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Research Article

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Wind-wave Climate Projections for the Indian Ocean from Satellite Observations

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Abstract

The oceans play a key role in climate change and their impact has profound implications on the marine ecosystem and multitude activities around the globe. The effects due to climate change can have long-term repercussion. The latest report on the Intergovernmental Panel on Climate Change had identified the importance of wind-wave climate and its key role in global climate models. The present study investigates the impact of climate change on variability of maximum significant wave height and wind speeds over the Indian Ocean basin. The study is based on analysis from the daily observation of satellite altimeter measured wind and waves derived from eight satellite missions covering a period of 21 years from 1992 until 2012. The results signify that the Southern Ocean belt encompassing latitudinal belts between 40°S – 55°S experienced the highest variability due to impact from climate change. Both wind and wave activity has shown an increasing trend in the Southern Ocean, and this rise is more conspicuous in the current decade. The implications from increased wave activity in the Southern Ocean results in swell field that can influence the local wind-generated waves in the North Indian Ocean basin. The wind-wave activity in certain sectors of the tropical North Indian Ocean also increased from impact of climate change.

Keywords: Wind-wave climate; Wave height; Wind speed; Satellite observations; Indian ocean

Introduction

The assessment report of the Intergovernmental Panel on Climate Change [1,2] provides a lucid elaboration on the effect of climate change across the globe. It also reports on the projections of future climate change suggesting likely increase in the frequency and intensity of extreme weather events [1]. The IPCC [2] report provides the updated findings of IPCC [1]. Interestingly, the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) highlights the importance on wind-wave study, and their implications during climate change. Wind-waves contributes a major role in the climate system having direct implications on coastal processes such as wave set-up during extreme weather events, coastal flooding and erosion with varied sediment budget loads. Hence, an increased activity of extreme waves in a changing climate will accelerate physical mechanisms having direct repercussion in a coastal environment. In addition, wind-waves can influence the exchange of momentum, heat and mass across the air-sea interface [3]. Previous studies [4] reported on increased wave activity linked with high winds associated with mid-latitude storms in many regions of the mid-latitude oceans.

Today with the availability of high performance computing systems, the present generation coupled atmosphere-ocean global climate models does not consider the two-way flux exchange from wind-wave component in climate studies [3]. This aspect was conversed amongst the community-working group on coordinated ocean-wave climate projections (COWCLIP) meetings [3]. The discussion during COWCLIP focused on the present status of activities on wind-wave climate research thereby providing an insight into the key scientific questions and challenges required in a climate change scenario. To summarize four themes were recommended and felt necessary to address this issue such as (i) understanding the variability in historical wave climate, (ii) global wave-climate projections, (iii) regional wave-climate projections, and finally the (iv) development of coupled wind-wave climate models.

Based on the first theme, there are inherent limitations with historical wave climate data. The reason attributes to the length of available wave records. In a global sense, the availability of in-situ ocean wave data is approximately not more than forty years. Some studies that relate the variability of historical wave climate for global ocean basins are reported in the work by [5-10]. In context, to Indian Ocean the in-situ wave data from moored buoys are available only the past 15 years. Hence, for the Indian Ocean it defies the purpose to study wind-wave climate variability on decadal scales with limited in-situ data available. Moreover, the in-situ data is local specific and provides information only for localized area of interest. The advent of satellite technology had revolutionized by providing an opportunity to study basin scale features due to repetitive passes on global oceans. The present status is that satellite altimeter records are available for the past 21 years covering the global oceans. Therefore, a comprehensive analysis of satellite measured winds and its effective utilization can improve our understanding on the evolution and variability of wind-wave climate for the Indian Ocean. Also based on IPCC findings the effect of climate change on wind-waves is an upcoming area of research and one can find very few studies reported in the literature connecting climate change to wind-wave projections. The studies reported are mainly for the Atlantic and Pacific Ocean basins, but not for the Indian Ocean basin. It is with this motivation the present study deals with wind-wave climate projections for the past two decades relevant to the Indian Ocean. The objective of this work is to identify the regions of

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maximum wind-wave variability, the trends of variability and quantify the overall findings based on observational evidence on a basin scale. Therefore, the study analyzes altimeter data records from eight satellite missions that had a very good coverage for the Indian Ocean basin. The final discussions cover aspects on the socio-economic impacts that can result from the impact of climate change on wind-wave variability. The present study covers four sections. The introduction follows data and methodology (Section-2); results and discussion (Section-3) and the last section (Section-4) deal with the summary and conclusions of this study.

Data and Methodology

In this study daily altimeter data from eight satellite missions covering the period from 1992 until 2012 (21 years) is used. The quality checked global altimeter data [11] from various satellites such as ERS-1, ERS-2, TOPEX-POSEIDON, GEOSAT Follow-ON (GFO), JASON-1, JASON-2, ENVISAT and CRYOSAT is critical for this analysis. These satellite missions provides global coverage data, and in this study the data (un-processed) for the Indian Ocean bounded by geographical coordinates 30°E - 120°E; 30°N - 60°S was extracted for further analysis. This study uses the data from the French Research Institute for Exploitation of the Sea/Laboratory of Oceanography from Space (IFREMER/CERSAT). The processed data is the altimeter-measured parameters corresponding to each swath record from various satellites. The URL link (ftp://ftp.ifremer.fr/ifremer/cersat/products/swath/altimeters/waves/data/) provides the source of data information used for the present study. The area of study domain (Indian Ocean) that covers both the North Indian Ocean and Southern Ocean. There are two transects (each with ten points) that covers the geographical extent from Southern Ocean until the North Indian Ocean. These transects are located along 60 °E (covering Arabian Sea) and 90 °E (covering the Bay of Bengal). These ten points covers the zones of South Indian Ocean, South Sub-tropical, South trade wind, Equatorial and tropical North East and North West Indian Ocean sectors. The present study investigates the impact of climate change on extreme wind and waves along these two transects at each represented points. The Basic Radar Altimetry Toolbox (BRAT) Version 3.1.0 [12] processes the compressed data format obtained for the Indian Ocean from these eight satellites. This study does not perform any data filtering techniques with BRAT to ensure that inferences made with actual ground truth data as measured by satellites. This will provide a clear depiction of the wind-wave climate projection based on observational evidence. Extreme weather events such as depressions and cyclones are quite active in the Indian Ocean. Therefore, daily satellite data that includes wind and significant wave heights during epochs of extreme weather events produce inferences that may lead to erroneous conclusions. Hence, in the present study data records for periods corresponding to depressions and cyclones is not accounted for analysis in the post-processed BRAT data. The objective is to understand the natural variability of extreme wind speed and wave heights in a changing climate. The changing frequency and intensity of Extreme weather events is an integral part of the changing climate system. Inclusion of the extreme weather events can lower the bias in mean values [10]. As the scope of this work confines to investigate the natural variability in the wind-wave system, it therefore does not include the extreme weather events, and their role in governing the bias of mean values. The bias variability in the mean values for wind-waves including the extreme weather events for the present study domain will be separate study. The implications of global warming and climate change on the natural system are diverse. Wentz et al. [13] report aspects on the effect of global warming on the hydrological parameters. The SSM/I retrievals from satellites over the ocean surface were used in their study. Young et al. [8] reports on the global trends in wind speed and wave height using 23 years of calibrated database from satellite altimeter measurements. [8] Young et al. study suggests that the rate of increase is greater for extreme events compared to the mean condition. Young et al. [8] used the monthly mean, 90th- and 99th-percentile values for wind speed and wave height on a global scale having a horizontal resolution of 2° × 2°. The horizontal resolution used for the present study is 1° × 1°. Also very recently using the SSM/I data, Zieger et al. [10] presented the changes in ocean surface wind focusing on trends in regional and monthly mean values. The archived JTWC (Joint Typhoon Warning Centre) best-track data of cyclones provides the number of cyclones and their corresponding track details. This archived database contains records of cyclones from 1945 until present covering the regions of Southern Ocean and North Indian Ocean. Therefore, the final data used for analysis contains only the satellite records of maximum wind speed and wave heights corresponding to fair weather period in the past 21 years. The subsequent section deals with data analysis of maximum wind speed and significant wave height for the Indian Ocean basin.

Results and Discussion

The operational center dealing with marine weather normally performs routine analysis of wind-waves on short- and medium-range scales having practical applications to the marine industry. In addition, there are numerous studies in the past reporting on long-term analysis of wind-waves from in-situ buoys for the global oceans. These studies are location specific and do not provide any relevant information on the basin scale variability due to climate change. Also in context to Indian Ocean, there are very few studies performed on climate projections for the wind-wave component [7,10]. Keeping in view the significance and the need for wind-wave study as per the [2] IPCC report, the present work performs a comprehensive data analysis based on measured wind-wave data for the Indian Ocean. Therefore, this study utilizes the observational evidence of wind and waves from ground truth data as measured by eight satellites. The data as obtained from satellites are pre-processed using the BRAT (Basic Radar Altimetry Toolbox). Preliminary analyses of the post-processed data reveal that the geographical region having the highest impact of climate change is the Southern Ocean (SO) belt encompassing the geographical coordinates between 40 °S - 60 °S. The Hovmoller diagram utilizes the post-processed BRAT data that represents the parameter variability in a space-time domain. The Hovmoller plot representing the decadal variability of daily averaged maximum wind speed for the SO sector in the Indian Ocean. The notable observation shows the increased wind magnitude as function of time. It brings to light that wind speed in SO had increased with time, and the decadal variability of wind speed maxima in the current decade (from 2002 until present) is higher than the variability observed in the past decade (1992 until 2001). On basin-wide scales, the current decade the occurrence of high winds (> 20 m s^{-1}) is quite common unlike the past (≈ 18 m s^{-1}) decade (1992 until 2001). In general, the observations show a considerable increased wind activity especially in the current decade. The extreme wind speeds especially in certain sectors of the Southern Ocean in the Indian Ocean basin are increasing by at least 4.5% per year. The 99th percentile of wind speed trend reported by Young et al. [8] suggest that extreme wind speeds are increasing over the majority of world ocean basin by at least 0.75% per year. They also mention that regions in the central north Pacific exhibited a statistically significant stronger trend of approximately 0.50% per year. These statistical values as reported by Young et al. [8] are spatially averaged representing basin wide characteristics. The altimeter data used for the present study clearly show that in the current decade increased wind activity along certain regions in Southern Ocean is comparatively higher to the reported values of Young et al. [8] It is clear that increased wind speeds extend all along the meridian notably in the current decade (from 2002 until present). This attributes to increased frequency and intensity of fast moving synoptic systems in the Southern Ocean belt. In a climate change perspective, the SO can influence the wave activity in global oceans. It is a well-recognized fact that one of the regions active for potential swell generation is the SO belt in the Indian Ocean. Therefore, in context to climate change increased wind activity in SO can enhance wind-waves thereby leading to generation of higher swells. The swells generated from synoptic disturbances propagate quickly crossing the hemisphere and reaching various coastal destinations in the North Indian Ocean. The recent study by Nayak et al. [14] highlight the importance of swells generated from SO that eventually reach the North Indian Ocean basin in approximately 4 days time. These distant swells modulate and modify the local wind generated waves in the Bay of Bengal.

The time series distribution of basin-wide averaged (30 °E - 120 °E) maximum significant wave height and wind speed from 1992 until 2012 at ten locations covering geographical areas from SO (55 °S) to North Indian Ocean (20 °N). The solid lines in each panel are the trend lines corresponding to the variability of waves and wind for the ten locations. The corresponding best-fit regression equation for all the ten locations for waves and wind speed that occurred in a changing climate scenario are listed in top of each panel. The effect of climate change variability on wind-waves are also shown summarizes the incremental change (ΔC) the difference between the present and corresponding value of maximum wave height and wind speed as on 1992. The study signifies that geographical area between 45 °S - 55 °S experienced the highest variability on wind-waves due to climate change. This is also evident from the linear trend analysis shown for waves and wind speed where the slopes (*m*) in the trend line $y = mx + c$ (m = slope; c = intercept on Y-axis) are seen higher in the latitude belt between 45 °S - 55 °S compared to regions elsewhere in the Indian Ocean. The parameters '*y*' and '*x*' in trend line equation $y = mx + c$ refers to *y* = maximum significant wave height, *y* = maximum wind speed and *x* = time (from 1992 until 2012). The trend line slopes decrease as one approach towards the equator from the SO. Above the Equator, the slopes increase marginally in the North Indian Ocean. In general, there is a strong correlation between wind and waves as noticed from the slopes (m) of trend line as well their corresponding intercept (c) given by respective equations in each panel. In the SO (50 °S) basin the overall increase in wave activity is about +1.057 m in the past two decades (meriodional averaged values were provided. It means the maximum wave height at 50 °S during 1992 was 6.482 m and because of climate change this maxima had linearly increased to 7.539 m at the end of year 2012. It signifies that on average there is a steady rise of about +5.03 cm in maximum significant wave height activity each year at this location. These are the averaged values between the longitudes 30 °E until 120 °E (meridian). However, as seen from the western side of the SO (transect along Arabian Sea) has the higher impact due to climate change compared to eastern side (transect along Bay of Bengal). The incremental change in maximum wave heights in western side of SO was +1.524 m, whereas on the eastern side the increase was +1.427 m for the latitudinal band between 45 °S - 50 °S. Wind speeds in eastern and western sector of SO had increased by +3.16 m s^{-1} and +2.65 m s^{-1} respectively. The equatorial regions show insignificant variation for wave heights, whereas the wind speeds along this band has an overall rise (≈ +1.8 m s^{-1}) in the eastern sector (Bay of Bengal) compared to regions in the western equator. The wave activity in the tropical North Indian Ocean has also increased resulting from climate change. Higher wind-wave activity is observed in the Bay of Bengal (along 10°N latitude compared to the Arabian Sea.

The consequences of climate change on ocean waves have significant socio-economic impacts. It can affect marine operations such as shipping, fishing and offshore activities. Increased maxima of extreme waves can pose danger to oilrigs and marine transportation. Hence, the reliable estimates of wave height maxima in changing climate are essential for safe design in shipping industry. Increased wave activity in conjunction with high astronomical tides and storm surges can accelerate coastal erosion and damage to coastal infrastructure. In context to marine ecology, possible long waves (swells) arriving continental shelf waters can affect the seabed inducing bottom currents and sediments under suspension thereby influencing the coastal and benthic habitats [15]. Therefore, the effect of climate change on wind-wave activity is an area that needs focus and a comprehensive understanding is required having wide practical implications.

Conclusions

The present study deals with the effect of climate change on maximum wind and wave climatology for the Indian Ocean basin. The inferences results from a comprehensive observational analysis of all available quality checked satellite data derived from various satellite missions. The study uses daily data from ERS-1, ERS-2, TOOPEX-POSEIDON, GEOSAT Follow-ON (GFO), JASON-1, JASON-2, ENVISAT and CRYOSAT missions. The altimeter data from these satellites processed using the Basic Radar Altimetry Toolbox (BRAT), and final analysis of maximum significant wave height and wind speeds follows the post-processed data from BRAT. The preliminary analysis of processed data reveal that the zone of maximum wind-wave variability is the Southern Ocean sector of the Indian Ocean located between the latitudinal belts 40° S - 55° N. Time series analysis of the post-processed BRAT data signify that higher wave activity generated in Southern Ocean migrate northwards reaching the North Indian Ocean crossing the hemisphere. The study clearly signifies an overall increase in the maxima for both wind speed and wave heights in the Indian Ocean basin. Increased activity may be attributable to the climate change; however, the exact meteorological and oceanographic parameter that leads to such an increased change is an area that requires a detailed research study. The rise is quite substantial in the current decade compared to the previous decade (1992 until 2001). Two transects were chosen one in the Arabian Sea and other in the Bay of Bengal to understand the effect of climate change. The results also signify that regions south of 10°N experience the impact of climate change on both wind and waves. In a quantitative sense, the analysis of two-decade satellite data shows the highest variability of maximum significant wave height occurred in the Southern Ocean (a rise of about +1.52 m in last 21 years), and the corresponding rise in wind speed was about 3.2 m s^{-1}. In context to the North Indian Ocean, there is an increasing trend seen both for wind magnitude as well significant wave height. There is an overall increase of about +0.3 m in wave height and ≈ 2 m s^{-1} for the wind speed. There is no significant impact of climate change in the equatorial regions. Based on this study, it is advocated that an increased wave activity especially in Southern Ocean can generate intense swell field that can modulate and modify the local wind-waves in the North Indian Ocean. In a practical sense, increased wave and wind activity has direct bearing on environmental loads of coastal and marine structures that may require accountability in the design and operational procedures. For the North Indian Ocean, higher wave activity in conjunction with high energetic storms in changing climate can have direct repercussion in coastal processes.

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