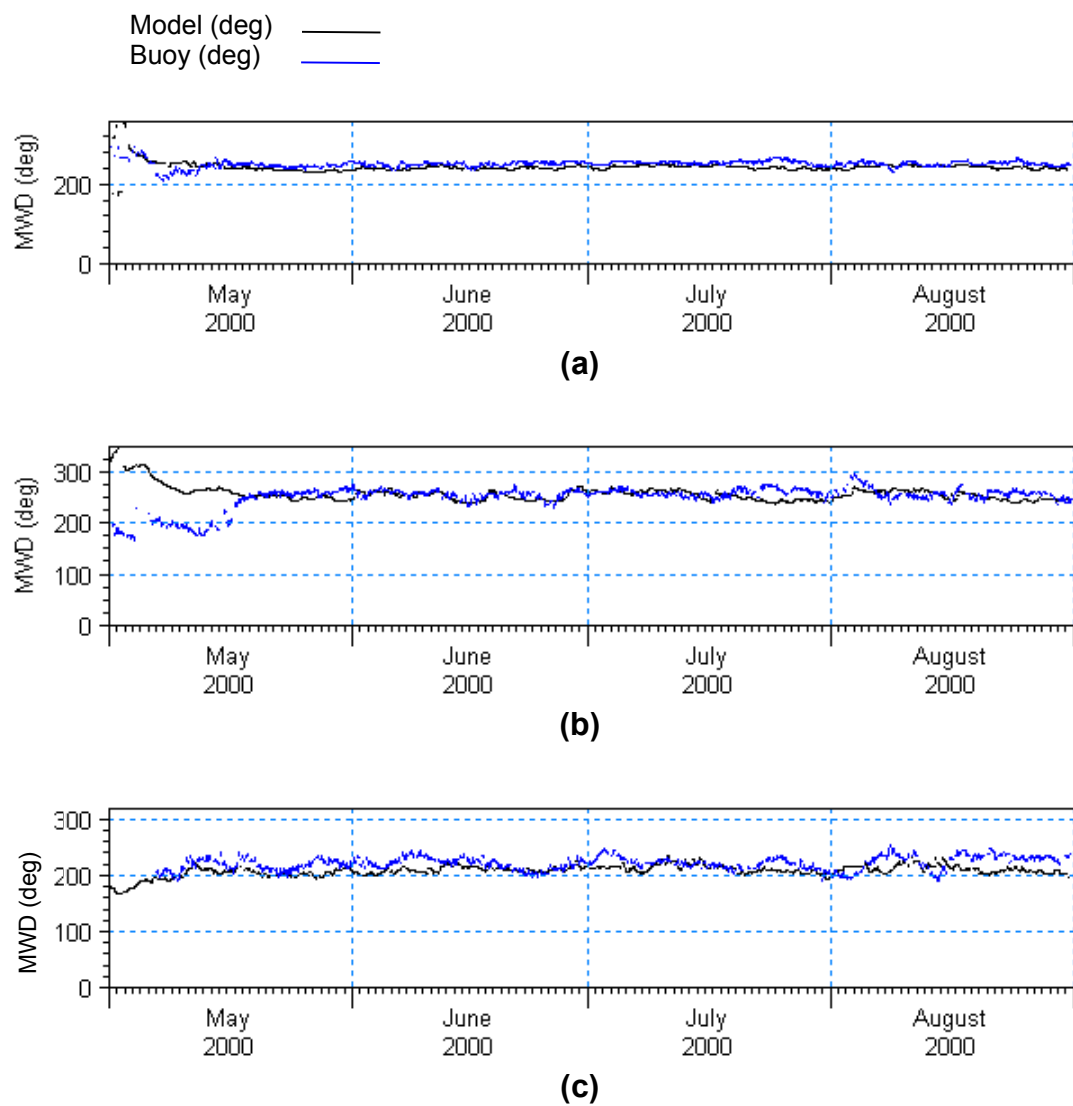


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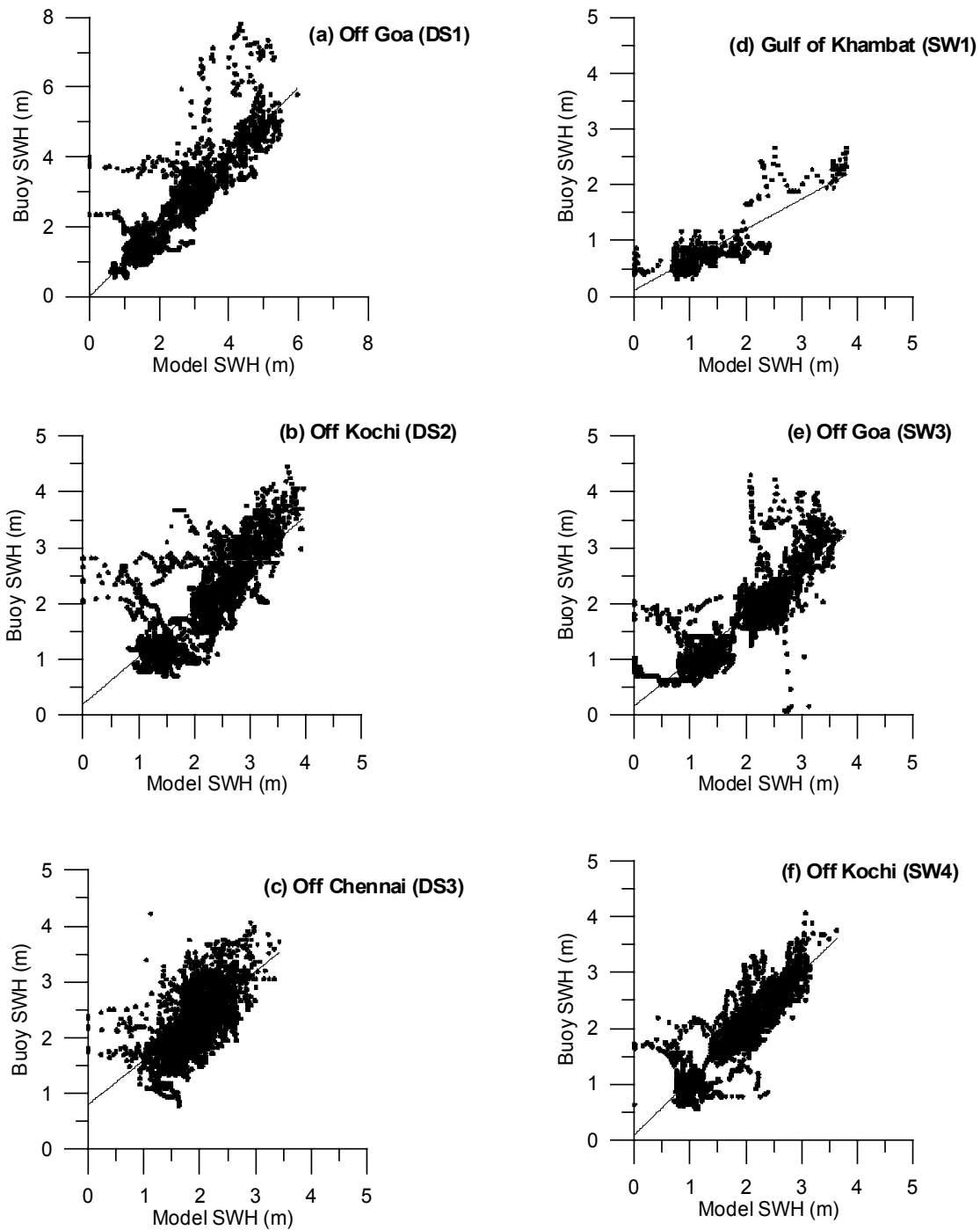


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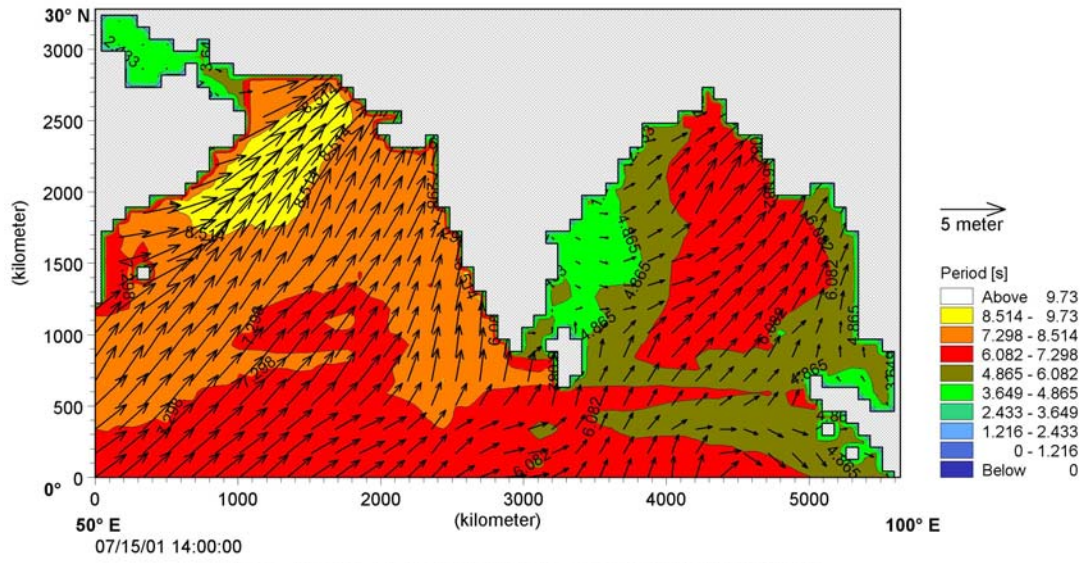
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