

## **Trends in surface wind speed and significant wave height as revealed by ERA-Interim wind wave hindcast in the Central Bay of Bengal**

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### **Abstract**

The Arabian Sea and Bay of Bengal regions are special interested sea areas in the Northern Hemisphere with large seasonal variability. Present study focused on the long-term wind and wave in the central Bay of Bengal from 1979 to 2012 based on the ECMWF ERA-Interim reanalysis data sets. Data were validated with the nearest available buoy data for the years 2003, 2004 and 2005, and good correlation was observed (root mean square error  $\approx$  0.17-0.43 m). A clear seasonality was noted with intensified wind and waves during the southwest monsoon season. We observed statistically declining trends in the mean and extreme wind speed (90<sup>th</sup> percentile) with increasing trend in extreme significant wave height (SWH). Seasonal analysis also investigated and found that the stronger events/winds during the SW monsoon season are weakening. Conflicting trends in the wind and wave height were mainly due to the swell dominance at the region which was identified by the separate trend analysis of wind-sea and swell height. The area average analysis is carried out to investigate the sensitivity of the identified trend results for the point location and found similar trends for extreme wind speed and SWH. The high (> 5 m) annual maximum SWH in the study area was attributed to the influence of tropical cyclones in the Bay of Bengal, and all of these high waves occurred before 1996 indicating that the influence of tropical cyclones in the study area decreased after 1996.

**Key words:** wave climate, tropical cyclones, long-term changes, monsoons, winds, North Indian Ocean

## 1. Introduction

Understanding the wind and wave climate of the global ocean is of increasing demand for a number of reasons. The scientific community aims to better understand and more precisely predict many environmental phenomena and processes related to global change in both large scale as well as in regional scale. It is well understood that the sea-state or the waves in the ocean play a dominant role in the air-sea interaction process of the coupled ocean-atmosphere system. The coexisting of wind-sea and swell can significantly affect sea-keeping safety, offshore structure designs, small boat operations and ship passages over harbor entrance, and surf forecasting (Earle, 1984). The mixed seas also affect the dynamics of near-surface processes such as air-sea momentum transfer (Dobson *et al.*, 1994; Donelan *et al.*, 1997; Hanson and Phillips, 1999). Long-term study of wind and wave climate at a location can reveal the inter-annual and decadal variability in the wind and wave parameters. Long-term study of wind and wave climate requires data sets covering longer periods of about 30 years. Analyses of long-term changes require homogeneous time series that cover the area of interest at high spatial and temporal detail, a requirement that is frequently not fulfilled by the available observational data (Weisse and Gunther, 2007).

Wind and wave climate are generally assessed based on the data obtained through i) in-situ measurements, ii) voluntary observing ships (VOS) data, iii) satellite altimeter and iv) model data sets. In-situ wave data coverage in the world ocean is sparse and is not be available for longer duration for most of the regions. From the wave climate point of view, accuracy and duration of the wave data without significant gaps are considered to be of equal importance. In some cases, wave measurements over a minimum period of one year is being used for coastal engineering applications, but it is too short a duration to yield reliable information on wave climate or extreme wave statistics (Swain,1997). VOS data, visual observations of wind and wave parameters from ships are available since 1784 and have always been of great importance, and will continue to be important, but such observations need to be calibrated with measurements (Soares, 1986). However, by their nature these observations are subjective and there are large un-sampled areas over the oceans due to missing ship routes (Gulev and Grigorieva, 2004). Satellite altimetry and its recent improvement in resolution as well as in the data quality are worthwhile, but the chances of missing the extreme events are present. Wave hind-casts with numerical models have therefore become a common tool to complement existing observations and to analyze trends and variability of severe wave events (e.g. Sterl *et al.*, 1998, Wang and Swail, 2002). Finally, the wave reanalysis data, which are driven by modelled and measured oceanic wind field, and validated can increase the available observations by interpretations and interpolations and allow evaluations of possible cause and effect of wind and wave variability (Woolf and Wolf, 2006). The main advantages of global reanalysis data are their physical consistency and relatively high

temporal coverage. The problem of inhomogeneity is not expected; although, the use of these data for regional climate studies presents some limitations due to their coarse spatial resolution (WASA Group, 1998). The Indian subcontinent divides the North Indian Ocean into two semi-enclosed seas, the Arabian Sea (AS) and the Bay of Bengal (BoB), both of which encroach onto the equatorial regime of the basin (Shankar and Shetye, 2001). A comprehensive understanding of the properties of the waves and their potential changes represents the major knowledge necessary for sustainable management of the offshore and coastal region. Moreover, the wave climate is one of the most sensitive indicators of changes in the wind regime and local climate in semi-enclosed seas (Weisse and von Storch, 2009). The BoB plays an important role in maintaining and modulating the monsoon over the Indian Ocean (Vinayachandran *et al.*, 1996). The monsoons of the Indian Ocean are an example of particularly strong ocean-atmosphere interaction over basin scales. The large-scale wind field in the northern Indian Ocean reverses between boreal summer and winter, leading to changes in the basin-scale ocean circulation. Significant changes in the wind field drive strong modulations in the ocean currents in the BoB (Riser *et al.*, 2008). The BoB region is an area generally prone to cyclone events and these events can cause large inter-annual variations in wave parameters.

As a part of the global study, Young *et al.* (2011) examined the long-term trends in SWH in the BoB from 1985 to 2008 based on satellite altimeter data. The long-term changes and decadal variation in the wave climate in the BoB region has not been investigated. Earlier studies in the BoB were mainly restricted to short-term studies or were based on the VOS data. Using the VOS data for a 19-year period, the wave statistics around the Indian coast were studied by Chandramohan *et al.* (1991). A similar study was carried out by Sundar (1986) along the southeast coast of India based on data for a 10-year period. However, trend analysis was not attempted in these studies. The wave characteristics were also studied based on the buoy-measured data covering an annual cycle (Nayak *et al.*, 1992; Glejin *et al.*, 2013; Kumar *et al.*, 2014). Kumar and Sajiv (2010) carried out a study on variations in the long-term wind speed by examining data from different decades in the AS and in the BoB. Kumar *et al.* (2013) using the altimeter data, studied the variation in significant wave height (SWH) and wind speed for the period 1993-2010 over the entire Indian Ocean by categorizing the area into six zones. No regionalised study has been performed on the temporal variations of wind speed and SWH in the BoB region. This study therefore carries out this analysis using the ERA-Interim European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis data sets from 1979 to 2012. The climatological variables used in the current study are the wind speed and SWH and the objective is to quantify the seasonal, inter-annual and decadal variability of the wind and wave climate. A deep-water location (14.25° N, 83.25° E) in the BoB was selected, because buoy-measured data were available near this location for comparison with the ERA-Interim data. We have also selected a 5° x 5° box area

at the central BoB in order to strengthen the result of the analysis. The wave climate of the BoB is different for different areas; the south-western BoB is a shadow area of Sri Lanka with relatively low wave height compared to the northern BoB (Glejin *et al.*, 2013). The northern BoB is under the influence of SW and NE monsoon (Kumar *et al.*, 2014) and the north-eastern BoB is a cyclone prone area and is rough during most of the seasons. So carrying out the area averaging for the entire BoB may not be correct and hence our study is restricted to the central BoB.

## **2. Data and methodology**

### **2.1 Data**

The data used in the study were taken from the ERA-Interim global atmospheric reanalysis produced by the ECMWF. The ERA-Interim is the most recent reanalysis data set provided by the ECMWF and contains selected improvements on the ERA-40, such as the complete use of four-dimensional variational data assimilation (Dee *et al.*, 2011). The system handles data events such as the appearance of a new radiance data stream, and it initialises, updates, and keeps track of bias estimates for radiances from all satellites and sensors present (Dee and Uppala, 2008). Updated atmospheric model (Integrated Forecast System Cycle 31r2) is used in the data analysis. This model includes increased pressure levels and additional cloud parameters, taking an advantage of improved model physics (Simmons *et al.*, 2007). The model also assimilates new wind observations from Meteosat reprocessed winds. ERA-Interim uses recent satellite altimeter data together with the built in ERA-40 data assimilation. The wave model incorporated in the IFS is based on the WAM approach (Komen *et al.*, 1994) and the version used in ERA-Interim includes several enhancements, both in physics and numerics, over the version that was used in ERA-40 (Janssen *et al.*, 2005; Janssen, 2008). The most significant for climate applications are the introduction of a scheme for treating unresolved bathymetry effects and a reformulation of the dissipation source term (Bidlot *et al.*, 2007). The horizontal resolution of the wave model in ERA-Interim is 110 km; wave spectra are discretised using 24 directions and 30 frequencies. Internal validation of the ocean wave height analysis produced with ERA-Interim also indicates a higher degree of homogeneity (Dee *et al.*, 2011).

An updated version of WAM includes a revised formulation of ocean wave dissipation which reduced the RMS error in SWH against buoy data and is smaller than that in ERA-40 (Bidlot *et al.*, 2007). Also there is reduced 10 m wind speed bias over extratropical ocean areas in the northern hemisphere (Uppala *et al.*, 2008). Wind speed and SWH data with a grid resolution of  $0.75 \times 0.75^\circ$  were downloaded for the period from January 1979 to December 2012 at 6-hour intervals and used in the study. The measured wave data collected using a moored Seatex buoy (Oceanor, Norway) in a deep

water location at 13.978° N, 83.260°E (Figure 1) under the National Data Buoy Programme (Premkumar *et al.*, 2000) during May–November 2003 and July 2004–May 2005 were used for comparison with the ERA-Interim SWH data. The buoy measures heaves in the range of -20 to +20 m with a resolution of 1 cm and an accuracy of 10 cm. Using the heave data recorded by the buoy for 17-min durations at 2-Hz intervals, the wave spectrum was obtained via Fast Fourier Transform (FFT) with a high frequency cut-off at 0.5 Hz. The SWH was obtained from the wave spectrum.

We have carried out the separation of wind-sea and swell using the method suggested by Chen *et al.* (2002). Since surface wind speed (U) and SWH follow a fully developed relationship, the wind–wave relation for fully developed seas is (Pierson, 1991);

$$SWH = 1.6 \times 10^{-2} U^2 \quad \text{for } 0 \leq U < 7.5 \text{ m s}^{-1} \quad (1)$$

$$SWH = 10^{-2} U^2 + 8.1 \times 10^{-4} U^3 \quad \text{for } 7.5 \leq U < 50 \quad (2)$$

To quantify the frequency of occurrences of wind-sea and swell, two probability indices were introduced by Chen *et al.* (2002).

$$P_s = N_s / N \quad \text{and} \quad (3)$$

$$P_w = N_w / N \quad (4)$$

Where,  $N_s$  and  $N_w$  are the numbers of swell dominated and wind-sea dominated events at the study area. Note that  $N = N_s + N_w$ ; thus, in a relative view, a true sea state is considered as either swell dominated or wind-sea dominated.  $P_s$  and  $P_w$ , which were seen as statistically meaningful descriptions of the proportions of the swell and wind-sea dominances, could be statistically approximated to the swell and wind-sea energy proportions to the total wave energy at the sea surface (Jiang and Chen, 2013).

From the combined SWH of wind-sea and swell height, the wind-sea height ( $H_w$ ) and swell height ( $H_s$ ) are estimated from the equations given below.

$$H_s = SWH \sqrt{P_s} \quad (5)$$

$$H_w = SWH \sqrt{P_w} \quad (6)$$

## 2.2 Comparison of reanalysis data with measured data

Although the ERA-Interim data sets are validated for different regions, before analysing the trend in wave climatology in the study area, the ERA-Interim SWH data were compared with the in-situ measured buoy data. The comparison statistics illustrate that the ERA-Interim data show good agreement with the in-situ buoy data (Figure 2). The gridded ERA-Interim data for the measured period 2003, 2004 and 2005 is collocated to the buoy location using bilinear interpolation. The correlation coefficient (CC) values for the SWH during 2003 (May-Nov), 2004 (July-Dec) and 2005 (Jan-May) were 0.88, 0.93 and 0.92, respectively. Figure 2 shows a difference in the slope due to the under-prediction of SWH of high waves (SWH > 2.5 m). Relatively high bias values were observed for high waves (SWH > 2.5 m) for which the ERA-Interim data under-predict the measured SWH data up to 15%. The RMSE (root mean squared error) estimates were 0.43, 0.31 and 0.17 m, respectively, and the SI (Scattering index) values fell in the range of 0.16-0.26.

The nonparametric method is used to calculate the trends in wind speed and SWH and is the widely used method to study the climate change (Wang and Swail, 2001). For the statistical significance test, the Mann-Kendal non-parametric test has been used in the study (Mann, 1945; Kendall, 1975).

## 3. Results

### 3.1 Observed trend in wind speed

Wind is an important driving force in both air-sea interaction processes and ocean circulation. The northern Indian Ocean experiences semi-annually reversing monsoon winds that blow from the NE during October-January (NE monsoon/post-monsoon) and from the SW during June-September (SW monsoon). February-May period are considered as pre-monsoon period. BoB region is at the influence of frequent tropical cyclone activity and other local storm events. These events can influence the wind and wave parameters significantly, even though for a short-term interval and can alter the trend pattern of the annual maximum wind speed and SWH of the region significantly. Hence the long-term trend analysis has been carried out only by considering the annual mean and the 90<sup>th</sup> percentile values of the wind speed and SWH.

The temporal variation of annual mean and 90<sup>th</sup> percentile of wind speed for the study period are plotted in Figure 3a and 3b. The annual mean wind speed shows statistically significant decreasing trend of  $0.75 \text{ cm s}^{-1} \text{ yr}^{-1}$ , whereas the higher events of wind speed, represented here as 90<sup>th</sup> percentile shows higher rate of decreasing with a statistically decreasing trend of  $1 \text{ cm s}^{-1} \text{ yr}^{-1}$ . The mean wind speed for the whole period at the location is  $5.94 \text{ m s}^{-1}$  and that for 90<sup>th</sup> percentile of wind is  $9.1 \text{ m s}^{-1}$ .

If we are considering the decadal scale variation, significant variation is observed during the first two decades and the variation is less during the last decade. First half of the twenty first century shows steady and gradual decreasing nature of wind speed, whereas the later half shows steady increase in wind speed. The maximum positive (0.56 and 0.62 m s<sup>-1</sup>) and negative (-0.43 and -0.62 m s<sup>-1</sup>) inter-annual variation in wind speed mean and 90<sup>th</sup> percentile occurs between 1998-1999 and 1991-1992 respectively. Kumar and Sajiv (2010) observed that during 1958 to 2000, the annual maximum wind speed has an increasing trend (1.2 cm s<sup>-1</sup> y<sup>-1</sup>) for the a location in BoB (13.75-16.25° N; 81.25-83.75° E) and no decreasing or increasing trend for another location in BoB (16.25-18.75° N; 83.75-86.25° E).

### 3.2 Observed trend in SWH

The long-term trends in mean and 90<sup>th</sup> percentile of SWH are presented in Figure 3c and 3d. During the study period, the annual mean SWH varied from 1.33 m (in 2006) to 1.46 m (in 1999), and the mean value of SWH was 1.38 m. During 1979 to 2012, a statistically insignificant weak decreasing trend (-0.014 cm yr<sup>-1</sup>) in the annual mean SWH was observed and was similar to the trend found for wind speed. In fact, it can be considered as no or negligible trend for annual mean SWH (Figure 3d). However, the 90<sup>th</sup> percentile of SWH shows a small (0.20 cm yr<sup>-1</sup>) positive increasing trend (Figure 3c).

Changes in the SWH in different decades were studied by classifying the decadal period in terms of the 1980s (1980-1989), 1990s (1990-1999) and 2000s (2000-2009). The average annual mean values of the SWH during different decades were the same, i.e., 1.38, 1.40 and 1.38 m during 1980s, 1990s and 2000s, and the annual maximum SWH values were 3.70, 3.73 and 3.25. During all three decades, the annual mean SWH showed a decreasing trend (0.23, 0.06 and 0.12 cm yr<sup>-1</sup>).

Two prominent peaks of 5.02 m in 1986 and 5.59 m in 1989 were observed in the annual maximum SWH during the 1980s, and the lowest value of 2.59 m occurred during 1987. A significant increase in the annual maximum SWH was observed during the 1980s with a positive trend of 0.18 m yr<sup>-1</sup>. The largest annual maximum SWH for the entire study period was observed during the 1990s when the SWH reached up to 5.66 m (Table 1). An overall decreasing trend in the annual maximum SWH was reported during the 1990s, with a negative trend of 0.10 m yr<sup>-1</sup>. During the 2000s, the increase in the annual maximum SWH was observed with a positive trend of 0.04 m yr<sup>-1</sup>.

Rather than focussing on a single point we have selected a 5x5 degree box at the central BoB to do the same analysis to check the sensitivity of the result obtained from the data for a single location. The study domain extends from 85 to 90° E and 10 to 15° N. The variation in 90<sup>th</sup> percentile of wind speed

shows decreasing trend of  $1.13 \text{ cm s}^{-1} \text{ yr}^{-1}$ , whereas the mean annual wind speed was small with an increasing trend of  $0.4 \text{ cm s}^{-1} \text{ yr}^{-1}$  (Figure 4a and 4b). Results indicate that at the central BoB, the intensity of stronger winds were decreasing and was similar to the result obtained for the point location, but the trend in mean wind speed for box average area was opposite of that observed for the point location. The analysis of the SWH data for the box average was similar to that obtained for the point location. The 90<sup>th</sup> percentile of SWH showed a small increasing trend and negligible or no trend for annual average SWH (Figure 4c and 4d).

### 3.3 Seasonal variations of wind speed and SWH

BoB and AS, are the only sea areas in the Northern Hemisphere with larger summer than winter energy levels, due to a combination of stronger summer monsoon winds and higher swell influx during southern ocean winter and hence has large seasonality (Barstow *et al.*, 2011). Seasonal variability was studied by classifying the year into three seasons: i) SW monsoon, ii) post-monsoon, and iii) pre-monsoon. It is noted that approximately 65% of the time, the annual peak in the SWH was observed during the SW monsoon season, whereas the pre-monsoon (only in May) and post-monsoon season (only during Oct-Dec) contributed 15% and 20%, respectively (Table 1). TC influence caused a shift of the peak to the pre-monsoon and post-monsoon season. The wind and wave climate in the BoB (Hastenrath and Lamb, 1979) suggests that, the wind and wave activity in the Bay during May-September was primarily controlled by the SW monsoon activity. Although more TCs were observed during November, the monthly mean SWH was higher in May than in November. The annual mean wind speed displays a decreasing trend ( $0.78$ ,  $0.97$  and  $0.49 \text{ cm s}^{-1} \text{ yr}^{-1}$ ) in all seasons (Figure 5a), whereas the 90<sup>th</sup> percentile of winds, shows that stronger events were decreasing during the pre-monsoon ( $0.7 \text{ cm s}^{-1} \text{ yr}^{-1}$ ) and monsoon season ( $1.5 \text{ cm s}^{-1} \text{ yr}^{-1}$ ) and increasing ( $0.47 \text{ cm s}^{-1} \text{ yr}^{-1}$ ) during the post-monsoon season. Significant decrease in 90<sup>th</sup> percentile of wind speed during the monsoon period shows the evidence of weakening of stronger events. The wind speed was low during both pre- and post-monsoon season, whereas it was high during the monsoon season (Figures 5a).

Figures 6a and 6b represent the seasonal nature of the wind and wave climates and show that the wind speed during the pre-monsoon season was low, with an average speed of  $4.7 \text{ m s}^{-1}$ . At the onset of SW monsoon, the average wind speed increases and reaches its maximum ( $8.2 \text{ m s}^{-1}$ ) in June. The average wind speed observed for the post-monsoon season was  $5.6 \text{ m s}^{-1}$ . The Indian Ocean wave climate exhibits a prominent seasonal cycle in the monthly mean SWH with the highest waves occurring during the SW monsoon. The waves were generally low during the pre- monsoon season, and the lowest monthly average SWH ( $0.9 \text{ m}$ ) occurs in February. During the SW monsoon, higher



waves (average SWH  $\approx$  1.5 m to 1.9 m) were observed, and the maximum SWH (2.3 m to 2.9 m) was noted during June. The small peak during the post-monsoon was due to the storms during that period. The seasonal variation of SWH was consistent with that of the wind speed. The annual percentage occurrence of waves with SWH > 1.5 m during January to April was less than 10 % (Figure 6c). During May, the SWH was reported as > 1.5 m for 50% of the time. During the SW monsoon, the SWH values were observed as > 1.5 m more than 75% of the time, except during September in which the occurrence of SWH > 1.5 m was 46%. The results were similar for the box averaged region also.

### **3.4 Wind-sea and swell height analysis**

Wind-sea and swell are two main classes of waves at the ocean surface (Munk *et al.* 1963). Nayak *et al.* (2013) reported that non-linear interaction from distant long period swells generated in the Southern Ocean can modulate the local wind waves in the south-western BoB. Swell/wind-sea characterisation of global ocean or specific basin has been done by several authors (Semedo *et al.*, 2011; Hanley *et al.*, 2010). As far as the present study is concerned the main aim is to understand how the trends in wind-sea and swells are varying at the study area.

The long-term trend analysis with the wind-sea and swell height at the region were done separately (Figure 7). The analysis shows that the average annual wind-sea heights were decreasing ( $-0.8 \text{ cm yr}^{-1}$ ), whereas the swell heights shows a small increasing trend. The statistical significance test shows positive result (Table 2). In all the seasons, the swell domination is observed ( $\sim 90\%$ ), which is in consistent with the findings of Semedo *et al.* (2011) that the North Indian Ocean is the most-swell dominated areas of the World Ocean. In the North Indian Ocean, the Somalian low level coastal jet and the Indian Monsoon have a clear impact in the swell probability pattern.

### **3.5 Peak events and tropical cyclones**

Gray (1985) found that the North Indian Ocean accounts for 7% of global tropical cyclones. Dube *et al.* (1997) found that the occurrences of TCs were more frequent in the BoB than in the AS, and the ratio of their frequencies is close to 4:1. Two TC seasons occur in the North Indian Ocean, namely, pre-monsoon (especially May) and post-monsoon (especially October and November). After analysing 122 years of cyclonic frequency over the North Indian Ocean, Singh (2001) reported enhanced cyclogenesis during November and May. Hence, the peak SWH and wind speed during the study period were analysed to examine the influence of the TCs on the waves and winds. During 1979-2012, five peak events occurred (peak 1 in 1979, peak 2 in 1986, peak 3 in 1989, peak 4 in 1990

and peak 5 during 1996) with wind speeds greater than  $16 \text{ m s}^{-1}$  and SWH greater than 5 m. The occurrences of TCs in the BoB were observed during these peak events (1979, 1990 and 1996).

For the period 1979-2012, although 7 TC tracks ([http://www.usno.navy.mil/NOOC/nmfcph/RSS/jtwc/best\\_tracks/ioindex.html](http://www.usno.navy.mil/NOOC/nmfcph/RSS/jtwc/best_tracks/ioindex.html)) (Chu *et al.*, 2012) fell within the spatial window of 250 km of the study location, only five events (Table 3) represented very severe cyclonic storms (wind speed  $>33 \text{ m s}^{-1}$ ). During 1986 and 1989, the TC track was more than 250 km away from the study area, but resulted in high SWH ( $> 5 \text{ m}$ ). Hence, the intensity of TC-generated waves at the study location depends on the TC track also. The changes in SWH are linked to changes in the two main sources: a) the local surface wind speed and b) the swell component, which is largely determined by the frequency and intensity of remote storms. In this work, the intensity of the cyclone generated wind wave acts as the swell component, which travels toward the study location based on the direction in which the cyclones move. The wave that reaches furthest from the study location still contains an intensity higher than the normal condition, but normally, it reaches the study location one or two days after the cyclone occurrence. Since the prevailing wind speed at the location is small which will not disrupt the swell, and these swells that travels towards the study area contribute to the total wave height of the surface waves, result is intensified SWH. Similar results were found in recent study at BoB during cyclone Phailin by Nair *et al.* (2014). They have reported the presence of long-period Southern Ocean swells in the buoy location along with the cyclone-generated wave. In the present study, the high annual maximum SWH ( $> 5 \text{ m}$ ) was a result of the influence of tropical cyclones in the BoB, and it is noted that all of the high wave events occurred before 1996. The influence of tropical cyclones in the study area after 1996 was decreased.

#### **4. Discussions**

There were many attempts by researchers to understand the variation of wind and wave obtained through ship observation, buoy measurements, satellite altimetry and numerical modelling. Study of global trends of mean and 90<sup>th</sup> percentile wind and wave by Young *et al.* (2011) based on the 23 year period (1985-2008) satellite altimeter measurements indicate a general trend of global increasing value of wind speed and, to a lesser degree in wave height. In our study, both the mean and 90<sup>th</sup> percentile of wind speed shows decreasing trend and the negligible trend in mean SWH and an increasing trend in 90<sup>th</sup> percentile of SWH. The trend in mean and 90<sup>th</sup> percentile of wind speed from 1991 to 2008 (the period considered in Young *et al.* 2011) for the study area is  $-1.4$  and  $-3.4 \text{ cm s}^{-1} \text{ y}^{-1}$ . The trend in mean and 90<sup>th</sup> percentile of SWH from 1985 to 2008 (the period considered in Young *et al.* 2011) is  $-0.05$  and  $0.18 \text{ cm y}^{-1}$ . Even though the trends in wind speed are small, it is contradictory to the results of Young *et al.* (2011). This difference can be attributed to the spatial averaging in both altimeter data

and ERA-Interim reanalysis data. The resolution of the grid used in the Young *et al.* (2011) analysis is of  $2 \times 2^\circ$ , and the satellite repeat itself on the same location is approximately once every 10 days, there is a chance of lesser measurements at a location. Srivastava *et al.* (2000) observed that the trends in annual cyclonic disturbances for the period 1891-1997 over the BoB and the AS has a significant decreasing trend in the annual frequency of storms over both the basins and maximum decreasing trends during the last four decades. Joseph (1995) studied the annual and the seasonal frequencies of depressions and cyclonic storms over the Indian seas and pointed out a strong decreasing linear trend. Dunn *et al.* (2012) based on the past 20 years in-situ and altimeter data reported that there is no change in wind wave environment in the central Indian Ocean. The study of Kumar *et al.* (2013) using altimeter data for a period of 18 years in the Indian Ocean indicates that the variation in significant wave height and wind speed is almost stable in BoB region.

The study shows that local events can alter the trend in SWH significantly; this can be clearly noticed in the annual maximum SWH analysis. First half of the 1990's associated with more extreme events caused significant increasing nature, whereas the periods after 1996 caused shift in this increasing trend to become overall negative trend. The individual events can shift the overall trend in the annual maximum value and hence, the extreme events are considered more reliable with 90<sup>th</sup> percentile values. The decreasing trend in the annual maximum and the 90<sup>th</sup> percentile of SWH observed was due to the decrease in the annual frequency (nearly 15% per hundred years) of TCs in the North Indian Ocean (Singh, 2001). Alam *et al.* (2003) investigated the frequency of BoB storms crossing different coastal zones and reported that the frequency of formation of cyclonic storms has decreased. There is also supporting facts that the monsoon depression at the BoB is weakening in the recent decades (Prajeesh *et al.*, 2013).

The opposite trend in the 90<sup>th</sup> percentile of wind speed and SWH could be due to the presence of Southern Ocean swells in the central BoB. The swells travelling from Southern Ocean enter the BoB with negligible loss of energy and result in domination of swells in the region. If the wind-seas were generated locally and were strongly coupled to the local wind field, then the higher waves will be mainly wind-seas. Since the wind speed was observed to be decreasing, the generation of wind-seas weakens. Extensive numerical modelling study of Alves (2006) showed that the swells generated at forties propagate eastward into the tropical and the extra tropical latitudes of the Indian Ocean and the Pacific Ocean. So increasing wind speed at the Southern Ocean together with storm events increases the generation of wind-seas which travel more towards the tropical regions as large ocean swells and results in increasing trends in SWH.

The seasonal variability of annual mean SWH indicates that a negligible trend was observed during all seasons, whereas the annual 90<sup>th</sup> percentile of SWH showed increasing trend during all seasons with slightly higher trend during post-monsoon season (Figure 5b). The increasing trend during the post-monsoon was in agreement with the changes in the intensity and frequency of occurrence of TCs during post-monsoon in the study area. Similarly, the significant decreasing trend of wind speed during the monsoon presents evidence for the diminishing frequency of TC occurrence during the monsoon or the weakening of wind speed and thus stronger events, whereas the increasing trend conflicting the wind speed during pre-monsoon and monsoon season shows the presence of swell dominance at the study region. The wind speed has a decreasing trend during the monsoon, but the swells from the Southern Ocean were dominant at the region and these swells increased during the last decades and caused increase in SWH.

The separate analysis of wind-seas and swells shows that the decreasing trend observed for the wind-seas are in agreement with the decreasing trend in wind speed for the study area. The decreasing of wind-sea at the study area also supports the fact that the study area is mostly dominated by swells. The local wind effects observed to be decreasing, whereas there is no significant increasing or decreasing trend found for the SWH. From the results it is clear that for the first decadal period 1979-1989 there is no significant decreasing trend in wind-sea as well as in swell height, but from the beginning of the second decadal period there is clear significant decreasing trend in the mean wind-sea component at the study location. Since the 90<sup>th</sup> percentile related to stronger events, the result will be weak decreasing trend if we cut the first 9 years. It is also noticed that the negligible positive trend in the combined SWH is due to the swell dominance of the region. Small increasing trend can be found in the swell height during the last decade.

## **5. Conclusion**

The primary focus of the study is to identify trends in the wind and wave climate in the central Bay of Bengal from 1979 to 2012. The annual and seasonal temporal variations of wind speed and SWH were investigated. Validation of ERA-Interim data sets was carried out against the buoy-measured data, and the comparison statistics show that for high waves (SWH > 2.5 m), the ERA-Interim data under-predict the measured data up to 15%. The correlation coefficient values for SWH during 2003 (May-Nov), 2004 (July-Dec) and 2005 (Jan-May) were 0.88, 0.93, and 0.92, respectively. An overall statistically decreasing trend was observed for both mean and extreme (90<sup>th</sup> percentile) wind speed. Declining trend for the annual mean and extreme wind speed observed were  $0.75 \text{ cm s}^{-1} \text{ yr}^{-1}$  and  $1 \text{ cm s}^{-1} \text{ yr}^{-1}$  respectively. On the other hand, almost stable or no significant trend was observed in annual mean SWH. However, a positive trend was found for the 90<sup>th</sup> percentile of

SWH. Strong seasonality was observed with higher wave occurrence during the SW monsoon period. From the seasonal analysis, it was found that the stronger events/winds during the SW monsoon season were weakening. Conflicting trends in the wind and wave height were mainly due to the swell dominance at the region which was identified by the separate trend analysis of wind-sea and swell height at the study region. Area average analysis in the central BoB indicate the trend in extreme wind speed and SWH was similar to that obtained for the point location. The TC occurrences and influences in the study area were also examined to study the peak events during the study period, and the results showed that the higher peaks in the wind speed and SWH during certain years were primarily due to the TC influence over the area. The highest SWH (5.66 m) observed during the year 1996 was due to the proximity of a cyclone track to the study location. Statistically significant trend was found for the annual mean and 90<sup>th</sup> percentile of wind speed.

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### **References**

- Alam MM, Hossain MA, Shafee S. 2003. Frequency of Bay of Bengal cyclonic storms and depressions crossing different coastal zones. *International Journal of Climatology* **23**: 1119–1125.
- Alves JHGM. 2006. Numerical modeling of ocean swell contributions to the global wind wave Climate. *Ocean Modelling*, **11 (1-2)**, 98-122.
- Barstow S, Mørk G, Lønseth L, Mathisen JP. 2011. Worldwaves wave energy resource assessments from the deep ocean to the coast. *Journal of Energy and Power Engineering* **5**, 730-742.
- Bidlot J-R, Janssen P, Abdalla S. 2007. Impact of the revised formulation for ocean wave dissipation on the ECMWF operational wave model. *Tech. Memo. 509, ECMWF*: Reading, UK.
- Chandramohan P, Sanil Kumar V, Nayak BU. 1991. Wave statistics around Indian Ocean. *Indian Journal of Marine Science* **20**: 87-92.
- Chen G, Chapron B, Ezraty R, and Vandemark D. 2002. A global view of swell and wind sea climate in the ocean by satellite altimeter and scatterometer. *Journal of Atmospheric and Oceanic Technology* **19**, 1849–1859.

- Chu JH, Levine AS, Daida S, Schiber D, Fukada E, Sampson CR. 2012. Best track archive- North Indian Ocean. Naval research lab, Monterey and JTWC “available online at [http://www.usno.navy.mil/NOOC/nmfcph/RSS/jtwc/best\\_tracks/ioindex.html](http://www.usno.navy.mil/NOOC/nmfcph/RSS/jtwc/best_tracks/ioindex.html).
- Dee DP, Uppala S. 2008. Variational bias correction in ERA-Interim. *ECMWF Technical Report Memorandum*. October 2008.
- Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda MA, Balsamo G, Bauer P, Bechtold P, Beljaars ACM, van de Berg L, Bidlot J, Bormann N, Delsol C, Dragani R, Fuentes M, Geer AJ, Haimberger L, Healy SB, Hersbach H, Hólm EV, Isaksen L, Kållberg P, Köhler M, Matricardi M, McNally AP, Monge-Sanz BM, Morcrette J-J, Park B-K, Peubey C, de Rosnay P, Tavolato C, Thépaut J-N, Vitart F. 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* **137**: 553–597. DOI: 10.1002/qj.828.
- Dobson FW, Smith SD, Anderson RJ. 1994. Measuring the relationship between wind stress and sea state in the open ocean in the presence of swell. *Atmos.–Ocean*, **32**, 237–236.
- Donelan MA, Drennan WM, Katsaros KB. 1997. The air– sea momentum flux in conditions of wind sea and swell. *Journal of Physical Oceanography* **27**, 2087–2099.
- Dube SK, Rao AD, Sinha PC, Murty TS, and Bahulayan N. 1997. Numerical modelling of storm surges in the Arabian Sea. *Applied Mathematical Modelling* **9**: 289–294.
- Dunn RJH, Willett KM, Thorne PW, Woolley EV, Durrev, Dai A, Parker DE, and Vose RS. 2012. HadISD: a quality-controlled global synoptic report database for selected variables at long-term stations from 1973–2011. *Climate Past* **8**, 1649–1679, doi:10.5194/cp-8-1649-2012.
- Earle MD. 1984. Development of algorithms for separation of sea and swell. National Data Buoy Center Tech. Rep. MEC-87-1, pp 53.
- Glejin J, Kumar VS, Nair TMB. 2013. Monsoon and cyclone induced wave climate over the near shore waters off Puduchery, south western Bay of Bengal. *Ocean Engineering*, **72**, 277–286.
- Gray WM. 1985. Technical Document WMO/TD No. 72, WMO, Geneva, Switzerland. **I**: 3–19.
- Gulev SK, Grigorieva V. 2004. Last century changes in ocean wind wave height from global visual wave data. *Geophysical Research letter* **31**, L24302, doi: 10.1029/2004GL021040.
- Hanley KE, Belcher SE, Sullivan PP. 2010. A global climatology of wind wave interaction. *Journal of Physical Oceanography* **40**, 1263–1282.
- Hanson JL, Philips OM. 1999. Wind sea growth and dissipation in the open ocean. *Journal of Physical Oceanography* **29**, 1633–1648.
- Hastenrath S, Lamb PJ. 1979. Climatic atlas of the Indian Ocean, Part-I, Surface Climate and atmospheric circulation. (USA: The University of Wisconsin Press) pp. 97.
- Janssen PAEM, Bidlot JR, Abdalla S, Hersbach H. 2005. Progress in ocean wave forecasting at ECMWF. *Tech. Memo*. 478, ECMWF: Reading, UK
- Janssen PAEM. 2008. Progress in ocean wave forecasting. *Journal of Computational Physics*. **227**, 572–594.
- Jiang H, Chen G. 2013. A Global View on the Swell and Wind Sea Climate by the Jason-1 Mission: A Revisit. *Journal of Atmospheric and Oceanic Technology* **30(8)**, 1833.
- Joseph PV. 1995. Changes in the frequency and tracks of tropical cyclones in the Indian seas. *In Workshop on ‘Global Change and Tropical Cyclones’*, Dhaka, Bangladesh, 18–21 December.

- Kendall MG. 1975. Rank Correlation Methods. Griffin, London, UK.
- Komen GJ, Cavaleri L, Doneland M, Hasselmann K, Hasselmann S, and Janssen PAEM. 1994. Dynamics and Modelling of Ocean Waves. Cambridge University Press.
- Kumar D, Sannasiraj SA, Sundar V, Polnikov VG. 2013. Wind Wave Characteristics and Climate Variability in the Indian Ocean Region Using Altimeter Data. *Marine Geodesy* **36**,303-313.
- Kumar VS, Sajiv C. 2010. Variations in long term wind speed during different decades in Arabian Sea and Bay of Bengal. *Journal of Earth System Science* **119**: 639–653.
- Kumar VS, Dubhashi KK, Nair TMB. 2014. Wave spectral characteristics off Gangavaram, East coast of India, *Journal of Oceanography* **70**:307–321.
- Mann HB. 1945. Nonparametric tests against trend. *Econometrica* **13**: 245– 259.
- Munk WH, Miller GR, Snodgrass FE, Barber NF. 1963. Directional recording of swell from distant storms. *Philos. Trans. R. Soc. London*, **A255**, 505–584.
- Nair TMB, Remya PG, Harikumar R, Sandhya KG, Sirisha P, Srinivas K, Nagar C, Arun NB, Prasad KC, Jeyakuma R, Kaviyazhahu K, Hithin, NK, Rakhi K, Kumar VS, Kumar MR, Sheno SS, Nayak S. 2014. Wave forecasting and monitoring during very severe cyclone Phailin in the Bay of Bengal. *Current Science* **106(8)**, 1121-1125.
- Nayak BU, Chandramohan P, Sakhardande RK. 1992. Seasonal distribution of wave heights off Yanam on the east coast of India. *Journal of the Institution of Engineers (India)* **72**: 187–193.
- Nayak S, Bhaskaran PK, Venkatesan R. Dasgupta S. 2013. Modulation of local wind waves at Kalpakkam from remote forcing effects of Southern Ocean swells. *Ocean Engineering* **64**, pp. 23–35.
- Pierson WJ. 1991: Comment on “Effects of sea maturity on satellite altimeter measurements” by Roman E. Glazman and Stuart H. Pilorz. *Journal of Geophysical. Research* **96(C3)**, 4973–4977.
- Prajeesh AG, Ashok K, Rao DVB. 2013. Falling monsoon depression frequency: A Gray-Sikka conditions perspective. *Scientific Reports* **3**, Article number:2989.
- Premkumar K, Ravichandran M, Kalsi SR, Sengupta D, Gadgil S. 2000. First results from a new observational system over the Indian Seas. *Current Science* **78**: 323-330.
- Riser SC, Nystuen J, Rogers A. 2008. Monsoon effects in the Bay of Bengal inferred from profiling float-based measurements of wind speed and rainfall, *Limnology and Oceanography* **53**, 2080–2093.
- Semedo A, Sušelj K, Rutgersson A, and Sterl A. 2011. A global view on the wind sea and swell climate and variability from ERA-40. *Journal of Climate* **24**, 1461–1479.
- Shankar D, Shetye S. 2001. Why is mean sea level along the Indian coast higher in the Bay of Bengal than in the Arabian Sea? *Geophysical Research Letters* **28(4)**: 563–565.
- Simmons A, Uppala C, Dee D, Kobayashi S. 2007. ERA-Interim: New ECMWF reanalysis products from 1989 onwards. *ECMWF Newsletter No.* **110**, 25-35.
- Singh OP. 2001. Long term trends in the frequency of monsoonal cyclonic disturbances over the North Indian Ocean. *Mausam* **52(4)**: 655-658.
- Soares CG. 1986: Assessment of the uncertainty in visual observations of wave height. *Ocean Engineering* **13**, 37–56.
- Srivastava AK, Sinha Ray KC, De US. 2000. Trends in the frequency of cyclonic disturbances and their intensification over Indian seas. *Mausam* **51(2)**: 113-118.

- Sterl A, Komen GJ, Cotton PD. 1998. Fifteen years of global wave hind casts winds from the European centre for medium range weather forecasts reanalysis: validating the reanalyzes winds and assessing the wave climate. *Journal of Geophysical Research* **103**: 5477-5492. DOI: [10.1029/97JC03431](https://doi.org/10.1029/97JC03431).
- Sundar V. 1986. Wave characteristics off the South East Coast of India. *Ocean Engineering* **13(4)**: 327–338.
- Swain J. 1997. PhD thesis: Simulation of Wave Climate for the Arabian Sea and Bay of Bengal. *Naval Physical and Oceanographic Laboratory*, Aug -1997.
- Uppala S, Dee D, Kobayashi S, Berrisford P, Simmons A. 2008. Towards a climate data assimilation system: Status update of ERA-Interim. *ECMWF Newsletter* **115**, 12–18.
- Vinayachandran PN, Shetye SR, Sengupta D, Gadgil S. 1996. Forcing mechanisms of the Bay of Bengal circulation, *Current Science* **71**, 753-763.
- Wang XL, Swail VR. 2001. Changes of Extreme Wave Heights in Northern Hemisphere Oceans and Related Atmospheric Circulation Regimes. *Journal of Climate* **14**, 2204–2221.
- Wang XL, Swail VR. 2002. Trends of Atlantic wave extremes as simulated in a 40-yr wave hindcast using kinematically reanalyzed wind fields. *Journal of Climate* **15(9)**: 1020–1035.
- WASA Group, 1998. Changing waves and storms in the Northeast Atlantic? *Bull. Amer. Meteor. Soc.*, **79**, 741–760.
- Weisse R, Günther H. 2007. Wave climate and long-term changes for the Southern North Sea obtained from a high-resolution hindcast 1958–2002. *Ocean Dynamics* **57**, 161-172.
- Weisse R, von Storch H. 2009. Marine Climate & Climate Change. Storms, Wind Waves and Storm Surges. *Springer Praxis Books* 200 p. hardcover. ISBN: 978-3-540-25316-7.
- Wolf J, Woolf DK. 2006. Waves and climate change in the north-east Atlantic. *Geophysical Research Letters* **33**: L06604. DOI:10.1029/2005GL025113.
- Young IR, Zieger S, Babanin A. 2011. Global trends in wind speed and wave height. *Science* **332(6028)**, 451–455.



Table 1. Annual maximum significant wave height grouped month wise during 1979-2012

Year	Month	SWH (m)
1979,1990,1997,2002,2010	May	<b>5.34,5.28</b> ,2.90,2.88,3.61
1980,1981,1983,1993,1996,1998,2007	June	2.69,2.96,3.93,3.19, <b>5.65</b> ,2.66,3.90
1982,1988,1989,1991,1994,1999,2001,2005,2009	July	3.13,4.05, <b>5.59</b> ,3.39,3.59 3.02,2.99,3.27,2.94
1986,1992,2000,2004,2006,2008	August	<b>5.03</b> ,3.20,3.17,3.48,2.74,4.00
2012	October	3.88
1985,1987,1995	November	2.98,2.59,4.46
1984,2003,2011	December	4.06,3.20,4.37

Table 2. Mann-Kendall significance test for identified trend.

Parameter	Mann-Kendall test		
	P value (two tailed)	Sen's slope	Significance
Mean SWH	0.77	-0.01	NS
90 <sup>th</sup> percentile of SWH	0.98	-0.10	NS
Mean wind speed	0.04	-0.80	SG
90 <sup>th</sup> percentile of wind speed	0.48	-3.40	NS

NS: not significant

SG: significant

Table 3. Severe cyclone track records within 250 km to the study location and simultaneous change in SWH and wind speed

Latitude (deg)	Lon (deg)	Distance to the study location (km)	Date and time of cyclone (yyyy/mm/dd :hr)	Date and time data presented (yyy/mm/dd:hr)	ERA- Interim SWH (m)	ERA-Interim wind speed ( $\text{m s}^{-1}$ )
14.1	81.9	146	1979/05/11:0	1979/5/11:12	3.50	15.6
14.3	81.2	221	6	1979/5/11:18	5.31	18.92
14.5	80.5	297		1979/5/12:00	5.34	18.99
13.5	81.6	197	1990/05/08:0	1990/5/08:06	3.79	17.22
14.1	81.3	211	6	1990/5/08:12	4.39	19.33
14.5	81.1	233		1990/5/08:18	5.28	19.80
14.9	81.0	253		1990/5/09:00	4.87	13.49
12.1	84.9	298	1995/11/24:0	1995/11/23:18	4.07	16.69
13.6	85.1	212	0	1995/11/24:00	4.47	14.66
15.1	85.7	280		1995/11/24:06	4.17	11.30
15.8	82.6	186	1996/06/14:1	1996/06/14:18	5.65	13.27
16.4	83.0	240	8	1996/06/15:00	4.79	15.21
16.8	83.3	283		1996/06/14:06	4.10	16.58
14.4	85.8	149	1998/11/14:0	1998/11/14:06	2.06	7.00
15.1	85.1	119	6	1998/11/14:12	2.21	7.31
15.6	84.5	109		1998/11/14:18	2.17	8.50

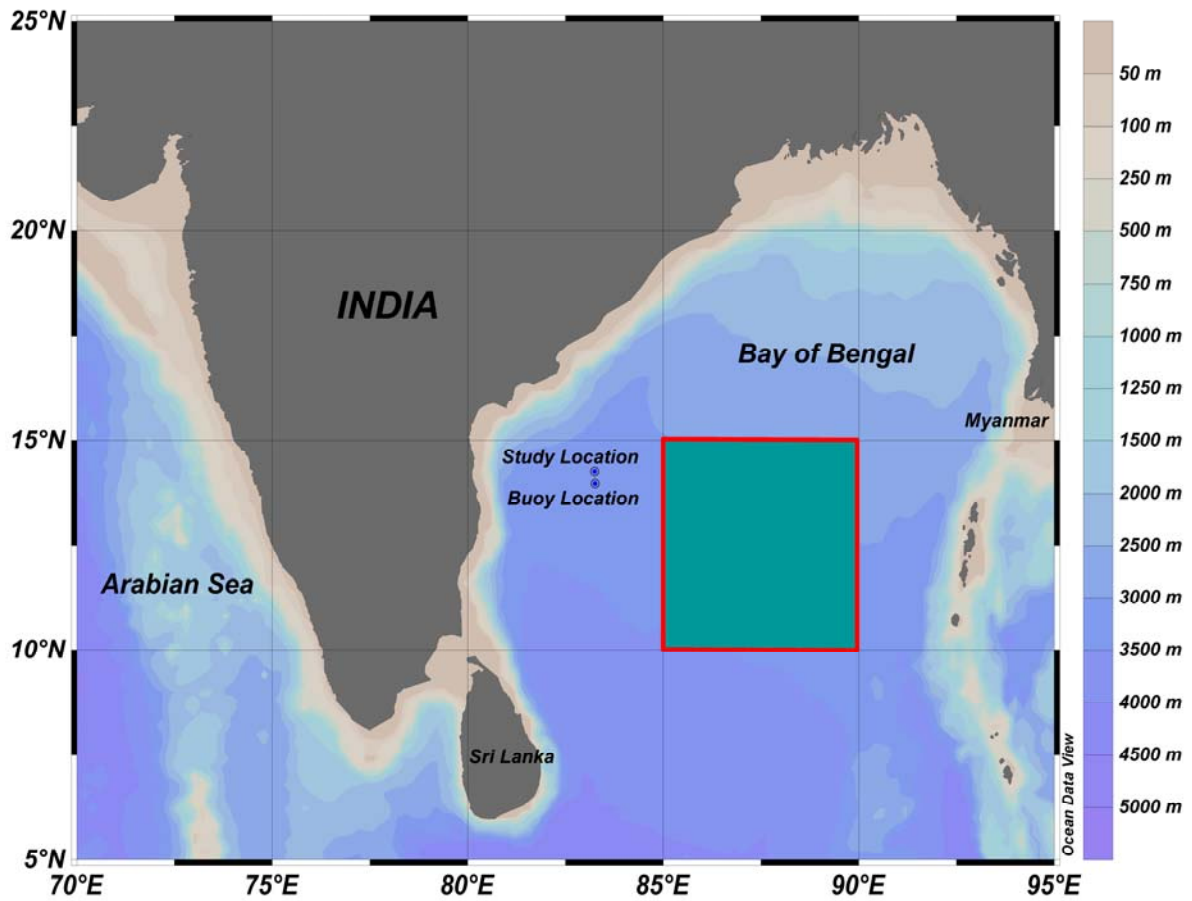


Figure 1. Map showing the study location and the location of buoy. The rectangle indicates the area used in the box-average analysis

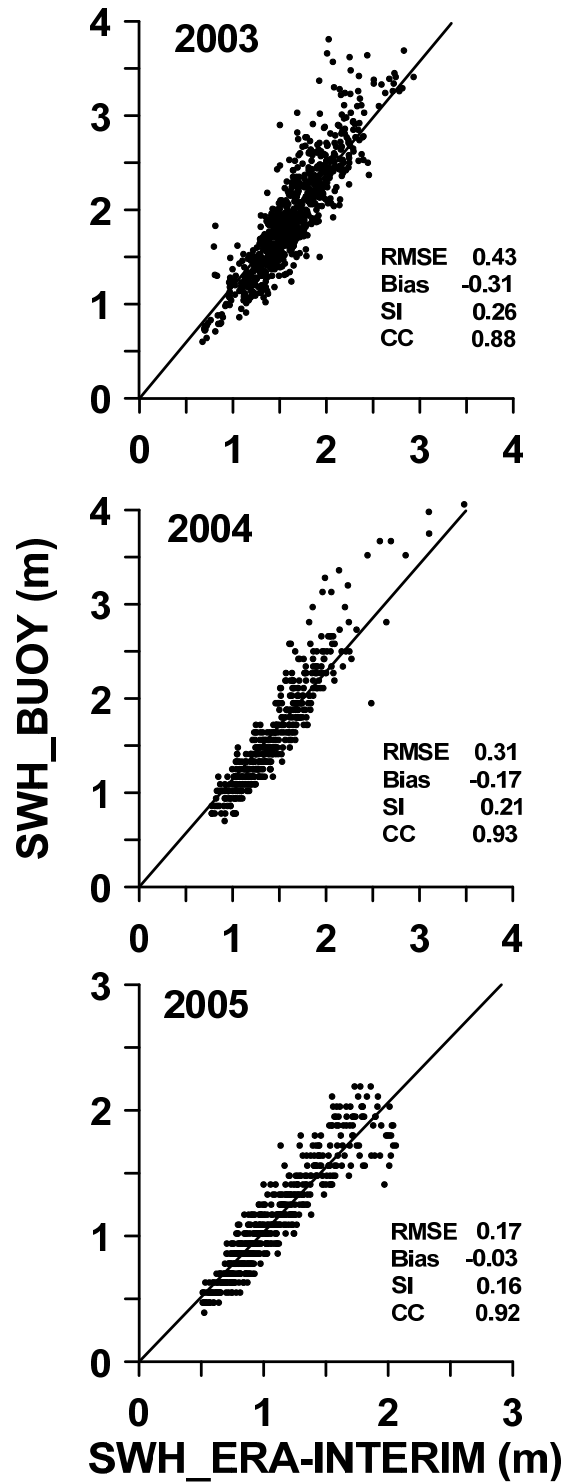


Figure 2. Comparison of ERA-Interim significant wave height with buoy-measured data during 2003, 2004 and 2005

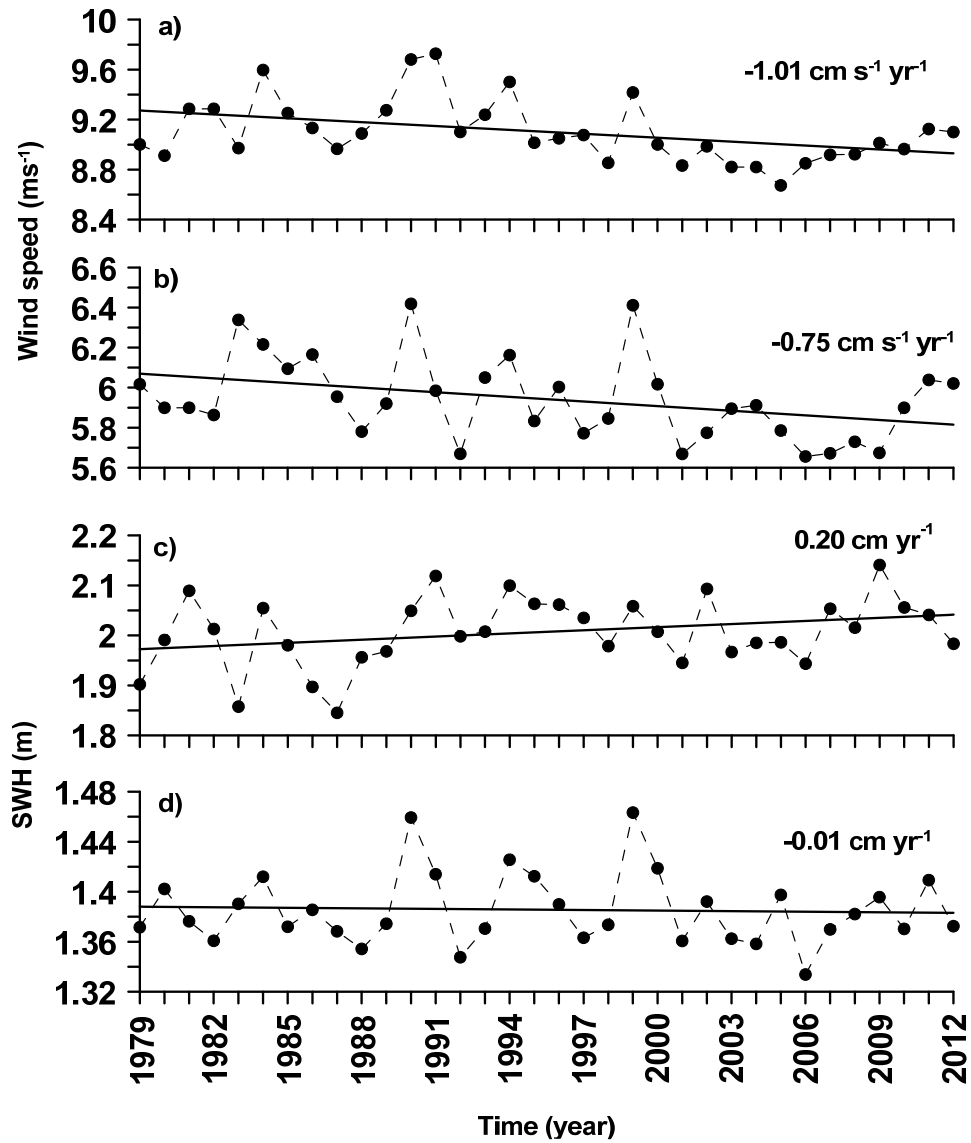


Figure 3. Long-term trends in annual: (a) 90<sup>th</sup> percentile of wind speed, (b) mean wind speed, (c) 90<sup>th</sup> percentile of SWH and (d) mean SWH from 1979 to 2012 for the study location

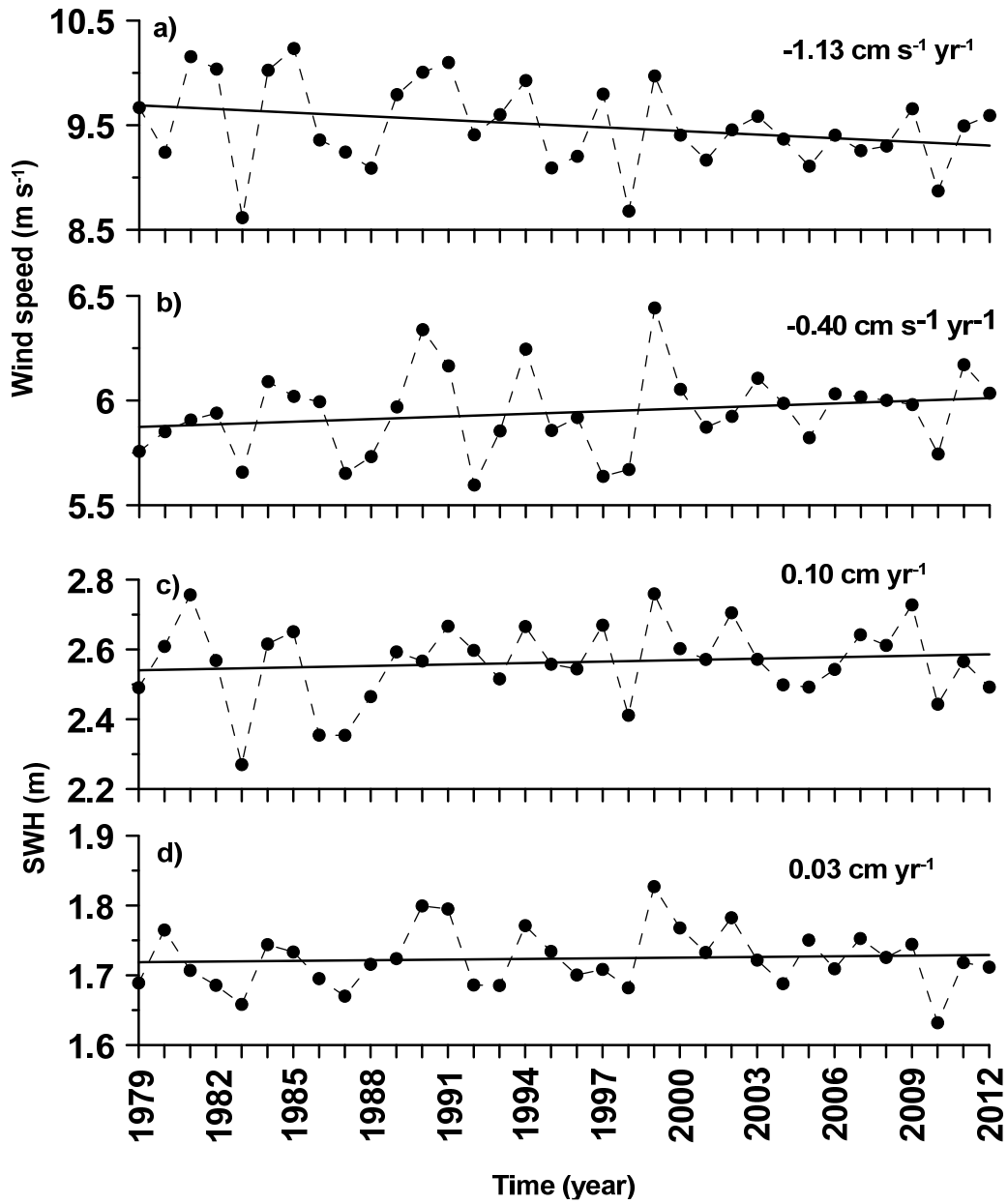


Figure 4. Long-term trends in annual: (a) 90<sup>th</sup> percentile of wind speed, (b) mean wind speed, (c) 90<sup>th</sup> percentile of SWH and (d) mean SWH from 1979 to 2012 for the box average region.

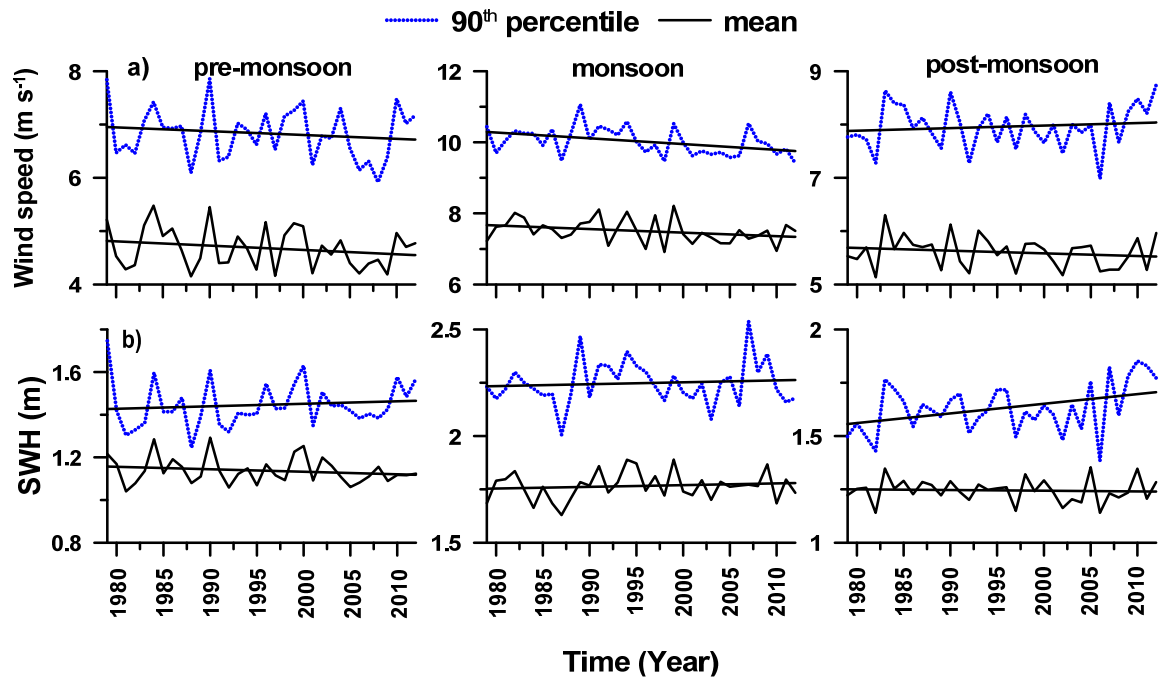


Figure 5. Long-term trends in a) annual mean and 90<sup>th</sup> percentile of wind speed and b) SWH during pre-monsoon, monsoon and post-monsoon period

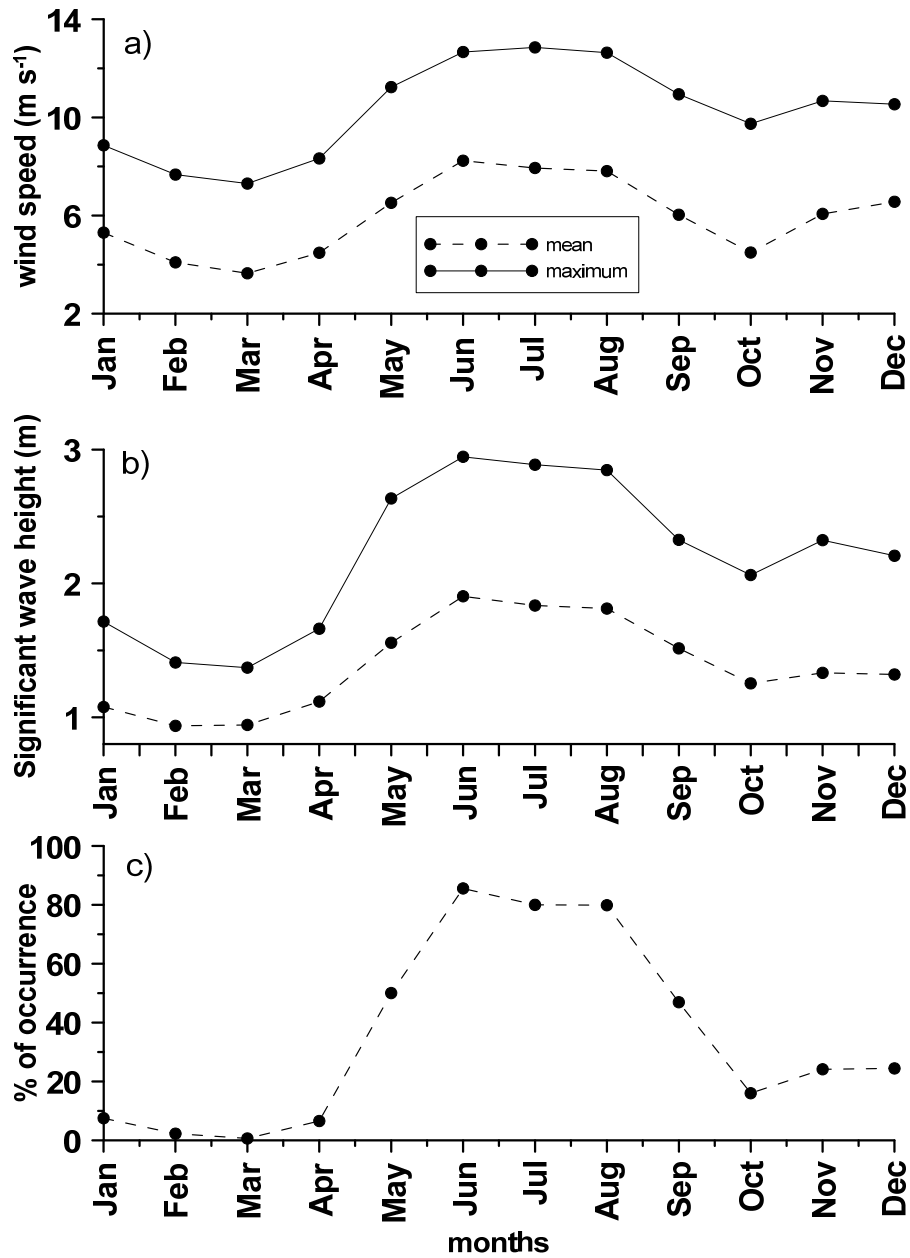


Figure 6. Seasonal variability of the wave climate in the Bay of Bengal: a) mean and maximum monthly wind speed, b) mean and maximum monthly significant wave height and c) percentage occurrence of wave height >1.5 m in different months from 1979 to 2012.



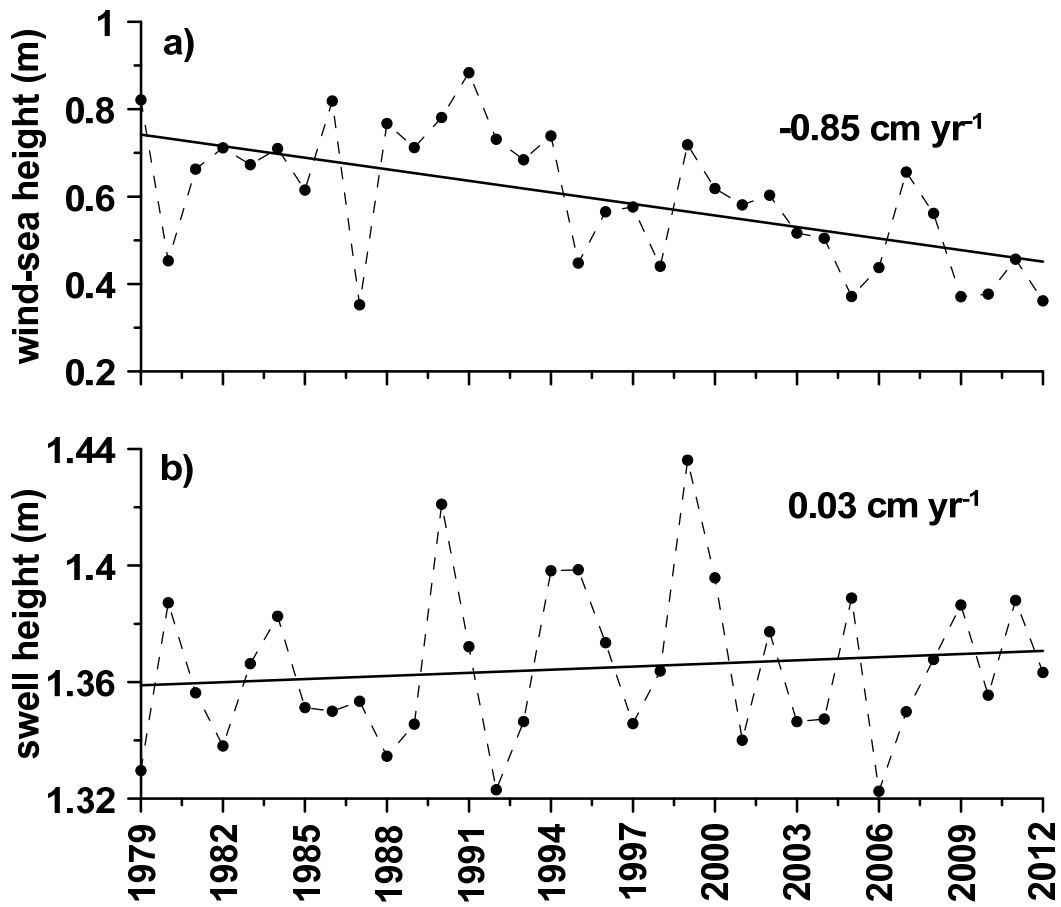


Figure 7. Long-term trends in annual mean: (a) wind-sea height, (b) swell height from 1979 to 2012