

Spatial variability of mud bank along the southwest coast of India and its impacts

S Santhosh Kumar^{1,2}, K N Reshma^{1,2}, R Mani Murali^{1*} and P J Vidya³

¹ CSIR – National Institute of Oceanography, Dona Paula- 403004, Goa, INDIA

²Department of Marine Science, Bharathidasan University,
Tiruchirapalli- 620024, Tamil Nadu, INDIA

³National Centre for Polar and Ocean Research, Ministry of Earth Sciences,
Headland Sada, Goa, INDIA

*Corresponding author Email: mmurali@nio.org
Telephone no: +91 832-2450-389

Abstract

The mud bank at Alleppey along the southwest coast of India is a persistent one that forms in June and dissipates by September during the southwest monsoon (SWM). A calm patch of turbid water with a thick fluid mud at the near bottom helps in dampening the large waves. This holds a high societal and economic importance as a large number of fishing boats access the shore using this mud bank as a gateway. This study explores the spatial variability of the Alleppey mud bank at the southwest coast of India through Synthetic Aperture Radar (SAR) remote sensing techniques and its effect on the coastline. The presence of the Alleppey mud bank at Punnapra beach was evident during 2007, 2015 and 2016 through the SAR signatures. However, since 2017, the mud bank has been forming at the Vandanam coast, which is around 3 km south of the Punnapra coast, i.e at a different location from its regular region of the formation. The observed beach erosion at Punnapra (~30 m/yr from 2015 to 2020) confirms the absence of a calm region, which was due to the migration of the mud bank. Conversely, the formation of a mud bank at the Vandanam coast makes the region calm and conducive for accretion (~ 8 m/yr). The shift of the spatial location of the mud bank in 2016 is attributed to the southern ocean swell which struck the coast in Aug 2016. We hypothesize that the shift in the mud banks formation region after 2016 in the Kerala coast were influenced by the swells, generated in the Southern Ocean during the last week of July 2016. Geospatial variations of Alleppey mud banks are not only influenced by the regional forcings, but also by remote forcings such as the swells generated far away. The mud bank area was observed to have reduced in 2018 as compared to other years. The formation, existence and dissipation of mud bank of the southwest coast of India are socially linked as it provides a conducive environment for the calm landing of the fishing boats during rough monsoon season. It provides livelihood to thousands of fishermen in that time. It also protects the coast from monsoonal erosion. This study explored the importance of the presence of mud bank and its influence on the adjoining coastal region.

Keywords: Mud bank, SAR, Alleppey coast, Shoreline, Swell, Southwest coast of India

Introduction

The mud bank along the southwest coast of India is a phenomenon that occurs during the onset of the southwest monsoon (SWM) by June and dissipates in September (Moni 1970). The mud bank forming at Alleppey, southwest coast of India is persistent in occurrence but dynamic in nature. Throughout the event, the area remains calm, turbid and acts as a landing site for the fishermen to access the coast during the rough monsoon season. Many studies investigated its formation mechanism and came up with different hypotheses such as a) existence of water-bearing stratum near the coast (Bristow R C 1938) but contrary to that as it was due to the through chemical analyses of water (Ducane et al. 1938), b) coastal upwelling and opposing this why mud bank do not occur all along the coast rather than selected locations (Ramasastry A A and Myrland P 1959; Ramamirtham C P and Rao D S 1973) and c) subterranean flow (Balachandran 2004) for the formation and its existence. But, none seems to square up because of the negations and the lack of proof in it. The presence of high suspended sediments in the near bottom dampens the waves and forming a calm region close to the nearshore. This protects the coast from high wave actions (Kurup P G 1977; Mallik et al. 1988; Purandara B K and Dora Y L 1991; Shynu et al. 2017) while the adjacent regions on either side of the mud bank region experience the strong monsoonal waves resulting in erosion (Gopinathan and Qasim 1974). The intensity of these waves are completely absorbed by the mud banks and in case of its absence, the coast would be affected by high wave energy resulting in erosion. The control of the surface waves in the seaward periphery of the mud bank by the bottom sediments results in fewer waves in the nearshore during the rough monsoon season compared to the non-monsoon season (Mathew et al., 1995). The study on the plankton community in the mud bank revealed that the water is not too muddy except for the presence of fluid mud in the bottom and the coastal upwelling during the southwest monsoon helps in plankton stock growth (Jyothibabu et al. 2018). The salinity changes in the near-bottom water of Alleppey mud bank from 2014 observations have eliminated hypotheses like the subterranean flow of freshwater, active trending faults, water-bearing stratum and river deposition as being responsible for the formation of mud bank at Punnappa beach (Muraleedharan et al. 2017). The formation mechanism was further given a new perspective, where the bed sediment movement was influenced by the strong wind, wave actions and occasional low-pressure events (LPE) during the SWM, which helps in forming the fluid mud. This fluid mud is dispersed by the onshore upwelling current to the coast and thus forms the mud bank. Further, the role of onshore current in the fluid mud is responsible for spatial orientation and the structure of the mud bank after formation (Muraleedharan et al. 2018). On introspection, the spatial variations of the mud bank help in understanding the behaviour of the hydrodynamic processes and their effects on

the coast. Remote sensing helps in identifying the spatial variation by reducing the cost and the laborious field visits to determine changes throughout the event. Geospatial techniques are very efficient in wetland management(Garg 2015), multi-hazard vulnerability assessment(Sahoo and Bhaskaran 2018), sea-level rise impacts(Mani Murali and Dinesh Kumar 2015), etc. As the mud bank appears and dissipates during the monsoon period, in-situ measurements are very challenging and cumbersome. Hence, geospatial techniques provide a better solution to understand the mud bank dynamics. Cloud free optical images are nearly scarce in monsoon time. So, Synthetic Aperture Radar (SAR) data is ideal for this study as it can observe during all weather conditions. It helps in the identification of the sea surface conditions of the coastal areas through the wave break signatures, which demarcates the periphery of the mud bank that eventually facilitates in understanding the spatial variation of the mud bank. Radar satellites were first used in the French Guiana coast for detecting and monitoring the mud bank and its coastline during 1997 and 2001 which explains the efficiency of the radar images in mud bank studies (Baghdadi et al. 2004). Later, high-resolution satellite images were used to estimate the rate of the migration of the mud bank in the French Guiana coast (Gardel and Gratiot 2005). Further, the satellite-derived values were compared with the bathymetric data to determine the migration of the mud bank precisely (Péron et al. 2013). SAR data determine the mud bank region by detecting surface roughness due to the wave break, which has a high radar backscatter compared to the adjoining regions (Rakotoarivony et al. 1996; Baghdadi et al. 2002). The increase in the surface roughness due to the wave breaks around the mud bank region appear in the images in the form of lineation which could be used to identify the periphery of the mud bank clearly (Vogelzang and Ruddick 1999). The smoother surfaces in the mud bank region due to the wave dampening in the periphery will show a lesser radar backscatter. This manuscript deals with identifying the mud bank through SAR data and its inter and intra annual variations, impacting the adjoining coast. The spatial variation of the mud bank has an adverse effect on the adjacent coast (Anthony et al. 2010). A recent study on the Guianas coast reveals that the alongshore shift of the mud bank eventually resulted in the drastic reduction of beach length (Anthony et al. 2019). This study dealt with two important aspects, a) The spatial variations of the Alleppey mud bank from 2007-2019 (intra and inter-annual) through SAR data, and b) morphological changes along the Alleppey coast due to the spatial variations of mud banks. The study area falls on the southwest coast of India, stretching from Alleppey beach in the north to Ambalapuzha in the south (Fig. 1). The length of this coast is approximately 15 km. The occurrence of the mud bank in this stretch was found to be persistent since 1974 (Gopinathan and Qasim 1974) and also observed till recent times (2007 and 2016). But, since 2017, mud banks have been forming at a different location that initiated

this study to explore the reasons for its shifting and its impact on the adjoining coast. The presence of the fluid mud makes the mud bank region shallow, with bathymetry drastically reducing after the 4m isobath inshore and gradually becoming gentle after the southwest monsoon (Narayana et al. 2008).

Materials and methods

The SAR datasets (Fig. 2) ALOS Palsar (2007) and Sentinel-1 (2015-2020) were obtained from the Alaska satellite facility website (<https://search.asf.alaska.edu/>). Sentinel 1 data which is shown in blue colour and ALOS Palsar in red colour in Fig 2 represents the acquisition during the monsoon season. The technical specifications, as mentioned in Table 1 indicated that both satellites operate in different wavelengths and have different polarization. Both being dual-polarization, ALOS transmits in a Horizontal direction, whereas Sentinel-1 transmits in a vertical direction which plays a major part in the identification of the structures in homogeneous surfaces. The mud bank periphery was determined from the SAR images through a basic pre-processing step of radiometric calibration, speckle filtering and terrain correction. The pre-processed ALOS images were able to identify the mud bank due to its higher wavelength. Whereas, the backscatter coefficient values for Sentinel-1 images were classified based on threshold values. The threshold was maintained from 0.01 to 0.05 and the higher wave breaks along the periphery were identified with the values around 0.03 to 0.04 and above to identify the wave breaks at the mud bank and also along the adjacent coastlines.

Table 1 Specifications of Sentinel-1 and ALOS

Landsat-8 images (Table 2) obtained from USGS earth explorer (<https://earthexplorer.usgs.gov/>) were used for the shoreline change estimation. They are shown in green colour in Fig 2. The satellite images were selected based on similar tidal conditions and the tide values were obtained from WX tide for the Cochin Port. The Landsat images were selected during the non-monsoon period due to the least cloud cover and the Sentinel-1 images were used during the monsoon season from 2015 to 2020. The shorelines were extracted by manual digitization for the shoreline change analysis. There are many studies on mud bank in the Amazon region, but a few at mud bank of the southwest coast of India. The best-followed methodology such as DSAS, SAR imaging has been used in this study as the study aimed at exploring the geospatial variability of the mud bank. As the images used in this study fall within a similar tidal range, the demarcated mud bank is not influenced by different wave attenuation characteristics due to water height. As the analysis is within the monsoon period, wave height and wave period was within the same range and must have contributed the same damping limit. We rule out these factors as responsible for the geospatial variations of the mud bank extent.

Table 2 Satellite image details

The seasonal changes due to the monsoon which are included in Sentinel-1 derived shorelines were used to eliminate the monsoonal effect on beaches using the Landsat-8 data. These extracted shorelines from Landsat-8 and Sentinel-1 data were used in the Digital Shoreline Analysis System (DSAS) to estimate the shoreline changes rate. The End Point Rate (EPR) was considered here, which is calculated by dividing the shoreline movement by the time elapsed between the oldest and youngest shoreline (Thierler et al. 2009).

Daily means of zonal (u) and meridional (v) wind at 10 m, the mean period of total swell and significant height of total swell for the period 23 July 2016 to 03 August 2016 (spatial resolution 0.5-degree x 0.5 degree) was taken from ECMWF ERA5 (Copernicus Climate Change Service (C3S, 2017) (source: <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form>). ERA5 is the fifth generation of ECMWF atmospheric reanalysis of the global climate. The mean period of total swell represents the average time taken for two consecutive wave crests on the ocean surface associated with a swell to pass through a fixed point. Similarly, the significant height of the total swell indicates the average height of the highest third of surface ocean waves associated with a swell.

Wind speed is calculated by using the formula;

$$\text{Wind speed} = \sqrt{u^2 + v^2}$$

Where 'u' is the zonal and 'v' is the meridional component of wind.

Identification of Mud bank through SAR data

The pre-processed Sigma₀ image derived from an L-band ALOS PALSAR was able to identify the location of the mud bank and the exact spatial extent of the mud bank for the year 2007. The sigma₀ image derived on 27-07-2007 (Fig. 3 a) appeared to have a less value between -25 to -30 (dB) in the mud bank region of the coast, whereas the rest of the areas were showing values between -15 to -20 (dB). The presence of a large group of boats inside the mud bank region is also evident, which gives a higher backscatter of -5 to 3 (dB). The semicircular shape of the mud bank is having a width of 1.5 km seaward and extending alongshore for a length of 6 km on the Punnapra coast. The ALOS image on 11-09-2007 appears to have no trace of mud bank, which reveals that the mud bank had dissipated by that time (Fig. 3 b).

This ability of the SAR images to identify the mud bank was attempted with the C-band Sentinel-1 data for recent times. Unlike ALOS, the shorter wavelength Sentinel-1 image's capability

to identify the mud bank region was carried out by determining the sea surface condition. As the mud bank occurs typically during the SWM when there is a high wave action along the coast. But in the mud bank region, the wave breaks along its periphery. High wave actions are experienced at the adjacent coast. An in-situ observation was carried out on 26-07-2016 to demarcate the periphery of the mud bank with the help of suspended sediment concentration in the water column. An averaged sediment concentration value with respect to the depth for 30 different stations was plotted and interpolated to obtain the mud bank region (Kumar and Murali 2018). The SPM measurements were part of this study which included demarcation of the mud bank periphery through in-situ measurements using the LISST-100x instrument. LISST-100X abbreviated as “Laser In-Situ Scattering and Transmissometry” is an optical instrument used for estimating the concentration of sediments in the water profile and its particle size distribution. The instrument is capable of measuring particles of size from 1.0 micron to 250 microns. The instrument was extensively used to identify the mud bank and non-mud bank region using 5 cross-shore transects and the delineation was done by the averaged values of sediment concentration and later validated through particle size distribution in the mud bank region. The ALOS derived mud bank region was compared with the in-situ derived extent from 2016, which was matching exactly. Later, the Sentinel-1 derived SAR signatures from the wave breaks on comparing with both ALOS and in-situ derived values were also matching well with the mud bank boundary (Fig. 4 a-c). These signatures with a Sigma₀ value of 0.03-0.04 in linear form was found on the periphery of the mud bank and also on either side of the coast of the mud bank regions, which was constant for all the mud bank occurrences which had a higher wave activity during the satellite pass. This helps in understanding that the wave breaking was stronger in the adjoining coast and less or null in the mud bank region due to the presence of fluid mud in the near bottom. It provides a comparatively higher backscatter coefficient value in the periphery due to the stronger wave breaking.

Results

Spatial Variations of Mud bank

The SAR derived backscatter values clearly show the presence of the mud bank during the monsoon of 2007 and its dissipation by the end of the monsoon in September 2007 (Fig. 3). This is the first study by SAR data for identifying the mud bank of the southwest coast of India. The shape of the mud bank was evident as a semicircular patch with an area of 4.86 km² located in the north of the Punnapra coast. This SAR derived mud bank region (Fig. 4 a) was compared with the in-situ derived periphery (Kumar and Murali 2018) for the year 2016 (Fig. 4 b), and the SAR derived wave

break signatures for the recent time were found to be matching well (Fig. 4 c). This capability of SAR data was utilized for delineating the mud bank periphery and to understand the spatial variations of the mud bank from 2015-2019 (ESM 1 – ESM 5). The spatial variation was studied for both inter-annual and intra-annual scales to interpret the migration of the mud bank and to identify its change in shape and size throughout its existence in a particular year, respectively.

The periphery derived from Sigma_0 values in the linear form for every year during June or early July was considered to understand the shift in the mud bank locations. The first SAR derived mud bank (Fig. 5) in 2007 was found to be appearing at the Punnapra coast and to its north. The change in the shape of the mud bank varies from year to year. The comparison of 2007 with other years is to confirm that the mud bank has been forming at the same geospatial location for a long time. Subsequently, the next SAR derived mud bank periphery from 2015 and 2016 was also found to be predominantly occurring at the Punnapra coast. The shift of mud bank to the northern side during the first week of August 2016 was puzzling, and the reasons for the shift was not much explored. The mud bank had shifted its location totally from the Punnapra coast to Vandanam and Neerkunnam region (4 km southward) and kept forming at the same location during the years 2017, 2018 and 2019. This shift in the mud bank from the regular Punnapra coast to the north during August 2016 and then to the south (Vandanam coast) of its regular formation region from 2017 poses ambiguity in its formation and spatial structure. As the presence of mud bank helps in dampening the waves, generally, the mud bank existing region does not undergo beach erosion and they are stable or accreting regions. This sudden migration to the southern region had an impact on the morphology of the coast and showed the erosion immediately after the shift.

The intra-annual changes in the mud bank during the years 2016 to 2019 revealed the evolution of its shape and size from formation till dissipation. The signatures derived from the SAR images during the June to September for the years 2016-2019 (Fig. 6) were measured by a polygon drawn along its periphery, and the size of the mud bank estimated through its area was found to be large during the formation. Eventually, through time it shrank before dissipation. A maximum of two signatures was identified from each year; one during June and the other during August. On comparing the signatures of all four years, the periphery of the mud bank was found to be maximum at the time of formation during June and reduced to half of its size by August. The area of the mud bank during June in 2016, 2017, 2018 and 2019 was 16 km², 14 km², 7 km² and 13 km² which reduced to 8 km², 7 km², 7 km² and 5 km² respectively by August (Fig. 6 and Fig. 7). The cross-shore width of the mud bank was found to be more during the formation and eventually reduced to half of its width during the dissipation, whereas the length of the mud bank along the coast remained the

same. The change in the area of the mud bank in 2016, 2017 and 2019 was clearly visible due to the reduction in the extent of the mud bank in cross-shore by more than 60% and thus the area of the mud bank became 50% lesser during the dissipation. The length of the mud bank along the coast was almost the same for all the years. But in 2017, the reduction by 1 km in both along and cross-shore extent was observed. It eventually resulted in the reduction of the area by 50 % by the end of July. The spatial variations of the mud bank from the time of forming till dissipation within the particular year resembles its dynamic nature, which can be studied with L-band SAR data for a better understanding of monthly variations in the shape and size of the mud bank.

Mud bank and its role on the adjoining shoreline

The spatial variation of the mud bank had a direct impact on the shoreline along the Alleppey coast as it acts as an impediment and protects the coast. These shoreline changes derived from Landsat -8 and Sentinel-1 revealed the shoreline behaviour during the non-monsoon and monsoon conditions, respectively (Fig. 8). The coast is subject to undergo heavy erosion due to the high wave action during the monsoon period and eventually recovers post-monsoon. The shorelines changes from 2015 to 2020 in the form of EPR (m/yr) revealed a large change in the Punnapra coast. As the mud bank presence and the adjoining morphology are interlinked, the impact of the spatial variability of the mud bank in the Punnapra coast to the morphology was studied from Alleppey beach in the north (76.3193 E, 9.4945 N) till Ambalapuzha in the south (76.359 E, 9.3767 N). The coastline of Alleppey receives a high wave action typically during the SWM, which eventually leads to the shoreline change in the form of erosion along the entire coast except at the mud bank region. The sudden shift of mud bank in August 2016 and severe erosion at the Punnapra coast landing site posed a question, and reasons for the same were not known. Punnapra beach was stable for a very long time because of the presence of a mud bank during the SWM, which made the coast calm and restricted erosion. Mud bank was safeguarding this coast naturally for a very long time. The overnight shift of the mud bank from that location to the northern side and the observed erosion made us to explore the cause for the same. In our study, we hypothesize that a swell that reached Punnapra coast on 01st August 2016 early morning (news service 2016) must have been responsible for the shift of the mud bank as well as the erosion at Punnapra coast. We explored the possibility of a swell strike at this coast from the available data. This swell event on 01-08-2016 triggered an erosion of 30 m in the southern part of Punnapra near the existing landing site location and also shifted the mud bank towards the north by 1 km. This shift in the mud bank affected the southern portion of the Punnapra beach, and they were exposed to the strong waves for the rest of the monsoon period. Despite the erosion caused by the swell, the rest of the Punnapra coast appeared stable in that particular year and

even till the pre-monsoon of 2017. Later in 2017, the mud bank appeared 3 km south of the Vandanam coast, and the Punnapra coast was entirely exposed to monsoon waves. Due to this shift, the Punnapra shoreline showed considerable erosion probably due to the absence of protection by the mud bank which was not existing during that period. A high erosion of 35 m/yr at Punnapra was evident from both satellite images, whereas the adjacent parts of the coast were found to be stable in the satellite images (Fig. 8 a&b).

This spatial alteration in the location of the mud bank in 2017 was the initiation for the erosion of the Punnapra beach. The beach had an area of 35 ha till July 2016 and reduced to 34 ha by January 2017. The non-occurrence of the mud bank made the beach vulnerable to the high waves resulting in drastic erosion (Fig. 9 a). The beach has further eroded from 30 ha in February 2018 to 15 ha by January 2020 (Fig. 9 b). This region may face more erosion in future too (ESM 6).

On the contrary, the beach closer to the Vandanam coast has been accreting gradually at a rate of 5 to 8 m/year where the mud bank has been forming for the past three years. This shift in the mud bank to this location has helped the coast to accrete around 25-30 m (Fig. 10 a&b). The anchoring of the boats in the shifted location is visible in the satellite image of 2020, which validates the existence of a mud bank at the new location (ESM 7).

Role of Southern Ocean swells in mud bank

We observed a strong wind disturbance (close 20 m/s) in the Southern Ocean(60-90°E and 40-60°S) on 25 July 2016 (Fig. 11 a). The westward propagation of the high wind band is evident during the period 25-27th July (Fig.11 b-f). The strong and persistent winds must have generated high waves (swell) on the same day (Fig. 12 a). The conditions of swell formation are also observed from 25 July (with a high wave period > 13 s) to 27 July 2016. The formation and propagation of swells (Fig. 12 a-h) towards the north with a high mean wave period are clearly noticed from 25 July 2016 onwards(Fig. 12 d-g). Consistent with the swell generation and its propagation, high significant wave height (> 5 m) was observed (Fig. 12 i-o) in the region where the swell formed and propagated. Similar to the period, significant wave height was also observed in its propagation towards the north and the swell reached the southwest coast of India on 01 August 2016, and it proceeded further north (Fig. 12 o). These swells struck at the Punnapra coast which triggered a severe erosion in this region, resulting in huge damage. More than the erosion by this swell, we hereby report and attribute that these swells were responsible for the migration of mud banks from Punnapra, where it has been forming for so many years. It revealed that this swell disturbed the overall mud bank forming environment as mud bank has not formed there again. It started forming at the south of Punnapra in

the subsequent years. These swells disturbed the existing mud bank in 2016 and pushed towards the north. This allowed the monsoonal waves to reach the Punnapra beach after this swell event, and the regular mud bank landing site was eroded after the swell event. This push of mud banks into the northern side could have been possible only with this kind of high energy swell. The swell which reached the Punnapra coast played a major role in repositioning the mudbank region and disturbed the regular formation environment. Since the event, the mud bank has been forming at Vandanam coast located 3 km south of Punnapra.

Discussion

We attribute the shift of mud bank to the northern side of Punnapra coast at the dissipating phase of 2016 (ESM2) which in turn triggered severe erosion of the coastline to the swell which struck the Punnapra coast on 01 August 2016. This observation was possible due to our physical presence in the field during the event where the shift of the mud bank by 1 km north was evident. This event was also reported by local media (news service 2016). The detailed analysis of swell caused was carried out from the days of its origin. It is known that Southern Ocean swells strike the Indian coast with very high energy very often (Remya et al. 2016). These long distant swells propagating from the Southern Ocean eventually bring higher energy as it reaches the coast, which is almost double (Nayak et al. 2013). So, available wind periods, significant wave height and strong winds were explored from the Southern Ocean region for the possibility of swell formation and propagation during that period. We could track a swell forming environment and the propagation of swell from the southern ocean to the Indian coast.

A mud bank formation, with a significantly smaller area compared to the rest of the years, was observed in the year 2018 (Fig. 7). The onset of the monsoon was on 29 May 2018, which is early compared to the other years. This particular year received excess rainfall resulting in floods in various parts of the Kerala state, India. But the mud bank periphery derived from 22 June 2018 was having an area of 7 km² only (Fig. 7). It is again attributed to a surge that occurred just before the onset of the monsoon in 2018. The surge was reported on 28 May 2018 with a significant wave height of ~ 4 m along the various parts of the Kerala coast (Fig. 13). The high waves were evident from 27 May 2018 at 09.00 am (Fig. 13 b-e), further intensifying and reaching a height of 4.2 m on 28 May 2018. Later by midnight of 28 May 2018, the swell started moving towards the south and the wave height reduced by 29 May 2018. This high wave activity contributed in restricting the mud bank from moving seaward and pushing the fluid mud to the bottom closer to the coast. Therefore the area of the 2018 mud bank was comparatively smaller at the formation time itself and sustained

with the same area till its dissipation. These swell events in 2016 and 2018 highlight the role of remote forcings in the regional or local processes such as mud bank. As mud bank is a socially linked oceanographic event, it is very important to understand the geospatial variations and controlling mechanisms for the better management of the livelihood of the people who depend on the mud bank. Though the swells were formed thousands of miles away, they had an impact on the seasonally forming mud bank event. We believe that many more similar impacts are not known and need to be explored. The presence of mud bank support the calm fish landing sites during the rough monsoon time and also protects the coast from monsoonal erosion. No one would have ever thought that the swell from the Southern Ocean would destroy the conducive mud bank forming environment in the Kerala coast.

Conclusion

The mud bank region, which acts as a calm region during the SWM by wave dampening, created an interest to study the spatial variability and its direct impact on the coast. Even though the formation mechanism of the mud bank is not yet fully comprehended, many researchers explore it further for a better understanding of its formation. This study on the variability of the size and shape of the mud bank and its migration dynamics helps in determining the behaviour of the mud bank.

The occurrence of the swell event on 01 August 2016 shifted the mud bank to the north of Punnapra, thus resulting in the erosion of the Punnapra beach and the landing site. This created a high amount of damage to the region, with the coast becoming completely exposed to the rough monsoonal waves during the rest of the period and preventing the formation of the mud bank again along the same coast till date. The inter-annual spatial variations revealed the shift in the mud bank towards the south rather than occurring in the expected location. The intra-annual variations of the mud bank carried out during 2016-2019 revealed that the size of the mud bank is larger during the formation and eventually reduces by time before dissipation. The 2018 mud bank remained in the same size during the entire period, and the disturbance before the onset of monsoon in 2018 was explored and attributed. The efficiency of the SAR images in identifying the spatial variations reveals the intra-annual structural changes in the mud bank. The role of the mud bank and its effect on coastline changes was depicted by the accretion trend in the mud bank location and erosion at the adjacent coastline. The Punnapra beach, which was found to be a stable accreting coast for a longer period eroded when the mud bank moved away from the coast. Thus, the spatial variability of the mud bank was influenced by various factors, and the formation requires its own set of conditions to form. This study explored the possibility of varying sizes of mud bank areas and the possible causes.

The migration of mud bank has to be observed through in-situ measurements for future events, and the role of causative physical parameters need to be well examined for a better understanding. The long-wavelength SAR in these types of studies has to be utilized to get a better insight into the temporal variations of the mud bank throughout the event. Mud bank formation is directly linked to the livelihood of many fishermen, and its impact on the coastline needs scientific attention for its efficient management.

Acknowledgements

The authors are thankful to the Director, National Institute of Oceanography, Goa, for permitting this study. This work is part of the first author's Ph.D. thesis registered at Bharathidasan University, Tiruchirappalli, India. Landsat 8 data was obtained from USGS earth explorer (<https://earthexplorer.usgs.gov/>), and the SAR datasets were obtained from the Alaska satellite facility (<https://search.asf.alaska.edu/>). The authors acknowledge Rajive Krishnan, Vishnu

Brahamanad and Rajmohan for providing field photographs. The NIO contribution is xxxx. The NCPOR contribution is xxxx.

References

- Anthony, E J., Brunier, G., Gardel, A., and Hiwat, M. 2019. Chenier morphodynamics on the amazon-influenced coast of suriname, South America: Implications for beach ecosystem services. *Frontiers in Earth Science* 7: 1–20. <https://doi.org/10.3389/feart.2019.00035>.
- Anthony, E J., Gardel, A., Gratiot, N., Proisy, C., Allison, M. A., Dolique, F., and Fromard, F. 2010. The Amazon-influenced muddy coast of South America: A review of mud-bank-shoreline interactions. *Earth-Science Reviews* 103: 99–121. <https://doi.org/10.1016/j.earscirev.2010.09.008>.
- Baghdadi, N., King, C., Bourguignon, A., and Remond, A. 2002. Potential of ERS and Radarsat data for surface roughness monitoring over bare agricultural fields: Application to catchments in Northern France. *International Journal of Remote Sensing* 23: 3427–3442. <https://doi.org/10.1080/01431160110110974>.
- Baghdadi, N., Gratiot, N., Lefebvre, J. P., Oliveros, C., and Bourguignon, A. 2004. Coastline and mudbank monitoring in French Guiana: Contributions of radar and optical satellite imagery. *Canadian Journal of Remote Sensing* 30: 109–122. <https://doi.org/10.5589/m03-059>.
- Balachandran, K K. 2004. Does subterranean flow initiate mud banks off the southwest coast of India? *Estuarine Coastal and Shelf Science* 59: 589–598. <https://doi.org/10.1016/j.ecss.2003.11.004>.
- Bristow R C. 1938. *History of Mudbanks*. Cochin Government Press, Cochin, India.
- Ducane, C. G., Bristow, R. C., Brown, J. C., Keen, B. A., and Russel, E.W. 1938. Report on the special committee on the movement of mudbanks. Cochin Government Press, Cochin, India.

- Gardel, A., and Gratiot, N. 2005. A satellite image-based method for estimating rates of mud bank migration, French Guiana, South America. *Journal of Coastal Research* 21: 720–728. <https://doi.org/10.2112/03-0100.1>.
- Garg, J K. 2015. Wetland assessment, monitoring and management in India using geospatial techniques. *Journal of Environmental Management* 148: 112–123. <https://doi.org/https://doi.org/10.1016/j.jenvman.2013.12.018>.
- Gopinathan, C.K, and Qasim, S. Z. 1974. Mud Banks of Kerala-Their Formation & Characteristics. *Indian Journal of Marine Sciences* 3: 105–114.
- Jyothibabu, R., Balachandran, K. K., Jagadeesan, L., Karnan, C., Arunpandi, N., Naqvi, S. W. A., and Pandiyarajan, R. S. 2018. Mud Banks along the southwest coast of India are not too muddy for plankton. *Scientific Reports* 8. Springer US: 1–13. <https://doi.org/10.1038/s41598-018-20667-9>.
- Kumar, S. S., and Murali, R. M. 2018. In-Situ Observations of Mudbanks of Southwest Coast of India and Mapping of its Extent in 2016. *Journal of Coastal Research* 85: 211–215. <https://doi.org/10.2112/SI85-043.1>.
- Kurup, P. G. 1977. Studies on the physical aspects of the mudbanks along the Kerala coast with special reference to the Purakad mudbank. *Bulletin of the Department of Marine Sciences, University of Cochin*. 7: 1–72.
- Mallik, T. K., Mukherji, K. K., and Ramachandran, K. K. 1988. Sedimentology of the Kerala mud banks (fluid muds?). *Marine Geology* 80: 99–118. [https://doi.org/10.1016/0025-3227\(88\)90074-6](https://doi.org/10.1016/0025-3227(88)90074-6).
- Murali, R. M., and Dinesh Kumar, P. K. 2015. Implications of sea level rise scenarios on land use /land cover classes of the coastal zones of Cochin, India. *Journal of Environmental Management* 148: 124–133. <https://doi.org/https://doi.org/10.1016/j.jenvman.2014.06.010>.
- Mathew, J., Baba, M., and Kurian, N. P., 1995. Mudbanks of the Southwest Coast of India. I: Wave Characteristics. *Journal of Coastal Research* 11: 168–178.
- Moni, N. S. 1970. Study of Mudbanks Along the Southwest Coast of India. *Coastal Engineering* 1970: 739–750. <https://doi.org/10.1061/9780872620285.045>.
- Muraleedharan, K. R., Dinesh Kumar, P. K., Prasanna Kumar, S., John, S., Srijith, B., Anil Kumar, K., Naveen Kumar, K., Gautham, S., and Samiksha, V. 2018. Formation Mechanism of Mud Bank Along the Southwest Coast of India. *Estuaries and Coasts* 41. Estuaries and Coasts: 1021–1035. <https://doi.org/10.1007/s12237-017-0340-0>.
- Muraleedharan, K R, Dinesh Kumar, P. K., Prasanna Kumar, S., Srijith, B., John, S., and Naveen Kumar, K. R. 2017. Observed salinity changes in the Alappuzha mud bank, southwest coast of India and its implication to hypothesis of mudbank formation. *Continental Shelf Research* 137: 39–45. <https://doi.org/https://doi.org/10.1016/j.csr.2017.01.015>.
- Narayana, A. C., Jago, C. F., Manojkumar, P., and Tatavarti, R. 2008. Nearshore sediment characteristics and formation of mudbanks along the Kerala coast, southwest India. *Estuarine, Coastal and Shelf Science* 78: 341–352. <https://doi.org/10.1016/j.ecss.2007.12.012>.

- Nayak, S., Bhaskaran, P. K., Venkatesan, R., and Dasgupta, S. 2013. Modulation of local wind-waves at Kalpakkam from remote forcing effects of Southern Ocean swells. *Ocean Engineering* 64. Elsevier: 23–35. <https://doi.org/10.1016/j.oceaneng.2013.02.010>.
- News service, Express. 2016. Unexpected sea surge at Alappuzha coast, 27 fishing boats washed away. *The New Indian Express*. Alappuzha. <https://doi.org/https://www.newindianexpress.com/states/kerala/2016.08.02>. August 2.
- Péron, C., Chatelet, A., Gensac, E., and Gardel, A. 2013. Mud bank migration from remote sensing and bathymetric data: The example of the Kourou River Estuary, French Guiana, South America. *Journal of Coastal Research* 65: 558–563. <https://doi.org/10.2112/si65-095.1>.
- Purandara, B. K., and Dora, Y. L. 1991. Textural variations of Narakkal and Saudi Mud banks, west coast of India. *Journal of Indian Association of Sedimentologists* 10: 1–11.
- Rakotoarivony, L., Taconet, O., Vidal-Madjar, D., and Bellemain, P. 1996. Radar backscattering over agricultural bare soils. *Journal of Electromagnetic Waves and Applications* 10: 187–209. <https://doi.org/10.1163/156939396X00964>.
- Ramamirtham, C. P., and Rao D. S. 1973. On upwelling along the west coast of India. *Journal of the Marine Biological Association of India* 15: 411–417.
- Ramasastri, A. A., and Myrland, P. 1959. Distribution of temperature, salinity and density in the Arabian sea along the South Malabar coast (South India) during the post-monsoon season. *Indian Journal of Fisheries* 6 (2): 223–255.
- Remya, P. G., Vishnu, S., Praveen Kumar, B., Balakrishnan Nair, T. M., and Rohith, B. 2016. Teleconnection between the North Indian Ocean high swell events and meteorological conditions over the Southern Indian Ocean. *Journal of Geophysical Research: Oceans* 121: 7476–7494. <https://doi.org/10.1002/2016JC011723>.
- Sahoo, B., and Bhaskaran, P. K. 2018. Multi-hazard risk assessment of coastal vulnerability from tropical cyclones – A GIS based approach for the Odisha coast. *Journal of Environmental Management* 206: 1166–1178. <https://doi.org/https://doi.org/10.1016/j.jenvman.2017.10.075>.
- Shynu, R., Purnachandra Rao, V., Samiksha, S. V., Vethamony, P., Naqvi, S. W. A., Kessarkar, P. M., Babu, M. T., and Dinesh kumar, P. K. 2017. Suspended matter and fluid mud off Alleppey, southwest coast of India. *Estuarine, Coastal and Shelf Science* 185. Elsevier Ltd: 31–43. <https://doi.org/10.1016/j.ecss.2016.11.023>.
- Thierler, E. R., Himmelstoss, E. A., Zichichi, J. L., and Ergul, A. 2009. DSAS 4.0 Installation Instructions and User Guide. *U.S. Geological Survey Open-File Report 2008 1278*: 291–294.
- Vogelzang, J., and Ruddick, K. G. 1999. Radar signatures of river outflow fronts. *International Geoscience and Remote Sensing Symposium (IGARSS)* 4: 1960–1962. <https://doi.org/10.1109/igarss.1999.774999>.

Table 2 Specifications of Sentinel-1 and ALOS

Description	Sentinel-1	ALOS
Acquisition mode	Interferometric Wide Swath (IW)	Fine beam mode
Processing Level	Level-1 Ground Range Detected	Level-1 Single Look Complex
Polarization	VH+VV	HH+HV
Swath	250 km	70 km
Wavelength	C band	L band

Table 2 Satellite image details

Satellite	Date of Pass	Tide (m)
ALOS PALSAR	27-07-2007	0.6
ALOS PALSAR	11-09-2007	0.8
Landsat- 8	03-04-2015	0.9
Sentinel-1A	08-07-2015	0.7
Sentinel-1A	20-07-2015	0.6
Sentinel-1A	30-09-2015	0.3
Landsat- 8	20-03-2016	0.8
Sentinel-1A	15-05-2016	0.7
Sentinel-1A	08-06-2016	0.4
Sentinel-1A	26-07-2016	0.7
Sentinel-1A	12-09-2016	0.6
Landsat- 8	02-01-2017	0.6
Sentinel-1A	10-05-2017	0.3
Sentinel-1A	03-06-2017	0.6
Sentinel-1A	21-07-2017	0.5
Sentinel-1A	02-08-2017	0.6
Landsat- 8	22-02-2018	0.5
Sentinel-1A	05-05-2018	0.4
Sentinel-1A	22-06-2018	0.6
Sentinel-1A	21-08-2018	0.6
Sentinel-1A	14-09-2018	0.5
Landsat- 8	21-09-2019	0.5
Sentinel-1A	30-05-2019	0.5
Sentinel-1A	17-07-2019	0.3
Sentinel-1A	10-08-2019	0.6
Sentinel-1A	22-08-2019	0.6
Landsat- 8	27-01-2020	0.7
Sentinel-1A	30-05-2020	0.6

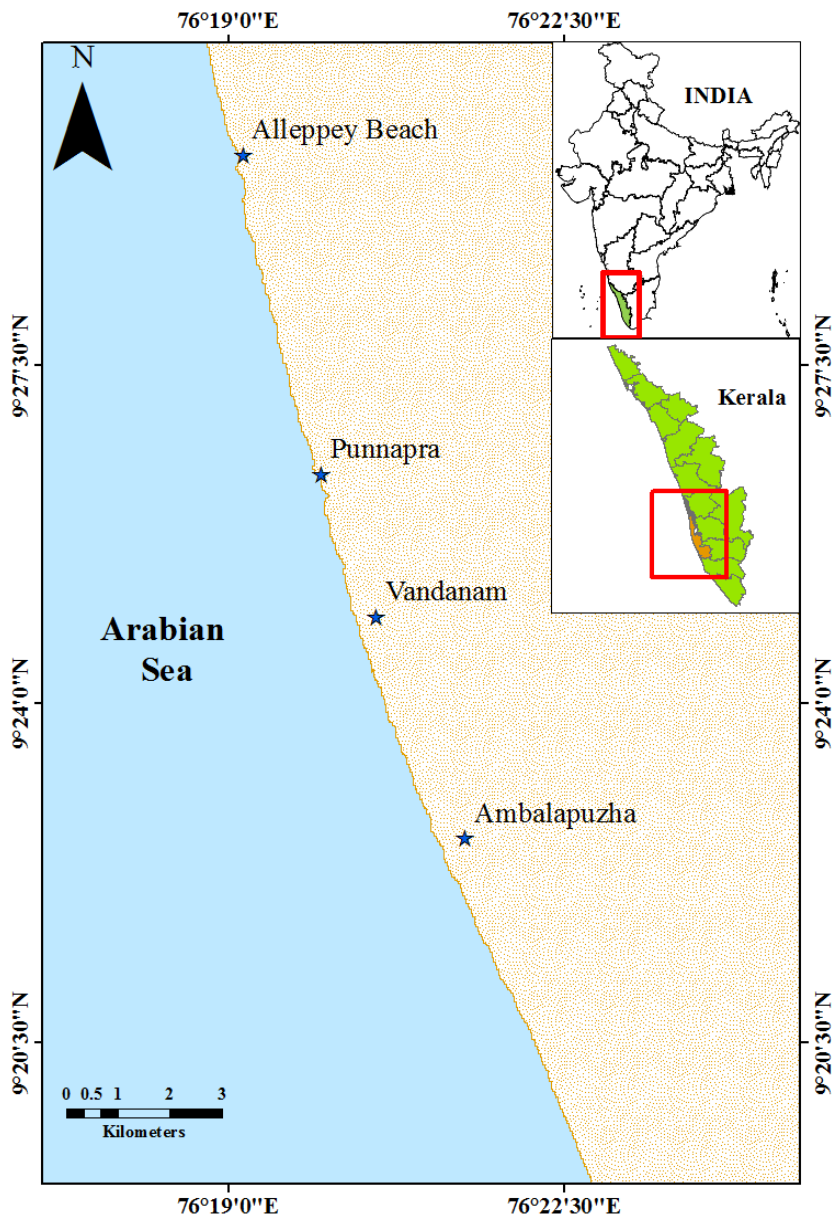


Fig. 1 Study Area

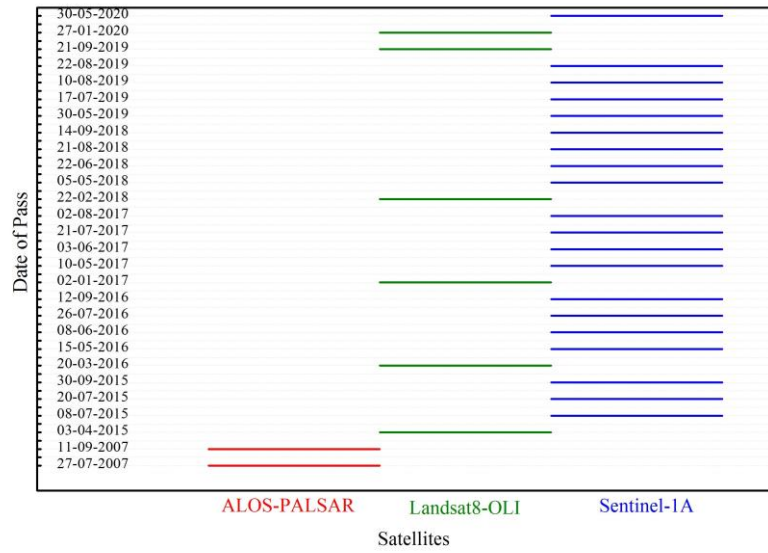


Fig. 2 Dataset details (Available ALOS –PALSAR (red colour) and Sentinel -1A (blue colour) during the monsoon period, Landsat 8 data during the non-monsoon period)

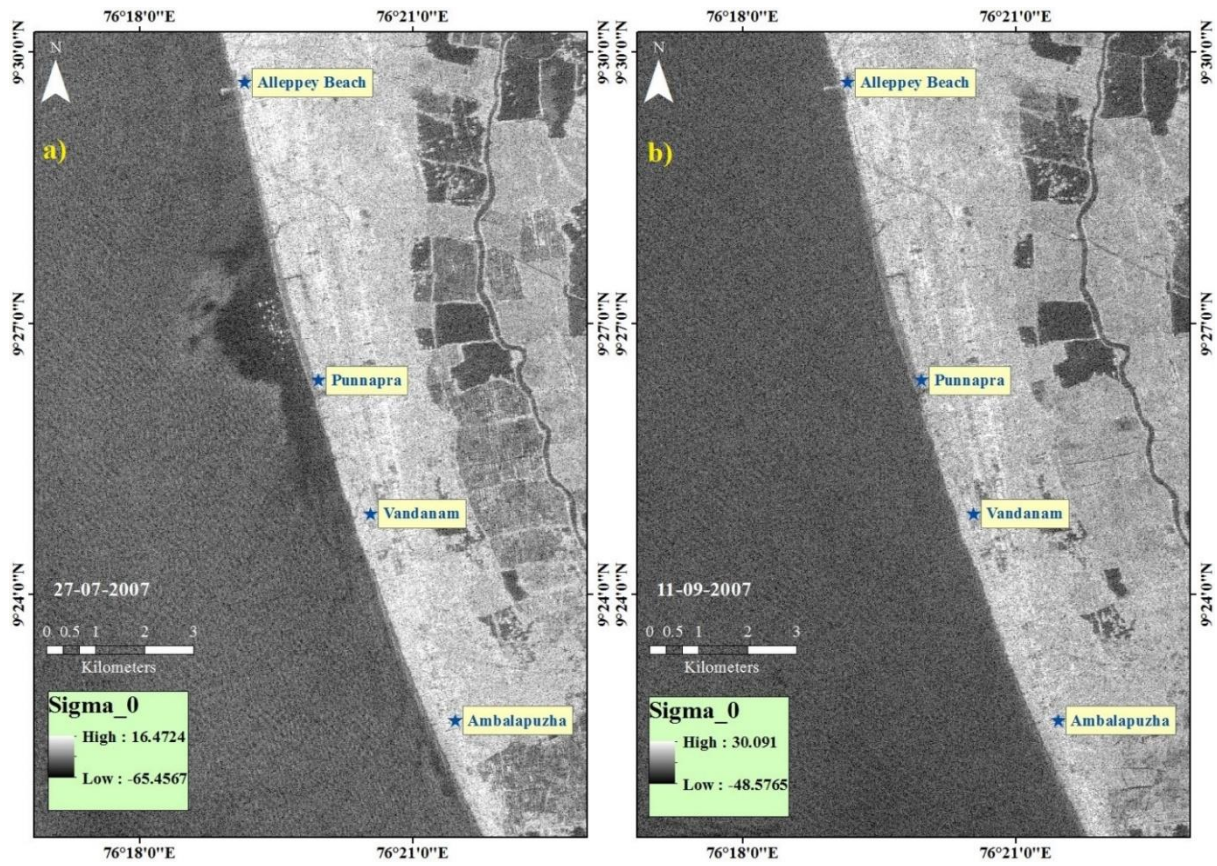


Fig. 3 Backscatter co-efficient image of ALOS on (a) 27-07-2007 (during the mud bank) and (b) 11-09-2007 (after the dissipation of the mud bank)

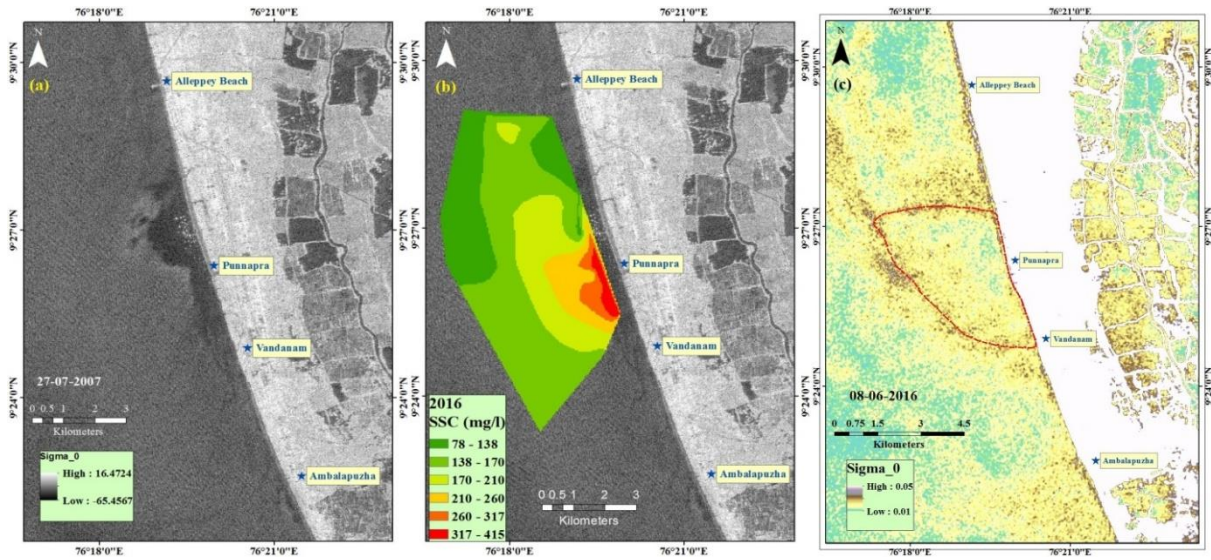


Fig. 4 Mud bank periphery identified from (a) 2007 ALOS PALSAR derived Sigma_0 values, (b) 2016 mud bank derived from in-situ observations and (c) Sentinel-1 derived Sigma_0 values and the red outline depicts the manually delineated signals for the wave break regions.

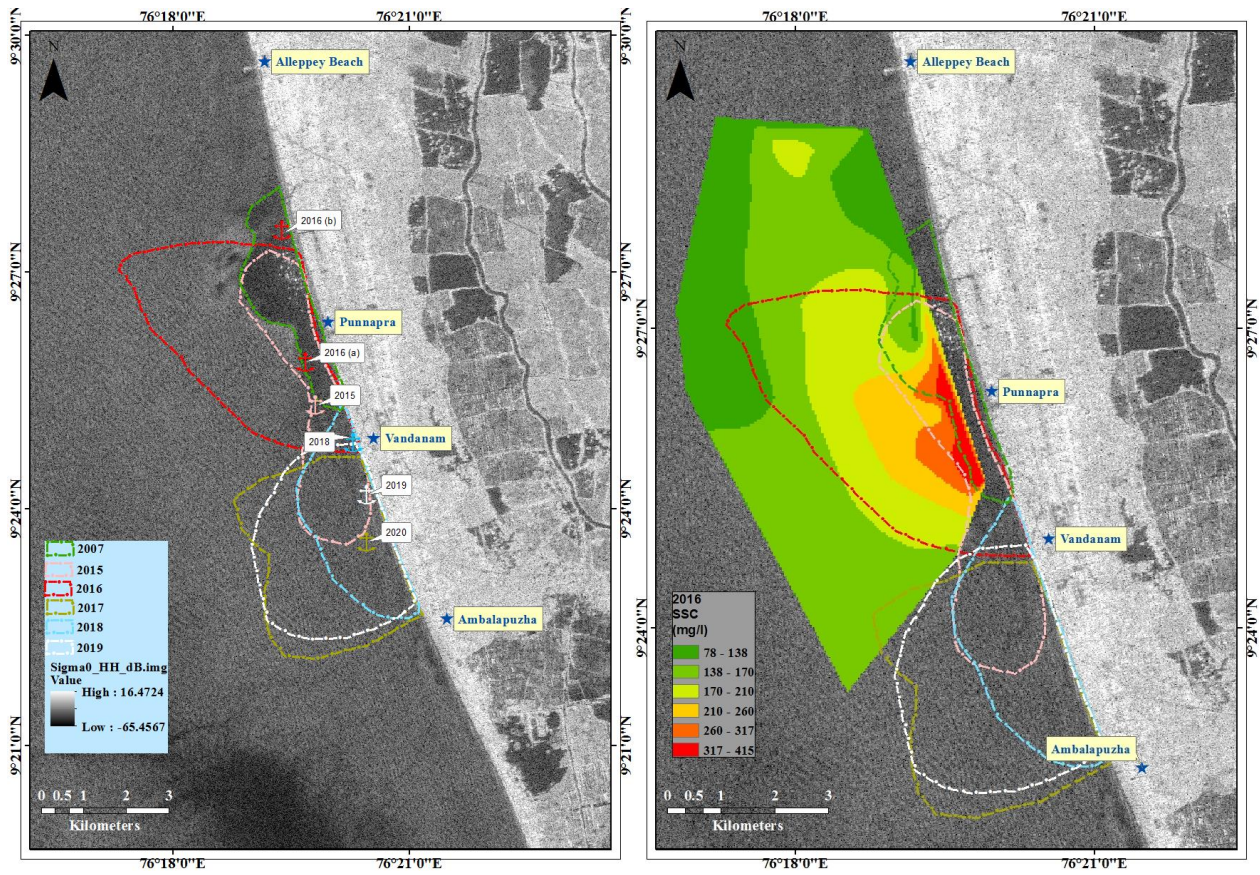


Fig. 5 Inter-annual geospatial variations of the mud bank for the years 2007, 2015, 2016, 2017, 2018 & 2019. Anchor symbol represents the boat landing sites during the mud bank in the mentioned years.

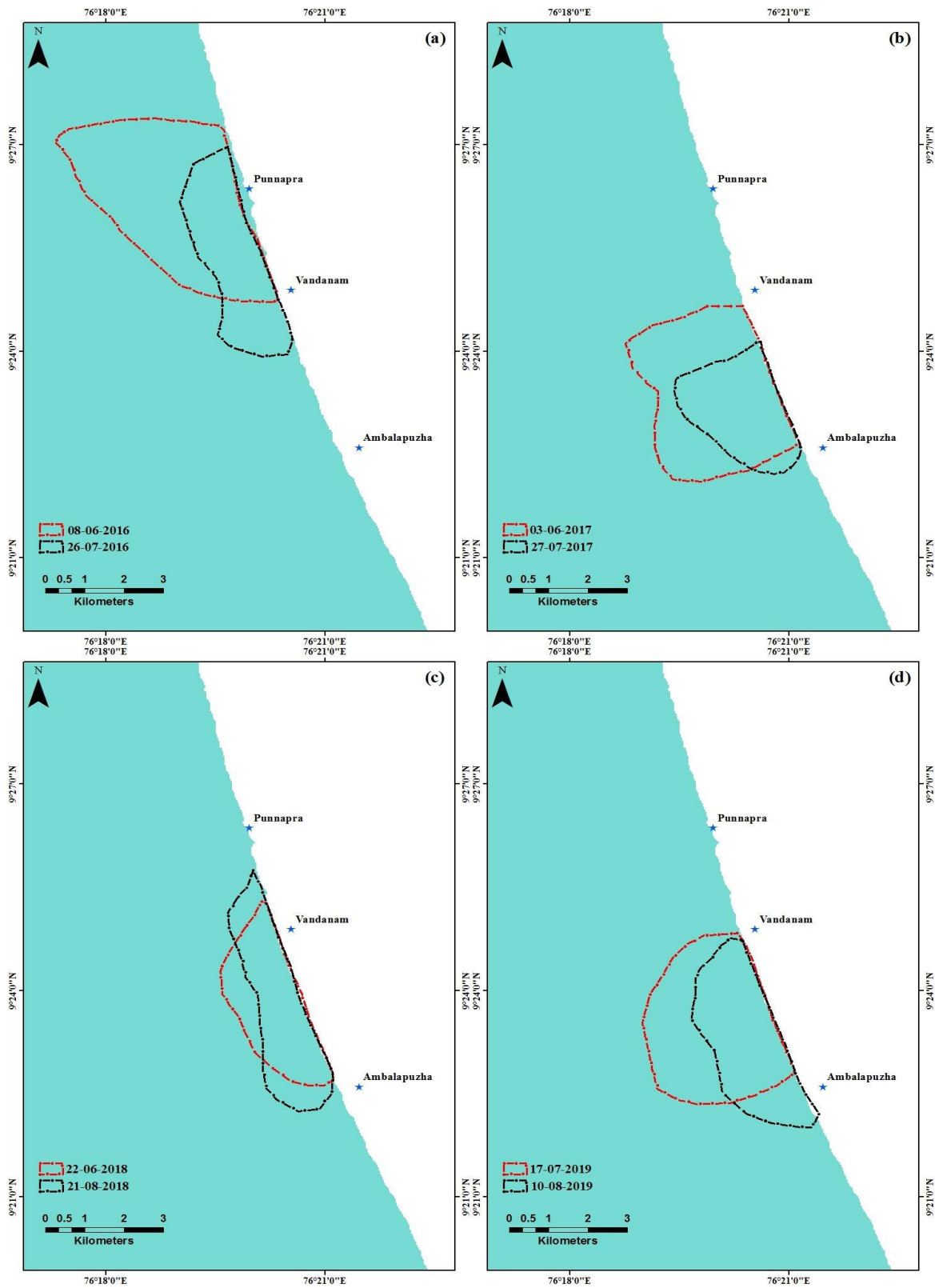


Fig. 6 Intra-annual variations of mud bank(a) 2016, (b) 2017, (c) 2018 and (d) 2019. The periphery limits show geospatial variations of mud bank within the respective years.

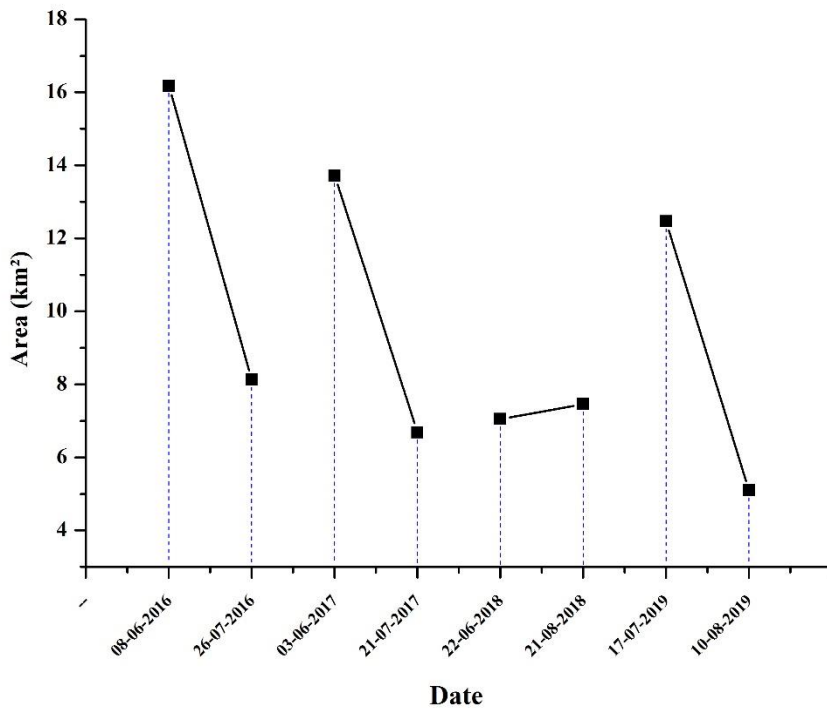


Fig. 7 Changes in the area (sq. km) of mud bank (2016-2019)

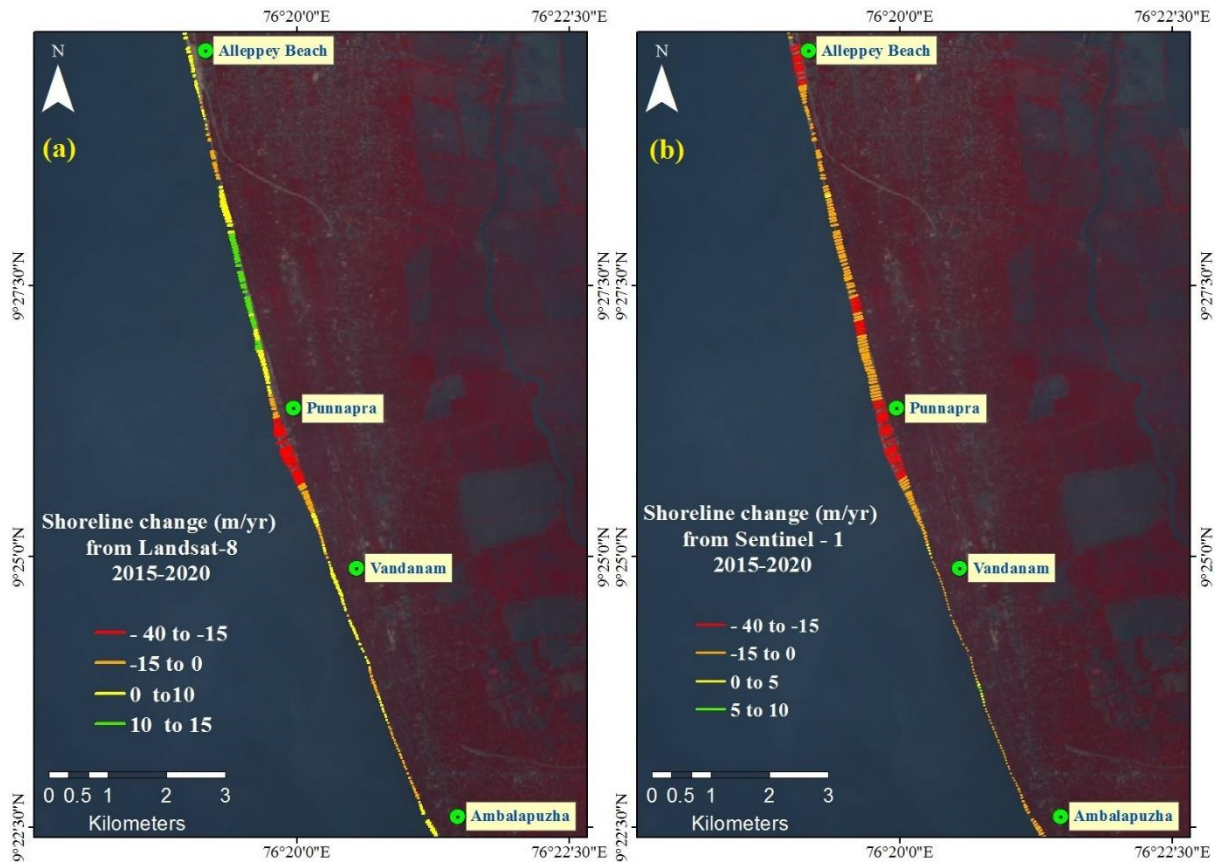


Fig. 8 Satellite-derived shoreline changes in EPR (m/yr) placed above the False Colour Composite (FCC) image Landsat-8 in Non-monsoon (Fig 8a) period and Sentinel-1- in Monsoon (Fig 8b) period. The maximum erosion is represented in red and accretion in the green line, respectively

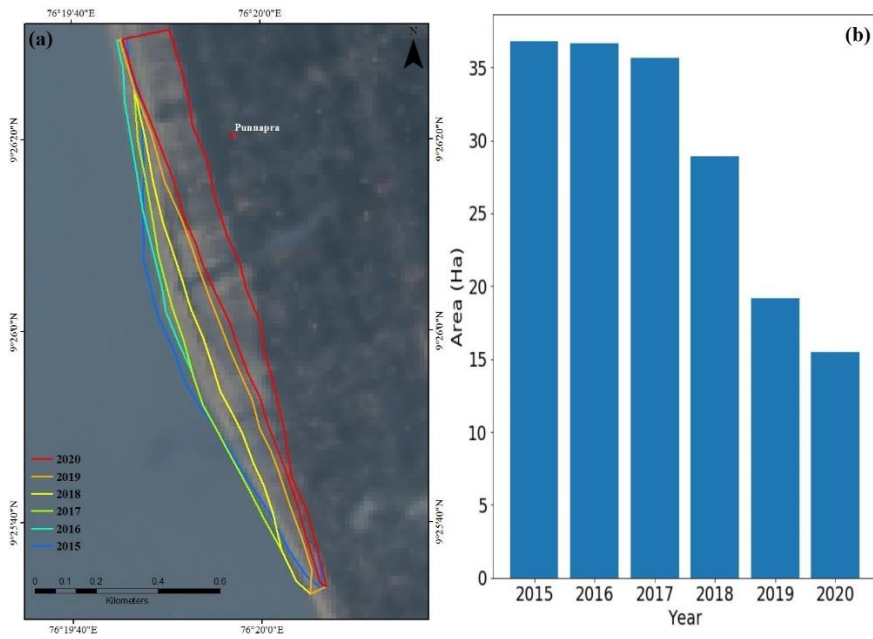


Fig. 9 (a) Beach width changes of Punnapra from 2015- 2020 and their corresponding area in hectares (b) indicating the reduction in the area by nearly 50% over 5 years

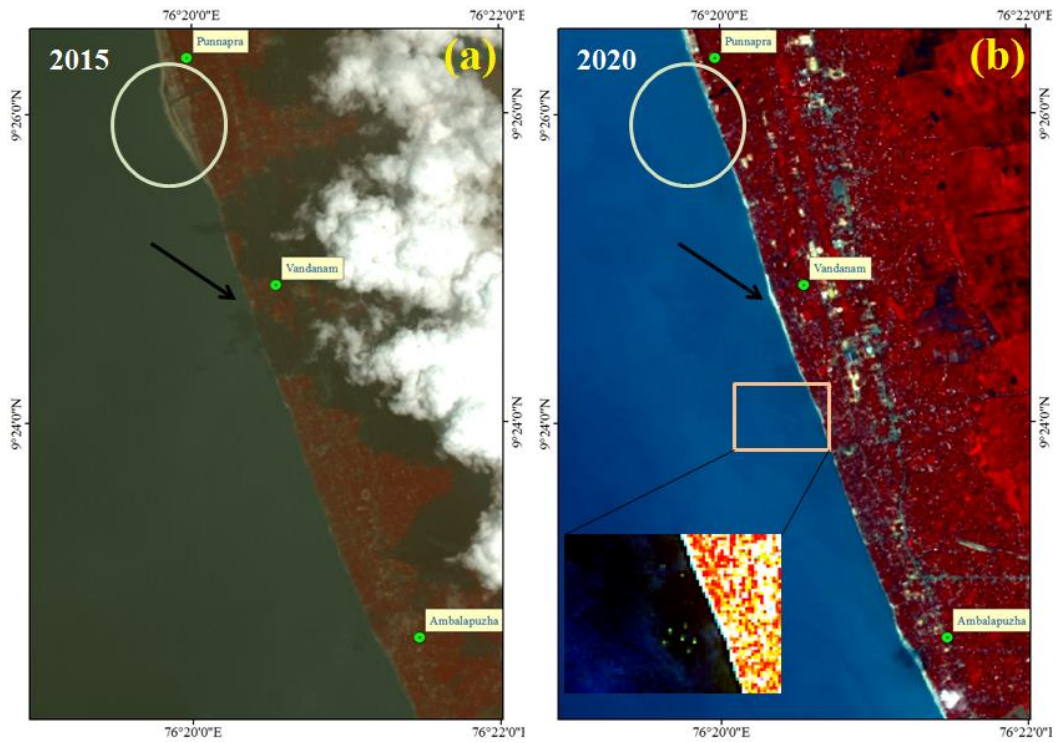


Fig. 10 Impact in the coastline due to the shift in the mud bank (a) Protruded Punnapra beach in 2015 shown in the circle where mud bank was forming regularly and a narrow coast in southern parts (black arrow) & (b) Erosion of Punnapra beach after the migration of the mud bank shown encircled and the accretion along Vandanam coast (black arrow region) with boats anchored(inside figure) resembling the mud bank existence. The figure (b) was enhanced to discrete range adjustment (DRA) to identify the boats.

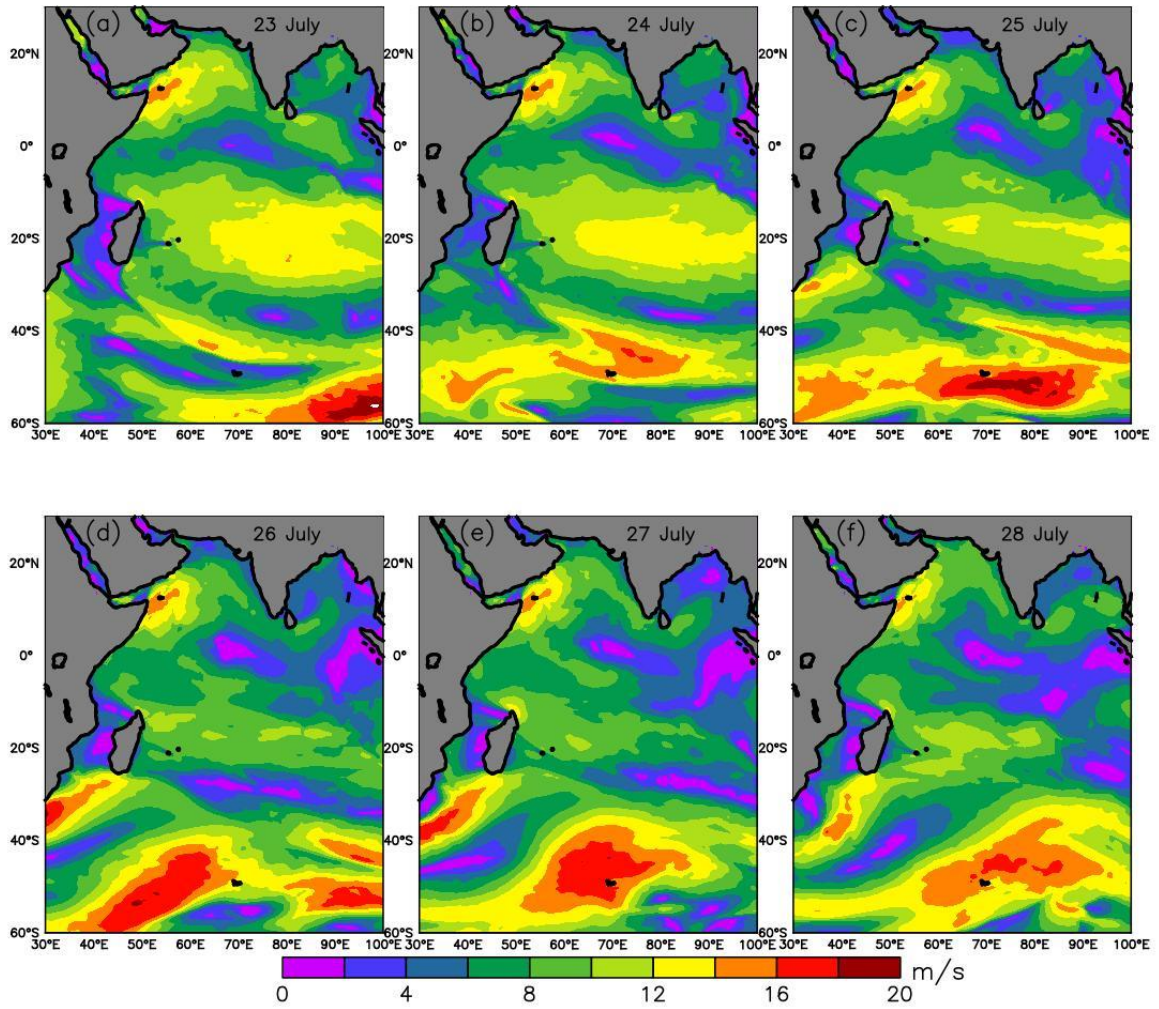


Fig. 11 Spatial pattern of wind speed from 23 - 28 July 2016

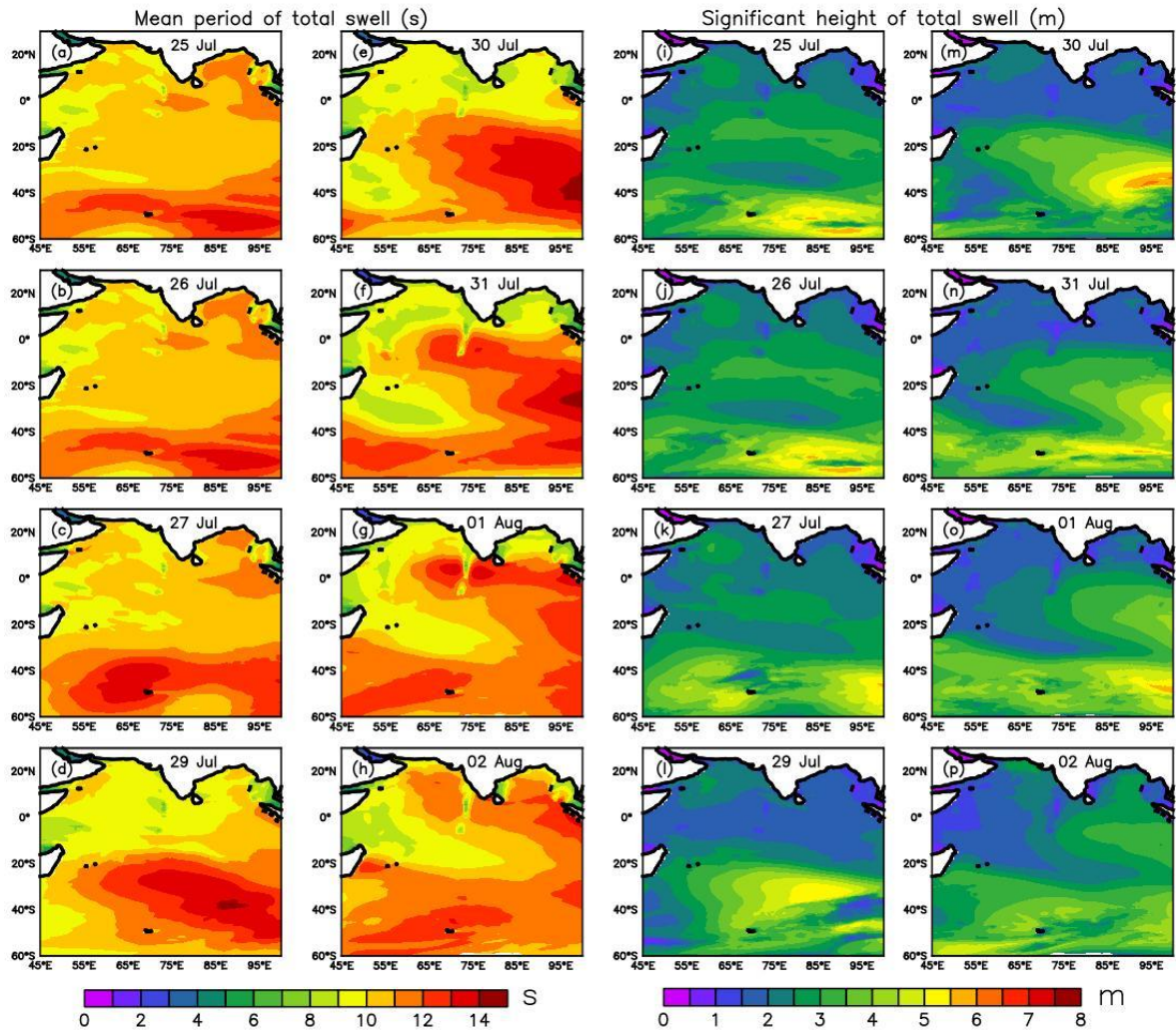


Fig. 12 Spatial pattern of Mean period of total swell (a-h) and Significant wave height of total swell (i-p) from 25 July 2016 to 02 August 2016.

Significant height of total swell (m)

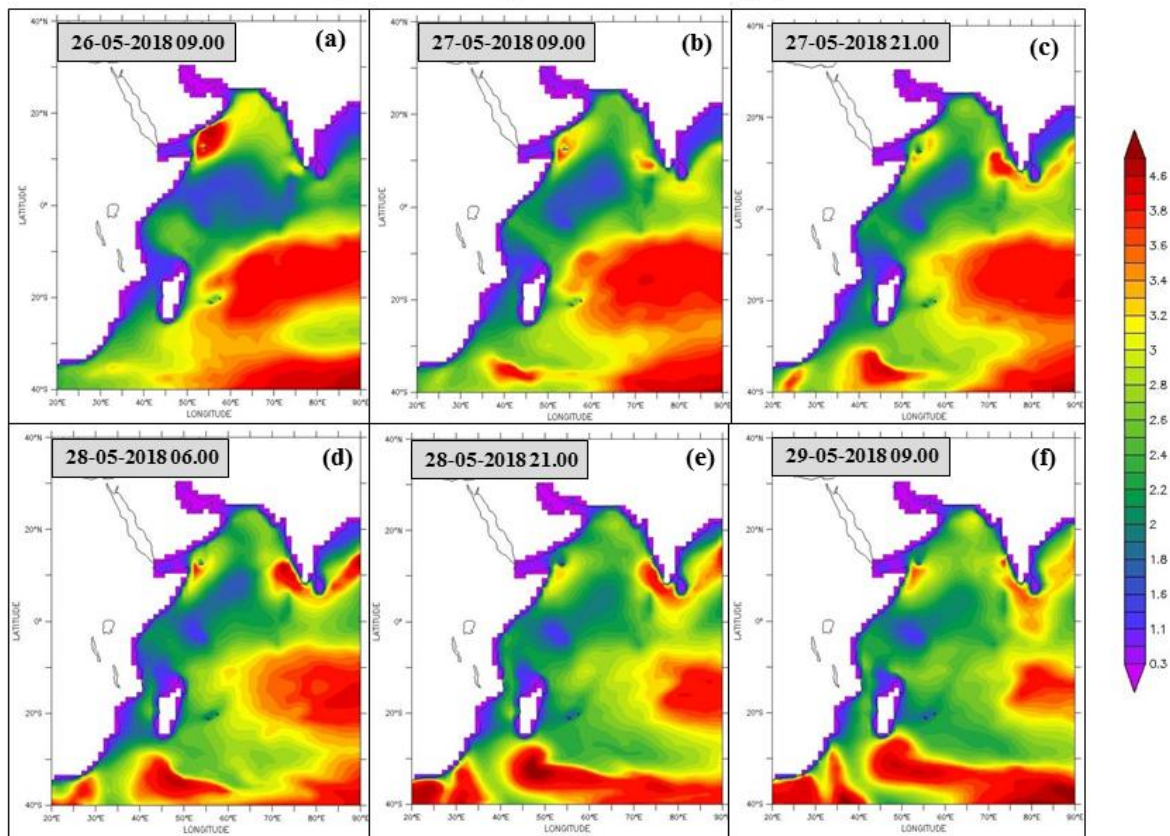


Fig. 13 Spatial pattern of significant wave height (m) for the swell event from 26-05-2018 to 29-05-2018 (a-f) before the onset of 2018 monsoon (Source: <http://apdrc.soest.hawaii.edu>)