

Near shore waves, longshore currents and sediment transport along micro-tidal beaches, central west coast of India

Sajiv Philip Chempalayil, V. Sanil Kumar, G. Udhaba Dora, Glejin Johnson

Ocean Engineering, CSIR-National Institute of Oceanography

(Council of Scientific & Industrial Research), Dona Paula, Goa - 403 004, India

Tel: +91 832 2450 327 Fax: 0091 832 2450 602 Email: sanil@nio.org

* Corresponding author

Abstract

Coastlines are undergoing constant geomorphologic changes with respect to the incident wave climate. Based on waves measured at 9 m water depth, simulation of near shore wave transformation is done using REFDIF-1 numerical model and the near shore breaker parameters are estimated at two micro-tidal beaches along central west coast of India. Model results are validated with measured values. From the breaker parameters, longshore current and longshore sediment transport rates (LSTR) are computed by using semi-empirical equations. Estimated longshore current and LSTR are showing dramatic variations with respect to seasons. Predominant direction of LSTR is observed towards north since the approach waves are from south west direction during pre-monsoon and post monsoon. During monsoon season, waves are from west south-west and resulted in southerly transport. The estimated annual net and gross LSTR by CERC at two locations are in the same order whereas LSTR estimated by Walton & Bruno and Kamphuis equations are showing different estimations because of difference in surf-zone width and foreshore slope between the two locations. For micro-tidal beaches with length less than 6 km, Kamphuis equation is giving agreeable estimation of LSTR. Sensitivity analysis of LSTR estimate shows that coastal inclination is the prominent factor in determining LSTR than incident wave angle.

Key Words: Nearshore sedimentation, littoral zone, wave refraction, wave measurement, coastal zone management, Karnataka coast

1. Introduction

Understanding of sediment transport along coastlines is crucial for policy makers in coastal zone management. Estimation of sediment transport rate and its predominant direction are important input in the planning of shore protection measures. Near shore waves are prominent among other oceanographic parameters such as winds, tides, and currents in modifying the coastal geomorphology. Wave forces and wave dominated processes such as wave transformation in shallow waters cause spatial variation in wave energy leading to beach erosion/accretion (Baba 1988; Short 1999). Longshore currents generated by the breaking waves are responsible in transporting the sediments along the surf-zone. In the tropical region, influx of sediments is highly variable with season, and the sediment circulation in the nearshore and the vicinity of river mouths also changes with season. In response to sediment influx, beaches in the vicinity of the river mouths and configurations of rivers undergo rapid changes and create management problems especially when the sediment influx is modified by damming of rivers or if the current pattern is modified by construction activities in the mouth region (Abadie et al., 2008). Sedimentation in the river mouth, narrowing of river mouths, shoreline erosion, and rapid changes of the mouth configurations are common problems observed along the central west coast of India (Nayak et al., 2010). In New Mangalore port, sedimentation is mainly due to deposition of seabed material brought into suspension by the monsoon waves (Dattatri et al., 1997), whereas in the Sharavathi estuary, sedimentation is related to the offshore source brought by tidal currents, and interaction of waves and river processes in the channel (Hegde et al., 2004). Sediment transport rate can be estimated mainly by three methods; (1) from direct measurements of longshore transport flux, (2) from empirical formulae using hydrodynamic and sediment data acquired in the field and (3) by inferring net LST from observing large scale changes in shoreline and beach erosion and accretion (Esteves et al., 2009). Approaches (1) and (3) require considerable resources to acquire the necessary data. Earlier sediment transport studies along the Indian coast are either based on visual observations of littoral environmental parameters or based on the ship reported data. In the current study we have adopted the second methodology by transforming the measured offshore waves by numerical wave model and estimated the LST by using semi empirical equations. The objective of the work is to study the near shore wave characteristics and compare the LSTR estimate based on different semi empirical equations. Sensitivity of the LSTR estimate with wave angle and coastal inclination also studied.

2. Study area

Study area is located along the central west coast of India and is off Honnavar (Figure 1). Sharavathi river meets the Arabian Sea at Honnavar and it separates the coastline into two as Pavinkurve beach in the north side and Kasarkod beach in the south side. Coastline is almost straight and open and it is inclined to west by 17° with respect to true north. Depth contours appears as almost parallel and the near shore steepens with the 10 m contour occurring at an average distance of 3.5 km from the coast and the 20 m contour occurring at an average distance of 10.75 km from the coast. Nearshore bathymetry usually becomes complicated because of presence of islands, sandbars, and shoals and hence these factors will influence the sediment transport phenomena. Offshore island named Basavrajadurg island located 1 km offshore of Pavinkurve beach influences the nearshore wave climate along the Pavinkurve beach. Wind field over the study area is showing dramatic variations with respect to seasons. During the months June to September which are generally referred as summer (south-west) monsoon and the winds are southwesterly and its strength is significantly larger than that during rest of the year. During November- February referred to as winter (north-east) monsoon and the winds over the study area are observed as northeasterly direction and October and April- May are time of transition between two monsoons (Shetye et al., 1985). The region experiences a tropical climate marked by heavy rainfall, high humidity and hot weather conditions in summer. 87% of the annual rainfall is during summer monsoon period and the remainder during the northeast (winter) and inter-monsoon months with an average annual rainfall of ~ 3.9 m (IMD, 1999). Sharavathi river influence the sediment dynamics at the river mouth and the river discharge is high during summer monsoon period and it brings inland sediments to the sea, whereas during other seasons river discharge is low and hence the input of inland sediments also will be low. This variation in the sediment influx into the beach environment results in a complex adjustment of sediments in the sea and the foreshore in the vicinity of the estuary (Hegde et al., 2009). Annual mean discharge of the Sharavathi river is 4545 million m^3 (Sugunan, 1995). Sand spit on the southern coast is growing from south to north and hence the river mouth is shifting northward causing erosion at north side of river mouth (Hegde et al., 2009; Vinayraj et al., 2011). Tides of the study area are mixed semi-diurnal dominant and its range is less than 1.5 m (Kumar et al., 2011) and hence the beach is classified under micro tidal beach. Cross shore sediment transport will dominate during the flood and ebb tidal conditions especially in the vicinity of the river mouth. Onshore transport of sediment will occur during the flood tide and offshore transport of sediment will occur during ebb tide (Dean et al., 1975). Masselink and Short (1993) studied the effect of tides on beach morphological changes as $RTR = TR/H_b$ where RTR is the relative tidal range and TR and H_b are

tidal range and breaker height respectively. According to them, for a micro tidal beach like Honnavar, the ratio will be less since the tidal range will be always lesser than the breaker height and this implicates wave dominance over the tide and hence the sediment dynamics of this area is predominantly determined by the waves.

Figure 1

3. Data and methodology

3.1 Data collection

As a part of long term shoreline studies, various oceanographic parameters are measured around Honnavar. Wave parameters are measured by a moored Datawell directional waverider buoy at 9 m depth, 2.5 km offshore of Pavinkurve beach (Figure 1) during 1 January 2009 to 31 December 2009. Wave data are recorded for 30 minutes duration at a frequency of 1.28 Hz. Wave spectrum is obtained through Fast Fourier transform (FFT). FFT of 8 series, each consisting of 256 measured vertical elevations of the buoy data, are added to obtain the spectra. The high frequency cut off is set at 0.58 Hz. Significant wave height (H_{m0}) and mean wave period (T_{m02}) are obtained from the spectral analysis. Period corresponding to the maximum spectral energy is referred as spectral peak period (T_p) and is estimated from the wave spectrum. Wave direction (θ) corresponding to the spectral peak is estimated based on circular moments (Kuik et al. 1988). The meteorological convention is used for presenting the wave direction data (0 and 360° for wave from North, 90° for East, 180° for South, 270° for West). In order to calibrate the numerical model, breaker parameters at shallow water is measured by using an S4DW electromagnetic current meter placed at 2 m water depth (Figure 1) during 21 September 2009 to 31 October 2009. S4DW records pressure that is converted into depth data and the data records are transformed from the time domain to the frequency domain using the Fast Fourier Transform. The data are sampled at a rate of 2 Hz at every three hours. Sediment samples collected from various locations of the swash zone are washed and oven dried. Grain size distribution is carried out in laboratory using electromagnetic sieve shaker machine that contains six sieves having mesh sizes 2000, 1000, 500, 250, 125, 63 μm and pan. Median grain size is obtained using GRADISTAT package (Blott et al., 2001) following logarithmic method (Folk and Ward, 1957).

3.2 Numerical model (REFDIF-1)

Wave measured at 9 m water depth are transformed by using numerical model REFDIF-1 version 2.5 (Kirby et al., 1994). This model is a parabolic formulation of the mild slope equation of (Berkhoff, 1972) and it takes into account of both refraction and diffraction and simulates the behavior of monochromatic waves over irregular bathymetry. A large number of studies have validated this model with measured data (Work et al., 1997; Raichle, 1998). Three hourly wave data is taken for model simulation for computing convenience. Since the coastline is inclined to 17° with respect to true north, the model domain is rotated clock-wise in order to bring positive x axis of the computation domain normal to coastline. Grid dimensions are taken as 800 x 400 and dimension of each grid cell is 9.66 x 8.33 m. Model is validated by using the nearshore wave data measured using S4DW located at 2 m water depth (Figure 1). Model results are post-processed and longshore currents and sediment transport is estimated using the semi-empirical formulae.

3.3 Theoretical longshore currents

Two commonly used equations to estimate the longshore currents are i) $V_G = KgmT \sin 2\theta_b$ (Galvin and Eagleson, 1965) and ii) $V_{LH} = 20.7m(gH_b)^{1/2} \sin 2\theta_b$ (Longuet-Higgins, 1970), where, V_G , and V_{LH} are mean longshore current velocities in the surf zone (m/s), K is a dimensionless coefficient depending solely on the geometry of the breaking wave which is taken as 1 (Galvin, 1965), g is acceleration due to gravity (m/s^2), m is the foreshore slope, T is wave period (s), H_b is breaking wave height (m) and θ_b is breaker angle (angle between the breaking wave crest and the shoreline). Longshore currents are estimated considering the sea and swell breaker angles and the resultant is estimated.

3.4 Longshore sediment transport

3.4.1 CERC formula (USACE, 1984)

LSTR is calculated from the empirical equation relating the longshore energy flux in the breaker zone as $Q = \frac{KA\rho g H_b^2 T \sin 2\theta_b}{64\pi}$, where, Q = LSTR (m^3/yr), K = dimensionless empirical proportionality constant (taken as 0.39) (Komar and Inman 1970), ρ_s = sediment density (2650 kg/m^3), ρ = density of water (1030 kg/m^3), g = acceleration due to gravity (m/s^2), p = Porosity factor (0.4).

3.4.2 Kamphuis (2002)

Kamphuis (2002) developed following formula which includes beach slope and sediment grain size

as $Q = \left(\frac{2.27 H_b^2 T_p^{1.5} m^{0.75} D_{50}^{-0.25} \sin \theta_b}{(\rho_s - \rho) g (1 - \rho)} \right)$ where T_p = peak wave period (s), D_{50} = median grain size (mm) and m = beach slope.

3.4.3 Walton and Bruno (1989)

Another formula used to calculate LSTR is that put forwarded by Walton and Bruno (1989). Using

the breaker height and longshore velocity, the LSTR is calculated as $Q = \frac{KA\rho g H_b W C_f}{0.78 \left(5\pi/2 \left(\frac{V}{V_0} \right)_{LH} \right)}$ where,

W = Surf zone width (m), C_f = friction coefficient (dimensionless) taken as 0.005, $\left(\frac{V}{V_0} \right)_{LH} =$

theoretical dimensionless longshore current velocity with the mixing parameters as 0.4 (Longuet-Higgins, 1970). The reason for selecting these three semi-empirical equations for the current study is that these equations have been extensively used by several researchers (Chandramohan et al 1992; Kumar et al 2000; Jena et al 2001) for estimating LSTR at different locations along Indian coast line. Besides it is possible to understand the influence of various littoral parameters in determining LSTR using these 3 formula. In CERC equation, the estimates of LSTR are influenced only breaker height (H_b), breaker angle (θ_b) and mean wave period. While in Walton and Bruno equation the estimates of LSTR depends on breaker height (H_b), surf-zone width, long-shore current velocity. Finally in Kamphuis equation the influencing parameters are breaker height (H_b), breaker angle (θ_b), peak wave period (T_p), median grain size (d_{50}) and beach slope.

4. Results

4.1 Wave characteristics at 9 m water depth

During pre-monsoon season (February-May), the predominant directions of swells are south-west (SW) and seas are north-west (NW) (Figures 2&3). Frequencies of the occurrence of NW seas are reducing during February to May with increase in the swells. The NW sea waves induce southward sediment transport. But the percent of occurrence of SW swell waves are higher (56%) than that of NW seas (41%) and the predominance of SW component of incoming waves will induce net direction of sediment transport towards north. Significant wave height is in the range of 0.3 to 1.9 m

with an average value of 0.8 m and is characterized by low energy waves (83% of waves are less than 1 m). In the late pre-monsoon season, wave heights are increasing due to strengthening of wind seas (Figure 3A). Kumar et al., (2012) studied the wave characteristics of Honnavar based on one month data each during three different seasons in 2009 and found that predominance of wind seas during the pre-monsoon season than during other seasons using normalized wave spectral energy density analysis. Sea breeze is very active during pre-monsoon period and it has an impact on diurnal cycle of sea state along west coast of India (Neetu et al., 2006). Co-existence of locally generated wind seas and pre existing swells results in a diurnal pattern of wave parameters during pre-monsoon season (Vethamony et al., 2011). End of pre-monsoon season is observed as the switching of high energy wind seas to high energy swells and the direction of wave approach shifts from SW to WSW (Figure 2&3). During monsoon season, low energy SW waves become high energy WSW waves. Compared to other seasons, wave heights are observed as higher during monsoon period and are observed within the range of 0.5 to 4.3 m with an average value of 1.6 m. Unlike other periods, the mean wave period during this period is higher than 5 s. This season is characterized as high energy period since 83% of waves are greater than 1 m. Maximum H_{m0} (4.3m) is observed during the month of July. Kumar et al., (2006) reported significant wave height up to 6 m during monsoon seasons and less than 1.5 m during rest of the period. Interannual and seasonal variations in nearshore surface wave parameters off Honnavar over a period of three years (March 2008 to March 2011) indicate that yearly average wave parameters are same during different years (Philip et al., 2012). During late monsoon in the month of September, the period observed as the transition phase from monsoon to post-monsoon, the wave direction of incoming waves are shifting from WSW to SW. Similar to the monsoon period, swell waves are still dominant over sea waves (Figure 3A) and 88% of incoming waves are from SW direction, the predominant direction of LSTR is towards north as seen earlier in the case of pre-monsoon period. Wave heights are observed as low (average value=0.6 m) similar to the pre-monsoon since 90% of waves are less than 1m. Unusual peak in wave height (2.7 m) during post monsoon period is during the month of November due to the cyclonic storm 'Phyan' developed over the south-eastern Arabian Sea. Coastline undergoes major erosional phase during SW monsoon season due to high SW monsoon waves and a secondary but minor period of erosion during December and January (northeast monsoon) and accretion during other months (Chandramohan et al., 1994).

Figure 2 and Figure 3

4.2 Nearshore wave characteristics

Near shore wave heights are estimated using REF-DIF-1 numerical model and also using Snell's law (analytical method) and are compared with the measured data. Correlation coefficient estimated for REF-DIF-1 model results and the measured data is 0.82 and the estimated correlation coefficient for analytical method is 0.76 which shows that REF-DIF-1 model can give better results than the analytical method (Figure 4). Measured waves at 9 m water depth are transformed by using the REF-DIF-1 model for the entire year 2009 and the model outputs are extracted for two locations (one off Pavinkurve beach and another off Kasarkod beach indicated in Figure 1). Monthly average offshore wave heights, breaking depths, closure depths, surf-zone width, beach slope, and median grain size (D_{50}) values are given in Table 1 for both locations. The surf-zone width is calculated by finding the grid distance from zero water depth to shallow water depth at which the monthly offshore wave heights are likely to break. Breaking depths for the respective average offshore wave heights are estimated by finding the ratio of average wave height by theoretical breaking criteria ($\gamma_b=0.78$). Since the grid dimension has taken as fine (which is less than 10 m) and so the low energy breaking wave heights are well reproduced from corresponding grid locations. Closure depths are calculated by Hallermeier method (1978). It is observed from the tables that the breaker zone characteristics such as surf-zone width, beach slope, and median grain sizes are changing with respect to the wave climate. At both locations the surf zone width is narrow since the low energy waves are breaking at shallow depths during both pre-monsoon and late post-monsoon periods and wider for monsoon period since the high energy waves are breaking at larger depths. Also beaches undergoes accretion during fair weather period and sediments are characterized by fine sediments with low D_{50} values, Whereas during high energy period beaches undergoes erosion characterized by high D_{50} values.

Figure 4

Model simulation for the case of waves coming normal to the shore is shown in the Figure 5. Here breaker characteristics at the leeward of island is not considered for the LSTR estimation since the model equations are based on parabolic approximation of mild slope equation and the model results at the leeward side of Basavrajadurg island will give large errors in estimation of breaker characteristics (Fengyan Shi, personal communication). The 3-hourly variation of breaker height and the breaker angles are of both Pavinkurve beach and Kasarkod beach are showing similar characteristics (Figure 6A&B). During pre-monsoon period breaker heights varied in the range of 0.4 to 1m with an average breaker height of 0.6 m at both beaches and breaker angles persisted between -28° to 28° at both beaches. As discussed earlier in the first session, during pre-monsoon season,

primary waves are from SW (83%) and secondary waves are from NW (16%). Breaker angle of waves which are from NW are denoted with negative sign and the waves from SW are denoted with positive sign (Figure 6C&D). Waves which are from NW will cause sediment transport towards south and waves which are from SW will cause sediment transport towards north. In the month of May the wave direction changes from SW to WSW thus the incoming waves are undergoing transition stage (Figure 2). During monsoon season the breaker height varied in the range of 0.6 to 2.2 m with an average breaker height of 1.3 m at both beaches. Percentage occurrence of breakers shows that majority of waves (50%) are from WSW direction and since the coastline is inclined 17° towards the west, this will cause southward movement of sediments during monsoon period. During late monsoon period, in the month of September, the wave direction is undergoing transition stage from WSW to SW indicating switching of SW monsoon to NE monsoon. The breaker heights are observed as 0.2 to 0.8 m with an average breaker height of 0.5 m. Here maximum breaker height during cyclone Phyan is 0.8 m. Predominant (91%) direction of breakers are from SW. During the entire year 2009, 80% of the breaker heights are below 1 m at both beaches and 78% of waves are coming from SW, 12% are coming from NW and remaining 10% are coming from WSW.

Table 1 & Figure 5

4.3 Longshore current

As discussed earlier, the coastline of Honnavar is inclined to 17° to the west and hence the current flow towards 343° is considered as north and the current flow towards 163° is considered as south. Three hourly variations of calculated longshore currents at Pavinkurve beach and Kasarkod beach are given in Figure 6E&F. Similar in the case of near-shore waves, the predominant direction of average long-shore currents are towards north and average current speeds are 0.44 and 0.3 m/s off Pavinkurve and Kasarkod beach. The reason for this increased longshore current off Pavinkurve beach is due to increased foreshore slope at Pavinkurve beach (Table 1). During pre and post monsoon, the estimated longshore currents are highly variable and changing its direction with respect to the direction of breakers which are coming from NW and SW directions (Figure 6C&D). At Pavinkurve beach, the estimated longshore current by Longuet-Higgins varied in the range of -0.65 to 1.6 m/s and by Galvin's equations varied in the range of -0.9 to 1.3 m/s. At Kasarkod beach, the estimated longshore current by Longuet-Higgins varied in the range of -0.3 to 1m/s and by Galvin's equations varied in the range of -0.7 to 0.8m/s. Kumar et al., (2003) reported longshore currents along the central west coast of India are in the range of 0.1 to 0.6 m/s with an average value of 0.3 m/s. Here estimated longshore current by Longuet-Higgins is taken as longshore current

component in the Walton and Bruno's equation for the calculation of LSTR.

Figure 6

4.4 Longshore Sediment Transport Rate

Differences in balance in sediment transport along the coastline will influence the erosion and deposition features mainly due to wave propagation directions (Horikawa, 1988). Calculated monthly sediment transport using the equations CERC, Walton & Bruno and Kamphuis for both locations Pavinkurve and Kasarkod beach are given in Table 2. Similar to the case of long-shore currents the direction of LSTR is determined by the breaker height, breaker angle and the coastal inclination of the beach. Hence during most of the year the primary direction of LSTR is towards north due to SW breakers and secondary but minor southward transport due to NW and WSW breakers. During pre and post monsoon periods the estimated LSTR are showing low values since the breaker heights are low. But during the late pre-monsoon and monsoon high LSTR are observed because the breaker heights are rising up during this period. Annual estimated net ($\sim 4.7 \times 10^5 \text{ m}^3$) and gross values ($\sim 7.4 \times 10^5$) of LSTR by CERC equation are showing the same range at both beaches (Figure 7A&B). Estimated seasonal gross LSTR at the both beaches based on CERC, Walton & Bruno, and Kamphuis equations during pre and post monsoon seasons are in the same order of 49%. The monsoon season contributes the remaining 51%. Since the directional window of incoming breakers is limited within the range of 295° to 225° , the waves are coming from the directional sector 225° to 253° and resulted in 84% of the annual net LSTR in northerly direction and the remaining 16% of estimated annual net LSTR are towards southward due to waves coming from the directional sector 253° to 295° . The sand spit on the southern bank of the Sharavathi river mouth is growing towards north due to the net northerly sediment transport. Sand spits formed at the river mouth are of great significance in understanding the morphodynamics of river inlets (Kraus, 1999). Orientation of a spit is commonly used as an indicator of the direction of net littoral drift.

5. Discussions

5.1 Influence of different littoral parameters in the estimation of LSTR

The LSTR estimated by Walton & Bruno and Kamphuis equations are showing different estimation at the both beaches (Figure 7A&B). Estimated LSTR by Kamphuis equation at Kasarkod beach is 53% lower in annual gross estimate than that of Pavinkurve beach. But the annual gross LSTR estimated by the Walton & Bruno equation at Kasarkod beach is showing 9% higher than that of Pavinkurve beach. The main reason for this difference in the LSTR estimation is due to increased

foreshore slope at Pavinkurve beach and increased surf-zone width at Kasarkod beach (Table 1). At Pavinkurve beach since the foreshore slope is 1.7 times steeper than Kasarkod beach, the estimated longshore current is higher at Pavinkurve beach as discussed earlier. These estimated longshore currents are the input in the Walton & Bruno equation. But it is seen that the increased surf-zone width at Kasarkod beach has more effect in determining the LSTR estimation in Walton & Bruno equation than longshore current. And also, the increased foreshore slope at Pavinkurve beach is the main reason of increased LSTR estimation by Kamphuis equation at Pavinkurve beach. At Pavinkurve beach, the computed net LSTR using CERC equation is approximately 1.6 times higher than Walton & Bruno and Kamphuis estimation and the computed LSTR of Walton & Bruno equation is 1.03 times higher than Kamphuis equation. At Kasarkod beach, the computed LSTR using CERC equation is approximately 1.5 times higher than Walton & Bruno and 2.55 times higher than Kamphuis estimation and the computed LSTR using Walton & Bruno equation is 1.7 times higher than Kamphuis equation. Major shortcomings of CERC equation are that there is no dependence of wave period, beach slope, breaker type and grain-sizes (Smith, 2006) unlike the case of Kamphuis equation. Miller (1999) measured the LSTR during storms and compared the values with CERC equations and found that the LSTR estimate by CERC equation sometimes over predict and sometimes under predict the LSTR. Hence Miller suggested that additional terms are required in CERC equation to predict the LSTR during storm conditions. Wang et al., (2002) examined laboratory LSTR for waves having similar wave heights but differing breaker types and they found that the difference in the LSTR between spilling and breaking wave is nearly the factor of three. Since the CERC equation is not dependant on sediment grain size, it gives only bulk transport rate. The LSTR estimates by CERC equation pertains only to the sediment grain size range of approximately 0.2 to 0.4 mm (Smith et al., 2006). In the present study, majority (92%) of measured grain sizes of sediments are within this range (Table 1). The estimations of LSTR using CERC is made based on the assumption of long and open sandy coast with adequate supply of sediments. Here the study is made at 6 km long sandy beach which is partially obstructed by an offshore island. Similar kind of LSTR measurement study made at a pocket beach bounded by headlands named as Arge beach (Kumar et al., 2003) showed that the estimation of LSTR using CERC resulted in high estimation of LSTR. Also another study made by Wang and Kraus (1999) in measuring the total longshore sediment transport rate in the surf zone at a temporary groin installed at Indian Rocks beach, west central Florida. They have found that the coefficient K which appears in the CERC formula is not constant and other factors may enter such as, breaker type, turbulent intensity and threshold for sediment transport. In modifying the K value in the CERC equation, (Dean and

Darlymble, 2002) have concluded that LSTR should decrease with increase in grain size of the sediment. Earlier, Komar (1988) analyzed the available field data and found some relationship between K and grain size as K value decreases with grain size increases. For sand sized grains, he recommended the value of $K_{(rms)}$ as 0.57. Schoones and Theron, (1993) compiled and reviewed 273 measurements of bulk transport rate. They divided the datasets into those with grain sizes less than 1 mm and those with greater grain sizes. They obtained the best fit $K_{(sig)}$ as 0.41 for grain sizes less than 1 mm from the highest quality field datasets and obtained correlation coefficient as 0.77. For the grain sizes greater than 1mm they obtained the best fit as $K_{(sig)}$ as 0.01 with the correlation coefficient of only 0.11. Also, CERC formulation assumes all of the energy is associated with a single peak in wave spectra. (Kumar et al., 2002) compared the LSTR estimate based on CERC formula including the sea and swell waves, and Walton and Bruno incorporation of site specific measurement of longshore currents and found that both the estimates are reasonably agreeing well for a long and open sandy beach. The presence of Basavrajadurg island off Pavinkurve beach influences the estimation of breaker parameters off Pavinkurve beach. Based on measured total LSTR by the streamer traps and short term impoundment along the low wave energy coasts, (Wang et al., 1998) found that the measured rates are lower than that predicted by various empirical formulas. Using the root mean square wave height in the CERC formula, the empirical coefficient K is found to be 0.08 instead of 0.78 used in the Shore Protection Manual. In the present study K value is taken as 0.39. In the present study the significant wave height values are used in place of root mean square wave height values for the estimation of LSTR and hence K value is taken as 0.39 (USACE, 1984). Wang et al., (1998) found that the values of LSTR calculated using CERC formula is nine times greater than trap measured values. The LSTR estimates by CERC equation can be accepted as reasonable confidence ($\pm 50\%$) only if the K is calibrated with site specific environmental parameters. Kumar et al., (2003) compared the LSTR values based on Walton and Bruno with measured values and they found that the average measured LSTR is found to be 0.65 times the value calculated using Walton & Bruno equation. They measured LSTR during pre-monsoon months (February to May) and obtained gross transport as $726 \text{ m}^3 \text{ day}^{-1}$. Among the estimated LSTR values at selected locations along Honnavar coast during the months February to May, Kamphuis equation is giving much closer values as $946 \text{ m}^3 \text{ day}^{-1}$ at Pavinkurve beach and as $700 \text{ m}^3 \text{ day}^{-1}$ at Kasarkod beach against the measured value of $726 \text{ m}^3 \text{ day}^{-1}$. Hence LSTR values estimated by Kamphuis equation can be considered as quite acceptable estimation along Honnavar coast. Unlike in the case of CERC equation, Kamphuis equation contains the wave period term that influences the breaker type. Wang et al., (2002) compared the results obtained from both CERC and Kamphuis equation with measured

data in a large scale flume and found that Kamphuis equation is giving more accurate estimates than CERC equation.

Figure 7 & Table 2

5.2 Sensitivity analysis of LSTR estimate

5.2.1 Variation of LSTR with respect to change in offshore wave angles

In order to analyze sensitivity of estimated LSTR values to the offshore wave parameters, the LSTR values are estimated by varying the offshore wave conditions in two seasons, one for monsoon and the other for post monsoon. The location off Kasarkod beach is selected for the sensitivity analysis since it is an open beach and is not obstructed by any kind of offshore island as in the case of Pavinkurve beach. During monsoon season as discussed earlier, waves are coming from WSW and hence normal to the coast. Here the sensitivity of LSTR is analyzed by varying the offshore angle, θ to $\theta+1$, $\theta+3$ and $\theta+5$ and the estimated gross LSTR for each case is compared with the original estimation (Figure 8A). While increasing the offshore wave angles from θ to $\theta+1$, $\theta+3$, $\theta+5$, the estimated gross LSTR reduced. As the offshore wave angle increases, the WSW breakers switches to more SW breakers and this will cause decrease in southward LSTR and hence both net and gross LSTR will get reduce. Whereas when the offshore angles are reduced from θ to $\theta-1$, $\theta-3$, $\theta-5$, and the WSW breakers switches their direction to more NW directions and this induces more southward LSTR and hence both net and gross LSTR will get increase. During post-monsoon season, the waves are from SW and resulted in northerly LSTR. When the offshore angles are varied from θ to $\theta+1$, $\theta+3$, $\theta+5$, the incoming waves are from more SW and resulted in increased net northward transport and hence both net and gross LSTR will increase (Figure8A). Whereas when the offshore angle is reduced from θ to $\theta-1$, $\theta-3$, $\theta-5$, the incoming waves which are from SW becomes more WSW and hence the net northward transport will reduce and hence both net and gross LSTR will also get reduce. It is observed that the offshore wave angle and offshore wave height during monsoon season has more influence on the LSTR estimation than during the post monsoon season.

Figure 8

5.2.2 Variation of LSTR with respect to change in coastal orientation

Sensitivity analysis for LSTR estimation is also done for varying the coastal orientation of Kasarkod beach. Here the coastal inclination is varied by changing the coastal orientation with respect to north. The actual coastal orientation of Kasarkod beach is 343° and the orientation is changed to 344 , 346 , 348 , 350 , 352 and 353° and LSTR is estimated for each case and compared with the original LSTR

value. When the coastal inclination is increased, it is observed that the sediment transport towards south is increasing because some of the SW breakers which are contributing northward sediment transport turning southward and induces more southward sediment transport (Figure 8B). Hence both net and gross LSTR decreased. Whereas while decreasing the coastal inclination to 342, 340, 338, 336, 334, 333°, northward LSTR increased since some of the NW breakers which are contributing southward sediment transport are turned northwards and resulted in more LSTR towards north. Hence both net and gross LSTR values increased. It is clear that the coastal inclination has more influence in estimation of LSTR than breaker angles (Figure 8A&B).

5.2.3 Variation of LSTR with different data intervals

Continuous coastal observations are costly and laborious affair. Hence many studies have reported the LSTR values based on daily, weekly and biweekly basis. The change in LSTR estimate based on different durations ranging from 3-hourly to bi-weekly is studied (Table 3). It is observed that there is no considerable variation in the LSTR values when it is estimated for the data interval up to 12 h. Beyond 12 h, the variation of gross LSTR are highly variable. Hence the estimated LSTR values are reliable up to the maximum data interval of 12 h.

Table 3

6. Conclusions

- Nearshore wave transformation is done using both numerical model and Snell's method. By comparing with the measured data, REF-DIF-1 model gave better results than Snell's method.
- Offshore wave characteristics are changing with seasons. It is observed that 78% of breaker waves are from SW, 12% from NW and remaining 10% are from WSW. Average breaker heights during pre-monsoon and post-monsoon are 0.6 and 0.5 m respectively and average breaker height during monsoon season is 1.3 m.
- Breaker heights and breaker angles are showing similar characteristics at both Pavinkurve and Kasarkod beach. But the observed fore-shore slope and surf-zone width are different for both the beaches. Since the foreshore slope at Pavinkurve beach is higher than that of Kasarkod beach, the estimated longshore currents are higher at Pavinkurve beach. Although the estimated LSTR by CERC is giving similar estimates of LSTR at both beaches, the estimated LSTR by Walton & Bruno and Kamphuis equation are giving different LSTR estimates. It is observed that even the long-shore current at Pavinkurve beach is higher, the LSTR estimated by Walton & Bruno equation is higher at Kasarkod beach since surf-zone width at Kasarkod beach is higher and this

influences the LSTR estimate than longshore currents.

- Kamphuis equation is giving much agreeable estimation of LSTR compared to CERC and Walton & Bruno equations. Hence the estimated net and gross LSTR by Kamphuis equation can be considered as acceptable LSTR estimate.
- About 51% of annual sediment transport occurs in monsoon period during which average breaker heights is about two times that of other seasons which occurs about one-fourth of the study period and 49% of annual sediment transport occurs during pre and post-monsoon period which is three-fourth of the study period. Among this estimates, 84% of annual LSTR are towards north by the waves coming from the directional sector 225° to 253° and 16% of annual LSTR are towards south by the waves coming from the directional sector 253° to 295°.
- Sensitivity analysis of LSTR estimation shows that the coastal inclination is more affecting factor than the breaker angle.
- Reliability check of LSTR estimation with different data intervals is showing that the LSTR estimates are reliable up to 12 h data interval.

Acknowledgement

We thank ICMAM PD, Ministry of Earth Sciences, New Delhi for funding the measurement program. Director, CSIR-National Institute of Oceanography, Goa and Project Director, ICMAM PD, Chennai provided encouragement to carry out the study. We thank Mr. P. Pednekar, Mr. Jai Singh, Mr. G.N.Naik and Mr. M. Mochemadkar for the help during the measurement. This work forms part of the Ph.D thesis of the first author. This paper is NIO contribution xxxx.

References

- Abadie, S., Butel, R., Mauriet, S., Morichon, D., Dupuis, H., 2006. Wave climate and longshore drift on the South Aquitaine coast. *Continental Shelf Research* 26, 1924-1939.
- Abadie, S.M., Briere, C., Dubranna, J., Maron, P., Rihouey, D., 2008. Erosion generated by wind-induced currents in the vicinity of a jetty: case study of the relationship between the Adour River mouth and Anglet beach, France. *Journal of Coastal Research* 24/1 59.
- Baba, M., 1988. Wave characteristics and beach processes of south west coast of India - a summary. In: Baba M, Kurian NP (eds) *Ocean waves and beach processes of south west coast of India and their prediction*. Centre for Earth Science Studies, India, pp. 225–239.
- Berkhoff, J.C.W., 1972. Computation of combined refraction-diffraction. *Proceedings of 13th International Conference on Coastal Engineering, ASCE*, pp.471-490.

- Blott, S.J., Pye, K., 2001. Gradstat: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms* 26, 1237–1248.
- Chandramohan, P., Nayak, B.U., 1992. Longshore sediment transport model for the Indian west coast. *Journal of Coastal Research* 8(4)775-787.
- Chandramohan, P., Sanil Kumar, V., Nayak, B.U., Raju, N.S.N., 1994. Surf zone dynamics along the coast between Bhatkal and Ullal, west coast of India. *Indian Journal of Marine Science* 23,189–194.
- Dattatri, J., Kamath, M.M., 1997. Littoral drifts and maintenance dredging at New Mangalore port. Second Indian National Conference on Harbour and Ocean Engineering Thiruvananthapuram, India, pp. 578–585.
- Dean, R.G., Walton, T.L., 1975. Sediment Transport Processes in the Vicinity of Inlets with Special Reference to Sand Tapping. *Estuarine Research*, Vol 2. New York: Academic Press, pp.125–1493.
- Dean, R. G., Dalrymple, R. A. (2002). *Coastal processes with engineering applications*. Cambridge University Press, United Kingdom, 475 pp.
- Esteves, L.S., Williams, J.J., Lisniewski, M., 2009. Measuring and modelling longshore sediment transport. *Estuarine, Coastal and Shelf Science* 83,47-59.
- Folk, R.L., Ward, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology*, 27(1), pp. 3–26.
- Fowler, J. E., Rosati, J. D., Hamilton, D. G., and Smith, J. M., 1995. Development of a large-scale laboratory facility for longshore sediment transport research. The CERCular, CERC-95-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Galvin, C.J., Eagleson, P.S., 1965. Experimental study of longshore currents on a plane beach: U. S. Army Corps of Engineers, Coastal Engineering Research Center, TM-10
- Hallermeier, R, J., 1978. Uses for a calculated limit depth to beach erosion. *Proceedings of the 16th International Conference on Coastal Engineering*. ASCE, New York, pp.1493-1512.
- Hegde, V.S., Kanchanagouri, D., Gosavi, X., Hanamgond, P.T., Huchannavar, G.K., Shalini, G., Bhat, M.S., 2004. Depositional environment and silting in the Sharavati estuary, central west coast of India. *Indian Journal of Marine Science* 33(3), 296–302.
- Hegde, V.S., Shalini, G., Nayak, S.R., Rajawat, A.S., Suryanarayana, A., Jayakumar, S., Koti, B.K., Girish K.H., 2009. Low scale morphodynamic process in the vicinity of a tropical estuary at Honnavar, Central West Coast of India. *Journal of Coastal Research* 25(2), 305–314.
- Horikawa, K., 1988. *Nearshore Dynamics and Coastal Processes*. Tokyo: University of Tokyo Press.
- IMD, 1999. *Climatological tables of observatories in India 1951-1980*. 5th edition, India Meteorological Department Pune India, p. xxxvi+782.
- Jena, B.K., Chandramohan, P., Kumar, V.S., 2001. Longshore transport based on directional waves along north Tamilnadu coast, India. *Journal of Coastal Research*, 17(2)322-327.

- Kamphius, J. W., 2002. Alongshore transport of sand. Proceedings of the 28th International Conference on Coastal Engineering. ASCE, pp.2478-2490.
- Kirby, J. T., Dalrymple, R. A. Kaku, H., 1994. Parabolic approximations for water waves in conformal coordinate systems. Coastal Engineering 23, 185-213.
- Komar, P. D., Inman, D. L. 1970. Longshore sand transport on beaches, Journal of Geophysical Research 75(30), 5514-5527.
- Komar, P. D., 1988. Environmental controls on littoral sand transport, Proceedings of the 21st International Conference on Coastal Engineering. ASCE, pp.1238-1252.
- Kraus, N.C., 1999. Analytical model of spit evolution at inlets. Proceedings of Coastal Sediments'99. ASCE, pp. 1739–1754.
- Kuik, A. J., G. Vledder, and L. H. Holthuijsen, 1988: A method for the routine analysis of pitch and roll buoy wave data. Journal of Physical Oceanography. 18, 1020–1034.
- Kumar, V.S., Chandramohan, P., Ashok Kumar, K., Gowthaman, R., Pednekar, P., 2000. Longshore currents and sediment transport along Kannirajapuram coast Tamilnadu, India. Journal of Coastal Research 16(2), 247-254.
- Kumar, V.S., Anand, N.M., Gowthaman, R., 2002. Variations in nearshore processes along Nagapattinam coast, India. Current Science 82(11) 1381-1388.
- Kumar, V.S., Anand, N.M., Chandramohan, P., Naik, G.N., 2003. Longshore sediment transport rate—measurement and estimation, central west coast of India. Coastal Engineering 48, 95–109.
- Kumar, V.S., Pathak, K.C., Pednekar, P., Raju, N.S.N., Gowthaman, R., 2006. Coastal processes along the Indian coastline. Current Science 91(4) 530–536.
- Kumar, V.S., Dora, G. U., Philip, S., Pednekar, P., Jai Singh., 2011. Variations in tidal constituents along the nearshore waters of Karnataka, West Coast of India. Journal of Coastal Research 27 (5), 824-829.
- Kumar, V.S., Johnson, G., Dora, G.U., Philip, S., Pednekar, P., Jai Singh., 2012. Variations in nearshore waves along Karnataka west coast of India. Journal of Earth System Science 121, 393-403.
- Longuet-Higgins, M.S., 1970. Longshore current generated by obliquely incident sea waves. Journal of Geophysical Research 75 (33), 6778–6789.
- Miller, H.C., 1999. Field measurements of longshore sediment transport during storms. Coastal Engineering, 36, 301-321.
- Masselink, G., Short, A.D., 1993. The effect of tide range on beach morphodynamics and morphology: a conceptual beach model. Journal of Coastal Research 9, 785–800.
- Nayak, S.R., Hegde, V.S., Shalini, G., Rajawat, A.S., Girish, K.H., Jayakumar, S., Suryanarayana, A., 2010. Geomorphic Processes in the Vicinity of the Venkatapur River Mouth, Central West Coast of India: Implications for Estuarine Sedimentation. Journal of Coastal Research 26 (5), 925–934.

- Neetu, S., Shetye, S.R., Chandramohan, P., 2006. Impact of sea breeze on wind-seas off Goa, west coast of India. *Journal of Earth System Science* 115, 229–234.
- Philip, S., Kumar, V.S., Johnson, G., Dora, G.U., Vinayaraj, P., 2012. Interannual and seasonal variations in nearshore wave characteristics off Honnavar, west coast of India, *Current Science*, 103 (3), 286-292.
- Raichle, A. W., 1998. Numerical predictions of surfing conditions at Mavericks, California, *Shore and Beach* 66(2), 26-30.
- Schoonees, J. S., Theron, A. K., 1993. Review of the field database for longshore sediment transport, *Coastal Engineering* 19, 1-25.
- Shetye, S.R., Shenoi, S.S.C., Antony, A.K., Kumar V.K., 1985. Monthly mean windstress along the coast of north Indian Ocean. *Journal of Earth System Science* 94, 129-137 doi:10.1007/BF02871945.
- Short, A.D., 1999. *Handbook of beach and shoreface morphodynamics*. Chichester, UK 37.
- Smith, E.R., 2006. Longshore sediment transport rate incorporating wave orbital velocity fluctuations, *Coastal and Hydraulics Engineering Technical Note*, ERDC/CHL TR-06-18, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Sugunan, V.V., 1995. *Reservoir Fisheries of India*, FAO Fisheries Technical paper No. 345, Rome , FAO, 423p.
- USACE, 1984. *Shore Protection Manual*, Coastal Engineering Research Center, Vicksburg, Mississippi, Vol. 1.
- Vethamony, P., Aboobacker, V.M., Menon H.B., Ashok kumar, K., Cavaleri, L., 2011. Superposition of wind seas on the pre-existing swells off Goa coast. *Journal of Marine Systems* 87(1), 47-54.
- Vinayaraj, P., Glejin Johnson, Udhaba Dora, G., Sajiv Philip, C., Sanil Kumar, V., Gowthaman, R., 2011. Quantitative estimation of coastal changes along selected locations of Karnataka, India: a GIS and remote sensing approach. *International Journal of Geosciences* 2, 385-393.
- Walton, T.L., (Jr.), Bruno, R.O., 1989. Longshore transport at a detached breakwater, Phase-II. *Journal of Coastal Research* 65 (9), 667-668.
- Wang, P., Kraus, N. C., and Davis, R. A., Jr. 1998. Total rate of longshore sediment transport in the surf zone: Field measurements and empirical predictions. *Journal of Coastal Research* 14(1), 269-283.
- Wang, P., Kraus, N.C., 1999. Longshore sediment transport rate measured by short term impoundment. *Journal of Waterway Port, Coastal and Ocean Engineering* 125 (3), 118– 126.
- Wang, P., Smith, E.R., and Ebersole, B.A., 2002. Large-scale laboratory measurements of longshore sediment transport under spilling and plunging breakers, *Journal of Coastal Research*, 18, 118-135.
- Work, P.A., Kaihatu, J.M., 1997. Wave transformation at Pensacola Pass, Florida. *Journal of Waterways, Port, Coastal and Ocean Engineering*. 123 (6), 314-321.

Figure captions

Figure 1 Map of Honnavar coastline. Locations of offshore wave rider buoy, Shallow water wave gauge (S4) are indicated in the figure. Locations of points at which near shore breaker parameters are extracted at Pavinkurve beach and Kasarkod beach are also indicated in the figure as P1 and K1.

Figure 2 Variation of wave direction at 9 m water depth in different months

Figure 3 Time history of Measured offshore wave characteristics at 9m depth (A) Significant wave height $H_s(m)$, (B) Mean wave period $T_{m02}(s)$, (C) Wave direction(deg)

Figure 4 The scatter plot of modelled wave height and analytical wave height with measured wave height.

Figure 5 Model simulated wave propagation for waves approaching normal to the coast during monsoon season

Figure 6 Time series variation of (1) breaker heights $H_b(m)$ in upper two panels (A) Pavinkurve beach and (B) Kasarkod beach, (2) breaker angle θ_b (deg) in middle two panels (C) Pavinkurve beach, (D) Kasarkod beach and Computed longshore currents in lower two panels (E) Pavinkurve beach and (F) Kasarkod beach

Figure 7 Annual LSTR calculated using CERC, Walton & Bruno and Kamphuis equations for (A) Pavinkurve beach and (B) Kasarkod beach

Figure 8 Variation of estimated LSTR with respect to the (A) variation in offshore wave angle and (B) Variation in coastal inclination at Kasarkod beach

Table 1. Monthly average wave height, breaking depth, beach slope, surf zone width and median grain size at Pavinkurve beach and Kasarkod beach

Pavinkurve beach						
Month	Average monthly offshore wave height (m)	Breaking depth (m)	Closure depth (m)	Beach slope	Surf zone width (m)	Median grain size D ₅₀ (µm)
January	0.53	0.78	0.9	0.028	28	254
February	0.59	0.78	0.9	0.028	28	289
March	0.64	0.78	1.0	0.028	28	590
April	0.78	1.00	1.1	0.027	37	285
May	1.01	1.22	1.4	0.026	47	303
June	1.51	2.06	2.1	0.024	84	334
July	2.21	2.79	2.9	0.021	131	333
August	1.45	1.87	2.1	0.025	75	313
September	1.17	1.44	1.5	0.026	56	348
October	0.83	1.00	1.1	0.027	37	318
November	0.60	0.78	0.9	0.028	28	300
December	0.68	0.78	0.9	0.028	28	196
Kasarkod beach						
Month	Average monthly Offshore Wave height (m)	Breaking depth (m)	Closure depth (m)	Beach slope	Surf zone Width (m)	Median grain size D ₅₀ (µm)
January	0.53	0.78	0.9	0.028	28.05	254
February	0.59	0.78	0.9	0.028	28.05	289
March	0.64	0.78	1.1	0.028	28.05	590
April	0.78	1.00	1.2	0.027	37.4	285
May	1.01	1.22	1.3	0.026	46.75	303
June	1.51	2.06	1.8	0.024	84.15	334
July	2.21	2.79	2.7	0.021	131	333
August	1.45	1.87	1.8	0.025	74.8	313
September	1.17	1.44	1.4	0.026	56.1	348
October	0.83	1.00	1.1	0.027	37.4	318
November	0.60	0.78	0.9	0.028	28.05	300
December	0.68	0.78	0.9	0.028	28.05	196

Table 2. Estimated monthly LSTR at Pavinkurve beach and Kasarkod beach

Mon th	Pavinkurve beach								
	CERC			Walton & Bruno			Kamphuis		
	Northerly (m ³)	Southerly (m ³)	Monthly Gross (m ³)	Northerly (m ³)	Southerly (m ³)	Monthly Gross m ³	Northerly (m ³)	Southerly (m ³)	Monthly Gross (m ³)
Jan	36805	-1945	38750	22789	-1153	23941	25146	-590	25737
Feb	18052	-6524	24576	10927	-3947	14874	10813	-1493	12306
Mar	18972	-2862	21834	10874	-1659	12533	11819	-589	12407
Apr	54884	-5112	59996	34333	-3108	37440	34772	-1160	35932
May	86577	-5155	91732	52301	-2917	55218	51110	-1735	52845
June	98939	-3705	102644	65524	-2334	67858	47920	-1858	49779
July	60391	-93201	153591	37775	-60209	97984	32307	-50917	83224
Aug	27410	-16255	43664	16362	-10547	26909	13925	-8701	22627
Sept	81279	-787	82067	52542	-512	53054	59012	-572	59584
Oct	54107	-281	54388	35373	-209	35581	28062	-140	28203
Nov	34788	-198	34986	21491	-126	21616	19050	-28	19078
Dec	31025	-2263	33288	20007	-1513	21521	19016	-572	19588
Mon th	Kasarkod beach								
	CERC			Walton & Bruno			Kamphuis		
	Northerly	Southerly	Monthly Gross m ³	Northerly	Southerly	Monthly Gross m ³	Northerly	Southerly	Monthly Gross m ³
Jan	36252	-615	36867	23109	-424	23533	16481	-158	16639
Feb	17070	-3814	20883	10794	-2428	13222	6832	-698	7530
Mar	26099	-2659	28757	15699	-1610	17309	10596	-414	11009
Apr	63628	-3482	67109	40960	-2315	43275	26588	-730	27318
May	96787	-2864	99651	62982	-1802	64784	37387	-809	38196
June	94478	-1810	96288	66522	-1179	67702	27024	-557	27581
July	28741	-119782	148524	20857	-80920	101777	10429	-38046	48474
Aug	35730	-7951	43681	24510	-5557	30067	9818	-2606	12423
Sept	85934	-451	86385	61131	-323	61453	37787	-250	38037
Oct	68813	-3	68816	47011	-2	47014	22092	-2	22094
Nov	41141	-301	41442	25980	-182	26162	14562	-29	14591
Dec	31246	-1534	32780	20695	-1023	21718	12659	-323	12981

Table 3. Estimated LSTR for different time intervals

Data interval	Estimated Net LSTR by Kamphuis equation (m ³)	Estimated Gross LSTR by Kamphuis equation (m ³)	Percentage Difference in gross estimation
3hourly	186094	275337	-1.3
6hourly	183355	278946	-0.7
12hourly	187582	277305	-3
24hourly	206413	283778	6.3
Weekly	168736	257981	14.6
Biweekly	115425	235243	-1.3

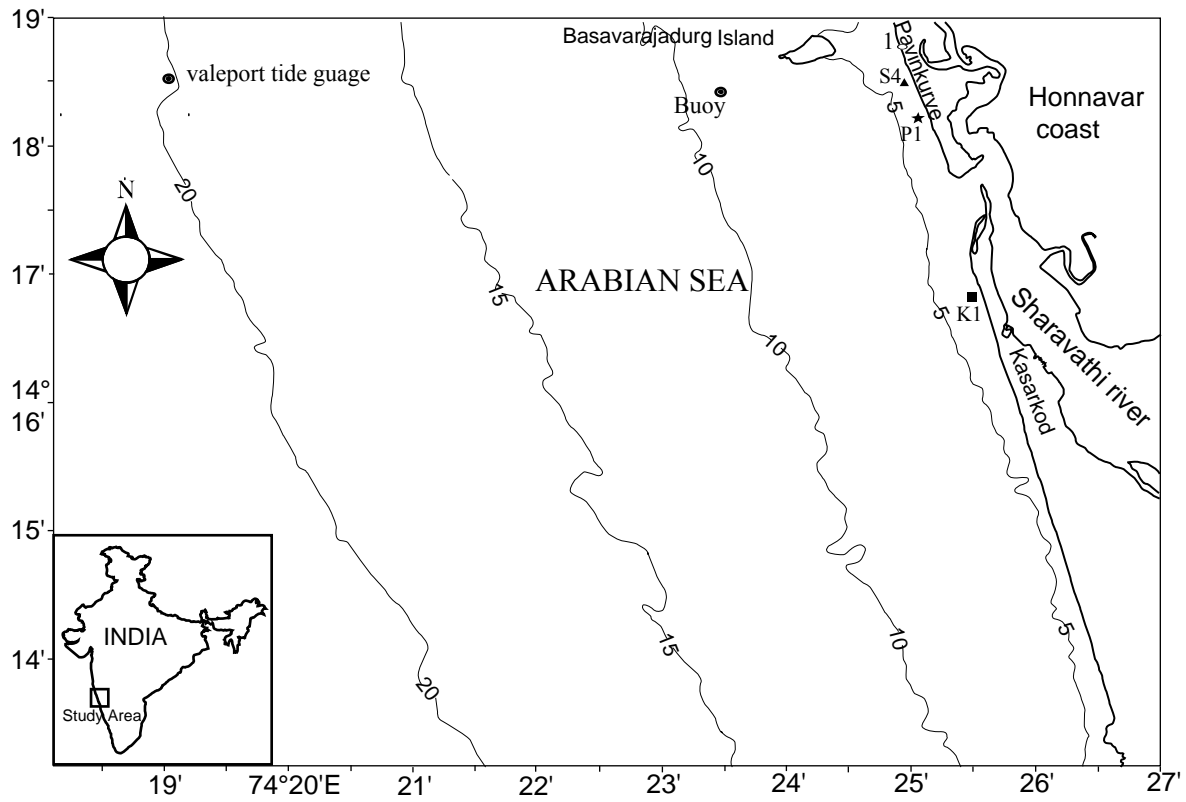
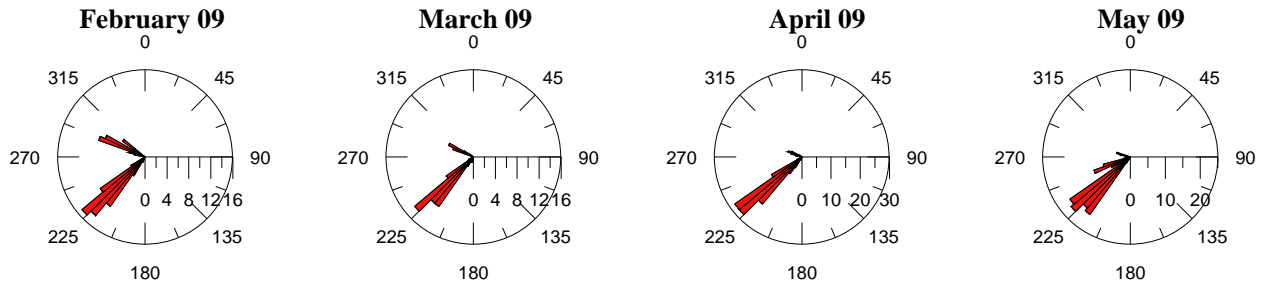
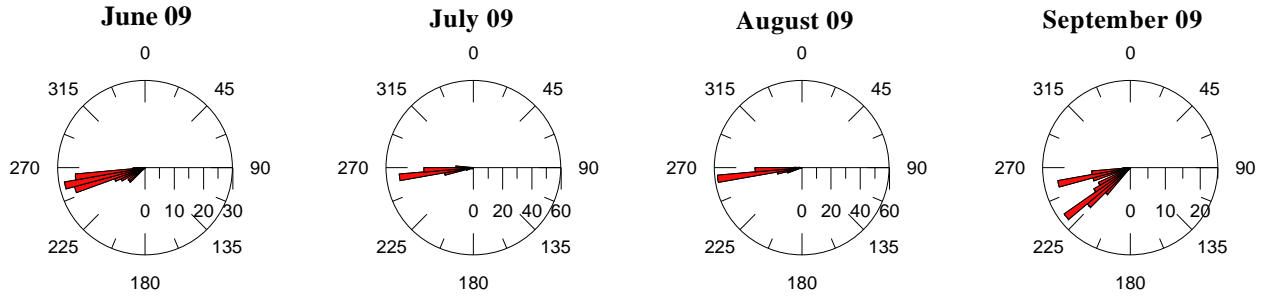


Figure 1 Map of Honnavar coastline. Locations of offshore wave rider buoy, Shallow water wave gauge (S4) are indicated in the figure. Locations of points at which nearshore breaker parameters were extracted at Pavinkurve beach and Kasarkod beach were also indicated in the figure as P1 and K1.

PRE-MONSOON



MONSOON



POST-MONSOON

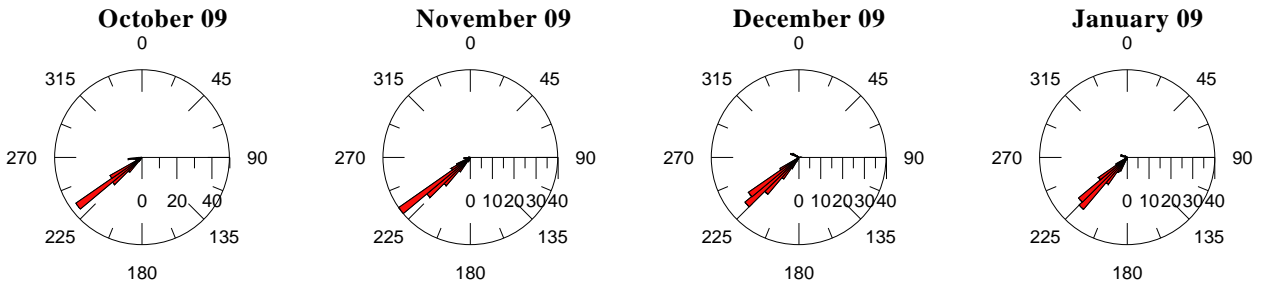


Figure 2 Variation of wave direction at 9 m water depth in different months

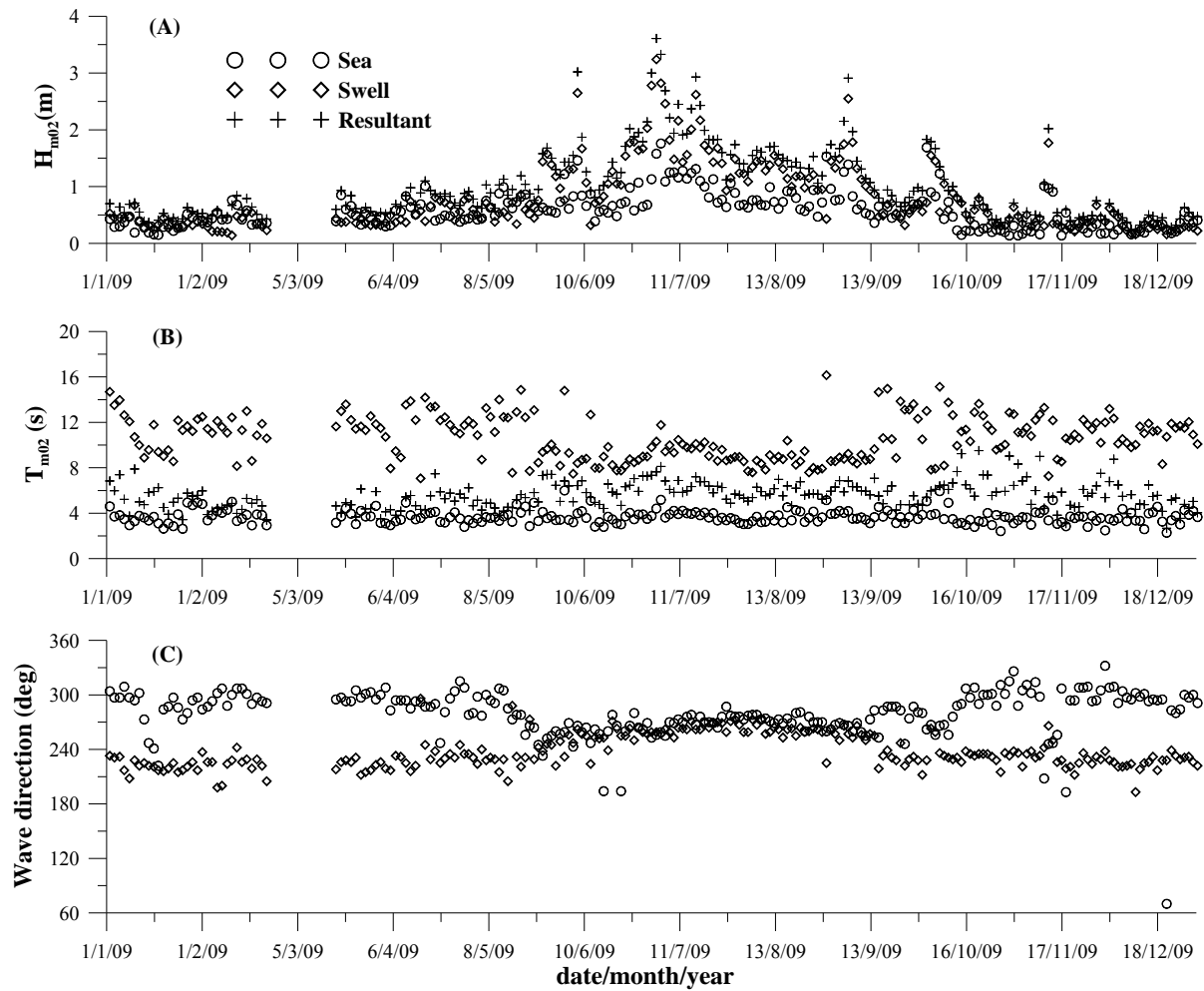


Figure 3 Time history of measured offshore wave characteristics at 9 m depth (A) Significant wave height H_{m0} (m) , (B) mean wave period T_{m02} (s) and (C) wave direction (deg)

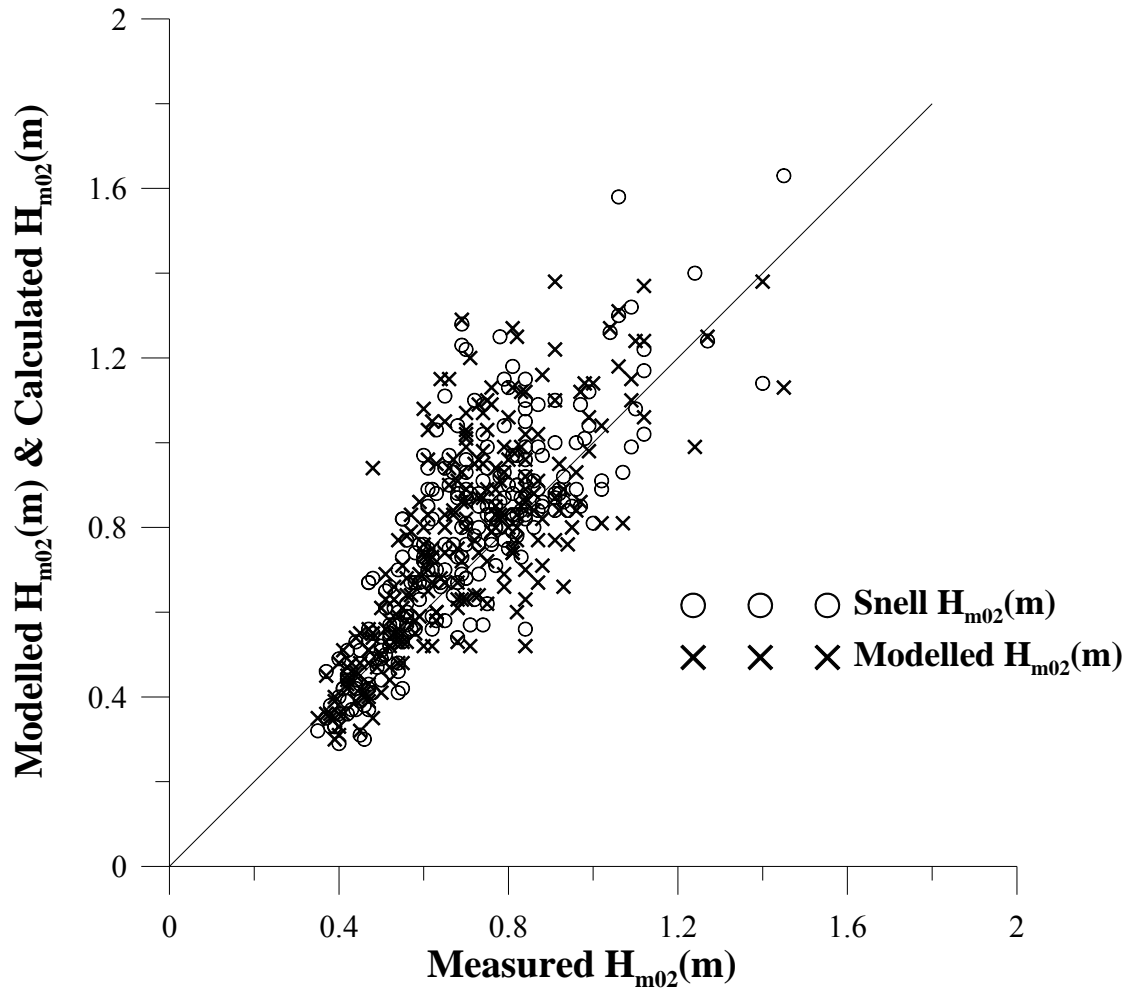


Figure 4 The scatter plot of estimated wave height using numerical model and analytical wave height with measured wave height.

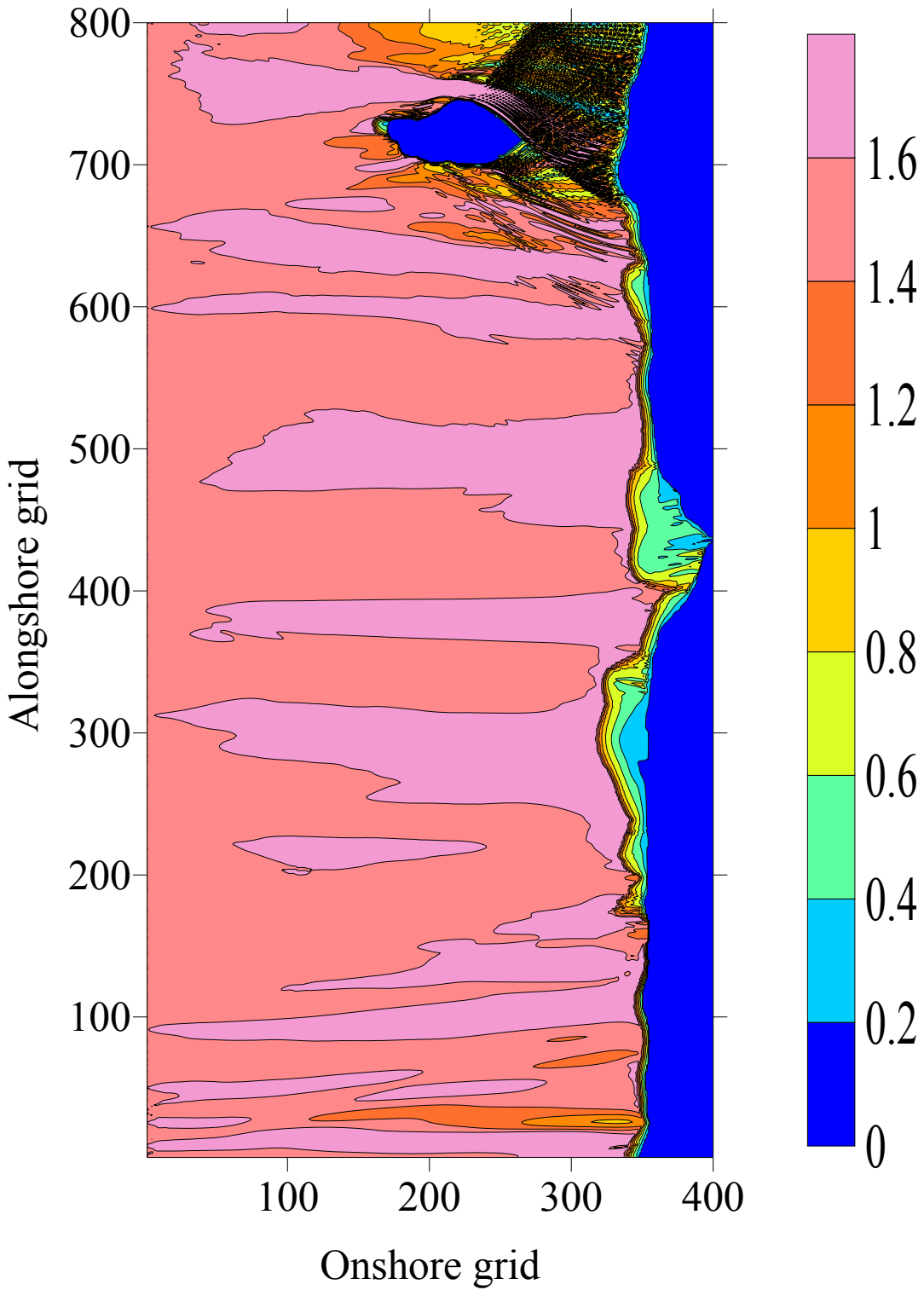


Figure 5 Model simulated wave propagation for waves approaching normal to the coast during monsoon season

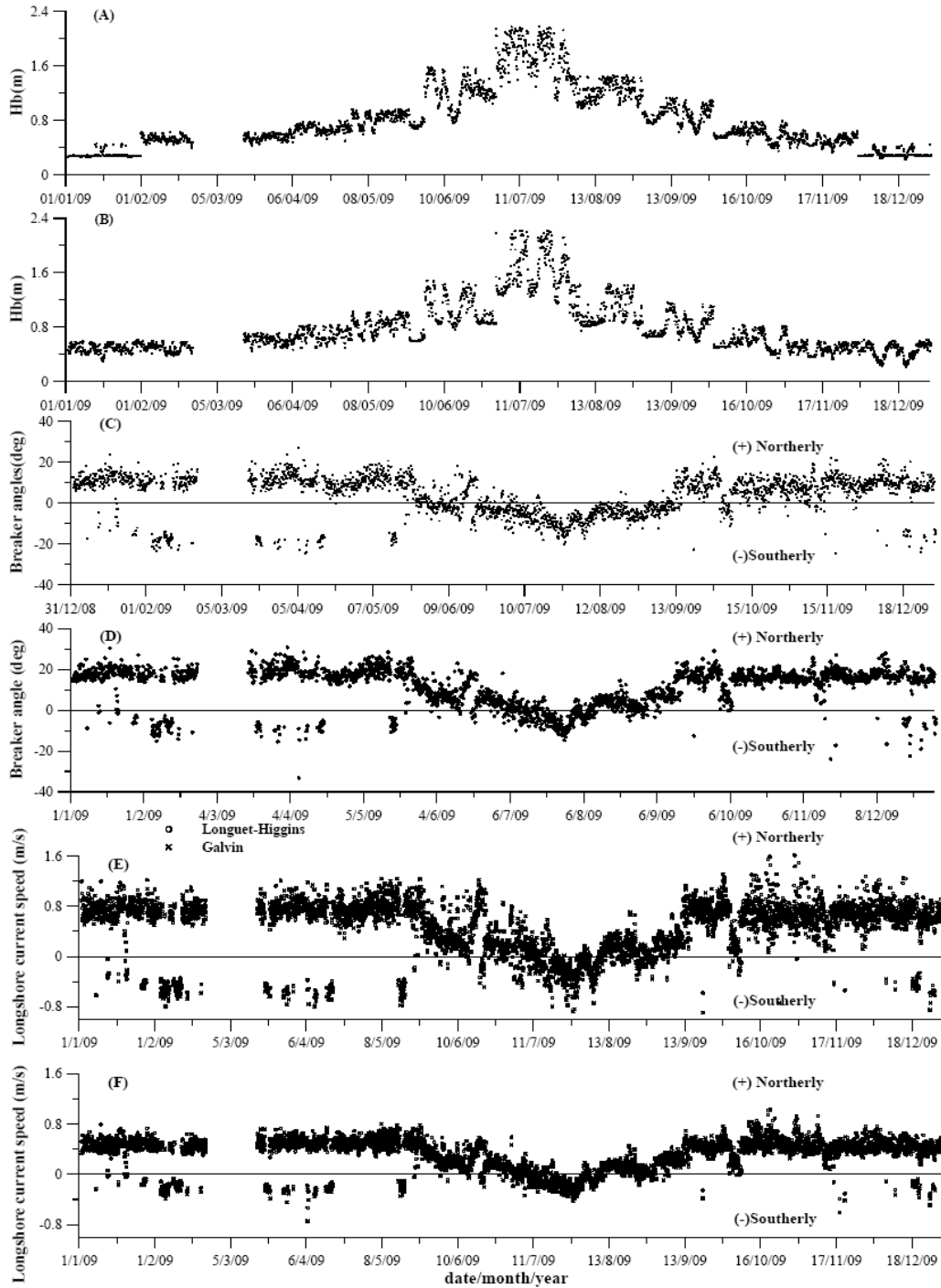


Figure 6 Time series variation of (1) breaker height, H_b (m) in upper two panels (A) Pavinkurve beach and (B) Kasarkod beach, (2) breaker angle θ_b (deg) in middle two panels (C) Pavinkurve beach, (D) Kasarkod beach and computed longshore currents in lower two panels (E) Pavinkurve beach and (F) Kasarkod beach

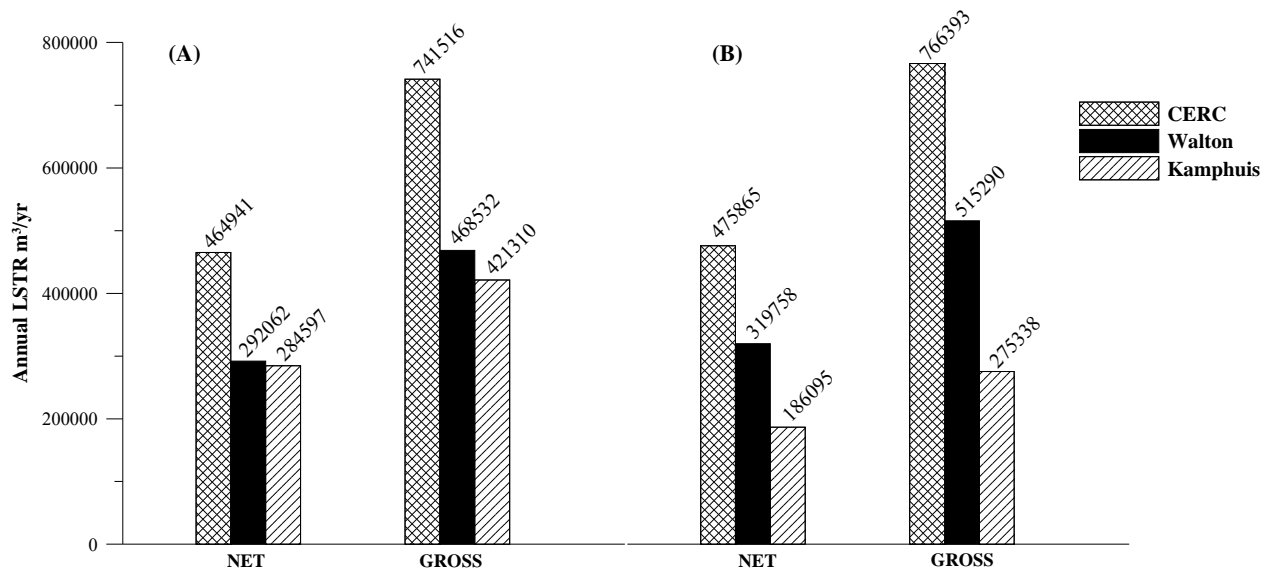


Figure 7 Annual LSTR calculated using CERC, Walton & Bruno and Kamphuis equations for (A) Pavinkurve beach and (B) Kasarkod beach

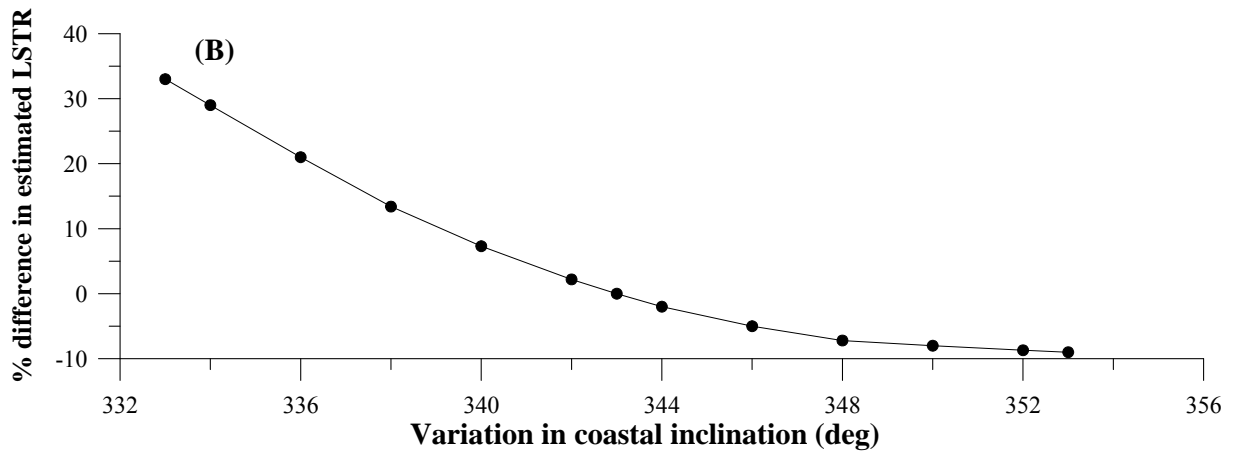
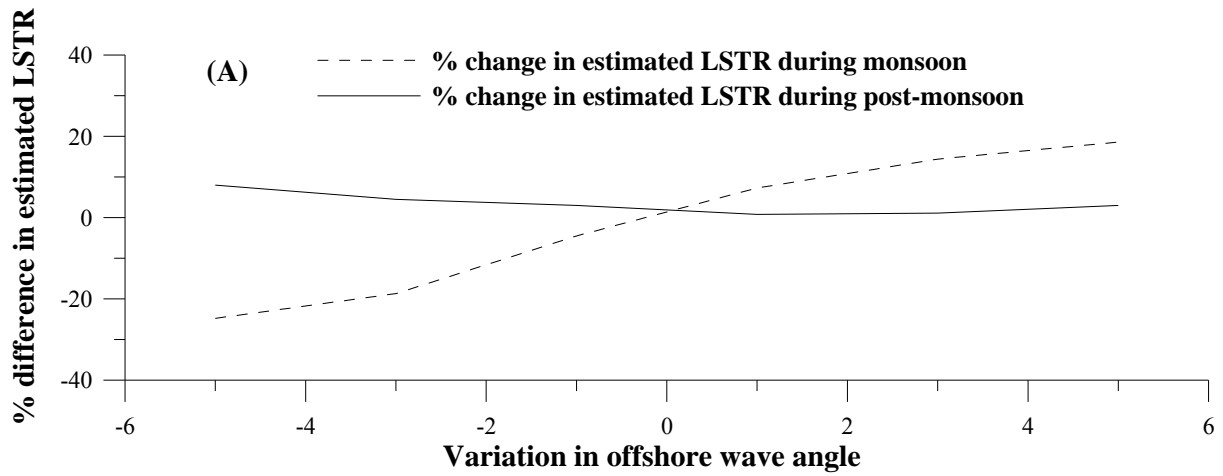


Figure 8 Variation of estimated LSTR with respect to the (A) variation in offshore wave angle and (B) Variation in coastal inclination at Kasarkod beach