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Directional characteristics of shallow water waves along southwestern Bay of Bengal

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ABSTRACT

The aim of the present research is to investigate the directional characteristics of waves along the southwestern Bay of Bengal based on the measured data during 2010 at 14 m water depth. Diurnal, monthly and annual variation of reflected waves is studied for waves within a frequency range of 0.03–0.125 Hz to eliminate the influence of local wave growth processes. High values of directional width during the annual cycle over the southwestern Bay of Bengal is associated with the swell reflection from the coast during southwest monsoon season (June–September) and intrusion of moderate easterly winds propagating from Gulf of Thailand over the narrow land mass of Thailand and Myanmar. The reflected wave energy is maximum (14%) during the southwest monsoon due to the presence of long period and intermediate period waves and minimum (9%) during the northeast monsoon season (October–January). During fair-weather period (February–May), 10% of the total energy is propagated towards offshore. We also analyzed the relationship between directional and non-directional wave parameters using continuous wavelet transform and wavelet coherence analysis (WCA). WCA shown that reflection coefficient and total energy is directly/inversely proportional to the swells, when signal of period approximately less/greater than one day is observed.

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1. Introduction

The wave directional characteristics of the sea states is a vital input variable in the design of marine structures, wave forecasting, shore protection and design of vehicles. Availability of measured data on wave directional spreading are limited and the designers have only estimates of wave height, period, direction, and theoretical models of wave directional spectra are used to generate representative wave conditions for practical applications (Lee et al., 2010). Directional spectrum is generally represented as a product of the frequency spectrum and the directional spreading function (Borgman, 1982) and the directional spreading function is estimated using parametric models (Longuet-Higgins et al., 1963; Borgman, 1982; Donelan et al., 1985). In most parametric models, mean wave direction (θ) is an input parameter (Kuik et al., 1988). The parameter used to estimate the directional spreading function is the spreading parameter (s). The studies on the directional spreading of shallow water waves are limited (Ewans, 1998; Herbers et al.,1999; Kumar et al., 1999, 2000; Deo et al., 2002; Kumar, 2006; Lee et al., 2010; Kumar and Anoop, 2013).

Wave reflection from natural beaches and coastal structures influence the hydrodynamics and sediment dynamics in the nearshore area. Energy and direction associated with reflected wave will also influence the directional properties of the nearshore waves (Ardhuin and Roland, 2012). Wave reflection at the shoreline is added as an important parameter in the recently developed third generation wave model WAVEWATCH III (Ardhuin and Roland, 2012), whereas Benoit et al. (1996) and Booij et al. (1999) provide an option for reflection in wave modeling. Elgar et al. (1994) found that, on natural beaches reflection is generally weak and is less than 5% of the wind–sea and swell wave energy. Studies dedicated to wave reflection are limited and only a preliminary study is carried out by Anoop et al. (2014) on the reflected/offshore propagating waves along the Indian subcontinent. Studies related to free surface gravity wave simulation in the Bay of Bengal (BoB) still uses only the growth, refraction and decay components to solve wave balance equation (Aboobacker et al., 2009). Seasonal changes in winds of east coast of India with winds from southwest (SW) during the SW monsoon period (June–September) and from northeast (NE) during the NE monsoon period (October–January) produce similar changes in the directional wave parameters and the nature of this seasonal variability is not studied. Glejin et al. (2013) studied the monsoon and cyclone induced wave characteristics over the southwestern BoB.

Wavelet transform is a recently developed analysis technique which expand time series into time frequency space and can find

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localised intermittent periodicities (Grinsted et al., 2004). By decomposing a time series into a time–frequency space, the dominant modes of variability and the variation of those modes with time can be determined (Erol, 2011). Erol (2011) applied the wavelet analysis (continuous wavelet transform, cross wavelet transform and wavelet coherence algorithms as extensions of wavelet analysis) to sea-level observations recorded by tide-gauge sensors. The continuous wavelet transform (CWT) expands a time series into a time frequency space where oscillations can be seen in a highly intuitive way. Erol (2011) observed that in the time-frequency analysis of the series and inspection of the coherence between two time series, the wavelet tool CWT is very useful and practical. The wavelet transform of the length of day, atmospheric angular momentum and the southern Oscillation Index during January 1970 to June 1999, indicate that they have similar time-varying spectral structure (Zhou et al., 2001). Elsayed (2006) applied the wavelet bicoherence to study the wind-wave interaction. Wavelet coherence analysis (WCA) is powerful method for testing proposed linkages between two time series. Wavelet bicoherence is used for analyzing wind–wave interaction (Elsayed, 2006). Camayo and Campos (2006) applied wavelet transform in the study of coastal trapped waves off the west coast of South America.

Hence in this article, directional characteristics of waves during one year period at a location in the southwestern BoB (at 14 m water depth) are studied based on the measurements carried out using a moored buoy. In addition, directional spreading of wind–sea and swell are studied. The objective of the research is to investigate the directional characteristics of shallow water waves in the south western BoB. Following research questions are addressed, What is the seasonal variation of directional width? How the directional spectrum changes with swells from the South Indian Ocean? What is the percentage of reflected energy along the east coast and its influence on directional characteristics?

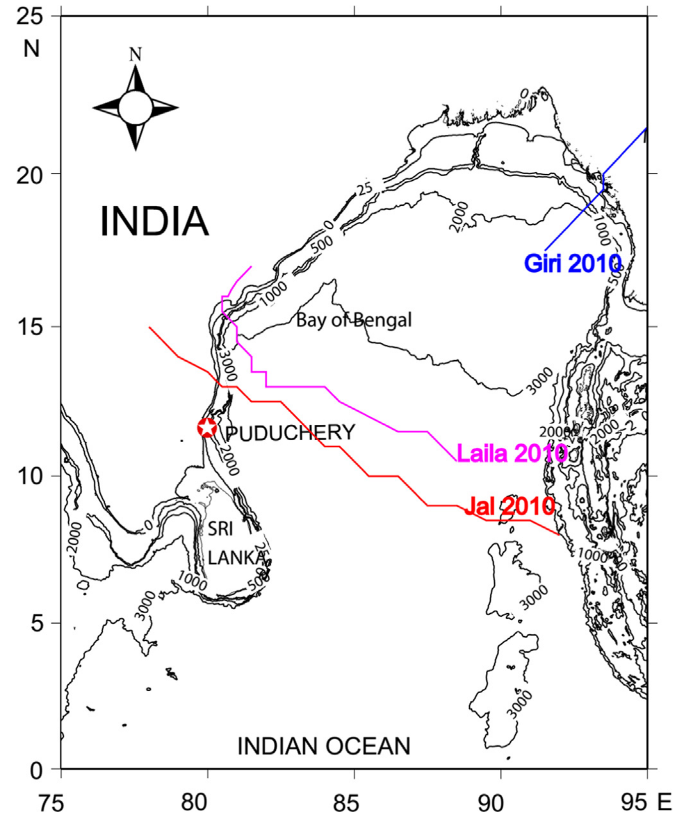

Fig. 1. Wave measurement location off Puducherry along the east coast of India in the Bay of Bengal (contours are in meters). The tracks of cyclones (Giri, Laila, and Jal) observed during 2010 are also shown in the figure.

2. Materials and methods

Measured wave data off Puducherry, southwestern BoB (Fig. 1) during 1 January to 31 December 2010 using the directional wave rider buoy, DWR Mk-III at 14 m water depth (11° 55′ 26″ N latitude and 79° 51′ 03″ E longitude) are used for the study. The wave rider buoy measures free surface gravity waves with heaves in the range of −20 and +20 m, with a resolution of 1 cm in heave, and periods between 1.6 and 30 s. The cross sensitivity of the heave is less than 3%. The range of measurement of the wave direction using DWR Mk-III is 0–360° with a resolution of 1.5° and an accuracy of 0.5° and is reference to the magnetic north. Data are recorded continuously at 1.28 Hz, and the data for every 30 min are processed as one record. The collected time series is subjected to standard error verification for spikes, steepness and constant signals and a total of 17517 records are used for further analysis. Measurements are made in Coordinated Universal Time (UTC) and the time referred in the paper is in UTC. The wave spectrum is obtained via. the Fast Fourier transform (FFT) of the measured vertical elevations of the buoy. At the low frequency end accelerations become very small and disappear in the sensor noise. Therefore, a digital high-pass filter with a cut off at 30 s (0.033 Hz) is applied to the samples. At higher frequencies, the wave wavelength becomes comparable to the buoy dimensions and the buoy will not be able to follow the particular waves anymore (geometric attenuation) (Datawell, 2009). As higher frequency measurements can only introduce noise, all outputs of the buoy sensors are filtered by applying a low-pass filter with a cut off frequency of 0.58 Hz. The frequency resolution is 0.005 Hz for frequency 0.033 to 0.1 Hz and is 0.01 Hz for frequency higher than 0.1 Hz. Significant wave height (H_{m0}) is obtained from the spectral moment. Period corresponding to the maximum spectral energy, i.e., spectral peak period (Tp) is obtained from the wave spectrum. Mean wave direction (θ) is estimated based on Kuik et al. (1988). Directional spreading is studied using directional width (σ) as given by Kuik et al. (1988) and mean spreading angle (θ_k) according to Goda et al. (1981). The details of wave parameters used in the study are presented in Annexure (Kumar and Anoop, 2013). Coastal inclination along the Puducherry coast is 15° to the north in the NE–SW inclination and hence 15–195° waves approach the coast. The waves with direction more than 195° and less than 15° will be propagating away from the coast. Energy associated with onshore (E_{in}), offshore (E_{out}), and total (E_{tot}) propagating waves is calculated as,

$$E_{in} = \int_{0.03}^{0.58} \int_{15^\circ}^{195^\circ} E(f,\theta)\, d\theta\, df \tag{1}$$

$$E_{out} = \int_{0.03}^{0.58} \int_{195}^{360} E(f,\theta)\, d\theta\, d f + \int_{0.03}^{0.58} \int_{0}^{15} E(f,\theta)\, d\theta\, df \tag{2}$$

$$E_{tot} = \int_{0.03}^{0.58} \int_{0}^{360} E(f,\theta)\, d\theta\, df \tag{3}$$

Percentage of onshore and offshore energy are calculated as the ratio between E_{in} or E_{out} to E_{tot} at the measurement location. NCEP/NCAR reanalysis data (Kalnay et al., 1996) of zonal and meridional components of wind speed at 10 m height real-time observations at 6 h intervals is used to study the wind pattern. The meteorological convention is used for presenting the wind and wave direction data (0 and 360° for wind/wave from North, 90° for East, 180° for South, 270° for West). Wave age is estimated as Cp/U, where Cp is the wave celerity at peak frequency and U is wind speed.

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