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Teleconnection Between ENSO and Wind-Wave Climate Under the Influence of Monsoon in the Bay of Bengal Region

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Abstract

Wind-wave parameters like the significant wave height (SWH) impacts considerably deep ocean and maritime activities and lives of all those dwelling near the coast. Prediction of such a parameter has immense utility during extreme conditions. Teleconnection features are explored between the most widely studied climate mode, the El Niño-Southern Oscillation or ENSO and the SWH parameter in the Bay of Bengal (BB) region under the influence of monsoon in this study. In two separate experiments the SWH data of the BB region for the period 1958-2001 and the period 2006-2016 is subjected to empirical orthogonal function analysis to split the data into spatial and temporal parts. The temporal variations are of annual periodicity for both the data sets. On analysis teleconnection feature of lower (higher) SWH during El Niño (La Niña) episodes is observed in the BB region. Significant correlation is observed between SWH and the ENSO indices during the summer monsoon months. The continuous wavelet power spectrum is generated using the first principal component (PC1) extracted above. It exhibits significant regions in the 0.5-1 year band resembling the monsoon variability in the BB region. To determine how SWH is related to the ENSO indices wavelet coherence is applied for the BB region. The higher coherency regions are found in the 0.5-1 year band which maybe related to the monsoon oscillation having similar periodicity. Thus the SWH and ENSO relationship in the BB region is influenced by the monsoon significantly.

Introduction

Random waves generated on the ocean surface play important role in local and global climate changes through various atmosphere-ocean interactions. Prediction of wind-wave parameter along the coasts during extreme conditions is of paramount importance. The concept of significant wave¹ is introduced to describe wind-waves quantitatively in

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Keywords

Bay of Bengal; Monsoon; Niño3.4 Index; Significant Wave Height; Wavelet Analysis. terms of the average wave height and the average wave period. Considering a wave spectrum, 33% of the waves which are maximum are averaged. The parameter SWH is measured as the average value of those highest waves. The relation between ENSO and Indian summer monsoon rainfall is one of the earliest observed teleconnections in global climate studies². There is high correlation between the dominant mode of monsoon circulation and the Indian Monsoon Rainfall³. The correlation between the Nino3 index and the first principal component of the circulation is stronger to that between the Nino3 index and the Indian Monsoon Rainfall. Thus the monsoon circulationis studied rather than the monsoon rainfall⁴. The characteristics and spatial patterns of each ENSO event is unique, although tropical circulation is shown to be influenced by warm ENSO episodes. It is reported⁵ the summer monsoon average SWH is relatively low in the eastern Arabian Sea during the strong El Niño years. Considering Brazil's coastal area the influence of the ENSO on the ocean surface wave height data is evaluated⁶. The correlations between SWH and ENSO indices are very less although statistically significant and having time lag of four months. During El Niño times there is reduced SWH and inverse pattern exists during La Niña times.

Considering the major cyclonic months, October to December in the BB region, for the period 1993-2010, there is a negative correlation between the Oceanic Niño Index and the cyclone energy⁷. The study shows that the during La Niña events the tropical cyclones get more active and the generation of the cyclones get shifted towards east 87°E in the BB region. During the El Niño events the reverse phenomenon is observed. In another study stochastic cyclone model is used to quantify the effects of ENSO on extreme significant wave heights8. The influence of ENSO is described on both the strength and the spatial distribution of the cvclonic waves. The effect of ENSO and Madden Julian Oscillation (MJO) are evaluated for a 14day mean SWH at three weeks lead time over the Western Pacific and Indian Oceans9. Spatial and temporal correlations are calculated and concluded that the spatial patterns of the SWH anomaly are in good agreement with the observations. In a similar study the SWH variability caused by ENSO and MJO is investigated in the New Zealand region¹⁰.

Again spatial variability and seasonal patterns of the SWH parameter is studied in the Taiwan Strait¹¹. It is found that the SWH anomaly is highly negatively correlated with the ENSO phases. Northeasterly monsoon months are characterized by negative (positive) SWH anomaly during the El Niño (La Niña) period. Southwesterly monsoon months in the Taiwan Strait witness increase (decrease) SWH values in the El Niño (La Niña) times¹¹. A nonlinear influence of ENSO was demonstrated¹² on SWH in the Indo-Pacific region and shown that during summer after an El Niño phase the wave height was smaller than normal. To reduce coastal hazards during natural calamities study of extreme wave heights is very important. The relationship between various climate modes like ENSO, Indian Ocean Dipole and the Indian Ocean wave climate is studied using the nonstationary generalized extreme value distribution¹³. Seasonal variations are explained using climate mode teleconnection patterns.

Analysis of the SWH parameter is beneficial to various maritime activities, ocean engineering, onshore and offshore industries. Particularly ship industries and the fishing community need short time forecasts with accuracy. Study of the surface wave-climate variability helps in the understanding and prediction of coastal hazards, offshore activities, coral reef biodiversity, extreme wave heights and so on. In this study the impact of the ENSO indices on the variability of the SWH are being explored for the BB region under the influence of monsoon. EOF analysis has been used for basin scale responses. Relationship between ENSO and SWH helps in the predictability of the later and hence various ocean activities.

Data and Methodology

The study region covering the BB extended from 78° to 98° east longitudes and 25° to 5° north latitudes. Two datasets have been used in this study. For the period 2006-2016, SWH data is downloaded and processed for the BB region. For the purpose six hourly NOAA WW3 model data having 50 km spatial resolution is considered¹⁵. For the second dataset, ERA-40 analyzed SWH data is downloaded16 from 1958 to 2001. The six hourly data having spatial resolution of one degree is considered for the BB region. To decompose the spatial and temporal components of the above 11 years and 44 years data efficiently, the empirical orthogonal function (EOF) analysis is applied. The ENSO indices namely, Southern Oscillation Index (SOI), Oceanic Nino Index (ONI) and Niño3.4 have been considered for the present study.

Negative (positive) SOI values¹⁷ are observed during El Niño (La Niña) episodes when warm (cold) ocean waters are measured across the eastern tropical Pacific. For the other two indices positive (negative) values coincide with El Niño (La Niña) episodes unlike the SOI index.The Niño3.4 index¹⁸ which is a monthly data and the ONI¹⁹ value which is a three month average SST anomaly data in the Niño 3.4 region have been used in this study.

Given any space-time field, EOF analysis finds a set of spatial patterns along with a set of associated time series or principal components. It is a powerful tool for data compression and dimensionality reduction which are found by computing the eigen values and eigen vectors of a spatially weighted anomaly covariance matrix of a field. The method compresses the spatial variability of the data into a few eigenmodes. As a result, a set of spatial modes which provide information about spatial patterns and the associated temporal amplitude functions which describe the dynamics are obtained. For the period 1958-2001,EOF analysis are conducted for the months of July (summer monsoon) and December (winter monsoon) separately and also taking three months SWH data at a time. The temporal variations of the SWH data of the BB region are tested with the ENSO indices for significant correlations. Next considering all the months together EOF analysis is applied on the SWH data for the BB region for the years 1958-2001 and then the years 2006-2016. The first principal components (PC1) are normalized by their standard deviation and then decomposed using the Morlet wavelet function¹⁴. The normalized wavelet power spectraare generated with the cone of influence, which determines the significant region. The black contours in the spectrum represents the 95% confidence level of the SWH data. Considering a red-noise process the significance levels are computed with a lag-1 coefficient of 0.9. Finally wavelet coherence is applied to PC1 of SWH data and the Niño3.4 index to examine possible relationships between them.

Results and Discussions

EOF analysis is applied on the SWH data of the BB region for July (summer monsoon) and December (winter monsoon) separately for the period 1958-2001. The mode which impacts the most, represents the maximum variability of the data. The first eigen mode accounts for 68% of the total variability of the SWH data in July (JUL) and 59% in December (DEC). Correlations between SWH-PC1 and SOI index (Table 1) shows only the month of July has p-value less than the significance level and hence significant correlation. In case of Niño3.4 in the month of July SWH is again significantly correlated (Table 2). Thus in the summer monsoon the ENSO and SWH relationship is significant than in the winter monsoon. In another experiment EOF analysis is conducted on the SWH data taking three months at a timefor the period 1958-2001. Considering January, February and March (JFM) the variability is 61%, February, March and April (FMA) 73%, March, April and May (MAM) 83%, April, May and June (AMJ) 83%, May, June and July (MJJ) 74%, June, July and August (JJA) 66%, July, August and September(JAS) 72%, August, September and October (ASO) 79%, September, October and November (SON) 76%, October, November and December (OND) 65%, November, December and January (NDJ) 59%, December, January and February (DJF) 62%. The variability in general is more during the summer monsoon than the winter monsoon. The Oceanic Niño Index (ONI) exhibited significant correlation during JJA (June, July, August) and JAS (July, August, September) as shown by the p-values in Table 3. Hence the ENSO and SWH relationship during the summer monsoon is strongly established in comparison to the winter monsoon.

Next EOF analysis is performed onthe SWH data for the BB region, considering all the months together. For the period 1958-2001,the first eigen mode accounts for 84% of the total variability of the SWH data and for the period 2006-2016 it is 80%. Figure1 adepicted the PC1 of the SWH data from 1958 to 2001, for the BB region. The temporal variations are of annual periodicity with a maximum occurring during the summer monsoon season. The maximum peak is observed in 1989 which occurred after a major La Niña year in 1988. The minimum peak occurred in 1998 which is after a major El Niño year in 1997.Figure1b gave similar annual periodic pattern of the SWH data for the BB region from 2006 to 2016. In this period 2015 is a major El Niño year and 2010 a major La Niña year. In 2016 during the summer monsoon season lower SWHis observed and in 2011 higher SWH in the winter months. Thus it can be concluded,teleconnection feature of lower (higher) SWH is observed during El Niño (La Niña) episodes in BB. Since there is significant correlation between SWH and ENSO indices in the summer monsoon season the above teleconnection feature is prominent during the same season too.

Table 1: To calculate p-values for correlation between SWH-PC1(44 years) and SOI

Table 2: To calculate p-values for correlation between SWH-PC1(44 years) and NINO3.4

| Months | Corr value (r) | p-value | Significant or not | Months | Corr value (r) | p-value | Significant or not |
|--------|-------------------|---------|-----------------------|--------|-------------------|---------|-----------------------|
| JUL | -0.423 | 0.004 | Yes | JUL | 0.439 | 0.0029 | Yes |
| DEC | -0.017 | 0.913 | No | DEC | -0.015 | 0.923 | No |

Table 3: To calculate p-values for correlation between SWH-PC1(44 years) and ONI

| Months | Corr value (r) | p-value | Significant or not |
|--------|----------------|---------|--------------------|
| JFM | 0.16 | 0.29 | No |
| FMA | 0.20 | 0.19 | No |
| MAM | 0.19 | 0.21 | No |
| AMJ | 0.03 | 0.85 | No |
| MJJ | 0.24 | 0.12 | No |
| JJA | 0.33 | 0.03 | Yes |
| JAS | 0.37 | 0.01 | Yes |
| ASO | 0.09 | 0.56 | No |
| SON | -0.12 | 0.44 | No |
| OND | -0.28 | 0.06 | No |
| NDJ | -0.01 | 0.95 | No |
| DJF | -0.04 | 0.79 | No |

If the p-value is less than the significance level α = 0.05 then the correlation is significant.

The continuous wavelet power spectra of PC1 of SWH data are generated for the BB region. The PC1 corresponding to the period 1958-2001 and then the period 2006-2016 is normalized by their standard deviation and then decomposed using the Morlet wavelet function. The normalized wavelet power spectra (Figures 2a and 2b) are generated with the cone of influence which determined the region to be considered for analysis. For a red-noise process, the regions having confidence greater than 95% are bounded by black contour. For both the spectra the significant regions occurred in the 0.5 to 1 year band. Thus the annual periodicity of the SWH data relating to the monsoon variability is most significant in the BB region.

To measure the proposed relation between the two time series wavelet coherence is applied next. With the help of arrows the relative phase relationship between the two time series is studied. The direction of the arrows can be referred to as a lead or lag. The arrows pointing right or left denotes in-phase or anti-phase relationship. Figures 3a and 3b displayed the wavelet coherence between PC1-SWH data and Niño3.4 index for the two different periods 1958-2001 and 2006-2016 respectively. There was high correlation in the 0.5-1 year period with both in-phase and anti-phase relationships. This can be related to the summer and winter monsoon pattern observed in the BB region. Thus a physical mechanism in the form of monsoon oscillation can be identified to establish a relationship between the SWH and ENSO indices in the BB region. Finally it can be stated that the teleconnection feature of lower (higher) SWH during El Niño (La Niña) phases is monsoon dependent in the BB region.



Fig. 1a: The first principal component (PC1) for BB SWH from 1958 to 2001 (44 years)



Fig. 1b: The first principal component (PC1) for BB SWH from 2006 to 2016 (11 years)



Fig. 2a: Continuous wavelet power spectrum of PC1-SWH for the period 1958-2001



Fig. 2b: Continuous wavelet power spectrum of PC1-SWH for the period 2006-2016



Fig.3a: Wavelet coherence between PC1-SWH and Niño3.4 for the period 1958-2001



Fig.3b: Wavelet coherence between PC1-SWH and Niño3.4 for the period 2006-2016

Conclusions

The study attempted to explore the influences ofthe monsoon on the ENSO and BB wind-wave data relationship. SWH data from two different sources has been utilized for 44 years and 11 years respectively. For both the periods the temporal variations are of annual periodicity. There is teleconnection feature of lower (higher) SWH during El Niño (La Niña) episodes in BB with lag of few months. The relationship is stronger during the summer monsoon season. The continuous wavelet power spectra of PC1 of SWH data are generated for the above mentioned periods. For both the spectra the significant regions occur in the 0.5-1 year period resembling the monsoon periodicity. The wavelet coherence between SWH and Niño3.4 show very high correlation in the one year band for all the years. The phase arrows demonstrate the fact that there is a lag between the SWH and the Niño3.4 index. The monsoon oscillation impacts significantly the relationship between SWH and ENSO in the BB region which is stronger during the summer in comparison to the winter.

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Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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