

Wave Height Trends off Central West Coast of India

Jyoti P. Kerkar¹, Jaya Kumar Seelam^{2*}, Basanta Kumar Jena³

¹DST-Woman Scientist, CSIR-NIO, Goa; Research Scholar,
Bharathidasan University, Tiruchirappalli, India

²Senior Principal Scientist, CSIR-National Institute of Oceanography,
Dona Paula 403 004, Goa, India (* Corresponding Author)

³Scientist-F, National Institute of Ocean Technology, Pallikaranai, Chennai-100, India

Abstract

Wave height trends off three sites along 100m and 20m depth contours off the central west coast of India have been estimated using 46 years hindcast-wind-wave data simulated for the Indian Ocean region. The wind waves were simulated with NCEP/NCAR winds as input to a third generation spectral wind wave model. This study showed an increasing trend for the annual mean significant wave heights from south to north ranging between 0.25 and 0.36 cm/year. The wave heights during the southwest monsoon and fair weather periods were observed to have similar trends. The study also showed increasing trends in water depths of 20m compared to that of 100m water depth, wherein a maximum increase of 0.22 cm/year is observed.

Additional Index Words: Significant wave height, NCEP-NCAR winds, trend estimates, Arabian Sea, MIKE21

Introduction

Understanding long-term variations in the wind and wave parameters is a critical element in studying the coastal environment. Long-term wind and wave records based on in-situ measurements are still sparse in the Indian seas, and only short-term records are available (e.g., Premkumar et al., 2000; Kumar, 2006). Given the sparse measured wave data, the numerical model derived wave data gains vital importance and many studies on numerical wave prediction have been carried out for the Indian Ocean region using scatterometer winds (e.g., Vethamony et al., 2006; Muraleedharan et al., 2009). For coastal regions of India, nearshore wave parameters have been estimated by using spectral wind wave model (Aboobacker et al., 2009). There is no long-term measured wave available for the north Indian Ocean. Wind-waves are crucial for coastal activities, and the prediction of waves through numerical models has been the primary source of information in the entire ocean. Owing to the sparse availability of wave measurements, a numerical model derived wave data gains vital importance, and few studies have been carried out for the Indian Ocean region using different wind inputs. Regional studies on the changes in wave climate, especially in the North Pacific and North Atlantic regions, have been conducted. Very few studies on wave climate trend variations in the north Indian Ocean exists based on the long-term wave modelling results.

This paper presents the trends of wind waves in the central west coast of India. The north Indian Ocean is divided by the Indian subcontinent into two semi-enclosed seas viz., the Arabian Sea and the Bay of Bengal, both of these seas encroach onto the equatorial regime of the basin (Shankar and Shetye, 2001). It is observed that the Arabian Sea shows high wind speed and wave conditions due to the monsoons (Young 1999; Kumar and Anand, 2004; Kumar et al., 2010).

Although there have been many studies on the change in wave climate especially in North Pacific and North Atlantic regions (Carter & Draper, 1988; Allan & Komar, 2000; Caires & Swail, 2004; Gulev & Gringorieva, 2004; Soomere & Raamet, 2011; Vanem & Walker, 2013). In the Indian Ocean, positive trends in wave heights were observed in the south Indian Ocean (Bhaskaran et al., 2014). Nitika et al., (2015) studied the trends in the wind wave climate in the Indian Ocean using altimeter data. Anoop et al., 2015 showed that there is an increasing trend of greater than 1 cm per year in the northern north Indian Ocean based on the 34 years of data. Hithin et al. (2015) studied the variability of annual mean and maximum SWH at a selected deep water location in the central Arabian Sea using along-track satellite altimeter data and showed a positive trend of 0.63 cm per year in the mean SWH and negative trend of 2.66 cm per year in the maximum SWH.

Study Area

The study area lies along the central west coast of India. The northeastern boundary of the study area is covered by the Arabian Peninsula and the Persian Gulf. The waves along the central west coast of India depends mainly on the wind conditions prevailing over three different seasons; viz. South West monsoon (June-September), Northeast monsoon (October-January) and the fair weather season (February-May).

Methodology

The trends in significant wave height (SWH) along the central west coast of India is the primary focus of this paper. There are little studies in this region on the long-term trends of SWH. The aim of this paper is to fill the gap using numerical wave modelling data. Wind-wave modelling has been carried out to hindcast the waves in the Indian Ocean during 1970-2015. The model has been validated with the available in situ measurements. MIKE by DHI's third generation spectral wind wave model (MIKE-SW) is used in this paper. MIKE-SW uses flexible mesh, which allows for coarse spatial resolution in the offshore area and high resolution in the shallow coastal waters. MIKE-SW model includes two different formulations: a directional decoupled parametric formulation and a fully spectral formulation of the wave action balance equation. The first formulation is suitable only for nearshore conditions whereas the second one is applicable in both nearshore and offshore regions, and therefore, the second formulation has been used in this paper to account for both the shallow and offshore regions. MIKE-SW includes the following physical phenomenon: (i) wave growth by action of wind, (ii) non-linear wave-wave interaction, (iii) dissipation due to white capping, (iv) dissipation due to bottom friction, (v) dissipation due to depth-induced wave breaking, (vi) refraction and shoaling due to depth variations (vii) wave-current interaction, (viii) effect of time-varying water depth and flooding and drying. The discretisation of the governing equations in geographical and spectral space is performed using a cell-centered finite volume method.

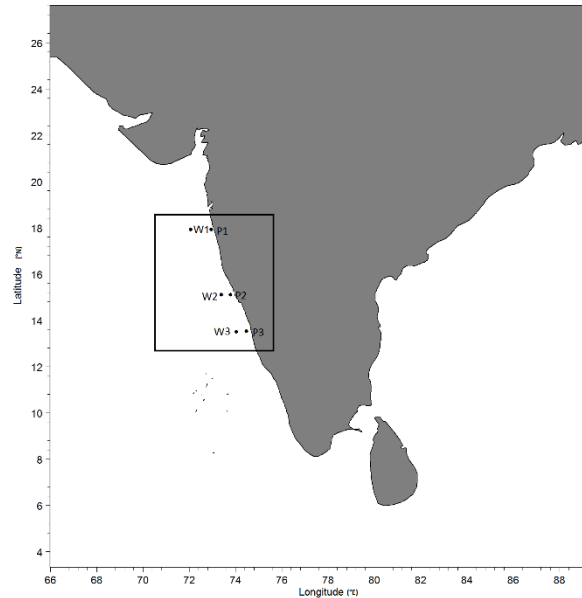


Figure 1. Study area.

An unstructured mesh technique is used in the geographical domain and the time integration is carried out using a fractional step approach, where a multi-sequence-explicit method is adopted for the propagation of wave action. The model domain considered in this study covers the Indian Ocean region from 60°S - 30°N and 20°E - 115°E (Fig 2). The consideration of such a large domain was necessary as the swells from the south-west or south directions strongly influence the wave climate along the west coast of India. The model uses a flexible mesh wherein the grid resolution varied from 0.25° near the coast to 1° as we move from coast to offshore. The bathymetry data was obtained from the Earth Topography and Bathymetry version 2 (ETOPO2) from the National Geophysical Data Centre USA for deep water and DHI coastal mapping data (MIKE CMAP) for the coastal region. The accuracy of the wave hindcast is dependent mainly on the accuracy of the input winds (Holthuijsen et al., 1996). NCEP/NCAR reanalysis wind data from 1970 to 2015 were used as input to generate the waves. These data are available in the form of daily 6 hourly mean zonal (east-west), and meridional (north-south) surface wind components, with a resolution of $2.5^{\circ}\times 2.5^{\circ}$ (<http://www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.shtml>).

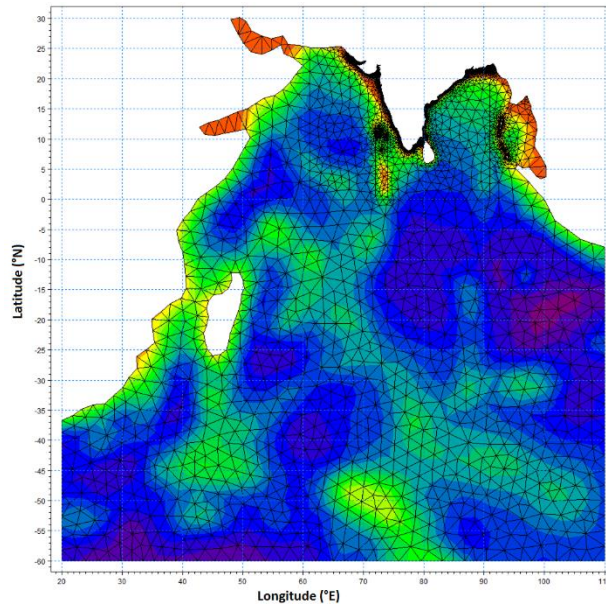


Figure 2. Model domain.

The NCEP/NCAR reanalysis wind represents the output of a high-resolution atmospheric model, run using observations collected from surface and upper air stations and satellite observation platforms, which are routinely used for climate change simulations when measured wind records are not available (Mujumdar & Ghosh, 2008).

Six locations that are considered to study the annual and seasonal trends, three at 100m water depth named as W1, W2, and W3; and three locations named as P1, P2 and P3, parallel to W1, W2 and W3 respectively, at 20m along the coast (Fig. 1). The linear trend analysis is carried out following the method as in Shanas and Kumar (2014), wherein the seasonal and annual significant wave heights at each of the location are subjected to statistical analysis to obtain maxima, mean and 90th percentile for each year or season in each year. For each of the location, 46 data points are obtained and are used further to obtain the linear trend.

Results And Discussion

The MIKE-SW model results have been compared with measured data available in the Indian Ocean (Fig. 3). Three locations in the Arabian Sea, viz., AD02, AD06, and AD09, wherein the measured data was available is used to compare with the MIKE-SW model results. The statistical parameters used for comparison are Bias, Root Mean Squared Error (RMSE), Scattering Index (SI) and the Correlation coefficient. The measured data showed an excellent comparison with the modelled data. The model results at locations AD02 and AD06 showed correlation coefficients of 0.95 and 0.94

respectively with a bias of about 0.5 for both locations. However, at location AD09 the correlation coefficient was relatively less of about 0.64 (Table 1).

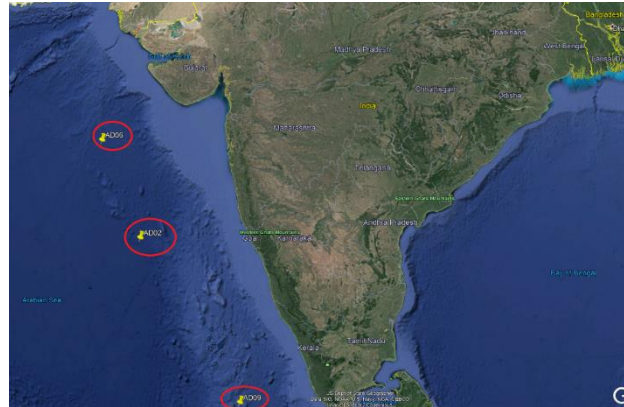


Figure 3. Locations of the measured data available for comparison

Table 1. Statistical Parameters derived for the comparison of modelled and measure data.

Location.	Bias	RMSE	SI	CC
AD02	0.50	0.64	0.33	0.95
AD06	0.49	0.63	0.37	0.94
AD09	1.37	1.48	1.03	0.64

The linear trend analysis of SWH for three different locations along the 100m contour viz., W1, W2, and W3, along the central west coast of India, was carried out. Trends of SWH for annual data as well as seasonal data, considering three seasons, viz., (1) Fair-weather (Feb-May), (2) NE monsoon (Oct-Jan) and (3) Southwest monsoon (Jun-Sep) are presented.

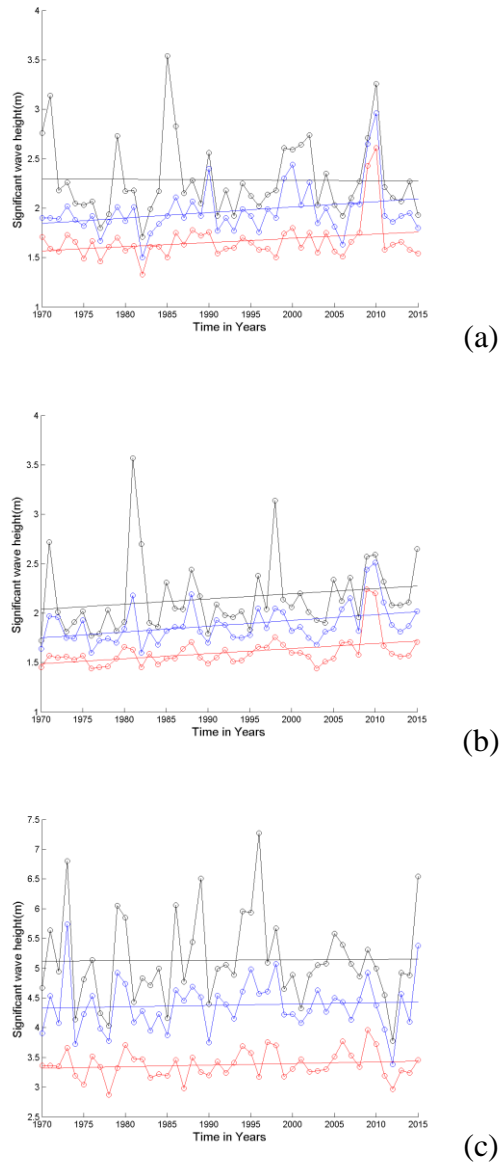


Figure 4. Trends of Max, mean and 90th percentile of SWH at Location W1 during (a) fair weather season (b) north east monsoon (c) south west monsoon.

During the fair weather season, SWH at W1 showed an increasing trend of 0.42 and 0.55 cm/year in mean and the 90th percentile of SWH, whereas, a negligible decreasing trend of 0.05 cm/year in maximum SWH (Fig 4(a)). Also at W2 (Fig 5(a)) and at W3 (Fig 6(a)) the maximum SWH showed a decreasing trend of the order of 0.19 and 0.18 cm/year respectively, but the mean and the 90th percentile SWH showed an increasing trend. During the northeast monsoon, SWH at all the three locations showed a positive trend for the maximum, mean and the 90th percentile. The maxima and the 90th percentile was almost similar for W1 and W3. However, for the mean SWH, a considerable increase of 0.51 and 0.46 cm/year was seen at W1 and W3 respectively (Fig 4(b) & 6(b)), whereas,

the SWH at W2 showed an increasing trend of about 0.39, 0.45 and 0.51 cm/year for the maxima, mean and the 90th percentile of SWH (Fig 5(b)).

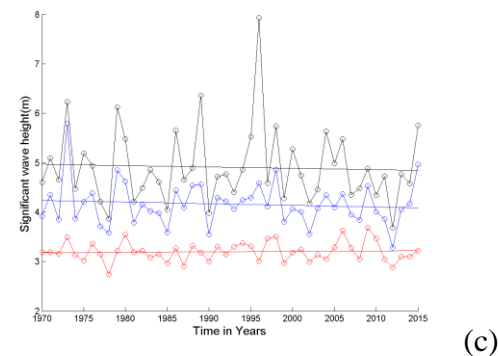
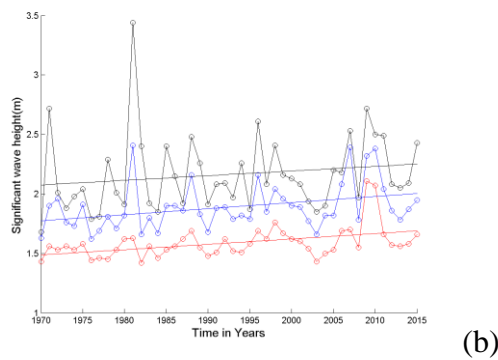
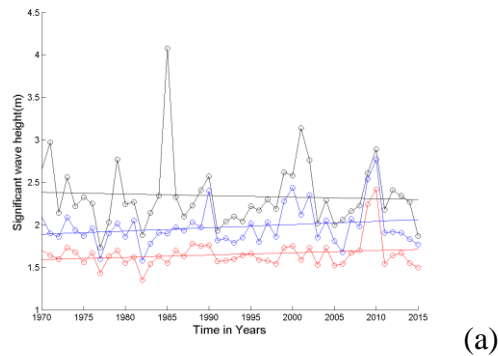


Figure 5. Trends of Max, mean and 90th percentile of SWH at Location W2 during (a) fair weather season (b) north east monsoon (c) south west monsoon.

During the south-west monsoon, at W1, the maximum SWH showed a negligible increase, whereas, the mean and the 90th percentile SWH showed an increase of the order of 0.2 cm/year (Fig 4(c)), however, decreasing trends were observed at W2 and W3 in the maximum and the 90th percentile of SWH. The mean SWH at W2 and W3 showed a negligible positive trend, whereas, the maximum SWH at W2 showed a negative trend of about 0.27 cm/year (Fig 5 (c)). Also, W3 showed a negative

trend of 0.53 cm/year in maximum SWH (Fig 6(c)). The 90th percentile of SWH at W2 and W3 showed a similar negative trend.

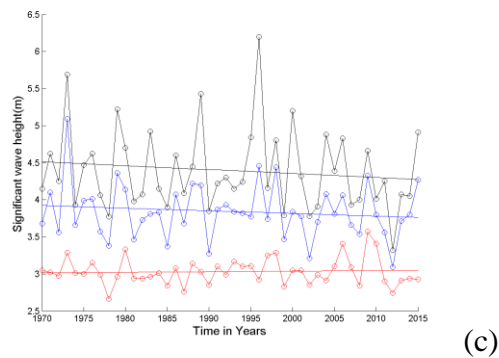
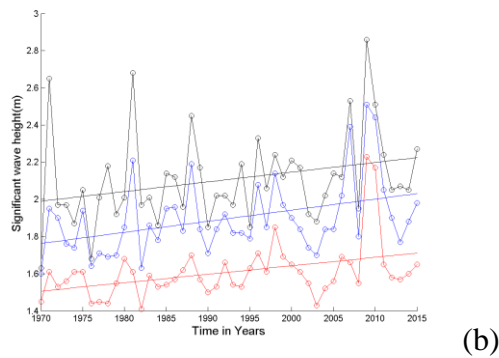
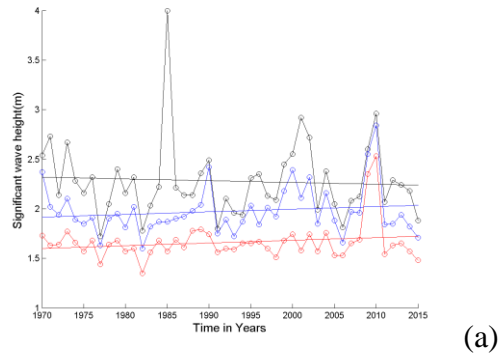
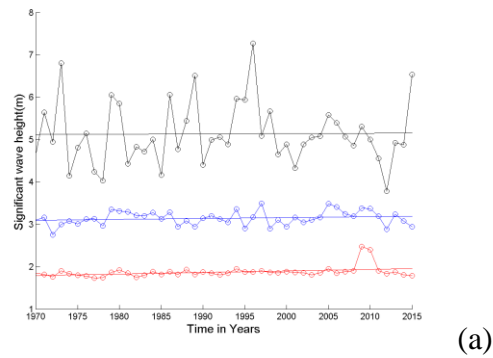
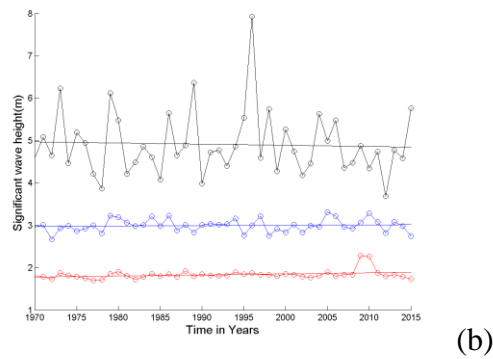


Figure 6. Trends of Max, mean and 90th percentile of SWH at Location W3 during (a) fair weather season (b) north east monsoon (c) south west monsoon.

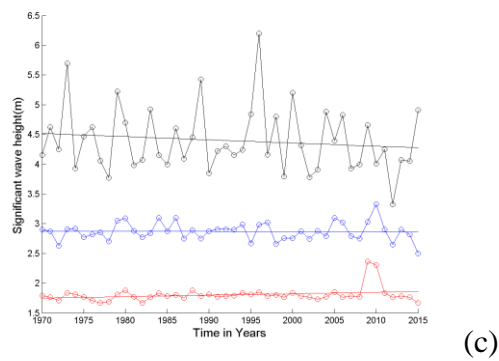
The annual trends showed an increasing trend in mean SWH with values of 0.36, 0.25 and 0.25 cm/year for W1, W2 and W3 respectively. W1 also showed a positive trend for maxima and 90th percentile of SWH (Fig 7a.). However, at location W2, the maximum SWH showed a negative trend of 0.27 cm/year and a negligible increasing trend of 0.06 cm/year for 90th percentile SWH (Fig. 7b). Similarly, at location W3 the maximum SWH showed a negative trend of about 0.54 cm/year and 0.03 cm/year in the 90th percentile of SWH (Fig. 7c).



(a)



(b)



(c)

Figure 7. Annual trends of Max, mean and 90th percentile of SWH at (a) Location W1 (b) Location W2 and (c) Location W3.

In addition to the SWH trends in water depths of 100m, annual trends were studied at a shallow water depth of 20 m at locations parallel to W1, W2, and W3, which are referred as P1, P2 and P3 respectively.

During the fair weather season, a decreasing trend in the maximum SWH was observed at P1, P2 and P3 of the order of 0.13, 0.24 and 0.37 cm /year respectively. However, the mean and the 90th percentile of SWH showed an increasing trend. At P1, the mean and the 90th percentile of SWH showed a positive trend of about 0.42 and 0.55 cm/year respectively (Fig 8(a)). The mean SWH at P2 and P3 showed similar values whereas the 90th percentile of SWH at P2 showed an increasing trend

of 0.55 cm/year. Also, P3 showed an increasing trend of the order of 0.26 cm/year of SWH (Fig 9(a) and 10(a)).

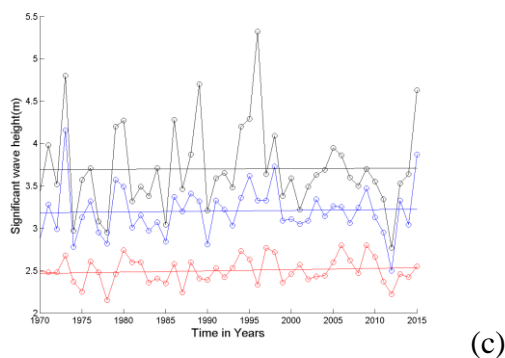
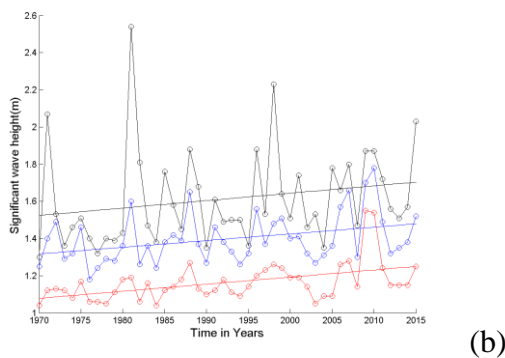
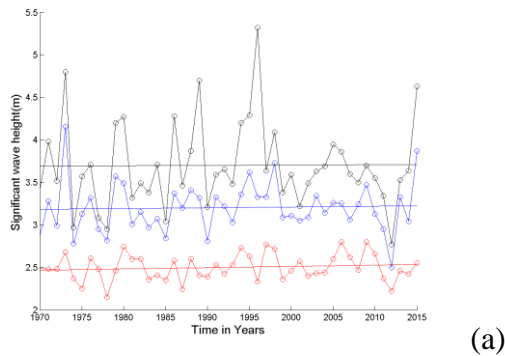
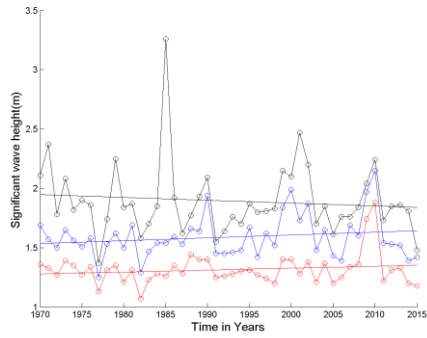
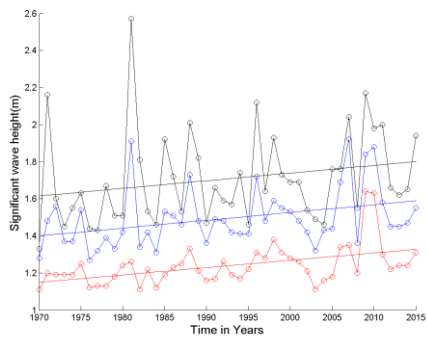


Figure 8. Trends of Max, mean and 90th percentile of SWH at Location P1 during (a) fair weather season (b) north east monsoon (c) south west monsoon.

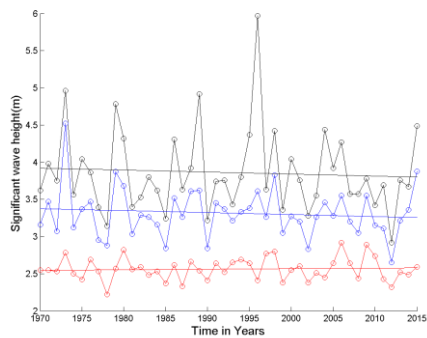
During the northeast monsoon, all the locations showed a positive trend for the maxima, mean and the 90th of SWH. At P1, the maxima, mean and the 90th percentile of SWH showed a positive trend of the order of 0.4, 0.38 and 0.36 cm/ year respectively (Fig 8 (b)). Also, P2 and P3 showed almost similar values of increasing trend in the maxima, mean and the 90th percentile of SWH (Fig 9(b) and 9(c)).



(a)



(b)



(c)

Figure 9. Trends of Max, mean and 90th percentile of SWH at Location P2 during (a) fair weather season (b) north east monsoon (c) south west monsoon.

During the southwest monsoon, a mixed trend was observed in the maxima, minima and the 90th percentile of SWH. At P1, a negligible increasing trend in the maximum, mean and the 90th percentile of SWH was observed (Fig 8(c)). However, at P2, a negative trend of about 0.27 cm/year was observed in the maximum, and the 90th percentile of SWH whereas a slightly increasing trend in the mean SWH was observed (Fig 9(c)). At location P3, a negative trend of about 0.49 and 0.30 cm/year was observed in the maxima and the 90th percentile of SWH (Fig 10(c)). The trend in the mean SWH at P3 was negligible.

The annual trends at P1 showed an increasing trend in the maxima, mean and the 90th percentile of SWH (Fig 11(a)). At P2 the maximum SWH showed a negative trend of 0.27 cm/year whereas the

mean, and the 90th percentile showed a positive trend of the order of 0.19 and 0.05 cm/year respectively (Fig 11(b)). A negative trend was observed at P3 in the maximum and the 90th percentile of SWH, but the mean showed a positive trend of 0.14 cm/year of SWH (Fig 11(c)).

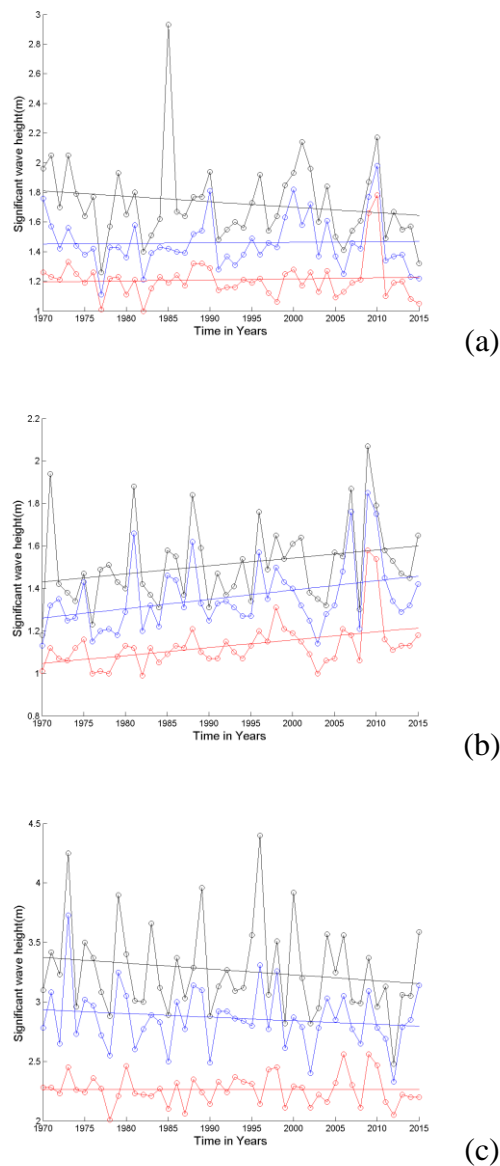


Figure 10. Trends of Max, mean and 90th percentile of SWH at Location P3 during (a) fair weather season (b) north east monsoon (c) south west monsoon.

Few researchers tried to study the variations in wave climate through ship observations, buoy measurements, satellite altimetry, and numerical modelling. Hemer et al. (2010) showed that SWH showed an increasing trend in the Indian Ocean sector. Alves (2006) showed that the swells generated in the southern ocean propagate into the tropical and extratropical latitudes of the Indian Ocean and the Pacific Ocean through numerical modelling. Hence, the annual mean SWH showed an

increasing trend due to an increase in the wave intensity. The annual mean SWH in the central Arabian Sea is increased by 0-25 % per year from 1985-2008 as studied by Young et al. (2011). The increase as per Young et al. (2011) is 0 -0.28 cm /year. On the regional scale Hithin et al., (2015) showed a positive trend in mean SWH of 0.63 cm/year and a negative trend of 2.66 cm/year in maximum SWH using altimeter data at a deep water location at around 3500m depth in the central Arabian Sea. This study also showed an increasing trend in mean SWH of the order of 0.3cm/year at a 100m water depth.

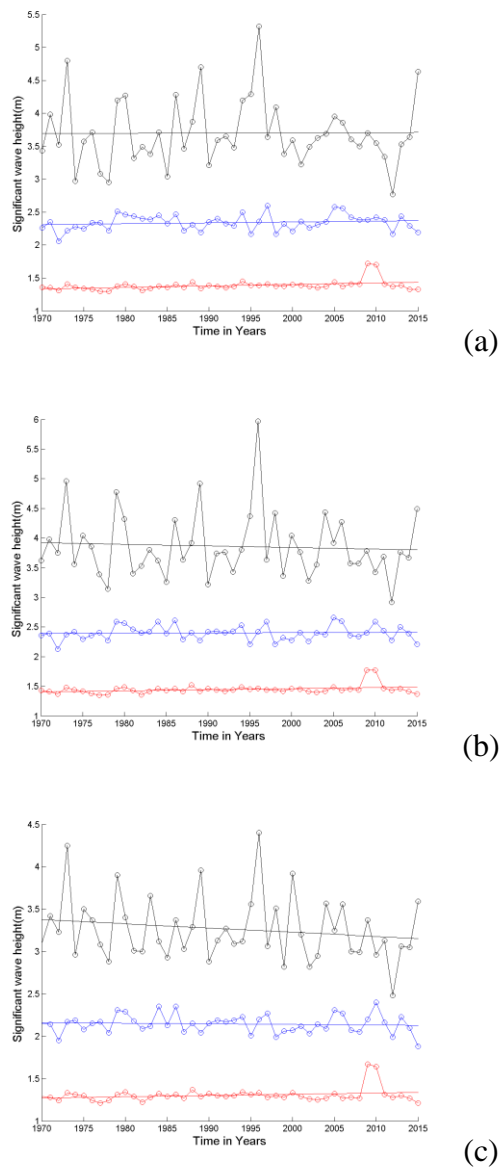


Figure 11. Annual trends of Max, mean and 90th percentile of SWH at Location (a) P1 (b) P2 and (c) P3.

The maximum SWH showed a negative trend of about 0.54cm/year in the deep waters. The shallow waters at 20m also showed similar trends. The maximum SWH showed a decreasing trend of 0.5 cm/year, and the mean SWH showed increasing trends with values varying from 0.14-0.22 cm/year.

This study showed an increasing trend in the mean of SWH at both shallow and deep water locations. However, the maxima and the 90th percentile of SWH showed mixed trends. Fair-weather season showed negative trends in maximum SWH but a positive trend for mean and the 90th percentile of SWH. However, the southwest monsoon showed mixed trends in the maximum and the 90th percentile of SWH but a positive trend in the mean SWH. During the northeast monsoon, the variations in the trends are insignificant. Similar results have been reported by Nitika et al. (2015), wherein, a seasonally positive trends in mean SWH were observed along a transect in the deep waters of the Arabian Sea.

Conclusions

Based on the study carried out, it has been observed that there is an increase in annual maximum SWH trends at 100m water depth as we go from south to north. Similar trend is observed in the shallow waters. Also, the wave heights during the southwest monsoon and fair weather season showed an increasing trend as we move from south to north. During the northeast monsoon, there is no much variation in the maximum, mean and the 90th percentile of SWH trends. There is no linear relationship between trends of shallow and deep water. SWH trends are mostly less than 1 cm/year for the central west coast of India.

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