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Reprinted from

International Journal of **Ocean and Climate Systems**

Volume 4 · Number 1 · March 2013

Multi-Science Publishing
ISSN 1759-3131



Recent studies on wind seas and swells in the Indian Ocean: a review

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Abstract

Winds and waves data measured at a few locations along the west coast of India as well as wave model results were analysed to study the wave characteristics in the deep as well as nearshore regions during different seasons. During fair weather season, we can observe distinct and systematic diurnal variation in wave height and wave period, especially, simultaneous increase in wave height and decrease in wave period with increase in local wind speed. This is due to superimposition of wind seas generated by the sea breeze system with the pre-existing swells. The swells observed in the Arabian Sea are from SW direction during SW monsoon season and from SW/SSW and NW directions during both pre-monsoon and post-monsoon seasons. The NW swells which occur during Shamal events show distinct characteristics such as an increase in wave height, decrease in swell period and a common propagation direction (northwest) for wind seas and swells. Also the swells generated at 40° S, propagate in the north Indian Ocean, and enter the Bay of Bengal without affecting the Arabian Sea. Fine resolution winds (say, MM5 or WRF) are necessary to understand the effect of land-sea breeze system on wind-sea generation in the coastal regions. Here, we review the recent work on wind seas and swells in the Indian Ocean and coastal regions that we have carried out using measured wave data and model results.

Keywords: Swells, Wind seas, Shamal winds, the Indian Ocean, WRF, WAVEWATCH III

INTRODUCTION

In general, an ocean wave spectrum consists of wind seas generated by local winds and swells of distant winds or storms. The characteristics of these waves are different in different seasons. Several attempts have been made to understand the wave characteristics at different regions in the Indian Ocean for all seasons using different methods and models (for example, Shahul Hameed and Baba, 1985; Sundar, 1986; Baba et al., 1987; Sarkar et al., 1987; Sundar et al., 1998; Sanil Kumar and Ashok Kumar, 2008; Aboobacker et al., 2009; Bhowmick et al., 2009; Pai et al., 2009; Raj Kumar et al., 2009; Deo, 2010; Prasad et al., 2010; Suresh et al., 2010; Pooja et al., 2011; Sanil kumar et al., 2011). Swells in the Indian Ocean vary in response to the prevailing wind systems according to the seasons. Recent studies show that sea state along the coastal regions of India is significantly influenced by these swells. Identification of potential swell generation areas during various seasons is important to understand the effect of swells along the Indian coast, as they superimpose with wind seas and create complex sea states. In general, along the west coast of India, swells are predominant during southwest (SW) monsoon (Kumar et al., 2000). Shamal swells are generated in the northwestern Arabian Sea due to strong northwest (NW) winds, called Shamal winds, which occur during post-monsoon and early pre-monsoon seasons (Aboobacker et al., 2011). They propagate in the Arabian Sea with mean wave period ranging between 6 and 8s. Sabique et al. (2012) found that Southern Indian Ocean swells play an important role in

determining the Northern Indian Ocean wave climate. However, during the pre-monsoon season, wind seas play a major role in controlling the wave characteristics (Rao and Baba, 1996). Moreover, sea breeze is very active during pre-monsoon season (Aparna et al., 2005), and it has an impact on the diurnal cycle of sea state along the west coast of India (Neetu et al., 2006). Co-existence of locally generated wind seas and pre-existing swells results in a diurnal pattern of wave parameters during the pre-monsoon season (Vethamony et al., 2009). Though wind seas are modified by swells, wind sea slope is preserved during their interactions (Hansen and Phillips, 1999). Aligned swells can shorten and attenuate the wind seas (Chu et al., 1992). The study by Lekshmi and Sannasiraj (2007) revealed that during wave breaking redistribution of spectral energy and energy loss is more towards the high frequency end. This can significantly affect the design of offshore structures, ship passages, small boat operations in the harbour entrance and sea-keeping safety (Earle, 1984).

Wave spectra along the Indian coast are generally multi-peaked (e.g., Harish and Baba, 1986; Rao and Baba, 1996; Kumar et al., 2003) and occurrence of double-peaked spectra is more frequent during low sea state (Kumar et al., 2004). Spectra during extreme events are single-peaked (Kumar et al., 2004; Aboobacker et al., 2009). Here, we present a review of recent studies that we carried out on wind seas and swells in the Indian Ocean and coastal regions (Fig.1) using measured wave data and model results.

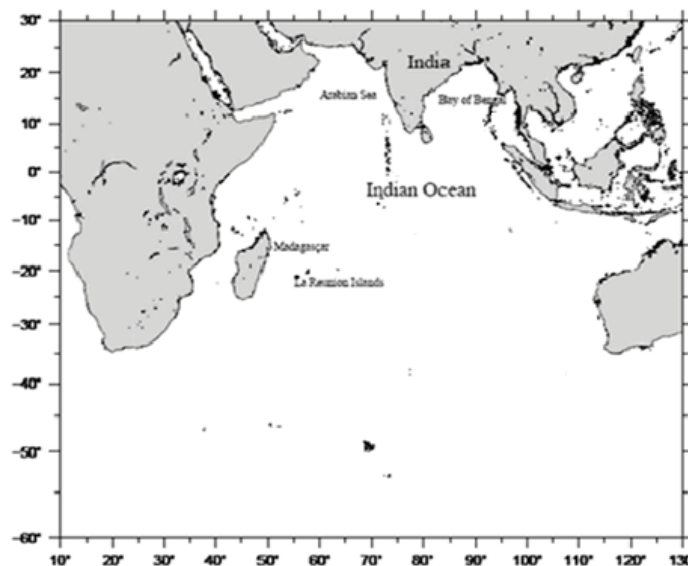


Fig. 1: Area of study covering the Indian Ocean and coastal regions

FINE RESOLUTION MODEL WINDS (WRF)

The basic input for any wave model is the wind. Wave model results will be accurate if the winds are reliable. For fine resolution wave information, we need to have similar winds, which are possible to get from atmospheric models such as MM5 and WRF. For example, fine resolution winds are necessary in order to understand the effect of land-sea breeze on wind-sea generation in the coastal regions (Vethamony et al., 2011). Land-sea breeze circulation along the central west coast of India has been modelled using the Mesoscale Model, MM5 (Dhanya et al., 2010), developed by the Pennsylvania State University / National Centre for Atmospheric Research (PSU/NCAR), which provides fine details of winds in reasonable temporal and spatial resolutions (Grell et al., 1994). The study provided a successful multi-day simulation of coastal wind circulations for three different seasons. Onshore and

alongshore wind components show diurnal variation which are due to the land-sea breeze circulation. The seaward extent of the onshore (sea breeze) flow estimated from the simulation agrees with earlier studies. Statistical analyses provided a rigorous indication of the model's ability to reproduce the observed circulation characteristics of the coastal winds. The results show that MM5 is able to simulate the magnitude, direction, timing, and vertical extent of the coastal atmospheric circulation accurately.

Another numerical modelling study has been carried out to regenerate the wind characteristics over the Arabian Sea during Shamal events (Vinod et al., 2013) using Weather Research and Forecasting model (WRF) (Skamarock, et al., 2008). It is based on fully compressible, non-hydrostatic Euler equations, third order Runge-Kutta (RK3) integration scheme and Arakawa C grid. The vertical mixing and diffusion was done by Asymmetric Convective Model with non-local upward mixing and local downward mixing (ACM2) (Pleim) scheme (Pleim, 2007) and surface physics by Pleim-Xiu scheme. The simulated wind parameters were validated with the measured Autonomous Weather Station (AWS) data of Ratnagiri and atmospheric temperature with that of Goa. It is found that the u-velocity (zonal component), v-velocity (meridional component), wind speed, wind direction and atmospheric temperature match reasonably well with measurements (Fig. 2). The Correlation coefficient, bias and r.m.s. error are 0.67, -0.01 and 1.68, respectively for u-velocity and 0.63, 0.13 and 1.64, respectively for v-velocity. We use NCEP, ECMWF, IFREMER Blended, NCMWRF, MM5 or WRF winds in the wave models such as MIKE SW, WAM, WW3 and SWAN, depending on requirement and research problem.

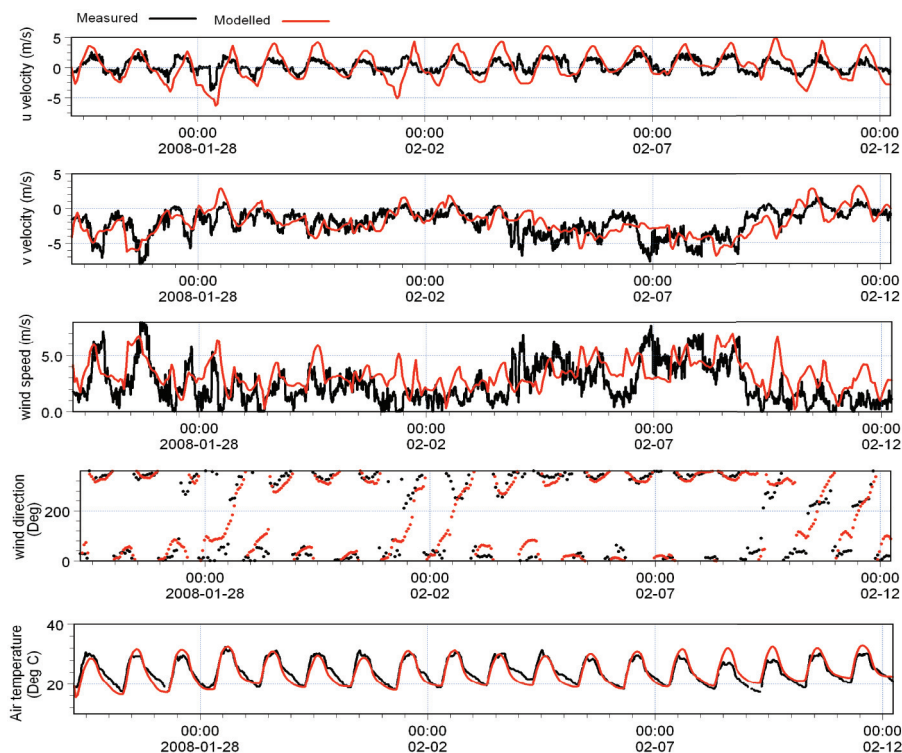


Fig. 2: Comparison between the measured and modeled (WRF) zonal velocity, meridional velocity, wind speed and wind direction at Ratnagiri and air temperature at Goa (Vinod et al., 2013)

DOMINANCE OF WIND SEAS AND SWELLS

Identification and separation of wind sea and swell energies from the measured spectra allow us to have a more realistic description of the sea state (Wang and Hwang, 2001). The wind sea and swell parameters can be separated using the methodology given by Gilhousen and Hervey (2001), which is based on the wave steepness algorithm (Rashmi et al., 2013). It is observed that during late pre-monsoon season, swells are dominant (54 % and 71 % at 25 m and 15 m water depths off Goa, respectively) (Table 1). During early pre-monsoon season, waves are primarily dominated by wind seas (44 % and 48 % at 35 m and 15 m depths, respectively off Ratnagiri) followed by swells (39 % at both the depths). However, during post-monsoon season, wind seas are dominated (45 %) at 30 m depth (away from the coast) while swells are dominated (61 %) at 15 m depth (closer to the coast) off Dwarka. This is attributed to generation of NE wind seas, and their growth is towards offshore. Sufficient fetch is available at 30 m depth for NE wind seas to grow compared to 15 m depth, and hence, wind sea energy is relatively higher at this location. Considerable amount of mixed seas was observed during late pre-monsoon season, whereas, during early pre-monsoon and post monsoon seasons it was the least. When swells dominate, mixed sea is less, and this happens at the fully developed stage. However, when wind seas dominate, mixed seas also increase as the waves are still in the developing stage.

Table 1: Percentage of swell, wind sea and mixed sea during non-monsoon season (Rashmi et al., 2013).

Location	Water depth (m)	No. of observations	Dominance (%)		
			Swell	Wind sea	Mixed sea
Goa (May 2005)	25	463	54	20	26
	15	717	71	11	19
Ratnagiri (Jan—Feb 2008)	35	1524	39	44	17
	15	1523	39	48	14
Dwarka (Dec 2007—Jan 2008)	30	1485	38	45	17
	15	1483	61	24	15

POTENTIAL SWELL GENERATION REGIONS

In order to identify potential generation areas of swells reaching the west coast of India, NCEP winds at 3 cells, namely, W1, W2 and W3 (Fig. 3a) have been extracted and analysed (Aboobacker et al., 2011b). During SW monsoon season (Fig. 3b), wind direction at W3 is predominantly between SW and WSW, at W2, between SW and W with dominating WSW direction and at W1, between SW and NW with dominating W direction. However, the swells off Goa are predominantly between WSW and W with dominating WSW direction during June–September. This indicates that the potential swell generation area during SW monsoon season is between W3 and W2, probably around 60°E and 10°N. During the pre-monsoon season (for example, Fig. 3c), winds at W3 are predominantly between NNE and E in February–April and between SW and WNW in May; at W2, between N and NE in February–March and between W and NE in April–May, and at W1, between W and N with dominant NW direction. However, two distinct swells (SW/SSW and NW) were present during the pre-monsoon season. NW winds are stronger in the northwestern Arabian Sea during winter Shamal events (Fig. 3d). Swells generated by the winds from N, NE and E do not have impact on the west coast of India. Since SW/SSW winds are not prevalent in the north Indian Ocean (as observed at W1, W2 and W3) during pre-monsoon season, it is possible that they are generated in the south Indian Ocean (Bhowmick et al., 2011, Raj Kumar et al., 2009). An analysis of wind pattern over the south Indian Ocean indicates that

these swells are generated at the mid-latitudes, probably around 40° S, where strong SW/SSW winds are always present.

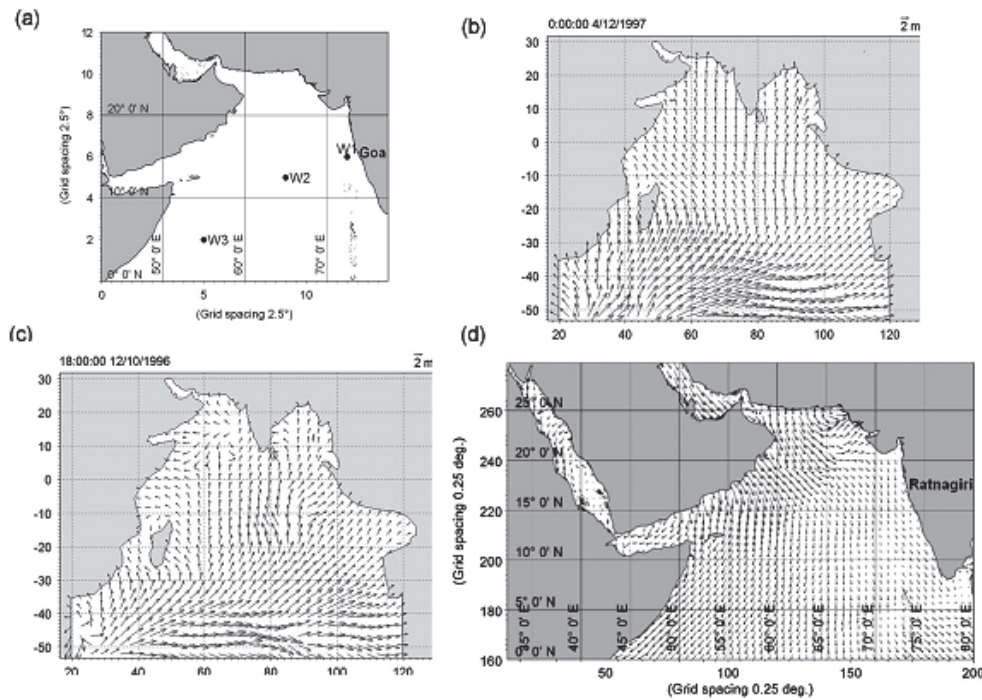


Fig. 3: (a) Locations of NCEP winds extracted for Feb 1996 to May 1997; typical swell patterns in the Indian Ocean during (b) pre-monsoon season (12 April 1997) and (c) post-monsoon season (10 December 1996); (d) Typical wind vectors over the Arabian Sea associated with Shamal event (02-02-2008 06:00) (Aboobacker et al., 2011b).

SHAMAL SWELLS ALONG THE WEST COAST OF INDIA

The word “Shamal” in Arabic literally means “north” and the winds during Shamal events are named as Shamal winds, and the corresponding swells as Shamal swells (Aboobacker et al., 2011a). Shamal winds normally occur in the Arabian Peninsula during winter (November to March) and summer (June to August). Based on the intensity, Shamal periodicities are classified as follows: (i) 24 to 36 hours and (ii) 3 to 5 days. The associated wind speeds can reach up to 20 m/s, and this can generate surface waves as high as 3.0 to 4.0 m in the Arabian/Persian Gulf. The characteristics of Shamal swells were analysed using the wave data collected off Ratnagiri during the winter season of 2008 (Fig. 4). An increase in wave heights, decrease in swell periods and common propagation direction (NW) for wind seas and swells were observed during the Shamal events. Shamal swells propagate to the Goa coast with a velocity of approximately 9 m/s (Aboobacker et al., 2011a). The mean periods associated with SW/SSW swells are predominantly 8–11 s, whereas those associated with NW swells are 6–8 s. Measured waves off Goa and Dwarka exhibit similar features during Shamal events. It is evident from the numerical simulations that winds during Shamal events generate high waves in the northwestern Arabian Sea, which propagate as swells in the NW direction and reach along the west coast of India. The potential swell generating areas are the Gulf of Oman and off the east coast of Oman. The significant wave heights associated with Shamal events reach above 3.5 m in the northwestern Arabian Sea and between 1.0 and 2.0 m along the west coast of India.

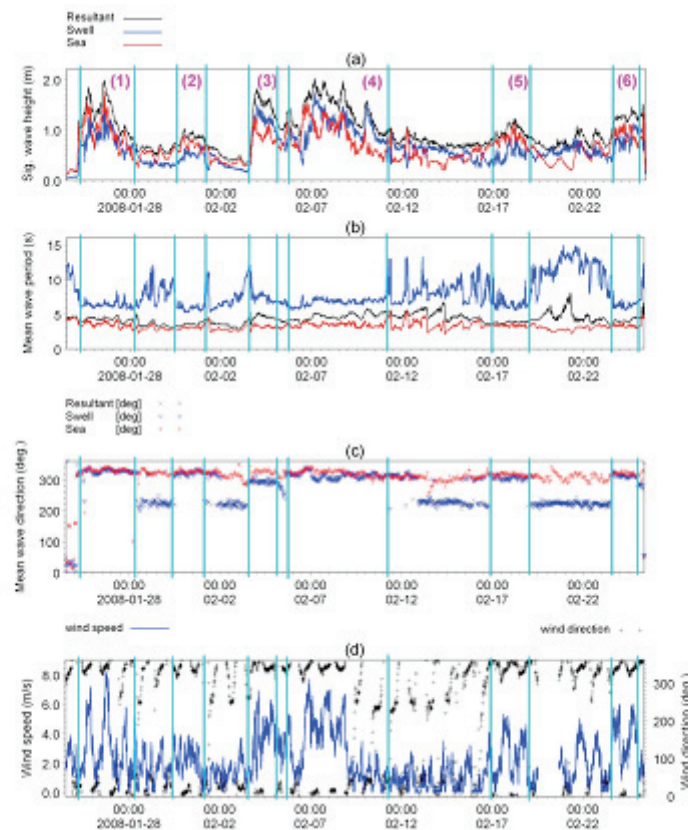


Fig. 4: Measured wave and wind parameters off Ratnagiri: (a) significant wave height, (b) mean wave period, (c) mean wave direction, and (d) AWS wind speed and direction. Well-defined Shamal features on wave and wind parameters are marked in zones (1) to (6) (Aboobacker et al., 2011a).

INTERACTION BETWEEN WIND SEAS AND SWELLS

Wave data collected off Goa revealed diurnal variations due to co-existence of locally generated wind seas over the pre-existing swells. It has been observed for a longtime that the calm sea off Goa during fair weather season becomes rough in the afternoon hours (Vethamony et al., 2011). Wave measurements and model simulations show that during the daily cycle, coastal winds (sea breeze) lead to the superimposition of locally generated waves from NW with the pre-existing swell from SW. This leads to an obvious increase in wave height; the superimposition of two wave systems with completely different dominant frequencies lead to a formal decrease of the mean wave period (Fig. 5a). This is perfectly shown by the directional wave energy spectra with the two systems - swell from SW and wind sea from NW, with completely different frequency and direction (Fig. 5b). Although relatively mild, the cross sea conditions will have a considerable impact on the local maritime activities and harbour management.

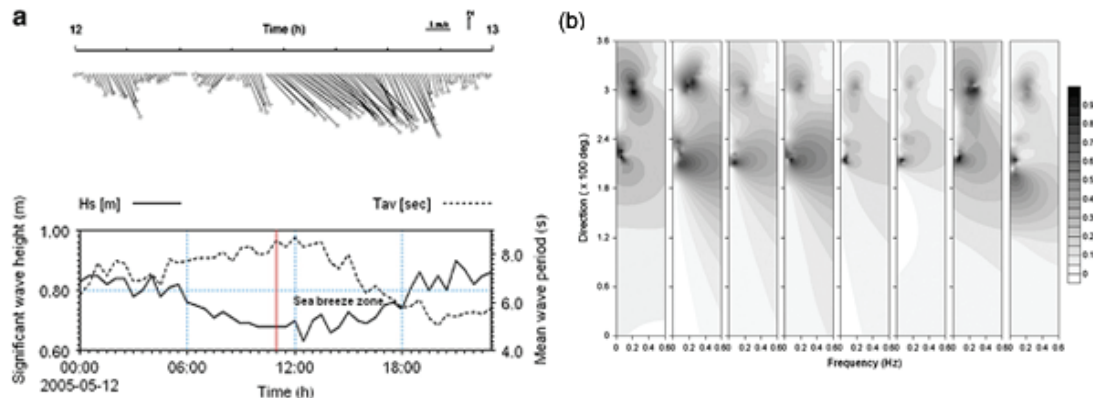


Fig. 5: (a) AWS wind distribution at Dona Paula and significant wave height and mean wave period at 20 m water depth off Goa (12 May 2005); (b) Measured directional energy spectra from 00 h to 21 h (for every 3 h) on 19 May 2005 (Vethamony et al., 2011).

INFLUENCE OF SOUTHERN OCEAN SWELLS

Recently, Remya et al (2012) have used MIKE 21 SW Model to study the impact of southern Ocean swells and for the assessment of wave climate in offshore and coastal areas of the Indian Ocean. In order to study in more details the impact of south Indian Ocean swells in the north Indian Ocean we took up a case study (Samiksha et al., 2012). A series of very high waves broke over La Reunion Island in the Indian Ocean on 12 May 2007, when there was an extreme weather event occurred off southern tip of South Africa in the Atlantic Ocean. The waves did numerous damages on property and lives of Reunion and neighbouring islands, and the maximum wave height was 11.3 m and significant wave height 6.4 m. During 14-15 May, the significant wave height was 8.0 m as measured by wave gauges (<http://www.aviso.oceanobs.com>). The storm engendered swells, which propagated in the Indian Ocean at a speed of about 1000 km/day, arrived at the Reunion, where low winds did not disrupt the swell. Lasting long enough, and with a rather large extension, it was observed by multiple altimeter tracks. This event which took place in May 2007 affected the north Indian Ocean wave characteristics, as the swell heights were very high of the order of 15.0 m near the generation area. The swells spread their energy as they travelled from the Atlantic Ocean towards the north Indian Ocean. The wave model, Wavewatch III (Tolman, 1999) was used to study the propagation of these swells in the Indian Ocean. The model was validated for the Indian Ocean using moored buoy data at 12 locations and merged altimeter wave data (IFREMER). A typical validation experiment is presented in Fig. 6. The wave model accurately reproduced the event of May 2007. Swell heights, of the order of 15.0 m, at the generation area reduced to 6.0 m near the La Reunion Islands. This study shows that the swells generated in the roaring forties of the Atlantic Ocean (between 15° to 80° E longitude) did propagate in the NE/NNE direction towards the north Indian Ocean, and wave characteristics of the Arabian Sea were least influenced by these waves compared to that of Bay of Bengal (Fig.7).

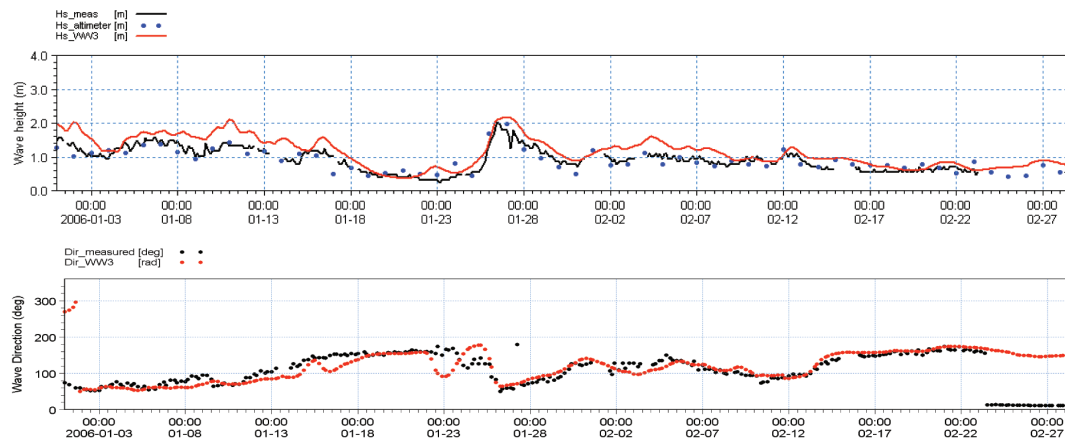


Fig. 6: Comparison between measured (black line) (wave rider buoy) and modelled (red line) wave heights and wave directions for the period Jan-Feb 2006 (calm weather season). Altimeter data (blue dots) (Deep Water: DS5, off Kakinada) (Samiksha et al., 2012).

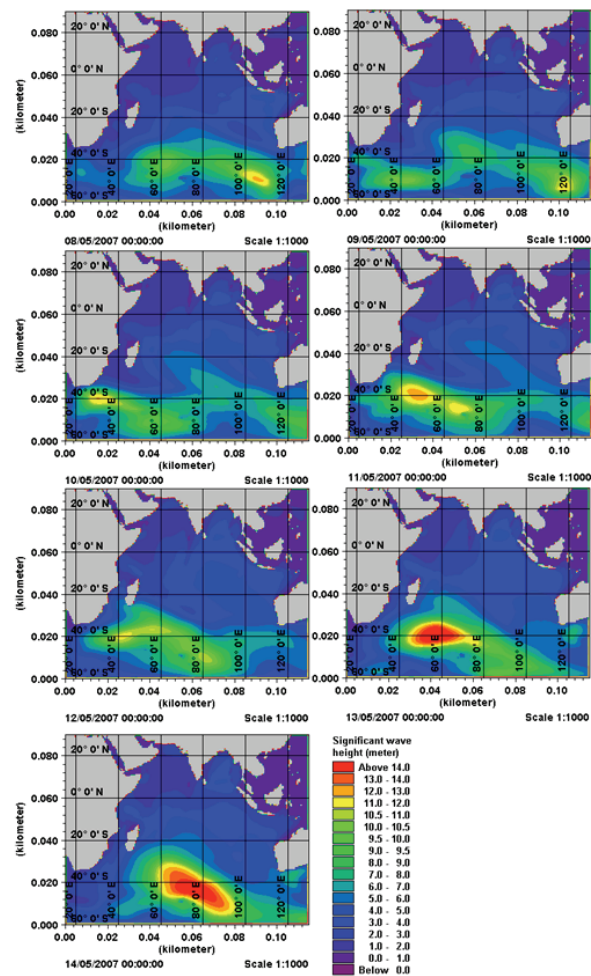


Fig. 7. Propagation of swells during May 2007 in the north Indian Ocean (Samiksha et al., 2012).

CONCLUSIONS

We have presented here the work that we have done at NIO on ocean surface waves in the last 5 years, by analyzing the measured and modelling (MIKE SW, WAVEWATCH III and WAM models) wave data. This research has yielded new information such as (i) effect of Shamal swells propagating in the Arabian Sea (in the northwest direction) from the Gulf coastal region, their speed, time of arrival along the west coast of India and swell properties and (ii) propagation of Southern Ocean and Atlantic swells in the north Indian Ocean, and the need to take the southern boundary upto 60°S for wave modelling. Presently, we are working in modifying the Original WAM model, especially the input, non-linear interaction and dissipation source terms to suit to the Indian Ocean, and we hope that NewWAM results would be better than the Original WAM results.

ACKNOWLEDGEMENTS

We thank Director, NIO, Goa, India for providing facilities to carry out this study. We are grateful to NCEP for providing the required *wind data CERSAT, IFREMER, France for providing the required altimeter data and INCOIS, Hyderabad* for providing the buoy data for model validation. The contents of this paper were presented at “Hydro-2012 Conference” held on December 7-8, 2012 at IIT Bombay, India. The NIO contribution number is 7018.

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