Author version: *Geophys. Res. Lett., vol.38(3); 2011; 7 pp., doi:10.1029/2010GL045736*

"Shamal" swells in the Arabian Sea and their influence along the west coast of India

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Abstract

Wave data collected off Ratnagiri, Goa and Dwarka along the west coast of India during winter season (NE monsoon and early pre-monsoon) present distinct wave characteristics with periodicity ranging between 2 and 5 days associated with shamal events. The notable wave characteristics during these events are: an increase in wave height, decrease in swell period and a common propagation direction (northwest) for wind sea and swell. IFREMER/CERSAT blended winds clearly show the presence of strong northwesterly winds in the Arabian Peninsula and northwestern Arabian Sea, which are associated with the winter shamal events. The winds during such events generate large northwesterly swells (shamal swells) in the northwestern Arabian Sea and propagate towards the west coast of India in the NW direction with mean periods ranging between 6 and 8 s. Numerical simulations reproduce the shamal swells over the Arabian Sea, and they can be traced all along the west coast of India, however, with lesser order of magnitude from north to south. Generation and propagation of shamal swells and their influence along the west coast of India have been described.

1. Introduction

The word “shamal” in Arabic literally means “north” and the winds during shamal events are named as shamal winds. Shamal winds normally occur in the Arabian Peninsula during winter (November to March) and summer (June to August). The onset, duration and strength of the shamal winds vary depending on the dynamic interaction of upper air jet streams and distribution of lower tropospheric pressure zones (Ali, 1994). . The winter shamal is associated with mid-latitude disturbances travelling from the west to the east, which has a high impact on the meteorological conditions over the Arabian Peninsula (Hubert et al., 1983). It usually occurs following the passage of cold fronts, and is characterized by strong northwesterly winds. 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 upto 20 m/s, and this can generate surface waves as high as 3.0 to 4.0 m in the Arabian/Persian Gulf (Hubert et al., 1983).

General swell patterns in the Arabian Sea are from the southwest or south, propagating from the south Indian Ocean (e.g., Sanil Kumar et al., 2000; Rajkumar et al., 2009; Kurian et al., 2009). On several occasions, swells propagating from the northwest were also observed. Studies on wave characteristics and storm surges due to shamal winds are very limited and restricted to the Arabian/Persian Gulf region only (e.g., El-Sabh, 1989; Parvaresh et al., 2005). Shamal winds could have a significant impact on the meteorological and oceanographic conditions of the Arabian Sea, and this has not been studied so far. Rapid changes in wind patterns during these shamal events can alter the wave characteristics of the Arabian Sea. This has motivated us to take up the present study with the following objectives: (i) generation and propagation of shamal swells in the Arabian Sea, and (ii) influence of shamal swells on the wave characteristics along the west coast of India.

2. Area of study

Figure 1a shows the study area. The Arabian Sea experiences three different seasons: pre-monsoon (February – May), southwest monsoon (June – September) and northeast monsoon (October – January). The winds are stronger during southwest (SW) monsoon season and generally weak during pre-monsoon and northeast (NE) monsoon seasons. Large scale winds are weak during pre-monsoon season and hence sea breeze has an impact on the diurnal cycle of the sea state along the west coast of India (Neetu et al., 2006). Co-existence of wind seas and pre-existing swells creates diurnal variations on the resultant waves along the west coast of India during pre-monsoon season

(Vethamony et al., 2009). During NE monsoon season, the predominant winds in the Arabian Sea are northeasterlies. The waves generated due to NE winds are relatively weak and propagate away from the coast. However, swells from SW or S dominate along the west coast of India during NE monsoon season.

3. Data and methodology

Directional waves are measured using a Datawell directional wave rider buoy for the periods 24 January – 25 February 2008 (off Ratnagiri at 35 m), 05 December 2007 – 05 January 2008 (off Dwarka at 30 m) and February 1996 – May 1997 (off Goa at 23 m) (Figure 1a). The data was collected at 1 hour interval off Ratnagiri and Dwarka, and at 3 hours interval off Goa with a sampling period of 20 minutes. The wave rider buoy has an accuracy of 3% for wave height and within 0.5 - 2° for wave direction. Wind sea and swell parameters were calculated from the measured wave energy spectra using the methodology provided by Gilhousen and Hervey (2001). Simultaneous wind measurements were carried out at Ratnagiri and Dwarka coastal stations using an Autonomous Weather Station (AWS) of the National Institute of Oceanography (NIO), Goa. The AWS provided wind speed and direction at 10-minutes interval. The accuracy of AWS is: 0.2 m/s for wind speed in the range 0-60 m/s and 3° for wind direction in the range 0-360°.

IFREMER/CERSAT blended winds (U and V components) were analysed and used as input for numerical simulations. These are remotely sensed retrievals from QuikScat (Ebuchi et al., 2002) blended to the operational ECMWF wind analysis over the global oceans by the IFREMER/CERSAT and available for every 6 hours with 0.25° x 0.25° grid spacing (Bentamy et al., 2006 and Bentamy et al., 2009). The quality of this data has been checked with buoy winds and the match is very good (Bentamy et al., 2007).

Numerical simulations have been carried out to reproduce wind sea, swell and resultant wave characteristics in the Arabian Sea using MIKE 21 SW - a spectral wind wave model developed by the DHI Water & Environment, Denmark (DHI, 2007). The model domain covers the entire Indian Ocean (65° S to 30° N and 20° to 125° E). A flexible mesh has been generated using Etopo 5 bathymetry data obtained from NGDC (National Geophysical Data Center, USA) for deep water and modified bathymetry data from Sindhu et al. (2007) for coastal region. The selected resolutions for the flexible mesh bathymetry are: 1.5° in the south Indian Ocean, 0.5° in the north Indian Ocean, 0.25° around the Indian coast and 5 km along the west coast of India. Major outputs from the simulations are integral wave parameters such as significant wave height, mean wave period and mean wave direction.

4. Results and discussion

4.1. Model validation

The modelled wave parameters have been validated with measured wave parameters off Ratnagiri during 24 January – 25 February 2008. It has been found that the modelled significant wave height (H_s) and mean wave period (T_m) match reasonably well with the measurements (Figures 1b and 1c). The scatter (Figures 1d and 1e) shows that measured and modelled H_s and T_m are linearly correlated. Correlation coefficient, bias, r.m.s. error and scatter index are 0.86, 0.02 m, 0.20 m and 0.21, respectively for H_s and 0.67, 0.51 s, 0.78 s and 0.18, respectively for T_m.

4.2. Characteristics of "shamal" swells

The measured waves off Ratnagiri show systematic variations in the wave parameters during several occasions (Figure 2). During NE monsoon and early pre-monsoon seasons, nearshore wave heights along the west coast of India are generally low (< 1.0 m). However, waves with H_s of the order of 1.0 - 2.0 m were observed at several occasions during 24 January – 25 February 2008. Further analysis shows that wave parameters exhibit distinct characteristics, namely, (a) increase in wave heights associated with decrease in swell period and (b) a common propagation direction (NW) for wind sea, swell and resultant waves (Figures 2a to 2c). Measured winds at Ratnagiri coast also show systematic variations during the above period (Figure 2d). The systematic features observed in the wind and wave parameters are indicated as (1) to (6) in Figure 2. During this period, the H_s is in the range of 1.0 to 2.0 m, mean swell periods are between 6.0 and 8.0 s and predominant wind and wave directions is NW.

The directional energy spectra show peak energy in the swell region, between the frequencies 0.1 and 0.2 Hz in the NW direction, contrary to the normal swell conditions along the west coast of India, wherein energy is distributed between 0.05 and 0.15 Hz in the SW or S direction (e.g., Vethamony et al., 2009). Typical directional energy spectra measured off Ratnagiri during shamal period and non-shamal period are shown in Figure 3a and 4b. Swells from the south Indian Ocean (S or SW direction) are generally observed along the west coast of India, which are mostly "old swells" (significant wave steepness, H_s/L < 0.004, where L is the wavelength) . However, NW swells generated in the northern Arabian Sea can propagate to the west coast within a short duration, and that is the reason for observing mostly "young" ($0.01 \leq H_s/L > 0.025$) or "mature" ($0.004 \leq H_s/L > 0.01$) swells from the NW direction. On an average, "young", "mature" and "old" swells (NW swells) were 76%, 21% and 3%, respectively during the study period.

The predominant winds in the Arabian Sea during the NE monsoon and early pre-monsoon seasons are from NE, and the wind speeds are of the order of 5 to 10 m/s. On several occasions, it was observed that the NE winds become weak, and NW winds become stronger, especially in the north-western Arabian Sea and in the Arabian Peninsula. These winds are associated with shamal events (active shamal area is marked in Figure 1a). Typical wind vectors in the Arabian Sea during NE monsoon and during shamal events are shown in Figures 3c and 3d, respectively. The wind speeds associated with shamal events range between 10 and 20 m/s. As evident from the AWS winds at Ratnagiri coast (Figure 2d), shamal winds can extend upto the west coast of India, though the magnitudes are relatively less along the coastal regions. These winds are stronger at the northern part of the west coast of India. The period and duration of the shamal events closely match with those of the systematic features observed in the measured wave parameters and AWS winds. Considering the above facts, it has been concluded that the systematic features observed in the wave parameters during the winter season are primarily due to the impact of shamal winds, which generate high energy waves and propagate to the west coast of India as swells. These swells are hereafter referred as "shamal" swells.

Waves measured at 23 m water depth off Goa during February 1996 – May 1997 also show similar features. It has been noticed that such well-defined features are observed between November and March, and more frequently in January and February. Winds associated with summer shamal events are relatively weaker, and their impact on the wave characteristics along the west coast of India is negligible due to the prevailing SW monsoon winds, which generate higher waves during this season.

4.3. Generation and propagation

Numerical simulations carried out using IFREMER/CERSAT blended winds during January – February 2008 reproduced the generation and propagation characteristics of shamal swells in the Indian Ocean. Analysis of swell, wind sea and the resultant wave parameters obtained from the simulations indicates that the waves generated due to strong shamal winds over the northwestern

Arabian Sea propagate in the NW direction towards the west coast of India. A gradual wind wave growth has been observed with respect to increase in wind speed during shamal events. H_s reaches above 4.0 m in the Persian Gulf. However, propagation of the waves generated in the Persian Gulf to the rest of the Arabian Sea is obstructed at Hormuz Strait due to the narrow opening and shallow water depths. It has also been found that the shamal winds generate higher waves in the NW direction at the northwestern Arabian Sea (excluding the Persian Gulf). The associated H_s reaches above 3.5 m within a fetch of ≈ 300 km. Once they leave the generating area, they propagate in the NW direction as shamal swells.

Figure 4a shows the H_s vectors (12 h interval) in the Arabian Sea representing the generation and propagation of shamal swells during 02 – 04 February 2008. It is evident that larger waves are generated in the Persian Gulf, Gulf of Oman and off the east coast of Oman due to strong shamal winds. The swells generated in the Gulf of Oman and the east coast of Oman propagate in the NW direction. Another swell system formed off Salalah coast (Figure 4a) propagates in the NNW direction. Since the present study aims at understanding the influence of shamal swells along the west coast of India, significance has been attached to the NW swells, generated in the northwestern Arabian Sea (Gulf of Oman and off the east coast of Oman).

It is evident that the shamal swells propagate towards the west coast of India in the NW direction. The arrival time of the swells depends on the distance of propagation to various locations along the west coast of India. The swells arrive early (< 20 h) along the Gujarat coast and later (around 48 h) along the Kerala coast. The swells observed off Gujarat coast have higher energy than those observed off the Kerala coast, indicating that the coastal region of Gujarat is impacted by the shamal swells to a high degree. The deep water group velocity of the shamal swells is approximately 9 m/s. The distance of swell propagation to the Ratnagiri coast is around 1200-1500 km. Hence, a propagation time of 37-46 h has been estimated for the shamal swells to reach the Ratnagiri coast.

4.4. Influence along the west coast of India

Swell heights obtained from the numerical simulations at 25 m depth off Kochi, Mangalore, Goa, Ratnagiri, Mumbai and Dwarka during the study period are presented in Figure 4b. Variations in swell heights associated with shamal events indicate that all the above locations along the west coast of India are influenced by shamal swells, though there are changes in patterns and heights according to the intensity and duration of the event. The swell heights are higher off Dwarka, indicating that the open coast of Gujarat is highly influenced by shamal swells. A similar pattern is observed off Mumbai, but swell heights are relatively low compared to those off Dwarka. The swell pattern off Ratnagiri, Goa, Mangalore and Kochi are nearly the same; the respective time lags have been estimated for all the locations according to the swell propagation time.

An analysis of the measured waves off Dwarka (at 30m depth) during 05 Dec 2007 – 05 Jan 2008 indicates that the shamal swells with short duration (< 24 h) are present though their heights are relatively less compared to the shamal swells observed off Ratnagiri during 24 Jan – 25 Feb 2008. During non-shamal periods the waves off Dwarka are dominated by wind seas, as evident from the measurements. Measured waves off Goa (at 23m depth) during November 1996 – March 1997 also show the presence of shamal swells. Increase in wave height associated with decrease in swell period and propagation of wind sea and swell in the NW direction are prominent during the shamal events. Even though shamal swells exist, at times, the wind sea energy in the NW direction (generated by shamal winds) dominates over the swell energy, which provides an indication to the extension of shamal winds upto the west coast of India. However, this has to be confirmed through detailed investigations.

5. Conclusions

The characteristics of shamal swells were analysed using the wave data collected off Ratnagiri during the winter season of 2008. An increase in wave heights, decrease in swell periods and common propagation direction (NW) for wind sea and swell were observed during the shamal events. Typical mean periods of the shamal swells are between 6 and 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.

Shamal winds can influence the wind-induced circulation in the Arabian Sea. Studies on shamal winds extension and their distribution along the west coast of India require fine resolution winds (e.g., MM5 winds). Even though swells from the south Indian Ocean are always present along the west coast of India, the shamal swells dominate over these swells. However, interaction between these multi-directional swells has to be investigated further.

Acknowledgments

We thank Dr S.R. Shetye, the Director, National Institute of Oceanography (NIO), Goa for providing necessary facilities and encouragement. We acknowledge all the project participants for their help during data collection. This study is carried out as a part of the partial fulfillment of Ph.D. work of the first author. The NIO contribution number is xxxx.

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Figures

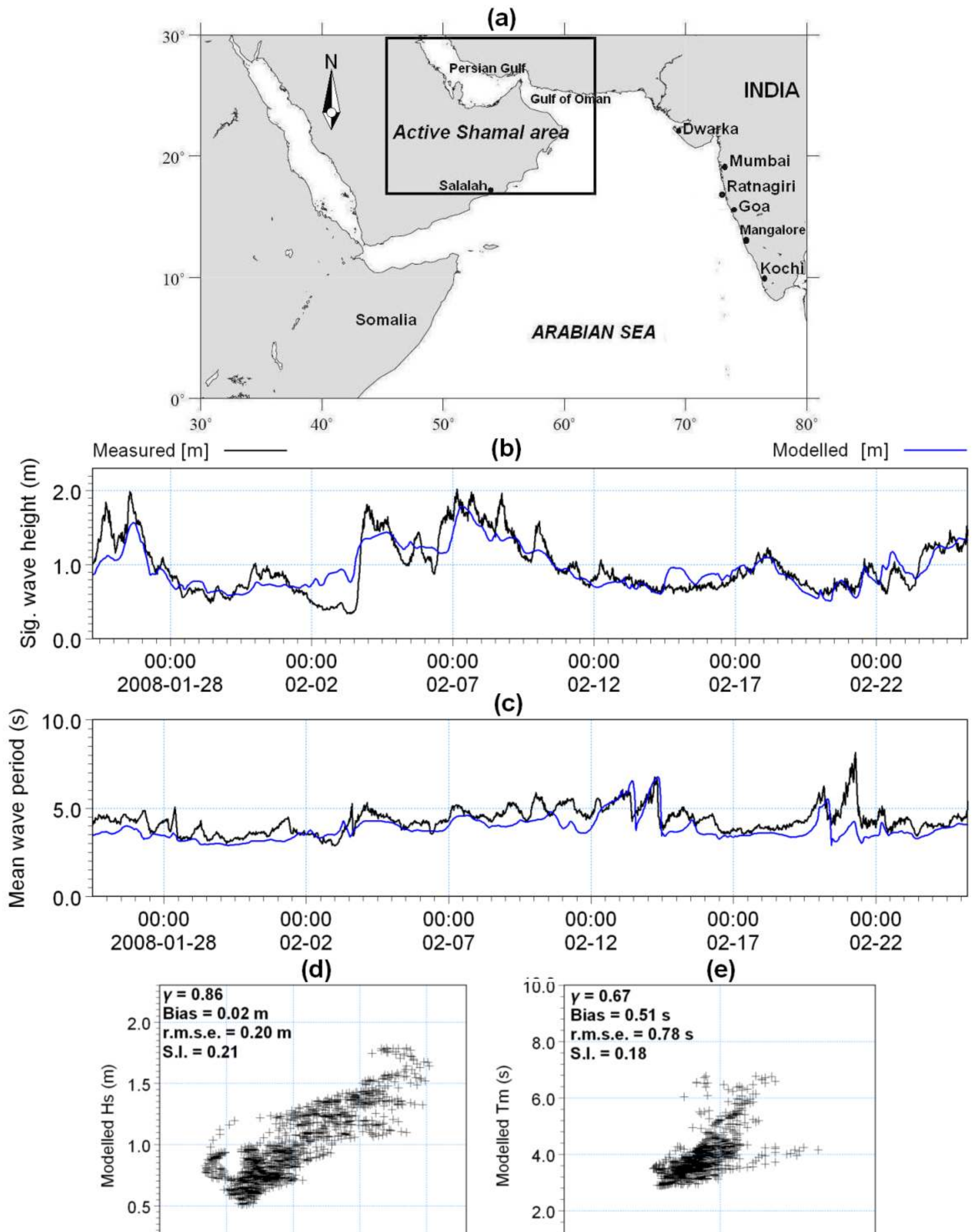

Figure 1. (a) Study area, (b) measured and modelled significant wave height, (c) measured and modelled mean wave period, (d) scatter of significant wave height and (e) scatter of mean wave period.

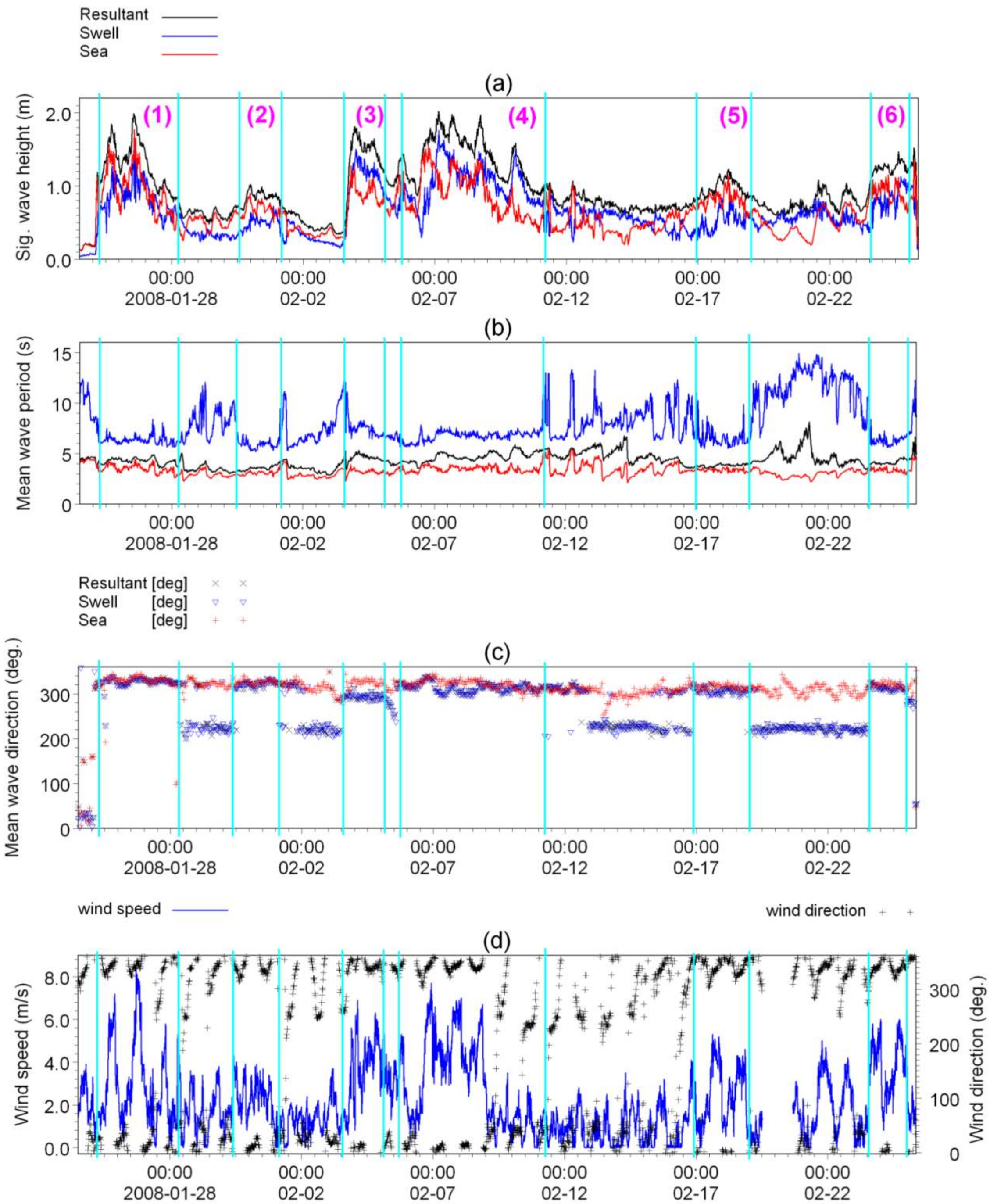

Figure 2. Measured wave and wind parameters off Ratnagiri; (a) significant wave height, (b) mean wave period, (c) mean wave direction and (d) AWS wind speed and direction. Well-defined features on wave and wind parameters are marked from (1) to (6).

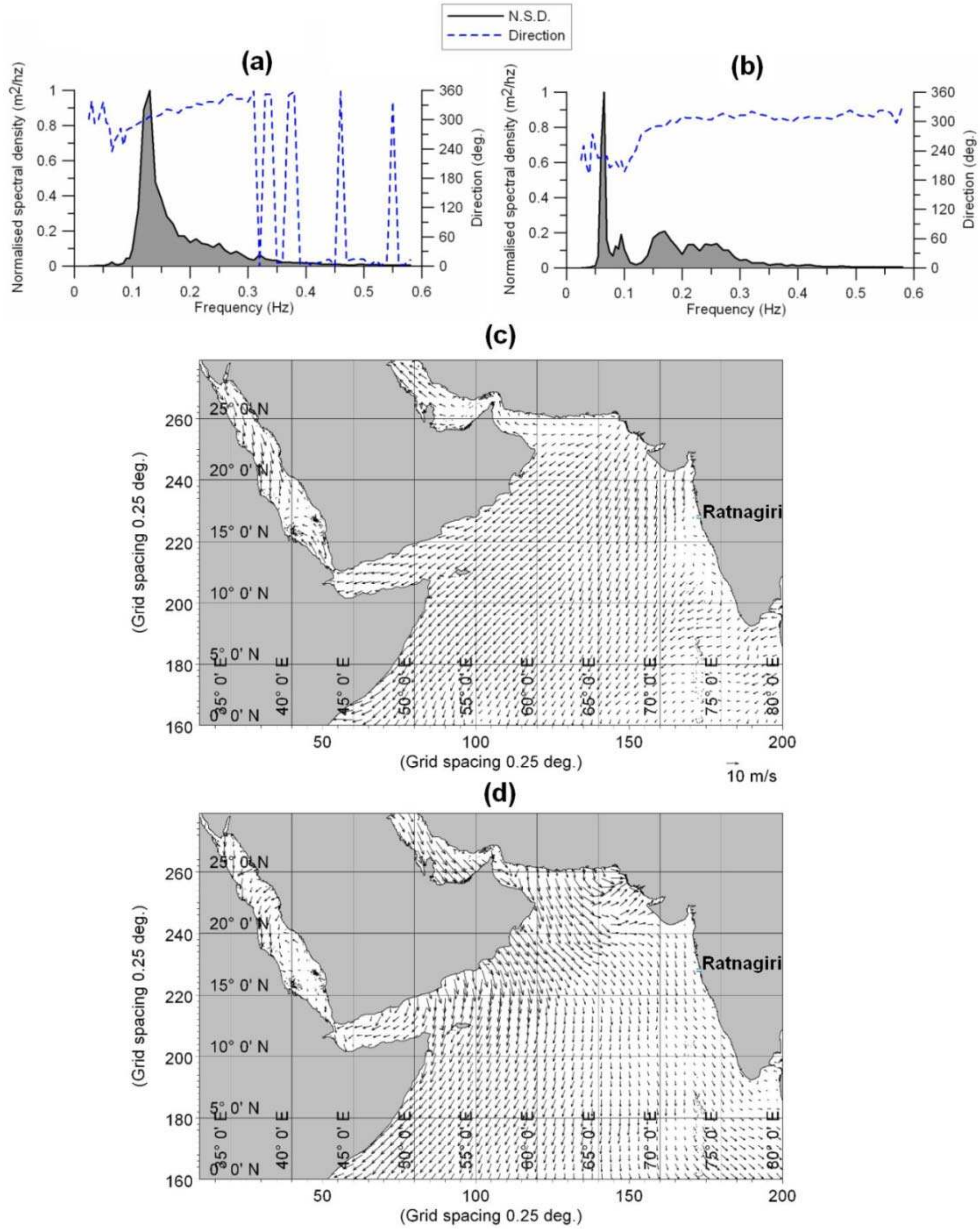

Figure 3. Typical directional energy spectra during (a) shamal period (07-02-2008 03:00) and (b) non-shamal period (15-02-2008 02:00), and Typical wind vectors over the Arabian Sea associated with (c) NE monsoon (12-02-2008 18:00) and (d) shamal event (02-02-2008 06:00).

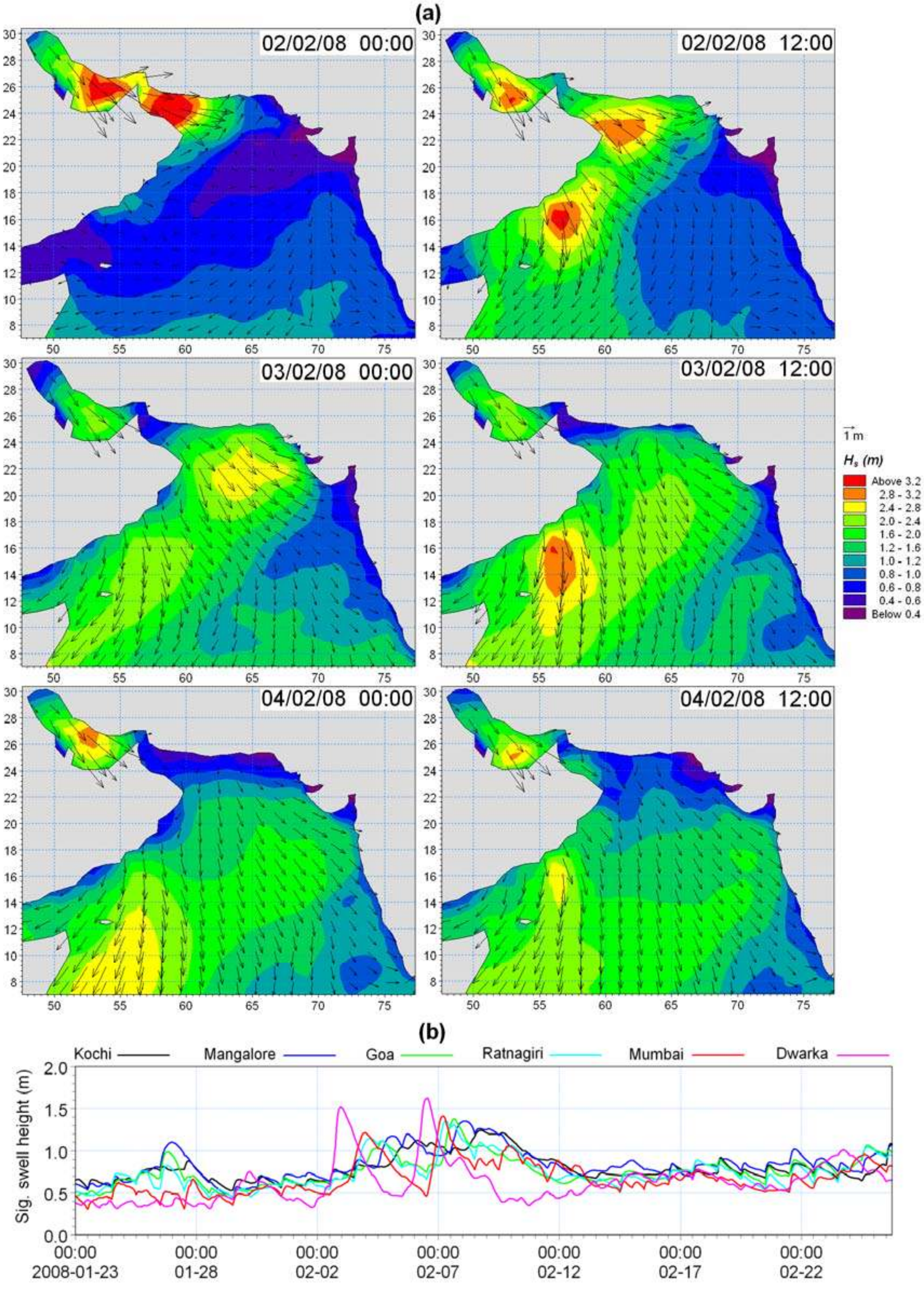

Figure 4. (a) H_s vectors in the Arabian Sea during 02-04 Feb 2008 and (b) swell H_s off Kochi, Mangalore, Goa, Ratnagiri and Mumbai at 25 m water depth.