

## **Trends of wave height and period in the Central Arabian Sea from 1996 to 2012: A study based on satellite altimeter data**

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### **Abstract**

The variability of annual maximum and annual mean significant wave height (SWH) and wave period in the Central Arabian Sea is studied using satellite altimeter data from 1996 to 2012 at a deep water (water depth  $\sim 3500$  m) buoy location ( $15.5^\circ$  N,  $69.28^\circ$  E). Altimeter wave heights are validated with in-situ measurements and are intercompared. Extreme tropical storm/cyclone events that affect the wave conditions are studied using Joint Typhoon Warning Centre best-track data. The study shows a positive trend of  $0.63 \text{ cm yr}^{-1}$  in the annual mean SWH. In contrast, a negative trend of  $2.66 \text{ cm yr}^{-1}$  is found for the annual maximum SWH due to the decreasing trend of extreme tropical cyclone events. The annual mean and maximum wave period shows a decrease of  $0.005 \text{ s yr}^{-1}$  and  $0.011 \text{ s yr}^{-1}$ , respectively.

**Key words:** Satellite altimeter, significant wave height, tropical cyclone, wind speed, climate change

## 1. Introduction

Winds blowing over the sea surface generate wind waves (also known as ocean surface waves), and the data on these waves are required for planning and designing facilities in the ocean. The major sources of wave data are i) in-situ measurements, ii) model hindcasts and reanalysis, iii) voluntary observing ships (VOS) data and iv) satellite altimetry or remote sensing data. A number of satellite instruments such as the Scatterometer, the Special Sensor Microwave Imager (SSM/I), the Synthetic Aperture Radar (SAR) and the Radar Altimeter are available for the determination of wave height and wind speed and direction (Young, 1999; Young et al., 2012). An important parameter that characterizes a wave is the significant wave height (SWH).

The Arabian Sea (AS) is an area of significant interest as it is marked by high wind speed and wave conditions due to the monsoon in a region that is otherwise calm (Young, 1999; Kumar and Anand, 2004; Kumar et al., 2010). In addition, the wind direction in the AS reverses between the two monsoons with winds blowing from the south-west (SW) during the summer monsoon period (June to September) and from the north-east (NE) during the winter monsoon period (October to January). The wave climate of the AS depends on the wind conditions prevailing over both monsoons and on swells coming from the Southern Ocean (Semedo et al., 2011; Glejin et al., 2013). Winds during the SW or summer monsoon result in high wave activity ( $SWH > 2$  m), but relatively calm conditions ( $SWH < 1.5$  m) prevail during the rest of the year.

Chen et al. (2002) observed an enhancement of wind-sea generation in the AS during the summer monsoon. Semedo et al. (2011) reported that the north Indian Ocean, with the exception of the summer monsoon period, is the most swell-dominated area of the world's oceans. Stronger storm events such as tropical cyclones produce higher waves in the AS (Kumar et al., 2010). Gray (1985) found that the north Indian Ocean accounts for 7% of global tropical cyclones. Occurrences of tropical cyclones are less in the AS compared to the Bay of Bengal, and the ratio of their frequencies is about 1:4 (Dube et al., 1997).

Long-term wave records based on in-situ measurements are still sparse in the AS and only short-term records are available (Premkumar et al., 2000; Kumar, 2006; Sajiv et al., 2012; Glejin et al., 2013). However, several studies have reported increases of SWH in the north Pacific and north Atlantic oceans. Carter and Draper (1988) and Bacon and Carter (1993) found that, from the 1950s to the 1990s, the mean SWH increased in the north Atlantic by 3.4 and 2.2  $\text{cm yr}^{-1}$ , respectively. In a  $5^\circ \times 10^\circ$  latitude/longitude box each in the north-west and north-east Atlantic, Bouws et al. (1996) reported increases in the mean SWH of 2.3  $\text{cm yr}^{-1}$  and 2.7  $\text{cm yr}^{-1}$ . Gulev and Hasse (1999) found

that the SWH increased by 0.1-0.3 cm yr<sup>-1</sup> in the north Atlantic during the period 1964-1993, except for the western and central subtropics. Allan and Komar (2000) and Gower (2002) reported an increase of 2.1 and 1.9 cm yr<sup>-1</sup> at buoys 46005 and 46002 on the north-western coast of the United States of America during the period 1972-1999. An extended study by Ruggiero et al. (2010) found that the annual average SWH increased at a rate of 1.5 cm yr<sup>-1</sup> from the mid-1970s to 2010, while averages of the five highest SWH have increased at the greater rate of 7.1 cm yr<sup>-1</sup>. Gulev and Grigorieva (2006) analyzed the variability of SWH in the north Atlantic and north Pacific using 45 years of VOS data and found that the winter SWH shows an increase of 0.1 to 0.4 cm yr<sup>-1</sup>.

Similar studies in the central AS are limited. In a global study, Caires and Swail (2004) found a negative trend of 1.9 cm yr<sup>-1</sup> in SWH in the AS from July to September. Based on altimeter data covering 23 years, Young et al. (2012) reported that the equatorial and tropical regions of all oceanic basins show a neutral trend for mean and 99<sup>th</sup> percentile of wave height. For the seas around India, the long-term trend in wave height is estimated based on the global atmospheric re-analysis product (ERA-I) of the European Centre for Medium-Range Weather Forecasts (ECMWF) from 1979 to 2012 (Shanas and Kumar, 2014, 2015; Kumar and Anoop, 2015; Anoop et al., 2015). The limited regional studies in the AS are mainly due to the unavailability of long time series of in-situ wave data.

Studies by Chelton et al. (1981), Dobson et al. (1987) and Monaldo (1988) have shown that active remote sensing satellites are capable of providing SWH and wind speed with an accuracy comparable to in-situ observations. In oceanographic studies, satellite-based data are highly advisable due to their global coverage compared to the sparse in-situ data available from point locations (Staabs and Bauer, 1997; Challenor et al., 2006). Wave climate across the ocean basins can be described using satellite altimetry (Young, 1999; Woolf et al., 2002). With the accumulation of lengthy and carefully calibrated datasets from a number of satellite altimeters, it is possible to evaluate the seasonality and inter-annual variability of wave climate globally (Woolf et al., 2003). Even though altimeters are unable to provide a direct estimate of wave period, a number of studies are carried out based on the wave period derived from altimeter measurements of backscatter coefficient, wind speed and SWH (Challenor and Srokosz, 1991; Sarkar et al., 1998; Hwang et al., 1998; Gommenginger et al., 2003; Kshatriya et al., 2005; Caires et al., 2005; Govindan et al., 2011). Young et al. (2011) used a 23-year database of satellite altimeter measurements to investigate global changes in oceanic wind speed and wave height. They found a general global trend of increasing values of wind speed and wave height and that the rate of increase is greater for extreme events as compared to the mean condition.

To the authors' knowledge, no regionalized studies have been carried out on the long-term variations of SWH and wave period in the Central AS based on satellite altimetry data. This work aims to fill this gap using altimetry SWH and computed wave period data. For this purpose, a deep water location (15.5° N, 69.28° E) in the Central AS was selected since buoy data available at this location for a limited period will enable validation of the altimetry data (Fig. 1).

## **2. Data and Methodology**

### **2.1 Altimeter derived SWH and wind speed**

Altimeter data from 1996 to 2012 was obtained from the TUDelft RADS database (Naeije et al., 2000) and used in the present study. Ku-band SWH data from the satellites *GFO*, *ERS-1*, *ERS-2*, *TOPEX*, *Jason-1*, *Jason-2* and *Envisat*, and the data available from the *Poseidon* and *Cryosat-2* missions were also used in the study. The resolution of the altimeter data used in the study depends on the sea condition and it ranged from 2 km (for clam sea) to 10 km (for rough sea). Altimeters provide wind speed at 10-m above the sea surface. In the study, all flagged data and data with a SWH greater than 25 m and a SWH equal to 0 are rejected. The period of data used and the satellite repeat cycle are tabulated in Table 1. *ERS-2* and *Envisat* have a 35-day repeat cycle; *Jason-1* and *Jason-2* have a 10-day repeat cycle and *Cryosat-2* has 30-day repeat sub-cycle. The most severe limitations of satellite altimetry are i) that a satellite takes at least 10 days to return to the same point, and ii) a satellite measures only the sea surface directly beneath the satellite (Hemer et al., 2010).

### **2.2 Buoy data**

Significant wave height, wave period and wind speed data measured by a buoy at location 15.5° N, 69.28° E (water depth  $\approx$  3500 m) in the AS during 2004 and 2005 under the National Data Buoy Programme (Premkumar et al., 2000) are used in the study. The buoy measures wind speed at 3 m above the sea surface and SWH at a 3-h interval. Wind observation is a 10-minute average with wind speed and direction sampled at 1 Hz by a cup anemometer with vane. The accuracy of wind speed measurements is 1.5% of full scale (0-60 m s<sup>-1</sup>). The buoy is equipped with a motion reference unit for wave measurements. The sampling duration and frequency for wave measurement is 17 minutes and 1 Hz. The resolution of the wave height measurement is 1 cm and the accuracy is 5 cm. Details of the buoy configuration and sensors, including their accuracy and range, are reported by Rao and Premkumar (1998).

### 2.3 Tropical cyclone data

We considered AS tropical cyclones during the study period (1996-2011) based on the position and wind speed reported in the Joint Typhoon Warning Centre (JTWC) best-track dataset available at 6-h intervals (Chu et al., 2002).

### 2.4 Methodology

Altimeters are always calibrated and validated during the dedicated commissioning phase of a satellite and then a few months after its launch. Before using such data, the measurements have to be validated, and the quality of the data for the region has to be checked (Queffeuou, 1996; Gower, 1996; Cotton and Challenor, 1997; Queffeuou and Bentamy, 1997). Zieger et al. (2009) carried out the calibration of multiplatform altimeter measurements of wind speed and wave height for the period 1985 to 2008. They found that the accuracies of the various altimeters were similar, with the root mean square (RMS) error being less than 0.25 m for SWH and 1.7 m s<sup>-1</sup> for wind speed. We carried out the validation of altimeter wave height through measured buoy data and satellite-satellite inter-comparison.

For the comparison between satellite altimeters and a buoy, the selection of space and time collocation windows is very important (Chen, 2000). According to Caballero et al. (2011), the size of the window ranges from 0 to 150 km in the space domain while it varies from 0 to 1.5 h in the time domain. The collocation criteria of 50 km and 30 min are widely applied (Dobson et al., 1987; Monaldo, 1988; Gower, 1996; Queffeuou, 2004). Since the collocation points obtained are smaller for a 50-km window, to get a sufficient number of collocation points, we used the collocation criteria of observations occurring within 100 km and 30 min of one another. The Gaussian weight function is applied for averaging the along-track altimeter data to the exact buoy location. The collocation points for a particular buoy data point is averaged using Eq. 1, which is the method adopted by Kessler and McCreary (1992).

$$SWH(x_0, y_0, t_0) = \frac{\sum_{n=1}^{N_p} (SWH'_n W_n)}{\sum_{n=1}^{N_p} (W_n)} \quad (1)$$

where  $N_p$  is the total number of collocated buoy data points,  $SWH'_n$  is the wave height measured by satellite and  $W_n$  is the Gaussian weight function given by,

$$W_n = \exp \left\{ - \left[ \left( \frac{x_n - x_0}{X} \right)^2 + \left( \frac{y_n - y_0}{Y} \right)^2 + \left( \frac{t_n - t_0}{T} \right)^2 \right] \right\}$$

The window size  $X=100$  km longitude,  $Y=100$  km latitude and  $T=30$  min (and  $x_0$ ,  $y_0$  and  $t_0$ , respectively) are the spatial grid points in  $x$  (longitude),  $y$  (latitude) and  $T$  (time) at the buoy location. The spatial grid points are  $x_n$ ,  $y_n$  and  $t_n$  in  $x$ ,  $y$  and  $T$  of satellite altimeter data. Using the same method, altimeter data within 100 km from the buoy location during 1996 to 2012 are averaged to the buoy location, where ‘ $t_0$ ’ is taken as the mean of ‘ $t_n$ ’. The monthly mean values from these altimeter data are compared against the monthly mean values from other altimeter data. The data from individual satellites are combined together and the annual mean and the annual maximum are plotted. To know the seasonal variation, the monthly mean and the monthly maximum values are estimated. In order to assess the dependence of extreme events on the annual maximum value of wave height, storm/tropical cyclone events in the box  $5-25^\circ$  N;  $60-80^\circ$  E are obtained and compared with the annual maximum SWH.

Using SWH and wind speed data, the wave period is computed using the recently developed algorithm GA-2, which is presented in Eq. 2 (Govindan et al., 2011).

$$T_{z=0} = \{[(\xi - 5.78) / (\xi \{U_{10} / (SWH \{U_{10} / SWH\} + SWH))\})] + [SWH + 5.70]\} \quad (2)$$

Where  $\xi$  is the wave age,

$$\xi = 3.25 \times (SWH^2 \times g^2 / U_{10})^{0.31}$$

$U_{10}$  is the wind speed at 10 m above the sea surface, SWH is the significant wave height and  $g$  is the acceleration due to gravity. The wind speed measured by the buoy at a 3-m height ( $U_3$ ) is approximated to a 10-m height above the mean sea level ( $U_{10}$ ) based on Eq. 3. Computed wave periods are validated with buoy-measured wave periods.

$$U_{10} = U_3 \left( \frac{10}{3} \right)^{0.125} \quad (3)$$

The nonparametric method, which is widely used to study climate change, is used to calculate the trends in wind speed and SWH (Wang and Swail, 2001).

### 3. Validation of altimeter data with buoy data

#### 3.1. Wave height

Altimeter SWH data from all satellites are individually compared with measured buoy data during 2004 and 2005. The purpose of the comparison is to find out whether the satellite altimeter dataset can provide a realistic estimate of SWH. Four satellites (*GFO*, *Envisat*, *Jason-1* and *TOPEX*) collocated with the buoy during 2004 and 2005. Scatter plots of the altimeter data with the buoy

shows that all four satellites agree well with the buoy data (Fig. 2). Less scatter is observed for lower SWH and the scatter is slightly higher for higher values. The statistical parameters of mean bias (MB), root mean square error (RMSE), scatter index (SI) and correlation coefficient (CC) are derived and tabulated in Figure 2. For all satellites, the mean biases are quite small ( $< 0.16$  m). Among the four satellites, *Envisat* overestimates the SWH (RMSE  $\sim 0.3$  m) while the other two satellites (*GFO* and *Jason-1*) underestimate it (RMSEs of 0.26 and 0.41 m). For *TOPEX*, the bias is 0.03 m and the RMSE is 0.13 m, which indicates a good comparison with the measured values. Kshatriya et al. (2001) carried out a comparison between the *TOPEX/Poseidon* SWH and the SWH measured by a set of ocean data buoys in the north Indian Ocean. They reported that altimeter-derived SWH values exhibited root mean square deviation as small as 0.3 m. Durrant et al. (2009) observed an overall RMS difference of 0.2 m between *Jason-1* data and buoy data. They also determined that *Envisat* overestimates low SWH and underestimates high SWH. Shanas et al. (2014) compared the multi-mission product of AVISO altimeter SWH with measured buoy data covering a 1-yr period at four stations off the east and west coasts of India. They found that the monthly average of buoy and altimeter data showed good correlations at three of the stations with a correlation coefficient ranging from 0.97 to 0.98.

Typically, altimeter measurements of SWH have an accuracy (RMS error) of within 0.5 m compared with buoy measurements. Following calibration, the RMS error will be less than 0.25 m (Zieger et al., 2009). We have also compared the buoy SWH data with the altimeter data after applying the correction based on the calibration function proposed by Zieger et al. (2009). The statistical parameters are presented in Table 2. After correction of the altimeter SWH of 2004 and 2005, the maximum RMS error changed from 0.41 to 0.36 m. The mean bias was also reduced slightly (Table 2). Since sufficient measured buoy data is not available for validation of the altimeter data and the altimeter mean SWH (1.20 m) is close to the buoy mean (1.23 m) without applying the correction, the altimeter data is used without applying the correction for studying the trend in wave characteristics at the study location.

### 3.2. Wind speed

Wind speed measured by the altimeter is validated against the approximated buoy-measured value for a 10-m height. The performance of all four satellites (*GFO*, *Envisat*, *Jason-1* and *TOPEX*) that were collocating with the buoy during 2004 and 2005 was found to be good (Table 3). The scatter index is in the range of 0.25 to 0.31 and good correlation is obtained for all the satellites except for *TOPEX*, where the correlation is 0.4. For all of the satellites, the RMSE is below  $1.85 \text{ m s}^{-1}$ . The RMSE of altimeter measurements for wind speed is within  $1.8\text{--}2.0 \text{ m s}^{-1}$  when compared with buoy

measurements (Zeiger et al., 2009). For *TOPEX* altimeter measurements, Kshatriya et al. (2001) obtained a RMSE value of  $1.6 \text{ m s}^{-1}$ .

### 3.3. Wave period

Wave periods estimated from different satellite altimeters are compared with wave periods obtained from the buoy. Due to insufficient collocation for individual satellites, we combined all the collocated data points and validated them. The wave period estimated using the GA-2 algorithm (Eq. 2) shows a RMSE of 1.16 s with a correlation of 0.58 (Table 4). Kshatriya et al. (2005) computed the wave period in the seas around India with *TOPEX/Poseidon* altimeter data, compared it with buoy measurements and found a RMS error of  $\pm 0.62 \text{ s}$ . Using nine buoys in the Indian Ocean region, Govindan et al. (2011) evaluated the performance of the algorithm and found a correlation of 0.79 and a RMSE of 0.82 s. The high RMSE in the present study is due to the limited buoy data used for the comparison.

### 3.4 Satellite-satellite inter-comparison of SWH

Using the validated four altimeters (*TOPEX*, *GFO*, *Envisat* and *Jason-1*), a satellite-satellite inter-comparison of the monthly mean SWH is carried out. This comparison is conducted for evaluating the performance of other satellites. Inter-comparison of the *Cryosat-2* monthly mean SWH is conducted with the monthly mean SWH of *Jason-2* due to insufficient collocations with the validated four altimeters. Statistical parameters derived for the satellite pairs have a minimum of 30 collocations except for the *Cryosat-2/Jason-2* pair and the *Poseidon/TOPEX* pair, where the number of collocations are 23 and 25, respectively. The statistical parameters derived for the comparison are tabulated in Table 5. The comparison statistics indicate that the RMSE is less than 0.5 m.

## 4. Trend analysis

We start with the analysis of the monthly average SWH and the monthly maximum SWH in the AS. Time series of monthly mean and maximum SWH values obtained from the buoy data and the values obtained from the collocated altimeter data are plotted for the available buoy data period (Fig. 3). The monthly mean SWH values derived from altimeter data match well with the buoy observation with a slight fluctuation on higher SWH values. The monthly variation of mean SWH during 1996 to 2012 shows that the values are higher during the SW monsoon period compared to other months (Fig. 4). Higher wave heights observed in the SW monsoon months are in line with the observation on monsoon wind speed and the earlier studies on waves in the AS (Kumar and Anand, 2004; Kumar et al., 2012; Sajiv et al., 2012). Based on satellite altimeter data from 1986 to 1995, Young (1999)



reported a monthly mean SWH as large as 5 m during July-August in the western AS close to the African coast.

In June and September, the mean SWH shows a positive trend ( $3.2 \text{ cm yr}^{-1}$ ), but the mean SWH shows a negative trend ( $0.38 \text{ cm yr}^{-1}$ ) during July and August and  $0.86 \text{ cm yr}^{-1}$  during May. From January to March and during November, the mean SWH shows a positive trend. During the months April, October and December, it shows neither a positive nor negative trend. The seasonal (July to September) mean SWH shows a positive trend ( $2.1 \text{ cm yr}^{-1}$ ), whereas a negative trend of  $1.9 \text{ cm yr}^{-1}$  is reported by Caires and Swail (2004) for AS-based VOS data.

Similar to the mean SWH values, the monthly maximum SWH values during the SW monsoon period are higher than those during other months (Fig. 5). The maximum SWHs in June, July and August show a negative trend ( $0.59 \text{ cm yr}^{-1}$ ), whereas the maximum SWH in September shows a positive trend of  $7.1 \text{ cm yr}^{-1}$ . The highest SWHs during the annual cycle are observed in June and July. The maximum SWH during a TC event in the non-monsoon months are above the best-fit line.

The annual mean SWH during the study period shows a positive trend (Fig. 6). In 1996, the mean SWH was 1.57 m. It was 1.68 m in 2012 with an annual increase of 0.63 cm. If the same trend continues for next 30 yrs, then the annual mean SWH after 30 yrs will be 1.87 m. In contrast, in the previous five decades in the north Atlantic, Carter and Draper (1988) and Bacon and Carter (1993) found that the SWH increased by  $3.4$  and  $2.2 \text{ cm yr}^{-1}$ , respectively. Bouws et al. (1996) reported an increase in the mean SWH of  $2.3 \text{ cm yr}^{-1}$  and  $2.7 \text{ cm yr}^{-1}$  in the north-west Atlantic and in the north-east Atlantic, respectively, but Gulev and Hasse (1999) reported a small increase in the SWH of  $0.1$ - $0.3 \text{ cm yr}^{-1}$  during the period 1964-1993. In the north Pacific, Allan and Komar (2000) and Gower (2002) reported a positive trend of  $2.1$  and  $1.9 \text{ cm yr}^{-1}$ , respectively, and an extended study by Ruggiero et al. (2010) found that the annual average SWH has increased at a rate of  $\sim 1.5 \text{ cm yr}^{-1}$  from the mid-1970s to 2010 and is  $0.4$  to  $0.6 \text{ cm yr}^{-1}$  less than the previous study.

Wind-sea and swell are two types of waves observed in the ocean surface (Munk et al., 1963). Glejin et al. (2013) reported that long period swells generated in the Southern Ocean can modulate the local wind waves in the eastern Arabian Sea. Swell/wind-sea characterization of global oceans has been done by several authors (Hanley et al., 2010; Semedo et al., 2011). In order to understand how the wind-sea and swells are varying at the study area from 1996 to 2012, wind-sea and swells were separated based on the method suggested by Chen et al. (2002) and the trend analysis with the wind-sea and swell height at the location were done separately (Figs. 7a and 7b). The analysis shows that the average annual wind-sea heights were increasing ( $2.1 \text{ cm yr}^{-1}$ ), whereas the swell heights show a

small positive trend ( $0.2 \text{ cm yr}^{-1}$ ). Zieger et al. (2014) observed that the annual trend of the mean wind speed in the north Indian Ocean is weak ( $1.6 \text{ cm s}^{-1}$  in altimeter and  $-0.6 \text{ cm s}^{-1}$  in SSM/I) and is significantly less than the global average. The trend in the annual mean wind speed for the study location is  $4.3 \text{ cm s}^{-1}$  (Fig. 7c) and it resulted in the positive trend in wind-sea.

In the Indian Ocean sector of the Southern Ocean, the SWH shows an increasing trend (Hemer et al. 2010). The numerical modelling study of Alves (2006) showed that the swells generated in the Southern Ocean propagate into the tropical and extra tropical latitudes of the Indian Ocean and the Pacific Ocean. The dominance of swells in the north Indian Ocean was shown in earlier studies (Sajiv et al., 2012; Glejin et al., 2013). Hence, the positive trend observed for the annual mean SWH is due to the increase in wave and wind intensity in the Southern Ocean apart from the increase in winds in the central AS.

A study by Young et al. (2011) shows that, in the central AS, the annual mean SWH increased by 0-0.25% per year from 1985-2008. The annual mean SWH for the study location is around 1.1 m (Sajiv et al., 2012) and the increase, as per Young et al. (2011), is  $0-0.28 \text{ cm yr}^{-1}$ , whereas the value obtained in the present study is slightly higher ( $0.63 \text{ cm yr}^{-1}$ ). Based on ERA-Interim data from 1979-2012, Shanasa and Kumar (2014) found that the annual mean SWH shows a slight positive trend ( $0.012 \text{ cm yr}^{-1}$ ), whereas a larger upward trend ( $1.4 \text{ cm yr}^{-1}$ ) is observed for the annual maximum SWH in a shallow water location in the eastern AS.

We also checked whether the entire storm/cyclone-induced wave heights at the study location are measured by the satellite altimeter. Tropical storm/cyclone periods and the number of satellites passing around the location are tabulated in Table 6 and the tracks are shown in Fig.1. For almost every storm/cyclone event except the 1998 October storm, a satellite pass covered the study location. The maximum SWH during the 1998 October storm at the study location is 3.8 m as per the ERA-40 reanalysis data (Uppala, 2005). This value is less than the annual maximum SWH ( $\sim 7.2 \text{ m}$ ) in 1998. Hence, missing altimeter data during October 1998 will not alter the trend of the annual maximum SWH.

Kumar and Sajiv (2010) carried out a study on variations in long-term wind speed estimates considering different decades in the AS. They reported that extreme wind speed has an annual negative trend of  $1.3 \text{ cm s}^{-1}$ . Since extreme events influence the trend in wind speed and the annual maximum SWH, we analyzed storm/tropical cyclone (TC) events in the AS that will modify the wave height in the study area. Hence, TC events in the area  $5-25^\circ \text{ N}$ ,  $60-80^\circ \text{ E}$  during the period 1996-2011 are studied (Fig. 1). In the north Indian Ocean, tropical cyclones are classified as tropical

depressions (wind speed  $< 17.5 \text{ m s}^{-1}$ ), tropical storms (wind speed between  $17.5$  and  $33 \text{ m s}^{-1}$ ) and typhoon/cyclones (wind speed  $> 33 \text{ m s}^{-1}$ ), as in the JTWC best-track dataset.

Several TCs passed near the study location. Among them, the ARB 02 (Gujarat cyclone) was a very severe cyclonic storm (Rao et al., 2010) and it generated the maximum SWH ( $\sim 7.2 \text{ m}$ ). This TC formed on June 4, 1998 and dissipated on June 10, 1998. On June 6, the ARB 02 TC had an intensity of  $33 \text{ m s}^{-1}$  ( $120 \text{ km h}^{-1}$ ). India Meteorological Department (IMD) marked the increase in intensity, upgrading ARB 02 to a severe cyclonic storm. It crossed the study location on June 7 and satellite *TOPEX* captured a SWH of  $7.2 \text{ m}$  near the study location on the same day. The track of the TC and the satellite pass is shown in Fig. 8. On June 9, ARB 02 attained its peak intensity with winds of  $54 \text{ m s}^{-1}$  ( $195 \text{ km h}^{-1}$ ) and made landfall near Porbandar in the Indian state of Gujarat.

Evan and Camargo (2011) analysed AS tropical cyclones during the period 1979-2008 using position and intensity estimates reported in the JTWC best-track dataset. They found that there has been an increase in the number, duration and intensity of AS cyclones. During the present study period, 23 TC events occurred, of which 9 were cyclones and 14 were tropical storms (Fig. 9). During the period 2002 to 2011, only two cyclone events occurred, but of the 14 tropical storm events, 9 occurred during the same period. Fig. 9 indicates that cyclone events are showing a negative trend and tropical storm events are showing a positive trend. Singh et al. (2001) found that the annual frequency of TCs in the north Indian Ocean has a negative trend of about 15% per one hundred years.

For the study location, the annual maximum SWH shows a negative trend of  $2.66 \text{ cm yr}^{-1}$ . The tropical cyclone activity and other local storm events can influence the wind and wave parameters significantly for a short-term interval and can alter the trend pattern of the annual maximum wind speed and the maximum SWH of the location significantly (Shanas and Kumar, 2014). Hence, the decreasing trend in the maximum SWH found in contrast to the positive trend in SWH is due to the decreasing trend ( $1.3 \text{ cm s}^{-1}$ ) of the extreme wind speed (Kumar and Sajiv, 2010) and the decreasing trend of cyclones in the AS (Singh et al., 2001). From the yearly SWH maximum, if the 1998 cyclone value ( $7.2 \text{ m}$ ) is excluded, then the maximum SWH is showing a weak positive trend ( $0.01 \text{ cm yr}^{-1}$ ).

## 5. Conclusion

This study shows the variability of annual mean and maximum SWH at a selected deep water location (off Goa) in the central Arabian Sea using along-track satellite altimeter data. Satellite altimetry data were validated with the buoy data for a limited period (2004-2005) and the data from

1996 to 2012 including the tropical cyclone events were analysed. Since the buoy data for the validation of altimetry data was only available for two years, no correction was applied to the altimetry data. For almost every storm/cyclone event except the 1998 October storm, a satellite pass covered the study location. The trend of tropical cyclones which influence the SWH at the study location were analysed, and we found that the cyclone events are showing a negative trend. The yearly mean SWH shows a positive trend of  $0.63 \text{ cm yr}^{-1}$  and the yearly maximum SWH shows a negative trend of  $2.66 \text{ cm yr}^{-1}$ . Whereas in the northern Pacific (Allan and Komar, 2000; Gower, 2002) and the northern Atlantic (Bacon and Carter, 1993; Bouws et al., 1996; Carter and Draper, 1988), the annual average SWH is increasing at a greater rate than that we observed in the AS. Finally, the annual mean and maximum wave period shows a negative trend of  $0.005 \text{ s yr}^{-1}$  and  $0.011 \text{ s yr}^{-1}$ , respectively.

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## Figure Captions

Figure 1. Arabian Sea cyclonic storm tracks for the period 1996- 2011. The genesis points for each storm represented by different symbols except for three storms with genesis in the Bay of Bengal, where the symbol is not representing the genesis point. Dashed lines represent Tropical storm (wind speed between  $17.5$  to  $33 \text{ ms}^{-1}$ ), thick lines represent cyclone (wind speed  $> 33 \text{ ms}^{-1}$ ). Location considered in the study is the buoy location.

Figure 2. Scatter plot of buoy SWH versus along-track SWH of four satellites (*GFO*, *Envisat*, *Jason-1*, *TOPEX*) during the years 2004 and 2005.

Figure 3. Comparison of monthly mean and maximum SWH derived from altimeter data and buoy observation for the period January 2004 to July 2005.

Figure 4. Monthly mean SWH at the study location derived from altimeter data during the period 1996 to 2012.

Figure 5. Monthly maximum SWH at the study location derived from altimeter data during the period 1996 to 2012.

Figure 6. Annual mean and maximum SWH at the study location derived from altimeter data during the period 1996 to 2012.

Figure 7. Trends in annual mean (a) swell SWH, (b) wind-sea SWH and (c) wind speed from 1996 to 2012.

Figure 8. Track of severe cyclone ARB 02 (open circles), track of TOPEX pass (dash lines) and the study location.

Figure 9. Cyclone events in the  $5\text{-}25^{\circ}\text{N}$ ,  $60\text{-}80^{\circ}\text{E}$  during the period 1996- 2011. Thick bar represents cyclone and cross lined bar represents Tropical storm.

Figure 10. Annual mean and maximum wave period at the study location computed from altimeter measured wind and SWH data during the period 1996 to 2012.

**Table 1.** Period of satellite altimeter data used and satellite repeat cycle

Satellite	Data periods	Repeat cycle (days)
<i>Cryosat-2</i>	28 Jan 2011- 24 Dec 2012	30
<i>ERS-1</i>	01 Jan 1996- 02 Jun 1996	35
<i>ERS-2</i>	01 Jan 1996- 04 Jul 2011	35
<i>Envisat</i>	14 May 2002- 24 Dec 2012	35
<i>GFO</i>	07 Jan 2000- 17 Sep 2008	17
<i>Jason-1</i>	15 Jan 2002- 24 Dec 2012	10
<i>Jason-2</i>	12 Jul 2008- 24 Dec 2012	10
<i>TOPEX/Poseidon</i>	01 Jan 1996- 08 Oct 2005	10

**Table 2.** Statistical parameters derived for the comparison of corrected altimeter along-track SWH with buoy during the years 2004 and 2005

Satellite	MB (m)	RMSE (m)	SI	CC	mean buoy (m)	mean altimeter (m)	mean altimeter before correction (m)
<i>GFO</i>	0.00	0.18	0.17	0.89	1.05	1.05	0.89
<i>Envisat</i>	0.04	0.29	0.23	0.87	1.27	1.31	1.42
<i>Jason-1</i>	-0.08	0.36	0.23	0.99	1.58	1.50	1.45
TOPEX	-0.01	0.12	0.12	0.88	1.01	1.00	1.05

**Table 3.** Statistical parameters derived for the comparison of altimeter along-track wind speed with buoy data during the years 2004 and 2005

Satellite	MB ( $\text{m s}^{-1}$ )	RMSE ( $\text{m s}^{-1}$ )	CC	SI	mean altimeter ( $\text{m s}^{-1}$ )	mean buoy ( $\text{m s}^{-1}$ )
<i>Envisat</i>	-0.55	1.56	0.70	0.25	5.59	6.15
<i>GFO</i>	-0.69	1.51	0.58	0.27	4.98	5.68
<i>Jason-1</i>	-0.52	1.83	0.84	0.31	5.46	5.98
<i>TOPEX</i>	-0.24	1.67	0.40	0.27	5.88	6.12

**Table 4.** Statistical parameters derived for the comparison of computed with buoy measured wave period during the years 2004 and 2005

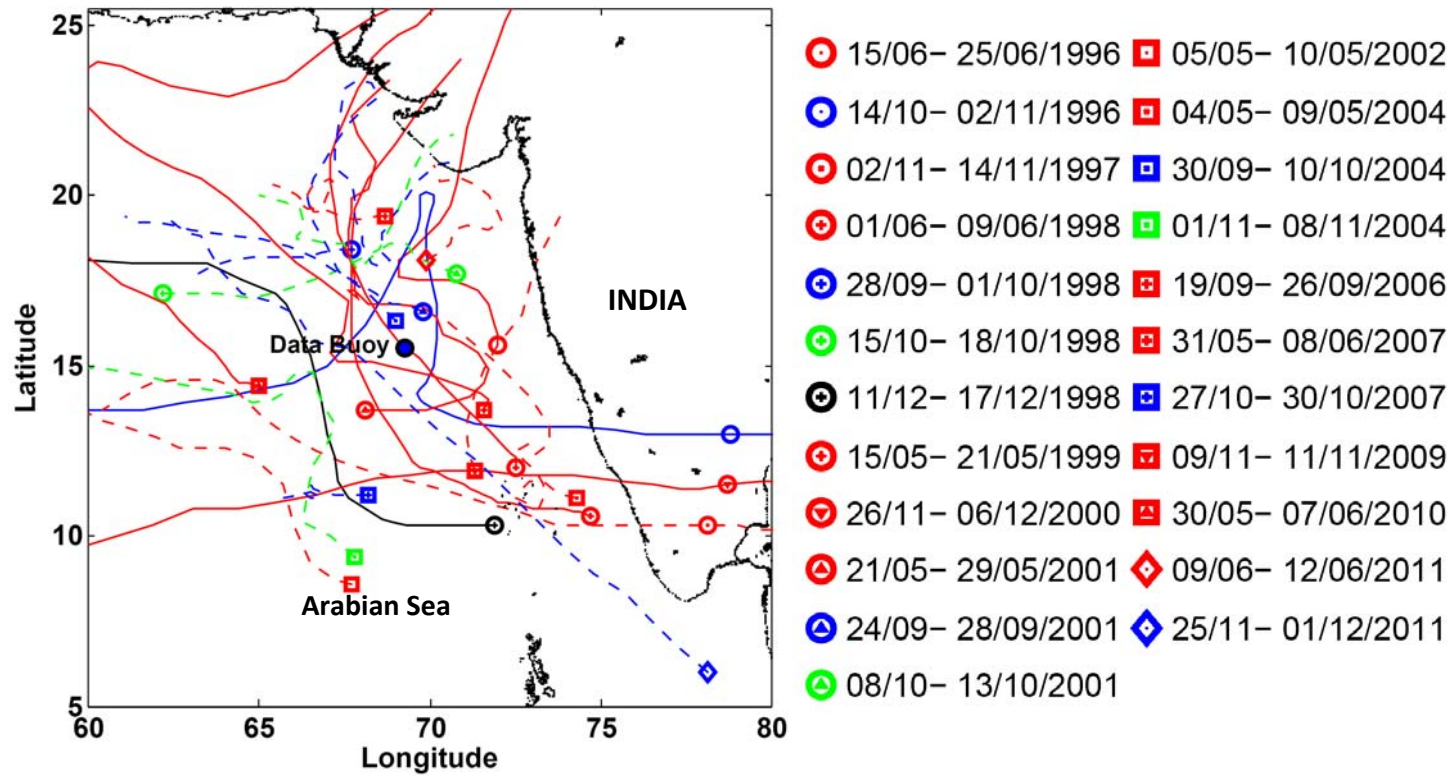
MB (s)	RMSE (s)	CC	SI	mean altimeter (s)	mean buoy (s)
-0.66	1.16	0.59	0.24	4.79	5.45

**Table 5.** Statistical parameters derived for the satellite- satellite inter comparison.

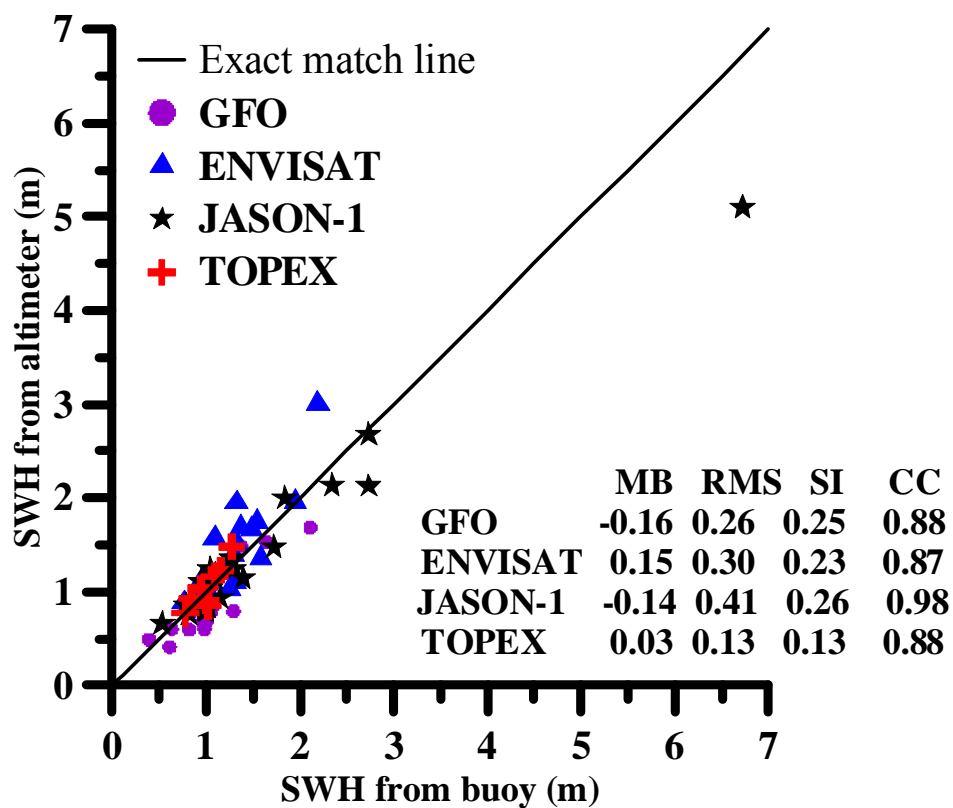
Satellite 1	Satellite 2	MB (m)	RMSE (m)	CC	SI	mean Satellite1 (m)	Mean Satellite2 (m)
<i>TOPEX</i>	<i>ERS-1</i>	0.32	0.43	0.96	0.33	1.64	1.32
<i>GFO</i>	<i>ERS-2</i>	0.02	0.27	0.95	0.19	1.42	1.40
<i>TOPEX</i>	<i>ERS-2</i>	0.17	0.36	0.94	0.24	1.66	1.48
<i>Envisat</i>	<i>GFO</i>	0.30	0.44	0.95	0.24	1.85	1.56
<i>Envisat</i>	<i>Jason-1</i>	0.06	0.42	0.91	0.25	1.68	1.62
<i>Envisat</i>	<i>Jason-2</i>	0.04	0.40	0.92	0.24	1.67	1.63
<i>GFO</i>	<i>Jason-1</i>	-0.17	0.30	0.97	0.20	1.49	1.66
<i>Jason-1</i>	<i>Jason-2</i>	-0.04	0.26	0.97	0.16	1.69	1.73
<i>Jason-2</i>	<i>Cryosat-2</i>	-0.07	0.40	0.91	0.22	1.71	1.78
<i>TOPEX</i>	<i>Poseidon</i>	-0.9	0.44	0.92	0.21	1.96	2.05

**Table 6.** Cyclone details and satellite pass along the study location during cyclone period

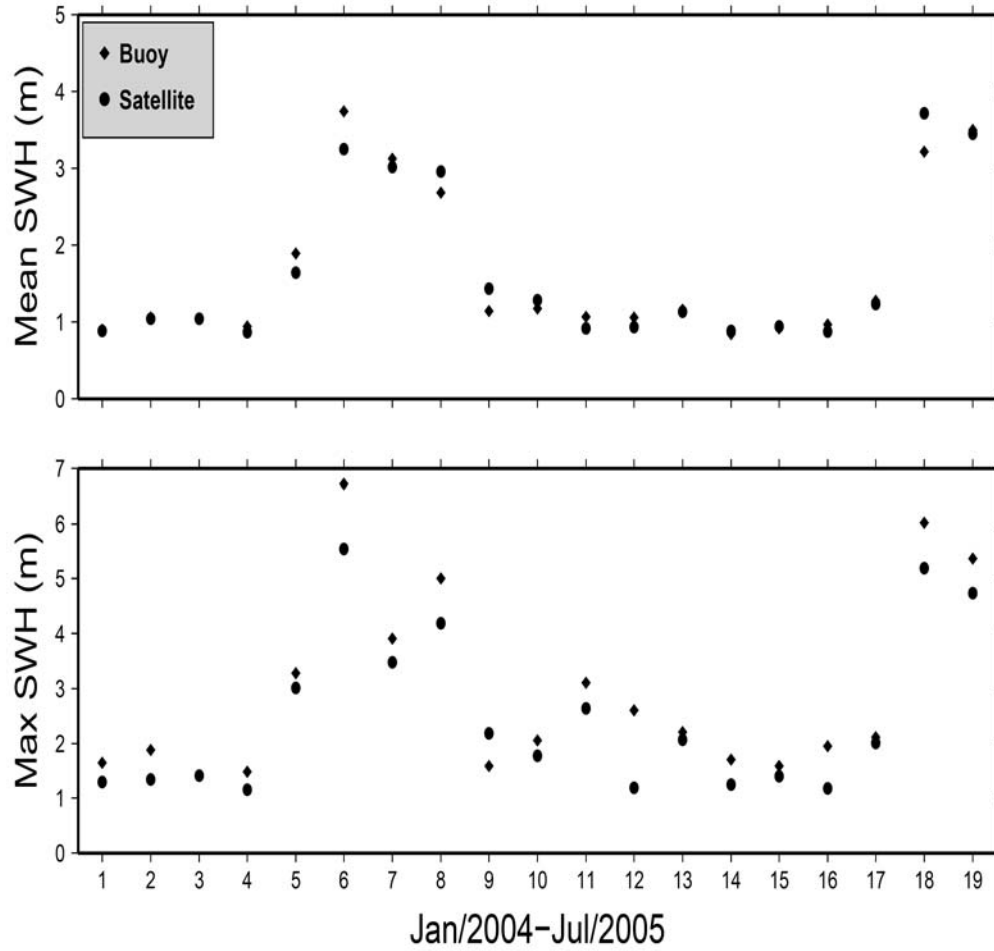
Cyclone start date	Cyclone end date	Minimum distance to the cyclone eye from the study location (km)	Maximum wind speed ( $\text{m s}^{-1}$ )	Satellite pass (days)
15-06-1996	25-06-1996	222.79	33.44	3
14-10-1996	02-11-1996	105.64	33.44	4
02-11-1997	14-11-1997	413.43	28.29	3
01-06-1998	09-06-1998	161.45	54.02	2
28-09-1998	01-10-1998	363.27	18.01	1
15-10-1998	18-10-1998	330.34	18.01	0
11-12-1998	17-12-1998	306.59	33.44	1
15-05-1999	21-05-1999	29.6	56.59	1
26-11-2000	06-12-2000	407.21	38.58	4
21-05-2001	29-05-2001	130.82	56.59	2
24-09-2001	28-09-2001	133.84	18.01	1
08-10-2001	13-10-2001	282.73	18.01	3
05-05-2002	10-05-2002	590.49	23.15	1
04-05-2004	09-05-2004	158.05	23.15	3
30-09-2004	10-10-2004	93.23	18.01	5
01-11-2004	08-11-2004	304.69	20.58	3
19-09-2006	26-09-2006	433.72	28.29	2
31-05-2007	08-06-2007	76.24	74.59	2
27-10-2007	30-10-2007	487.69	20.58	2
9-11-2009	11-11-2009	263.6	25.72	1
30-05-2010	07-06-2010	486.1	64.31	3
09-06-2011	12-06-2011	294.02	18.01	2
25-11-2011	01-12-2011	117.78	18.01	3



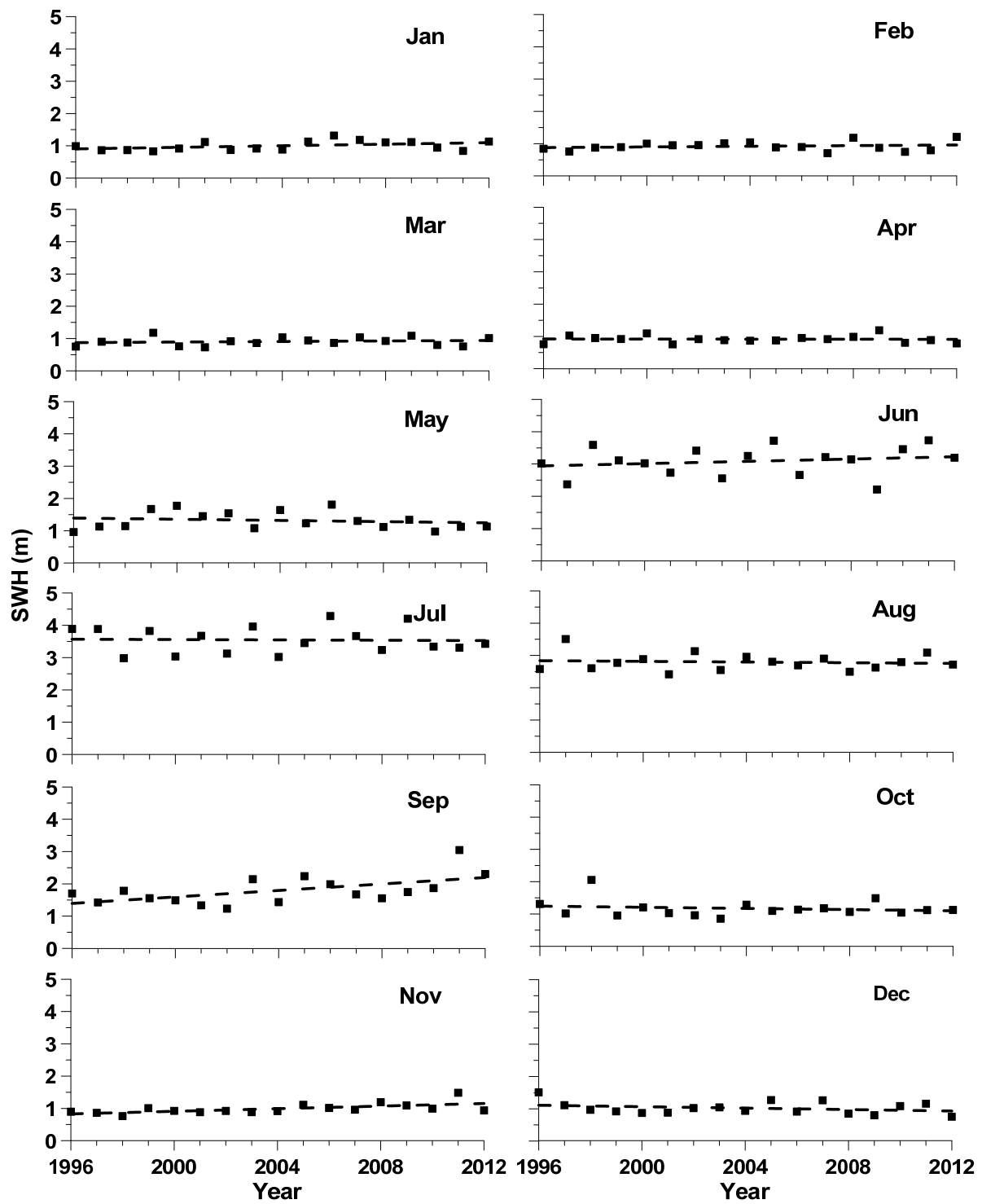
**Figure 1.** Arabian Sea cyclonic storm tracks for the period 1996- 2011. The genesis points for each storm represented by different symbols except for three storms with genesis in the Bay of Bengal, where the symbol is not representing the genesis point. Dashed lines represent Tropical storm (wind speed between  $17.5$  to  $33 \text{ ms}^{-1}$ ), thick lines represent cyclone (wind speed  $> 33 \text{ ms}^{-1}$ ). Location considered in the study is the buoy location.



**Figure 2.** Scatter plot of buoy SWH versus along-track SWH of four satellites (GFO, Envisat, Jason-1, TOPEX) during the years 2004 and 2005.

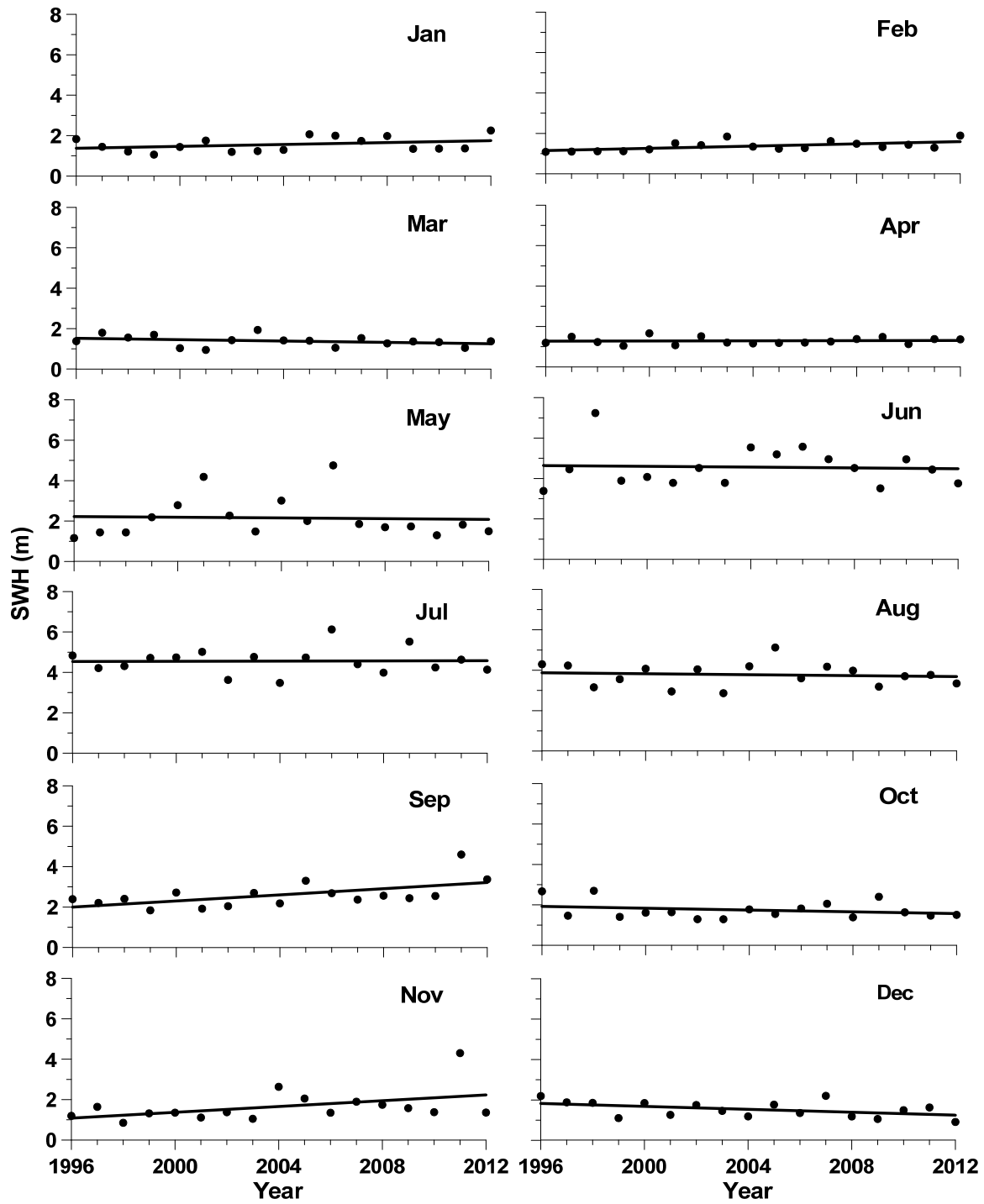


**Figure 3.** Comparison of monthly mean and maximum SWH derived from altimeter data and buoy observation for the period January 2004 to July 2005.

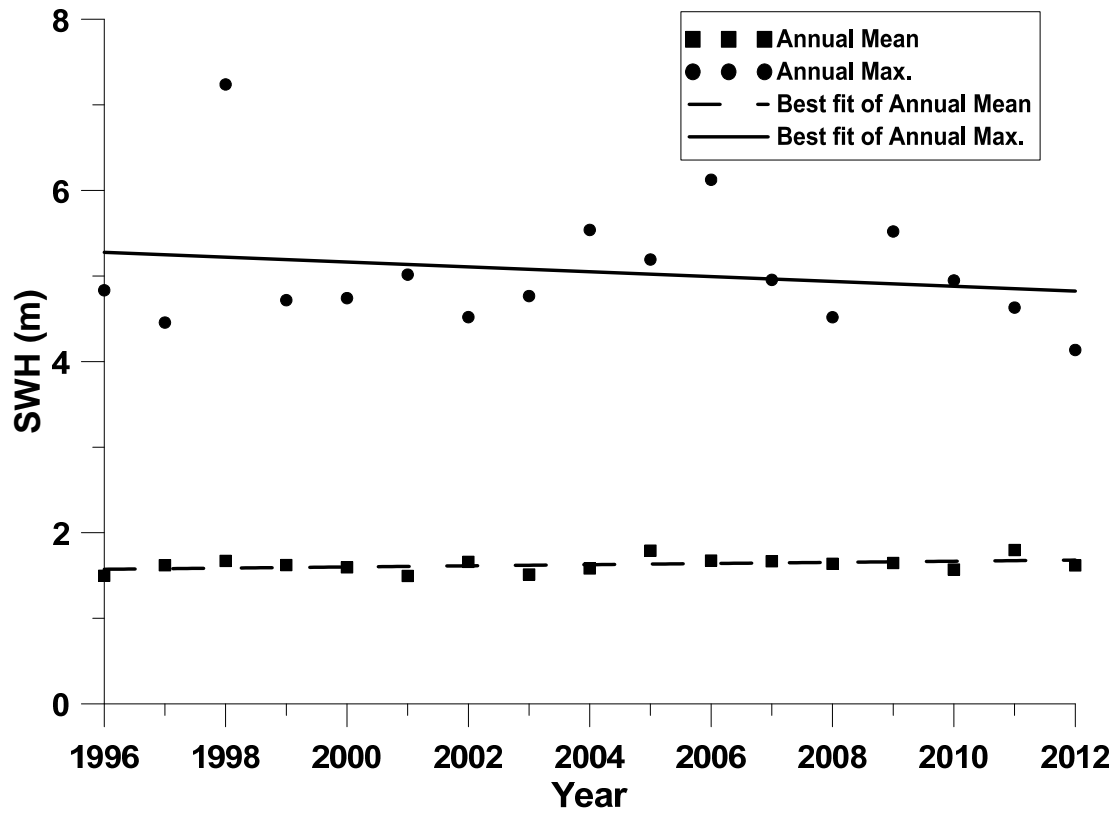


**Figure 4.** Monthly mean SWH at the study location derived from altimeter data during the period 1996 to 2012

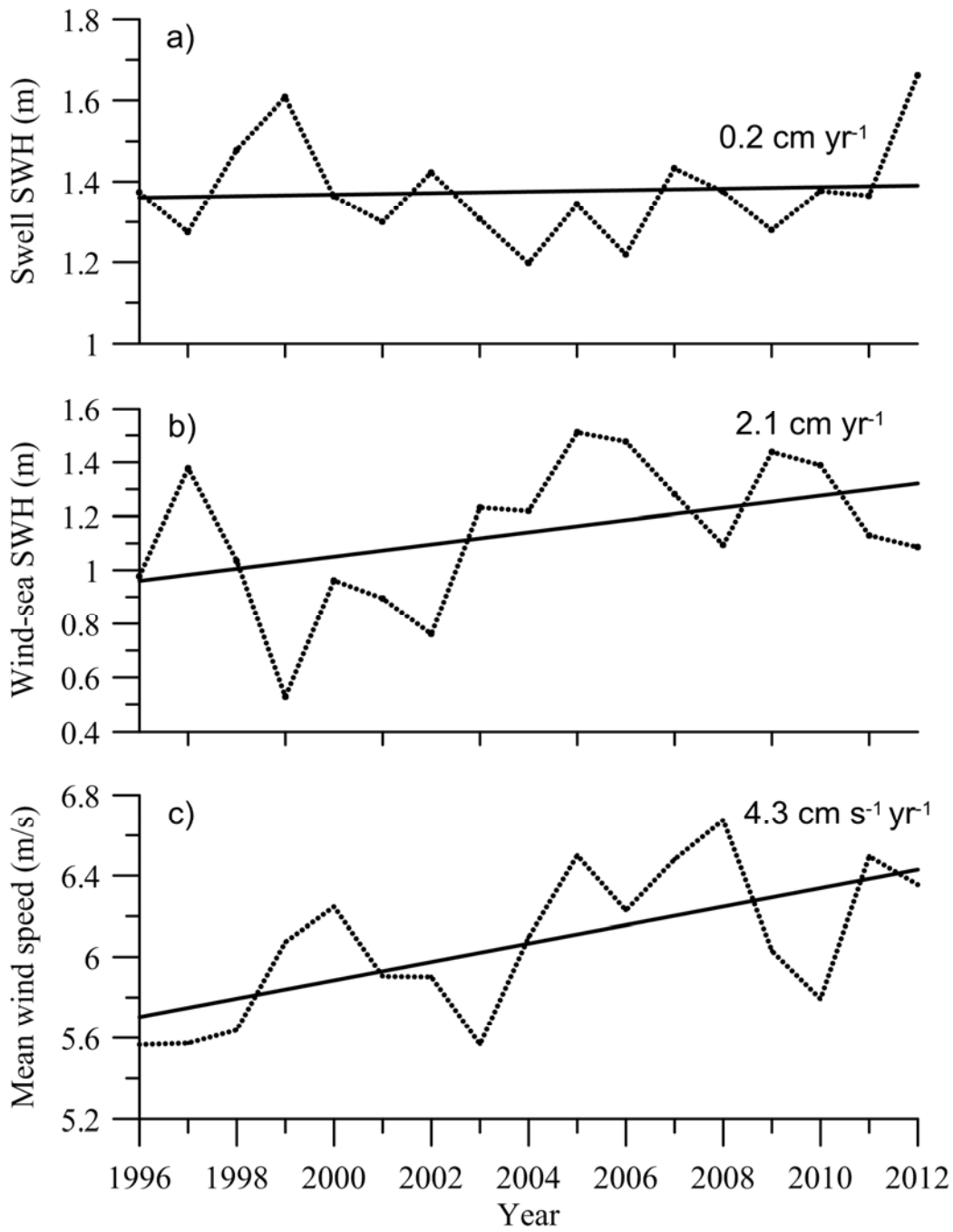




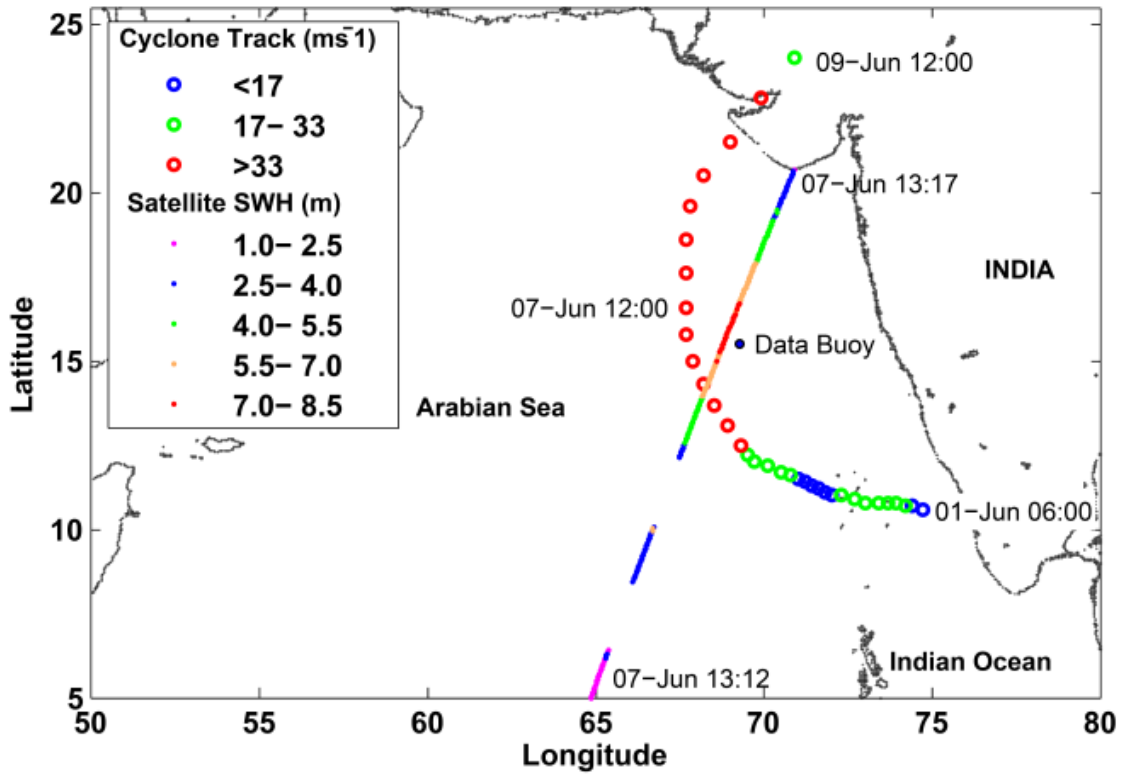
**Figure 5.** Monthly maximum SWH at the study location derived from altimeter data during the period 1996 to 2012



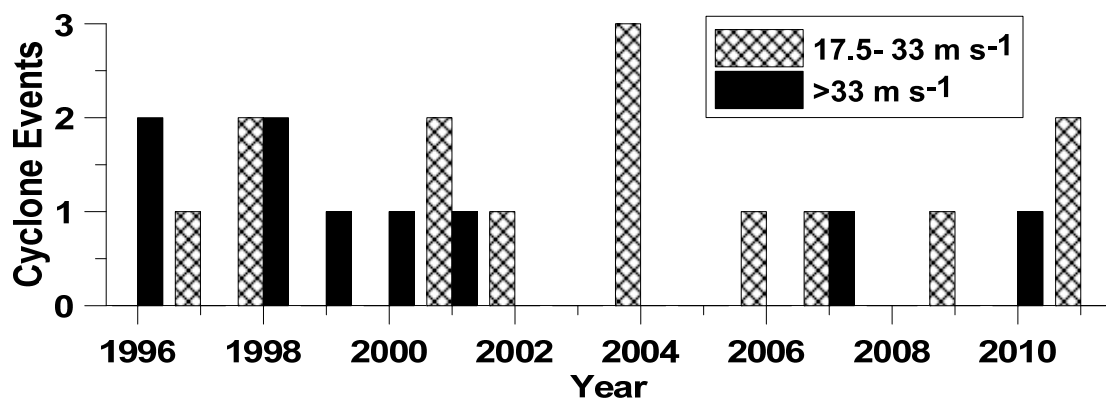
**Figure 6.** Annual mean and maximum SWH at the study location derived from altimeter data during the period 1996 to 2012



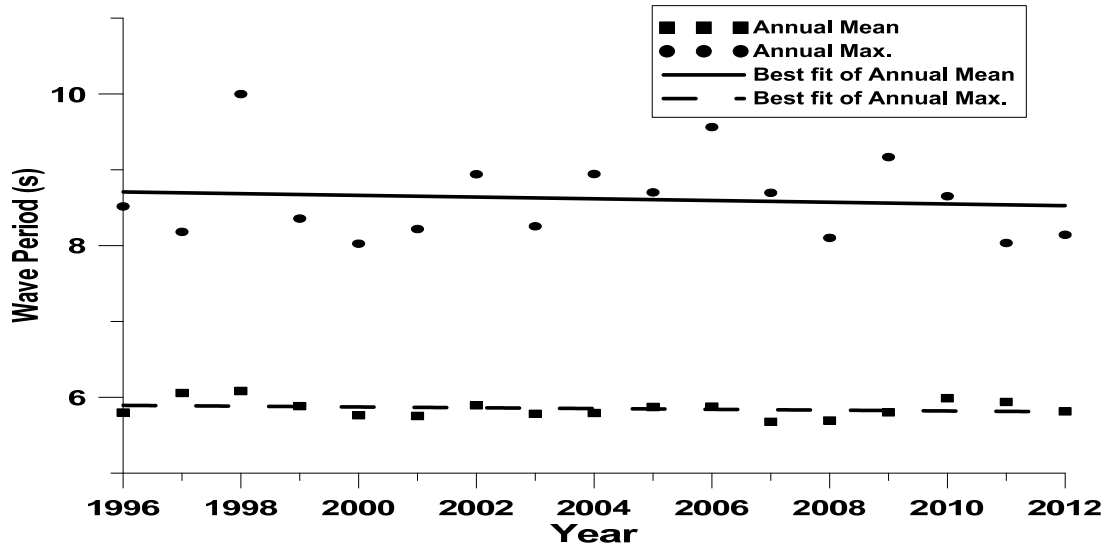
**Figure 7.** Trends in annual mean (a) swell SWH, (b) wind-sea SWH and (c) wind speed from 1996 to 2012.



**Figure 8.** Track of severe cyclone ARB 02 (open circles), track of TOPEX pass (dash lines) and the study location



**Figure 9.** Cyclone events in the 5-25<sup>0</sup> N, 60-80<sup>0</sup> E during the period 1996- 2011. Thick bar represents cyclone and cross lined bar represents tropical storm.



**Figure 10.** Annual mean and maximum wave period at the buoy location computed from altimeter measured wind and SWH data during the period 1996 to 2012.