Nearshore Sediment Transport in a Changing Climate

Piyali Chowdhury and Manasa Ranjan Behera

Abstract The impact of changing wave climate on the most important nearshore process, longshore sediment transport (LST), along the central west coast of India is investigated. The main purpose of this study is to provide a better understanding of the meteo-marine climate of the central west coast of India, which is highly influenced by the Arabian Sea and the Indian Ocean. To understand the contemporary evolution of the coastline, hindcast wave climate from ERA-Interim wave data (1979–2016) is used. The annual average significant wave height (H_s), wave period (T_p) and wave direction (α_0) are obtained and used to estimate annual LST. This region receives oblique waves from the W-SW direction which induces a huge gross northerly transport. It experiences two types of waves, swell waves (remotely generated waves that travel thousands of kilometres before hitting the coastline) and wind waves (also known as seas, which are locally generated), both of which are responsible for coastal sediment transport. The swell waves are the major component of a total wave system. It has more strength than the locally generated wind waves and dictates the wave direction and significant wave height at any given point of time. Therefore, the swell wave-induced LST is an order of magnitude higher than the wind wave-induced LST. It was observed that the sediment transport has a seasonal nature due to the influence of monsoonal winds in this region. The total LST in the central west coast of India shows a decreasing trend due to the reduced swell generation in the lower latitudes of the Arabian Sea and the Indian Ocean.

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1 Introduction

The nearshore region is an ecologically complex and important part of the marine ecosystem. It is a transition zone between land and continental shelf, which includes wetlands, estuaries, beaches, dunes, cliffs, surf zones (regions of wave breaking) and the inner shelf (approximately upto 15 m depth). The nearshore region is a constantly evolving and highly populated region which is under increasing threat from sea-level variability, increased storminess, long-term erosion/accretion processes and anthropogenic activities (Fig. 1). The breaking waves in the nearshore zone produce nearshore currents which transport beach sediments. Sometimes this transport results in a local rearrangement of sand into bars and troughs, or results in extensive longshore displacements of sediments. This transport is the most important nearshore process which controls the beach morphology and determines whether the beaches erode, accrete or remain stable. An understanding of longshore sediment transport is essential to integrated coastal zone management practices.

Climate change-driven rising sea levels, storminess and extreme wave heights have the potential to increase the frequency and magnitude of coastal hazards, increasing risks to coastal community and environment. The latest report by International Panel on Climate Change (IPCC 2014) highlights a lack of information on the potential changes in the wave climate and their impacts. Most of the coastal population live within an elevation of 5–10 m from current mean sea level (ISRO 2011). Long-term
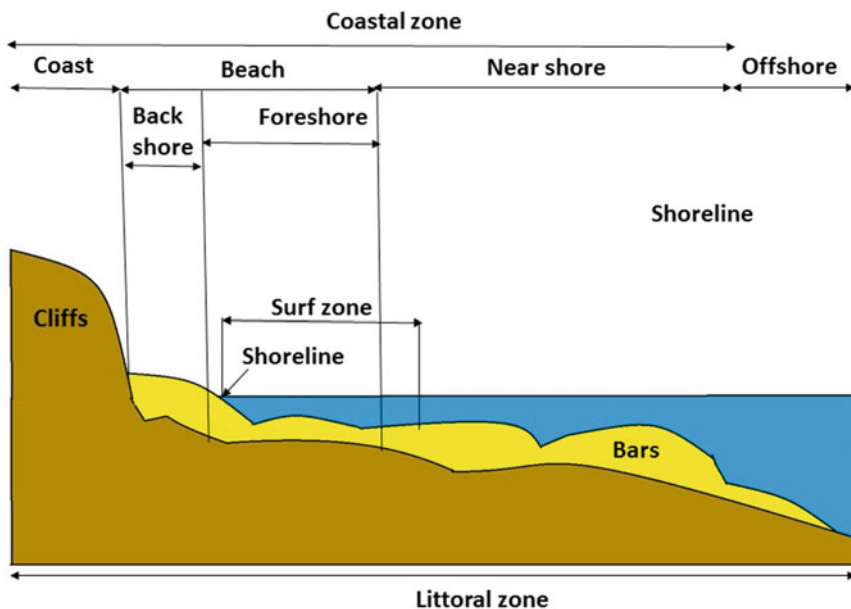

Fig. 1 Schematic of a typical nearshore zone

erosion/accretion may cause changes to the existing ecosystem and infrastructures. Damages worth of millions of rupees every year are seen with increasing number of cyclones. Prediction of changes in nearshore processes under the changing climate scenario is important to effectively manage the constantly evolving yet vulnerable environment.

Coastal ecosystems and infrastructure are threatened by long-term coastal erosion owing to climate change, limited sediment availability and anthropogenic activities. Naturally occurring long-term (10–1000 years) coastal change is a result of the cumulative response of short-term processes that are in turn influenced by surface waves and water levels. Anthropogenic activities in the coastal zone can alter these natural processes (Hapke et al. 2013), potentially inducing change in coastline orientation, which may affect future coastline response (McNamara and Werner 2008). Such two-way interaction processes and feedbacks between coastline dynamics and manmade activities make the coastal zones complicated systems. Understanding future coastal conditions and accurately predicting change over long temporal scales is needed for long-term coastal sustainability.

With growing dependency on coastal areas for urbanization and settlement, it is becoming immensely important to identify the future threats and challenges on these environments. The understanding of the nearshore processes has improved in the last couple of decades. With the availability of climate data and sophisticated wave and current models, it is now possible to predict the future wave climate and its impacts on nearshore processes like sediment transport, wave–wave interactions, wave–current interactions and many more. To have a clear understanding of the evolution of nearshore processes, it is required to investigate the long-term coastal evolution under changing climate and anthropogenic activities, prediction of future waves and storminess, and the physical, chemical and biological processes impacting these processes. In this chapter, we aim to present the hindcast wave climate in the Arabian Sea (1979–2016) and its impacts on coastal sediment transport along the central west coast of India.

1.1 Coastal Geomorphology and Nearshore Sediment Transport

The coastal geomorphology of the western continental shelf of India was studied better after the International Indian Ocean Expedition (1962–1965). The western Indian continental shelf is classified as stable Atlantic-type margin where the shelf is wide near river mouths of north-west India and narrow towards south-west India (ISRO 2011). Transport of sediments and other minerals is influenced by high-energy conditions existing on the shelf. Presence of numerous sedimentary basins in this region indicates the accumulation of sediments since Eocene. This relatively straight shelf of western coast is considered to be a result of an offshore fault extended from south to north-west India. This region forms the nearshore zone of the west coast

of India. Most of the coastal processes often take place in this nearshore zone. The most important of which is the nearshore sediment transport, which is responsible for the shoreline evolution and orientation. These processes maintain the topography of beaches by either erosion or accretion processes. Coastal sediment transport is mainly driven by wave-induced or tide-induced currents. The currents interact with seabed and agitate the sediments, which then entrains in fluid flows and gets transported along and/or across the shoreline. There are two types of current systems in the nearshore zone which are responsible for the sediment transport—currents within the surf zone and currents beyond the surf zone. However, the currents in the surf zone are most important for sediment transport. It derives its energy from breaking of waves.

2 Study Area

The study investigates the impact of changing wave climate on the temporal dynamics of longshore sediment transport (LST). LST governs the overall coastal geomorphology of regional coastlines. Shoreline erosion, sedimentation near river mouth, narrowing of deltas and rapid changes in the river mouth configuration are commonly observed problems in the central west coast of India (Nayak et al. 2010). The west coast of India experiences three major seasons: pre-monsoon (JFMAM), monsoon (JJAS) and post-monsoon (OND). The Indian coastline is exposed to significant changes in seasonal to annual wind and wave climate. Winds are south-westerly and significantly high in strength during the Indian summer monsoon (June–September), whereas it is north-easterly during the winter monsoon (November–February). The wave climate is also influenced by the changing wind patterns which makes the wave climate highly seasonal. The study area is located in the central west coast of India (Fig. 2). This region consists of numerous headlands, river deltas, cliffs, bays, sand spits and sandy beaches (Shanas and Kumar 2014). This region is exposed to an energetic wave climate with swell waves travelling from the Arabian Sea and the Indian Ocean. The nearshore wave climate is governed by both wind and swell waves. Wind waves are generated by the local wind conditions and swells propagate from deep ocean. Waves are directed differently in different seasons. Variation in wave direction is an important factor that determines the impact of a changing wave climate on coastal processes, altering the LST direction and rates, and consequently, the overall coastal sediment balance. Beaches in this region are mainly reflective to intermediate in nature (Kumar et al. 2003; Manoj and Unnikrishnan 2009), making it a micro- to meso-tidal region (Short 1991). The presence of several deltas in this region makes the sediment interaction process complicated, especially during monsoon. The varying nature of inflowing sediment complicates the distribution process of sediments in the nearshore zone. These sediments are distributed along the coast by the action of waves and tides. The influx sediment grain size varies from medium to coarse (average $D_{50} = 0.6$ mm) (Veerayya and Varadachari 1975).
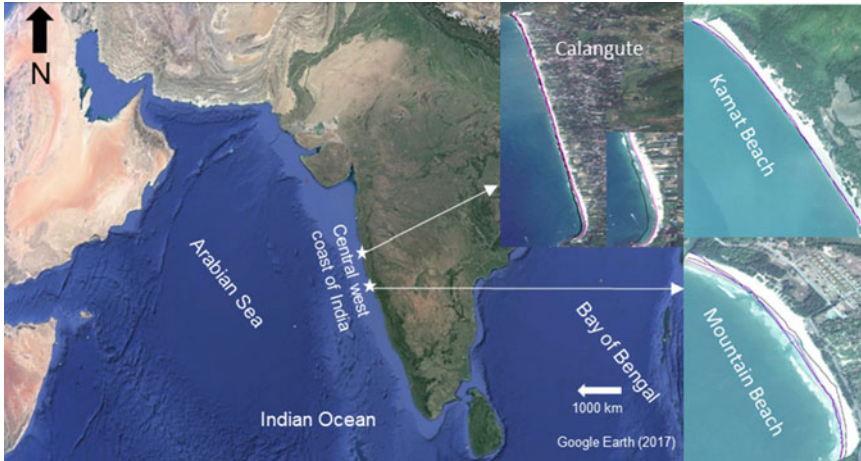
Fig. 2 Selected study regions along central west coast of India

Cyclonic activities in this region are major drivers of the sediment dynamics. It was observed that the Arabian Sea has a bimodal nature of cyclogenesis occurring during the south-west and north-east monsoon periods (Evan and Camargo 2011). However, the sea surface temperature is always above 26.5 °C which facilitates cyclogenesis and high-energy swells. Increased wave heights were observed in regions where the wave climate is subjected to swell propagated from the Arabian Sea and the southern Indian Ocean (Hemer et al. 2010). A large number of extra tropical Indian Ocean swells freely propagate into tropical and subtropical latitudes of the Indian Ocean (Alves 2006) and form an important component of the Arabian Sea and the Bay of Bengal wave climate. However, the tropical north Indian Ocean storms have minimal impact on the global wave climate but can have very rough local wave systems, which impacts coastal processes along the coasts located in this region (Young and Holland 1996). Another type of wave affecting the nearshore wave climate in the Indian region is the locally generated wind waves. The seasonality in the swell and wind waves leads to the seasonal variation of nearshore wave climate and the resulting LST along the west coast of India.

3   Data and Methodology

3.1   Wave Data

Wave parameters like (significant wave height (H_s), wave period (T_p) and wave direction (α_0)) are important inputs in estimating wave-induced LST. ERA-Interim wave data were used to derive these parameters (Dee et al. 2011). The ERA-Interim

wave data were extracted on a $0.5° \times 0.5°$ grid with a 6-h-temporal resolution for a period of 38 years. Data were extracted for the grid cell encompassing the study region. Annual and monthly averages of the wave parameters were computed and used in the estimation of LST.

3.2 Methodology

LST is estimated by numerous longshore transport formulae worldwide. Many research works on improving the longshore sediment transport formula are in progress. Also, there is no general rule on the choice of formula. The most commonly used formulae are the Coastal Engineering Research Center (CERC, Shore Protection Manual 1984), Walton and Bruno (1989), Kamphuis (1991), Van Rijn (1989) and the recently developed Kaczmarek et al. (2005) formula. In this study, we used the recently developed Kaczmarek et al. (2005) formula.

Kaczmarek et al. (2005) formula assumes that the volume of LST 'Q' for the entire surf zone is proportional to the wave energy flux (V) and is given as:

$$Q = \begin{cases} 0.023\left(H_b^2 V\right) \text{ (m}^3\text{/s)}, & \text{if, } H_b^2 V < 0.15 \text{ (low and medium wave climate)} \\ 0.00225 + 0.008\left(H_b^2 V\right) \text{ (m}^3\text{/s)}, & \text{if, } H_b^2 V > 0.15 \text{ (higher waves and storms)} \end{cases} \quad (1)$$

where H_b is the breaker wave height and V is the average longshore current velocity in the surf zone which is determined as:

$$V = 0.25k_v\sqrt{\gamma_b g H_b} \sin 2\theta_b \text{ (m/s)} \quad (2)$$

where γ_b is the constant wave breaker parameter (0.78), g is the gravitational acceleration, θ_b is the breaker wave angle and k_v is a site specific constant chosen as 2.9 based on Bertin et al. (2008) for wave-dominated regions with similar grain size features as that of the present study. The breaker wave properties were estimated using the breaker wave predictor formula proposed by Larson et al. (2009) in which deep water wave characteristics were used. The detailed methodology of this model can be found in Chowdhury and Behera (2017) and hence is not repeated here for brevity.

Wind sea and swell heights are computed from the ERA-Interim derived wave data and are used to estimate wind wave-induced LST and swell wave-induced LST. To study the shoreline changes in an interrupted and uninterrupted beach, we identified littoral drift cells that are close to such locations (Calangute Beach, which is an uninterrupted beach and Karwar Naval Beach, which is interrupted by the construction of a naval base since 2005). Landsat imagery (USGS 2014) was used to describe the shoreline evolution on a regional scale. Satellite images with minimal cloud coverage over the area of interest were extracted since 1990. All these images were referenced to the latest 2015 image with clearly visible reference points which are identifiable in the entire period since 1990. This approach is expected not to

affect the final result because our ultimate aim is to track relative shoreline position change. Shoreline evolution was computed at both the locations using DSAS tool of Arc-GIS. Model-estimated LST was compared with the Landsat data.

4 Nearshore Sediment Transport in a Changing Climate

4.1 Wave Climate

Annual and monthly average values of H_s, T_p and α_0 were extracted at the grid points encompassing the study region and were used to obtain the nearshore breaker wave characteristics as shown in Fig. 3. The average annual H_s and T_p were found to be 1.32 m and 8.12 s, respectively (Chowdhury and Behera 2017). The annual wave climate experiences dominant waves from the west–south-west direction (~238° clockwise from true north). H_s was the highest during the south-west monsoon (1.4–2.6 m) and low during rest of the year (0.7–1.0 m). The monthly wave data were decomposed to obtain swell and wind wave components using the methodology given by Chen et al. (2002) (Fig. 3). Like swell waves, wind waves also showed seasonal variations, with lower wave heights during October–May and higher wave heights during monsoon months (JJAS). The Arabian Sea has a very calm wave climate in non-monsoon months compared to the monsoon months. This variation was expected to impact the seasonal variability of LST in this region. It was observed that during non-monsoon months the wave activity is low, with monthly breaker height ranging from 0.7 to 1.2 m. With the onset of monsoon in the month of June, a steep increase in the magnitude of breaker wave height is observed with values ranging from 1.2 to 2.3 m.

4.2 Sediment Transport Due to Swells and Wind Seas

The waves in the central west coast of India are oblique (W–WSW) to the coastline. These oblique incident waves generate a large northerly transport. LST is found to be southerly only when the wave direction is between 250–270°. The annual net swell wave-induced LST and wind wave-induced LST are shown in Fig. 4. The average annual swell wave-induced LST is 412,000 m^3/year, which is an order of magnitude higher than the wind wave-induced LST, which is only 25,200 m^3/year. The overall LST shows a decreasing trend of about 5% over the study period of 38 years.

Net monthly LST was also estimated to understand the seasonal variations in LST along the central west coast of India as shown in Fig. 5a. A directional shift in LST from northerly (positive LST values) to southerly (negative LST values) is observed with the onset of monsoon which may be attributed to the directional shift in the winds and longshore current. A similar shift in direction of LST was
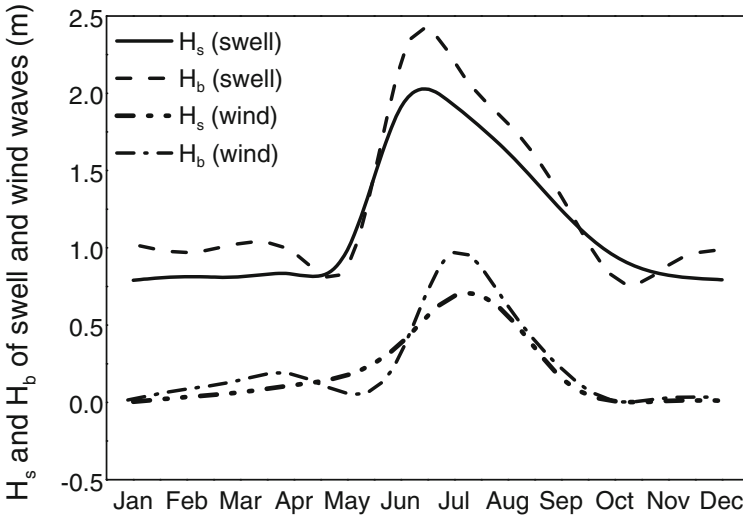
Fig. 3 Significant (H_s) and breaker (H_b) wave height of swell and wind waves (*Source* Chowdhury and Behera (2017))
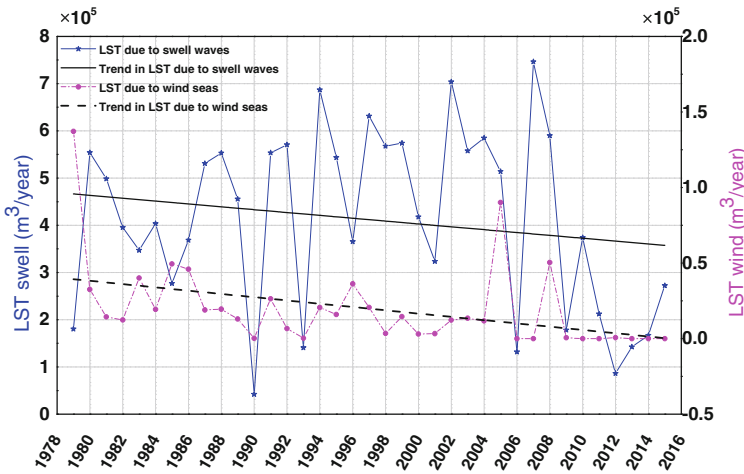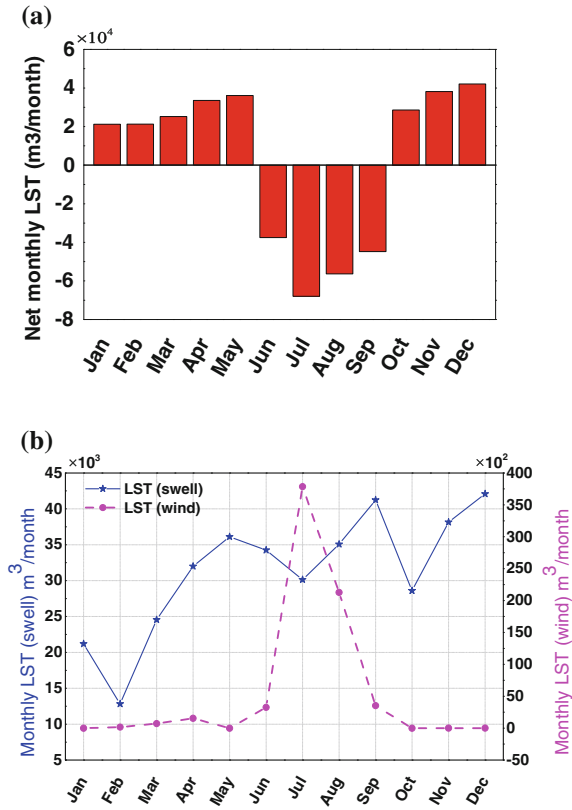

Fig. 4 Swell wave-induced LST (blue) and wind wave-induced LST (magenta) (1979–2016)

again observed towards the end of monsoon season which directed the sediment transport towards the north. The total LST directed towards north is more than that towards south. Also, the monthly LST induced by both swell and wind waves were estimated (Fig. 5b). The wind wave-induced LST is low throughout the year, whereas during monsoon it is higher than the swell wave-induced LST. Intensity of the sea breeze–land breeze system increases during monsoon which in turn amplifies the wave height and hence wind wave-induced LST is the maximum during monsoon.

(a)

(b)

Sea breeze–land breeze system influences wave parameters along the west coast of India (Glejin et al. 2013) and Masselink and Pattiaratchi (1998) reported that the sea breeze—land breeze system has an important influence on LST. Swell wave-induced LST peaks in December due to the cyclogenesis phenomenon in the Arabian Sea. The net swell wave-induced LST during JJAS is only 125,500 m^3/month and that during rest of the year is 250,000 m^3/month, making the total annual transport northerly in nature.

Swells in the Arabian Sea are influenced by cyclonic activities which have a bimodal nature (Evan and Camargo 2011) that peaks in May–June and October–December and are minimum during monsoon. This phenomenon affects the seasonal variation of LST in the west coast of India. Further, Evan and Camargo (2011) state that there is an increase in the cyclonic storm days over the period of 1992–2008 when compared to 1979–1991. This increased trend in cyclonic activity over 1992–2008 is coherent with increase in LST intensity during this period. It is observed that wind blowing over the Arabian Sea is strong during the onset of monsoon which causes strong swells that travels towards the Indian coast and dominates the coastal processes. During monsoon, the wind speed is very high and blows towards the

coast causing high rates of swell wave-induced LST with the highest in September (Fig. 5b). During the same period, the wind waves also start growing stronger which is caused by the sea breeze–land breeze system and induces higher rates of LST. With the reversal of wind direction in September, the rate of swell wave-induced LST also peaks up. Again with the onset of cyclogenesis in November, the LST increases. In January, soon after the cyclogenesis, the LST drops down and is the lowest in February. LST continues to rise during March–May. It is concluded that LST along the west coast of India varies seasonally depending upon the wind and wave characteristics. Remote swells also play an important role in determining regional LST by influencing the nearshore wave parameters.

4.3 Shoreline Changes in Interrupted and Uninterrupted Beaches

The evolution of any beach depends on the erosion, and deposition pattern of the beach which in turn depends on the LST rates. Two locations were considered to study their evolution over the past few decades based on LST computed using Kaczmarek et al. (2005) formula, and the same was compared with the shoreline evolution obtained from satellite images. Satellite data from Landsat (USGS 2014) available since 1990, with a resolution of 30 m, are obtained for both the locations (Calangute Beach, which is an uninterrupted beach and Karwar Naval Beach, which is interrupted by the construction of a naval base since 2005) and is used for shoreline change detection. All the satellite images were geo-rectified using a reference image to assign real-world coordinates. These images were projected on to UTM projection system and WGS-84 datum. Shoreline changes from 1990 to 2015 were calculated in Digital Shoreline Analysis System (DSAS) tool of Arc-GIS. Transects at 50-m intervals were drawn along the coastline for determining the shoreline change rate over this period.

Calangute Beach
Coastline evolution over the past decades at Calangute Beach is shown in Fig. 6a. The undisturbed coastline of Calangute Beach shows mild accretion during this period with most of the accretion (+ve value) occurring in the northern part of the beach following erosion (−ve value) in the southern part. The shorelines extracted from Landsat imagery at Calangute Beach since 1990 show an accretion of approx. 2.5 m/year over a period of 26 years, which is similar with the findings obtained from Kaczmarek et al. (2005) formula.

Karwar Naval Base Area (Kamat Beach and Mountain Beach)
Kamat and Mountain beaches were selected for this study as they represent the site condition with anthropogenic activities. The beaches are located on the north and south, respectively, of a newly constructed naval base in Karwar, Karnataka. Shoreline evolution since the construction in 2005 is determined using Landsat images, and it is observed that post-construction of the naval base, the beaches have accreted
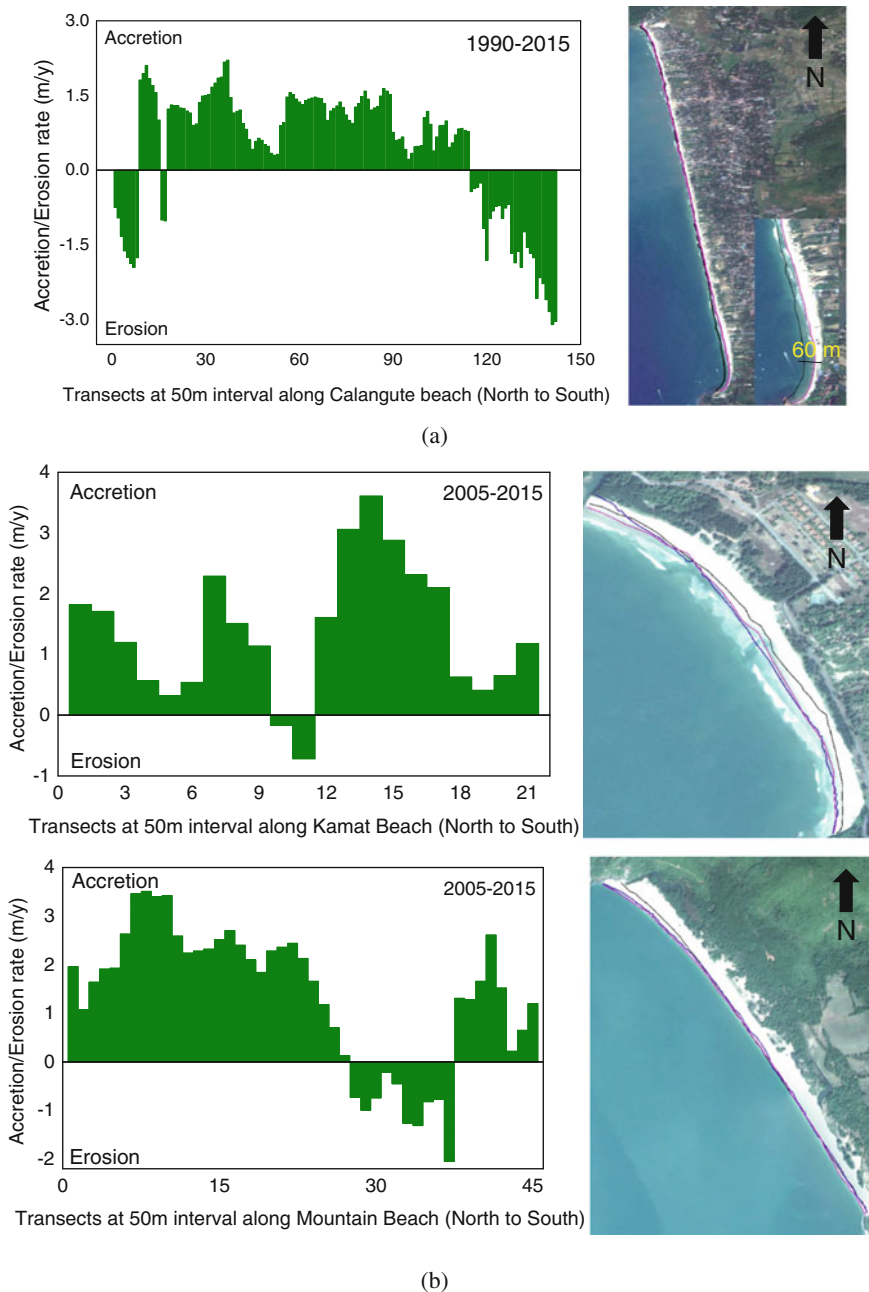
(a)

(b)

Fig. 6 Accretion/Erosion rate (m/year) and Shoreline changes in **a** Calangute Beach (1990 (black) and 2015 (magenta)) and **b** Kamat (north of naval base) and Mountain (south of naval base) beaches (2005 (black), 2010 (violet) and 2015 (magenta))

significantly. Using DSAS tool, the annual shoreline evolution since 2005 is computed and presented in Fig. 6b, which shows the rate of accretion along Kamat and Mountain beach to be ~+1.6 m/year and ~+2.8 m/year, respectively, over a period of 10 years. Kaczmarek et al. (2005) formula is used to determine the annual LST in this region and compared with the shoreline evolution rate obtained from Landsat imagery. Owing to the proximity of Kamat and Mountain beaches, it is acceptable to consider them as a single drift cell. It is observed that the beaches show a high amount of variability in annual LST post-construction. However, the variability in annual LST has reduced since 2009. Changes in variability of annual LST indicate the disrupted equilibrium of both the beaches, which has resulted in massive accretion over a small period of 10 years.

5   Conclusions

This study is an effort to provide insights on the contemporary sediment transport regime and resulting shoreline evolution at selected beaches located along the central west coast of India. Considering the scantily available measured sediment data and the difficulty in obtaining them, it was aimed to find the suitability of applying an empirical model (that requires minimum observation data) to estimate long-term LST (with acceptable accuracy) for the micro–meso-tidal beaches of India. The results were found to be comparable with satellite images and other observed/measured sediment transport data. To understand the contemporary evolution of coastline, hindcast wave climate from ERA-Interim was used. The annual average significant wave parameters (H_s, T_p, and α_0) were used to estimate annual LST. The central west coast of India receives oblique waves (swell waves and wind waves) from the W–SW direction which induces a huge gross northerly transport. The swell wave-induced LST is an order of magnitude higher than the wind wave-induced LST. The changes in sediment transport quantity were mainly governed by the swells generated during the cyclogenesis months. LST in this region shows a seasonal nature due to the influence of monsoonal winds. The total LST in the central west coast of India shows a decreasing trend, which is attributed to the reduced swell generation in the lower latitudes of the Arabian Sea and the Indian Ocean. It was also observed that effect of anthropogenic activities is significant on the long-term variation of LST rates and coastline orientation, which is capable of disturbing the equilibrium of beaches. It is suggested that any future predictions of shoreline evolution should be carried out considering the regional socio-economic developments and climate change scenarios.

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