

## **Suspended matter and fluid mud off Alleppey, southwest coast of India**

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### **ABSTRACT**

Time series measurements on suspended particulate matter (SPM) were made at one non-mud bank (M1) and two mud bank stations (M2 and M3) off Alleppey, south west coast of India. The mean SPM was low in surface (6.2 mg/l) and mid-depth (3.7 mg/l) waters and higher in bottom-depth waters (24.6 mg/l) of these stations, during both pre-monsoon and monsoon seasons. Near bed suspended sediment results indicated low SPM during July (0.042 g/l) and September (0.018 g/l) at M1, but very high SPM at M2 (9.2 g/l) and M3 (6.2 g/l) during July that decreased (M2: 0.033 g/l; M3: 0.1 g/l) again in September. Observations based on LISST-25X indicated that optical transmission (OT) was high (80-100%) in surface and mid-depth waters but decreased with increasing depth. Near bed waters at M2 and M3 stations showed ~1 m thick fluid layer with 0% OT and with high particle volume concentrations (150-200  $\mu$ l/l) during monsoon. Bottom sediments were clayey silts. Sediments of <63  $\mu$ m fraction were skewed towards finer size at M1 but to coarser size at M2 and M3 stations during monsoon. The water content of the sediment decreased and wet bulk density increased at M2 and M3 stations, while it was the opposite at M1 station during the monsoon. Our results indicated the presence of fluid mud close to the bottom at M2 and M3 stations. As the wave height decreased from ~3 m in May to 0.76 m in July, the dissipated wave energy probably liquefied, eroded and re-suspended the bottom sediment to form fluid mud. Upwelling currents may have been involved in the up keep and transportation of fluid mud. The suspended mud resettled at the bottom soon after the monsoon event.

**Keywords:** suspended matter, fluid mud, re-suspension, mud banks, southwest coast of India

## 1. Introduction

The concentrations of suspended particulate matter (SPM) in coastal regions are controlled by the estuarine supply of sediment, erosion of bottom sediments by tides, waves and high intensity wind events, depositional and advective processes, biological processes and human activities (Schoelhamer et al., 2002; Chang et al., 2007; Fettweis et al., 2010). The estuarine turbidity maximum (ETM) plays an important role in the variability of SPM and its transportation to the continental shelves. Near bed highly concentrated mud suspensions (HCMS) or fluid mud (Wells et al., 1977) have been reported on muddy coasts, along 1500 km stretch between the mouth of Amazon and the Orinoco Rivers in northeast South America (Kineke et al., 1996; Anthony et al., 2010), Mississippi coast (McBride et al., 2007), the Gulf of Papua (Wolanski and Alongi, 1995; Walsh and Nittrouer, 2004), the East China Sea (Liu et al., 2006; Wei et al., 2007) and the Mekong delta coast (Tamura et al., 2010). In these examples, rivers supplied huge amounts of mud in the form of suspended sediment and the settlement of this material during estuarine circulation or fluidization of cohesive sediment beds by waves resulted in the formation of fluid mud (Maa and Mehta, 1987; Li and Mehta, 2000). The fluid mud results in very high sediment fluxes that are easily facilitated by waves and currents leading to the development of muddy coasts, mud banks or submarine deltas (Wells et al., 1977; 1979). On the other hand, rivers such as Huanghe River, China and Jaba River, Indonesia debouch high SPM mud slurries to the coast and rapid deposition of which results in the formation of pro-delta mud close to their mouth (Wright, 1989).

The mud banks of Kerala, SW coast of India are defined as 'deposition and prevalence of dense mud suspensions in the littoral waters' (Bristow, 1938) or 'patches of calm, turbid water with heavy load of suspended mud, occurring at depths <10 m close to the shore'(Gopinathan and Qasim, 1974; Kurup and Varadachari, 1975; Mallik et al., 1988; Mathew and Baba, 1995; Mathew et al., 1995). Mud banks of Kerala coast are unique in several respects: (a) they occur only during the southwest monsoon, where there are no major rivers,(b) presence of two types of mud banks: the non-persistent type mudbanks that are characterised by non-periodicity and inconsistency and their recurrence in the same area, which sometimes takes place after several years (Jayaprakash and Dinesh, 2009). Therefore, they are unpredictable in space and time and are formed by aggregation of coastal mud (e.g. Parappanangadi-Tanur mud banks) and settling of sediments and organic debris discharged from minor rivers (e.g. Chellanam–Manassery mud bank) or accumulation of mud resulting from dredging operations (e.g. Vypeen mud bank; Anonymous, 1984). The persistent type mud banks recur year after year in the same area only during the southwest monsoon (Gopinathan and Qasim, 1974) and(c) the mud banks of Kerala are indeed not banks with regular-relief forming geomorphic features, but could be more accurately described as high mud suspensions, similar to those of fluid mud (Mallik et al., 1988). The fluid mud thus formed, settle to the bottom immediately after the monsoon and therefore no fluid mud / mud banks are formed during non-monsoon period.

Mud banks are of great socio-economic significance and scientific interest. High biological productivity in this region leads to rich fishery grounds (Damodaran, 1973; Gopinathan and Qasim, 1974). The reduced wave energy in the mud banks minimises coastal erosion in the shore adjoining mud banks (Kurup, 1977; Nair, 1985). Nair (1976) described mud banks as a potential modern analogue of the ancient hydrocarbon generation environment, whereas, Narayana et al. (2001 and 2008) reported them as palimpsest, marshy and lagoonal deposits.

Several investigators studied oceanographic and sedimentological factors involved in the formation of mud banks off Kerala. The role of wave activity (Shenoi et al., 1986; Fass, 1995; Mathew et al., 1995; Tatavarti et al., 1999, Tatavarti and Narayana, 2006) and converging littoral currents (Kurup and Varadachari, 1975) in fluidizing fine sediments of the sea floor were suggested for the formation of mud banks. Several others related the benthic fluid mud layer to the textural characteristics of the bottom sediments and suggested the re-suspension of bottom sediment by waves caused fluid mud (Ramachandran and Mallik, 1985; Ramachandran and Samsuddin, 1991; Mallik et al., 1988; Mathew et al., 1995; Narayana et al., 2008). Balachandran (2004) reported a subterranean flow of clay/mud from an activated trending fault that originated from a lake which subsequently transformed into flowing fluids in the mud bank region. Philips et al. (2013) stressed the role of meteorological factors and suggested that the increased alongshore wind stress and coastal upwelling caused the formation of mud banks. The mechanisms offered are still debatable and a consensus has not yet been evolved on the processes of formation of mud banks.

Systematic time series measurements of suspended particulate matter (SPM) were lacking in and around mud banks. The importance of this study is that we report time series data on SPM concentrations and, textural and geotechnical properties of surface sediments, both in the mud bank and non-mud bank regions during pre-monsoon and monsoon months. Further, the sensor, LISST-25X (Laser In-Situ Scattering and Transmissometer) was used for the first time to measure optical transmission and understand suspended sediment characteristics. Wave and current data collected during sampling period were used to explain the role of hydrodynamics in the mud bank evolution. The aim of this paper is to investigate seasonal variations in the distribution of SPM, bottom sediment characteristics and hydrodynamic conditions off Alleppey, southwest coast of India and identify the mechanisms involved in the formation of fluid mud.

## **2. Study area**

The southwest coast of India is characterized by the occurrence of persistent and non-persistent mud banks along the coast (Fig. 1). Near-shore bathymetry of the area increases steeply seaward from 4 m depth contour (Narayana et al., 2008). The mean wind direction over the Indian Ocean is from the southwest during the southwest monsoon (June-September). The monsoonal winds set in mid-May, reach maximum speed in July and August, and abate through September and October

(Sharma, 1978). Wind direction changes during the active and weak phases of the monsoon and is north-westerly to westerly during the active monsoon phase (Babu and Hamza, 2007). The wind speed reaches upto 11 m/s along this coast during the monsoon and the coastal area experiences high wave activity. The waves arriving at this coast during monsoon have higher wave heights (up to  $\approx 2.5$  m) and shorter periods (Kurian, 2002). Strong monsoonal winds cause heavy rainfall ( $\approx 300$  cm/y) and intense coastal upwelling. Upwelling results in divergence as the cold subsurface water surfaces (Banse, 1959; Johannessen et al., 1981; Rao et al., 2004; Philip et al., 2013). Tidal range is  $\approx 1$  m (Tatavarti et al., 1999) and tides in the region are semi-diurnal and of mixed type. The mean alongshore currents on the west coast of India are southward during March-May (Shenoi and Antony, 1991). The alongshore components of large-scale circulation indicate a southerly component during March – September and a northerly component during November – January (Shenoi and Antony, 1991; Shankar, 2000).

The coastal geology (Fig. 1) comprises of Tertiary and Quaternary sedimentary formations, which unconformably overlie the Precambrian gneissic rocks (GSI, 1979). One of the important landform features is the straight coastline with narrow barrier island separated by sea. Vembanad lake which receives freshwater from six rivers is located just north of Alleppey (Fig. 1). Further, an activated trending fault extending to the coastal sedimentary basin appears to be important, because mud banks occur close to this structural feature (Mallik et al., 1988; Padmalal et al., 2014).

### **3. Materials and methods**

The CSIR-National Institute of Oceanography (CSIR-NIO) in collaboration with Central Marine Fisheries Research Institute (CMFRI), Cochin conducted a multi-disciplinary oceanographic field program under the project 'Alleppey Mudbank Process Studies (AMPS)' during April-September 2014. Three stations (M1, M2 and M3; Fig. 1) 3 to 3.5 km away from the coast were selected for systematic time series data collection. Station M1 is located in the non-mud bank region. Station M2 is in the mud bank formation region off Alleppey at  $\sim 7.70$  km south of M1. The water depth is  $\sim 6$  m at both stations. Station M3 is located 1.73 km seaward of M2 and at a water depth of  $\sim 12$  m. Field trips were conducted at regular intervals and 3 types of data were obtained: viz. (a) discrete water column data, (b) sensor based water column data and (c) bottom sediments data.

(a) Water samples were collected from surface, mid-depth and bottom-depths, using Niskin samplers to compare SPM variations at different water depths at each station and between shallow and deep stations. Mid- and bottom depths were decided based on bathymetric charts for these stations. Mid-depth water samples were collected from 3 m at M1 and M2 stations and 6 m at M3 station. Similarly, the bottom-depth water samples were collected at 1 m above the bottom. Water samples were filtered for SPM using  $0.45 \mu\text{m}$  polycarbonate membrane filter. SPM retained on the filter was dried and weighed. SPM concentrations are expressed as mg/l (Table 1).

(b) The sensor, Laser In-situ Scattering and Transmissometer (LISST-25X@Sequoia) was used for measuring in situ particle volume concentration (PVC), sauter mean diameter (SMD) of particles and optical transmission (OT) in the waters. It is basically a diffractometer (Agrawal and Pottsmith, 2000) developed by Sequoia Scientific Inc. The LISST-25X obtains the mean size and total concentration using a different approach. By weighting the scattering in a particular way, the total area concentration and total volume concentration can be obtained. The ratio of volume and area gives the mean size (Sequoia Scientific Inc., 2008). The instrument was calibrated in the laboratory using standard grain size material provided by Sequoia and background measurements were subsequently made using deionised water to ensure transmission of the laser. This instrument was deployed onboard a boat in profile mode with a sampling interval of 3s. This instrument gives total PVC in  $\mu\text{l/l}$ , SMD in  $\mu\text{m}$ , OT in percentage and operating depth in meters. Some representative water samples were filtered using 0.45  $\mu\text{m}$  filter paper and SPM concentrations were measured. The SPM concentrations plotted against particle volume concentration indicate that both are directly correlated ( $r=0.72$ ;  $n=53$ ;  $p=0.0001$ ). Optimum range for the laser to transmit in order to get correct grain size and volume concentration is reported to be 30-98% (Sequoia Scientific Inc., 2008). Data were first filtered with 30-98% transmission and data with  $<30\%$  and  $>98\%$  were removed. Optical Transmission (OT) depends on particle concentrations in the water. If SPM concentrations exceed 1000 mg/l OT percentage becomes zero due to the upper limit of the used transmissometer. The LISST-25X was operated 11 times and data were collected from 22 April to 4 July and no data was collected during the remaining monsoon months. The time difference for operation of LISST-25X including boat travel time was  $\sim 2$  h between M1 and M2 stations and  $\sim 1$  h between M2 and M3 stations. The depth sensor in LISST-25X recorded high resolution depths at M1, M2 and M3 stations (see Fig. 3) compared to those in the bathymetric charts and also exhibited zero percent optical transmission in waters close to the bottom, indicating the presence of a turbid water layer. Therefore we have also collected near bed water sample of 2.5 l at depths between 5 m and 6 m at M1 and M2 stations, and between 11 m and 12 m at M3 station, during July and September. SPM was filtered, dried and weighted. SPM concentrations are shown in Table 1.

(c) Bottom sediments were collected at 3 stations using a Van-Veen grab. After opening a flap of the grab,  $\sim 1$  cm thick top layer of sediment was collected into a plastic bag. The sand, silt and clay contents of the sediment were determined from 18 representative samples (3 stations; monthly sampling for 6 months), following Folk (1974). The  $<63 \mu\text{m}$  fraction was also used for measuring size fractions of clay ( $<4 \mu\text{m}$ ) and silt ( $<63->4 \mu\text{m}$ ), using Malvern Laser Particle Size analyzer (Master Sizer 2000). Geotechnical properties of sediments were also measured on 18 representative samples. The water content was determined by the weight loss method. A representative sub sample of the wet sediment was weighted accurately first and then dried overnight in an oven at  $100^{\circ}\text{C}$ . The dried sediment was reweighted at room temperature. The

difference in the weight of wet and dry sediment was taken as water content of the sediment and expressed in percentage. A unit volume ( $5 \text{ cm}^3$ ) of plastic container was used in the field. Wet bulk density was calculated from the weight of the wet sediment, divided by the volume of the container and denoted as  $\text{g/cm}^3$ . Plasticity index is defined as the difference between the plastic limit (PL) and liquid limit (LL) of the sediment (Kwon et al., 2011); these limits are used to determine the minimum amount of water content at which the sediment behaves as plastic and liquid material, respectively. These limits were measured using Casagrande apparatus and by following the procedure reported in ASTM-D4318 (1994).

The location and period of deployment of wave rider buoys and current meters was determined based on previous studies (Mathew, 1992; Mathew and Baba, 1995a; Narayana et al., 2008; Elgar and Raubenheimer, 2008). Two wave rider buoys (WRB), one at 15 m (location B1) and another at 7 m water depth (location B2 in Fig. 1) were deployed during 21 May-30 July and 26 June – 30 July 2014, respectively. The data were collected for 10 minutes duration with 30 minutes intervals. The wave rider buoy has an accuracy of 3% for wave height and within  $0.5^\circ$ – $2^\circ$  for wave direction. A recording current meter (RCM) was also deployed at 7 m depth to collect current data for every 10 minutes interval during 26 June - 2 August 2014. The wave data obtained from the wave rider buoys were analysed, and compared with ECMWF Re-analysis Interim significant wave heights (ERA-I  $H_s$ ) to understand the features of mud bank attenuated waves. The present observations cover both pre-mud bank and mud bank scenarios.

## **4. Results**

### **4.1 SPM concentrations**

Table 1 lists complete data on SPM concentrations at M1, M2 and M3 stations during April-September 2014. Fig. 2 shows its mean monthly and seasonal variations. During the pre-monsoon, the mean SPM at surface and mid-depth was low at all three stations with comparable levels at M1 and M2. The mean SPM in bottom-depth was at least 4-7 times higher than the surface water at M1 and M2 stations while it was 15 times higher at M3 station. The mean SPM (values shown in Fig. 2) increased marginally from pre-monsoon to monsoon at surface and mid-depths of all the stations. However, the mean SPM decreased from pre-monsoon and monsoon at bottom depths of M1 and M2 stations with similar value at M3 station. SPM concentrations of the near bottom waters collected at M1, M2 and M3 stations in July and September were 42.4 mg/l, 9179 mg/l and 6187 mg/l and, 18.7 mg/l and 32.9 mg/l and 100.9 mg/l, respectively (Table 1).

### **4.2 Optical transmission, particle volume concentration and sauter mean diameter**

Fig. 3 shows variations in optical transmission (OT) with depth at M1, M2 and M3 stations. Optical transmission was 90-95% from surface to 5 m at M1 station and, 95-100% from surface to ~10 m at M3 station during both pre-monsoon and monsoon seasons. At M2 station, the patches of low OT

(70-80%) occurred even in surface waters. The percentage of OT decreased with increasing depth at all the stations. OT decreased from <40% to 10% at depth close to 6 m at M1, <20% to 0% at depth close to 6 m at M2 station and between 11 m and 12 m at M3 station during June and July. The depth-wise distribution of particle volume concentrations (PVC), showed largely low values (<25  $\mu\text{l/l}$ ) at all the stations in April and May (Fig. 4A). Patches of high PVC occurred close to the sea bed at M1 and M2 stations in May. Nearly uniform distribution of relatively high PVC (125-150  $\mu\text{l/l}$ ) occurred in the water column below 5 m at M2 during May end – July. At station M3 the PVC was more uniform with ~50  $\mu\text{l/l}$  at depths <10 m during April-May and increased with increasing depth. A patch of high PVC (200-250  $\mu\text{l/l}$ ) was present close to the sea bed during May/June. The sautermean diameter (SMD) of particles (Fig. 4B) was low (25-50  $\mu\text{m}$ ) throughout the water column at all the depths during April – May, but patches of high SMD occurred at different depths during June-July at M1 and M2 stations. Relatively high SMD particles were concentrated at mid-depths at M3 station during June and July (Fig. 4B). The low SMD (<25  $\mu\text{m}$ ) particles were more uniformly distributed at bottom waters at all the stations from April to July.

#### **4.3 Texture and geotechnical properties of surface sediments**

The percentage of sand, silt and clay, <63  $\mu\text{m}$  size particles distribution and mean grain size of the <63  $\mu\text{m}$  fraction of surface sediments at M1, M2 and M3 stations are depicted in Fig. 5A-C. Surface sediments were clayey silts with ~70% silt at all the stations. The percentage of sand, however, increased at M2 during monsoon months (Fig. 5A). The <63  $\mu\text{m}$  particle size distribution skewed towards finer size at M1 station but towards coarser size at M2 and M3 stations during May to July (Fig. 5B). This trend was distinct in the distribution of mean particle size (Fig. 5C), which decreased at M1 and increased at M2 and M3 stations. The water content of the sediment (Fig. 6A) was low (70%) at M1 in May but increased gradually to 200% towards June and July and then maintained similar values. The sediment water content was 250% at M2 in May, but decreased gradually to 50% in July and then remained at ~150% in August and September. The sediment water content was ~200-250% at M3 during May–June, but varied marginally between 170 and 250% during July-August. Similarly, the wet bulk density decreased gradually at M1 from May to June and then maintained constant during July-September. It, however, increased gradually at M2 station from May to July and then decreased. The bulk density at M3 showed marginal increase from May to August and decreased subsequently (Fig. 6B). Sediment water content showed an inverse relationship with wet bulk density. The correlation between sediment water content and plasticity index was strong at M1 but decreased gradually at M2 and M3 stations (Fig. 6C).

#### **4.4 Wave and current characteristics**

ERA-I data were model validated wave data downloaded from ECMWF database. The model from which the ERA-I data have been derived does not have the mud physics. Therefore, it represents

no-mudbank condition. The deviation of measured wave data from ERA-I indicates the change in wave parameters due to the formation of mudbank. When the measured data were compared with the ERA, it was found that up to 12<sup>th</sup> June the ERA-I data matched very well with the measured data, indicating no-mudbank, but after that there was a steep reduction of  $H_s$  in the measured data, indicating the formation of a mudbank near 15 m (B1 location).

At B1, the maximum significant wave height observed was 3.16m in May and minimum 0.76 m in July 2014 with the wave period ranging from 4s to 8s and predominant wave direction from 200° to 280°. Similarly, at B2, the maximum and minimum  $H_s$  recorded were 1.56m and 0.68m, respectively, with wave period ranging from 4s to 8s and predominant direction from 200° to 250°. A steep reduction in  $H_s$  was observed from 12<sup>th</sup> June to 12<sup>th</sup> July 2014 after the formation of the mudbank in the vicinity of B1 (Fig. 7). After 12<sup>th</sup> July, there was attenuation in wave heights at B2, whereas the waves were nearly of same heights like  $H_s$  of ERA-I at B1, indicating a shift of the mudbank from B1 to B2. Though the ranges of wave periods and wave directions were the same (before and after the mudbank formation), there were minor changes in the wave parameters between the two depths, which were definitely due to the mudbank.

The data extracted from current meter deployed at 7 m water depth indicated a maximum current speed of 0.80 m/s in the southeasterly direction and 0.4 m/s in the westerly direction (Fig. 8). The data was further resolved into zonal and meridional components. It was observed that the zonal components remained weak within the range of -0.2 - 0.2 m/s, whereas the southward components of meridional currents were stronger than the northward components.

## **5. Discussion**

### **5.1 Near-bed fluid mud off Alleppey**

Wells et al. (1977, 1979) used the term 'fluid mud' for dense near bed suspensions with SPM concentrations >10 g/l. The near bed water sampling in the study area revealed very high SPM at M2 (9.2 g/l) and M3 (6.2 g/l) stations in July (Table 1) suggesting the presence of a fluid mud layer. A distinct layer with zero percent optical transmission (OT) close to the bottom at ~6 m at M2 and ~12 m at M3 station in June and July (Fig. 3) suggests that the SPM concentration in this layer was >1000 mg/l (the upper limit of SPM that the instrument can measure), confirming the presence of fluid mud. This fluid mud layer extends vertically upto 1 m from the sea bed from 22 May till July at M2 and in July at M3 station (Table 1; Fig. 2). Mathew and Baba (1995) reported 2 m thick fluid mud layer with SPM concentrations upto 17.4 g/l. Narayana et al. (2008) reported SPM concentrations >5 g/l in fluid mud off Alleppey. The mechanisms for the formation of fluid mud are discussed below.



## 5.2 Is suspended particulate matter a cause for the formation of fluid mud?

Several investigators reported that the major rivers, such as Amazon River supply abundant suspended sediment, which gets flocculated and form fluid mud near sea bed (Wells et al., 1977; Kineke et al., 1996; Anthony et al., 2010). Major rivers are absent on the southwest coast of India. But strong southwest monsoon winds bring high rainfall to the hinterland and as a consequence abundant suspended matter is expected in the coastal waters. The SPM concentrations at surface and mid-depth waters at M1 (1.6-9.2 mg/l), M2 (1.2-21.3 mg/l) and M3 (0.6-14.1 mg/l) stations were, however, very low (Table 1) and mean SPM values do not change significantly at surface and mid-depth waters from pre-monsoon to monsoon (Fig. 2). This implies that the monsoon-induced suspended sediment has little effect on SPM at M1, M2 and M3 locations, and fluid mud may not have formed by the flocculation of suspended sediment on the southwest coast of India. The very low SPM concentrations at M1, M2 and M3 stations further indicate that the river discharge in the area is directed into backwater lagoons/lakes which trap most of the suspended sediment. Mathew and Baba (1995) reported high SPM in surface water (600-900 mg/l) and suggested that 'quiet and turbid waters' are characteristics of mud banks. In contrast, our measured low SPM at surface and mid-depth waters (mean SPM: <10 mg/l; Table 1, Fig. 2) both in pre-monsoon and monsoon months of the year 2014 suggests that the waters are not turbid at these stations like earlier years and hint at changing characteristics of the surface water from time to time during mud bank formation. Very high optical transmission (75-100%) also attests clear waters at surface and mid-depth waters of all the stations (Fig. 3).

The mean SPM at bottom-depth of all the stations was higher than at surface and mid-depth waters (Fig. 2). Very high SPM at bottom waters has been reported in the near-shore zone of the Belgian-Dutch coast (Fettweis et al., 2010) and San Francisco Bay (Schoellhamer, 2002) and suggested that relatively high SPM concentrations are common at bottom depths in the coastal waters, as they are influenced by mutual interaction of cohesive and non-cohesive sediments during erosion and advection processes at shallow depths.

## 5.3 Evidence of re-suspension from bottom sediment characteristics

Fig. 5A shows that silts are the dominant component in the bottom sediment. The sediments of <63  $\mu\text{m}$  fractions are skewed towards coarser particle size that increased from fine silts during pre-monsoon to medium silts during monsoon at M2 and M3 stations (Fig. 5B). The sand content of the sediment also increased at M2 station during the monsoon. These changes point out that the clays and very fine silts have been re-suspended from bottom sediments and favoured the formation of fluid mud. Further, the gradual decrease in sediment water content (Fig. 6A) and increase in bulk density towards June/July (Fig. 6B) and strong inverse relationship between these two at M2 and M3 stations (Fig. 6C) suggest that the superficial sediment slurry from the sea bed surface might have

been lost to the fluid mud and exposed the relatively dense and partly consolidated subsurface sediment. In other words, the changes in sediment characteristics point out in situ formation of fluid mud and its development that may be due to wave activity on bottom sediment (see below). In contrast to the changes at M2 and M3 stations, the sediments at M1 became gradually finer in size towards June and July (Fig. 5C) with increasing water content and decreasing bulk density (Fig. 6A-B). This implies that finer sediments are accumulating at this station and the impact of wave energy on the bottom sediment may not be sufficient enough to form fluid mud. Plasticity index of the sediment usually increases with increasing fine size of the particles. The strong correlation between the water content and plasticity index of sediment at M1 station ( $r=0.98$ ;  $p<0.0001$ ) may be due to high clay content (Fig. 6C) and moderate correlation between the two at M2 ( $r=0.7$ ;  $p<0.08$ ) and M3 ( $r=0.7$ ;  $p<0.1$ ) stations may be due to decreased clay content of the sediments. The gradual changes in particle size, water content, bulk density and plasticity index of the sediment thus point out to wave activity on bottom sediments caused by the formation of fluid mud.

The relatively high particle volume concentrations (PVC) at bottom waters compared to surface (Fig. 4A) suggest that re-suspension of bottom sediment caused high SPM. Stations M1 and M2 are located at same depth (~6 m), but the former is in the non-mud bank formation region and the latter in the mud bank region. The PVC of bottom water indicates that re-suspension occurs at both the stations, but sufficient wave energy was provided on bottom sediment only at M2 to yield greater resuspension and fluid mud. The uniform high PVC layer at M3 indicates that the impact of wave energy on the bottom sediment must be less than that of M2 because of higher depth. The patches of high PVC at mid-depth waters (Fig. 4A) indicate that the suspended matter was introduced into the waters by different processes (including wave induced bed shear stress, re-suspension and upwelling) at different times and 'pinched off' into the intermediate water column (see Cheriton et al., 2014).

Near uniform distribution of low SMD particles during April/May (Fig. 4B) indicates the prevalence of normal coastal conditions at all the stations. This may be due to the low productivity and nutrients in coastal waters during the pre-monsoon (Feb. - May). Heavy fresh water discharge and high productivity prevail in coastal regions during monsoon. The patches of high SMD particles during monsoon months (June/July) both at surface and mid-depth waters may be due to dynamic hydrographic conditions associated with high productivity, leading to the aggregation and coagulation of particles and their sinking to the bottom. The uniform distribution of very low SMD particles at bottom waters of all the stations during June/July indicates that the re-suspended sediments are predominantly fine-grained. Very low SPM concentrations at near bed during September (Table 1) suggest that the fluid mud formation is indeed a seasonal phenomenon. As soon as the monsoon conditions subside, the wave energy decreases and therefore fluid mud cease to form.

#### **5.4 Influence of wave activity on the formation of fluid mud**

Wind-generated waves remobilise fine sediment from the sea bed to form highly concentrated fluid mud in the Gulf of Papua (Wolanski and Alongi, 1995) and mud deposits on the beaches of Brazil (Calliari et al., 2009; Pereira et al., 2011) and northeastern South America (Wells et al., 1977; Winterwerp et al., 2007; 2012). Wave measurements on the southwest coast of India indicate strong monsoon winds and prevalence of high wave activity (Fig. 7) by May (pre-monsoon) itself and a steep reduction in wave height during fluid mud formation, both at 7 m and 15 m water depths (Fig. 7). For example, a significant wave height of 3.16 m at 15 m water depth has attenuated to 0.96 m over a period of 20 days. The dissipated wave energy may have eroded the bottom sediment. In other words, the wave-induced stress probably exceeded the yield stress of the sediments and caused fluidization or liquefaction of mud layers (see Silva Jacito and Le hir, 2001). Mathew (1992) reported that wave heights were attenuated ~75-85% by the time it reached the near-shore at ~5 m water depth and almost 100%, before it reached the shoreline. We found maximum reduction of 65% wave height at 7 m water depth in 2014, implying that mud bank activity has reduced relatively to earlier years (Samiksha et al., 2016; paper under revision). Jia et al. (2014) reported re-suspension of surface sediment at the initial stage of wave action, and transportation of re-suspended sediment upward due to wave-induced liquefaction to form fluid mud at a later stage. The fluid mud developed may have attenuated the wave activity and therefore resulted in calm conditions in the mud bank region. Several investigators emphasized the role of wave activity on the formation of mud banks on the southwest coast of India (Shenoi et al., 1986; Mathew et al., 1995; Fass, 1995; Tatavarti et al., 1999, 2006). If wave energy alone was involved, one would expect fluid mud even at M1, which is at the same depth as M2 and distance between the two stations is only ~7 km. The occurrence of persistent mud banks every year in the same place may be because of complex interplay of diverse processes occurring during the monsoon.

#### **Other possible mechanisms for the formation of fluid mud**

Organic-rich sediments with oxygen deficient bottom waters are characteristic of mud banks. The decay of organic debris leads to the formation of gases in sub-surface sediments. The gases would then escape into the waters abundantly during the monsoon because of the continuous impact of wave energy on the sediments, favouring re-suspension of sediment, formation and up keep of fluid mud. Methane concentrations have been reported in the waters at M1 and M2 stations but their concentrations were lower during the monsoon (30-40 nM) than in pre-monsoon (300 nM; Anil Pratihary, personal communication). Low methane during monsoon was attributed to the abundant presence of methanotropic bacteria, which oxidised methane in oxygen-deficient bottom waters. Bristow (1938) and Narayana et al (2008) attributed the formations of mud banks due to forcing of subsurface gas to the surface sediments.

Coastal currents transport sediments from offshore to nearshore. Intense upwelling occurs in this region during the SW monsoon. Ramasastry and Myrland (1959) suggested that upwelling currents can remobilise the fine sediment deposits from the sea bed and are capable of transporting fluid mud. Kurup (1972) and Balachandran (2004) attributed the formation of mud banks to the subterranean channel flow of mud from the backwater lagoons/lakes to the sea, probably through an activated fault. They suggested that the clay/mud in the injected waters gets transformed into flowing fluids because of the thixotropic property of the clays. However, it is difficult to realise the above mechanism as there are no changes in salinity (32) from surface to bottom waters during the formation of fluid mud and, does not explain the occurrence of mud cones on the beaches of Alleppey (Anonymous, 1984). Gopinathan and Qasim (1974) proposed mud moving from depths greater than 20 m to the near-shore areas as source for mud banks. It is well known that strong southerly currents prevail on this coast during the SW monsoon. The current measurements made in July 2014 showed southerly current with a maximum speed of 0.80 m/s (Fig. 8) and on several occasions, the southward flow receded at an interval of 3-5 days, giving rise to weak northerly currents with the maximum speed of 0.40 m/s. Dinesh and Jayaprakash (2008) reported zaherite (hydrated aluminium sulphate) in the surface sediments of the mud banks, and suggested that this mineral keeps the sediments porous, loosely packed with a high water content. The mud can be easily re-suspended to form fluid mud upon wave action.

Comparison of our results with the earlier results indicates that the characteristics of waters in mud banks are changing with time. It is therefore likely that more than one process is involved in the formation of fluid mud. Our study, however, points out re-suspension of bottom sediments by wave activity as the main process. Upwelling may have contributed to the up-keep and migration of fluid mud.

## **6.0 Conclusions**

The mean SPM concentrations were low at surface and mid-depth waters and relatively high at bottom-depth waters at both mud bank and non-mud bank stations and during pre-monsoon and monsoon seasons. Near-bed SPM concentrations and LISST-25X observations indicated 1 m thick fluid mud layer only at the mud bank stations. Bottom sediments are silt-dominated in the mud bank area and were skewed towards coarser size when passing from pre-monsoon to monsoon. Wave data showed strong reduction in wave height from May to July. We suggest that the dissipated wave energy might have probably eroded the bottom sediment and formed the near-bed fluid mud. It is likely more than one process is involved in the formation of fluid mud.

## **Acknowledgments**

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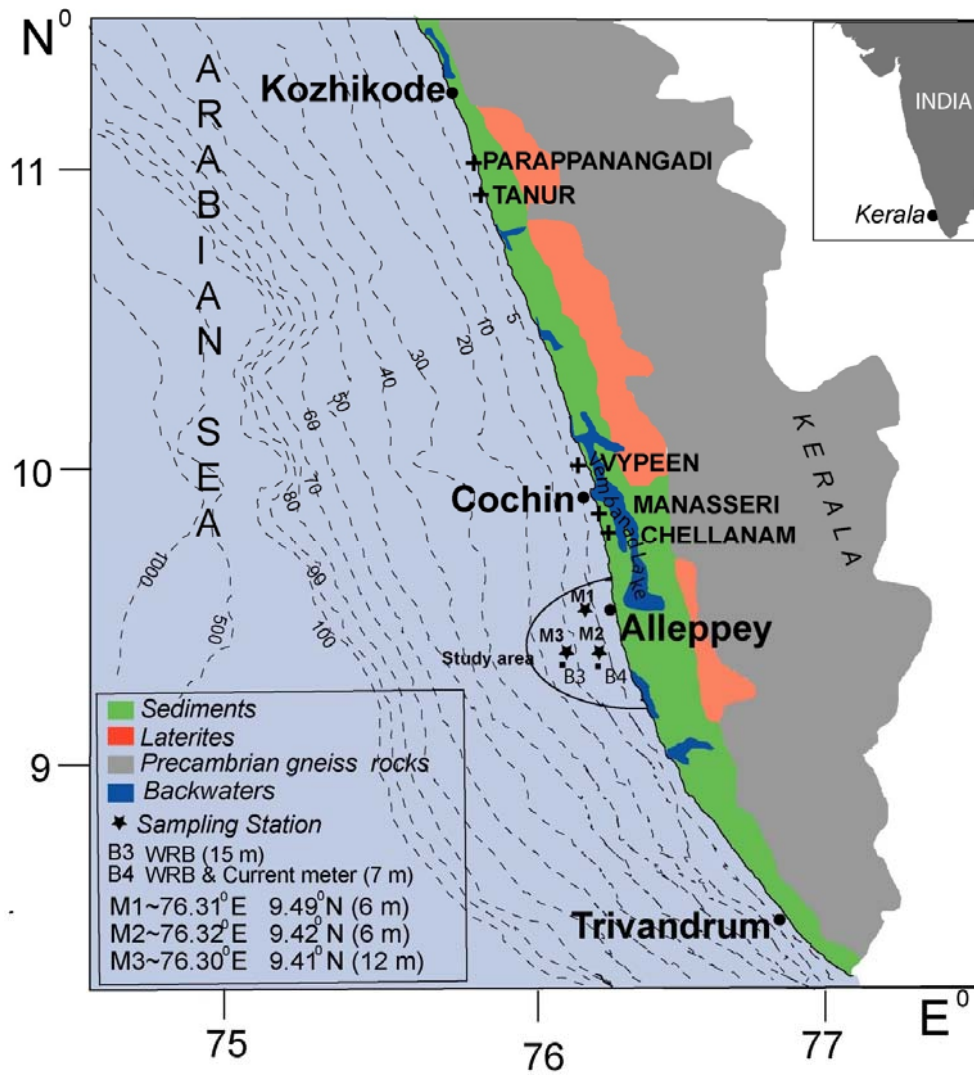


Fig. 1. Sample location map on the coast of Alleppey, Kerala, southwest coast of India.

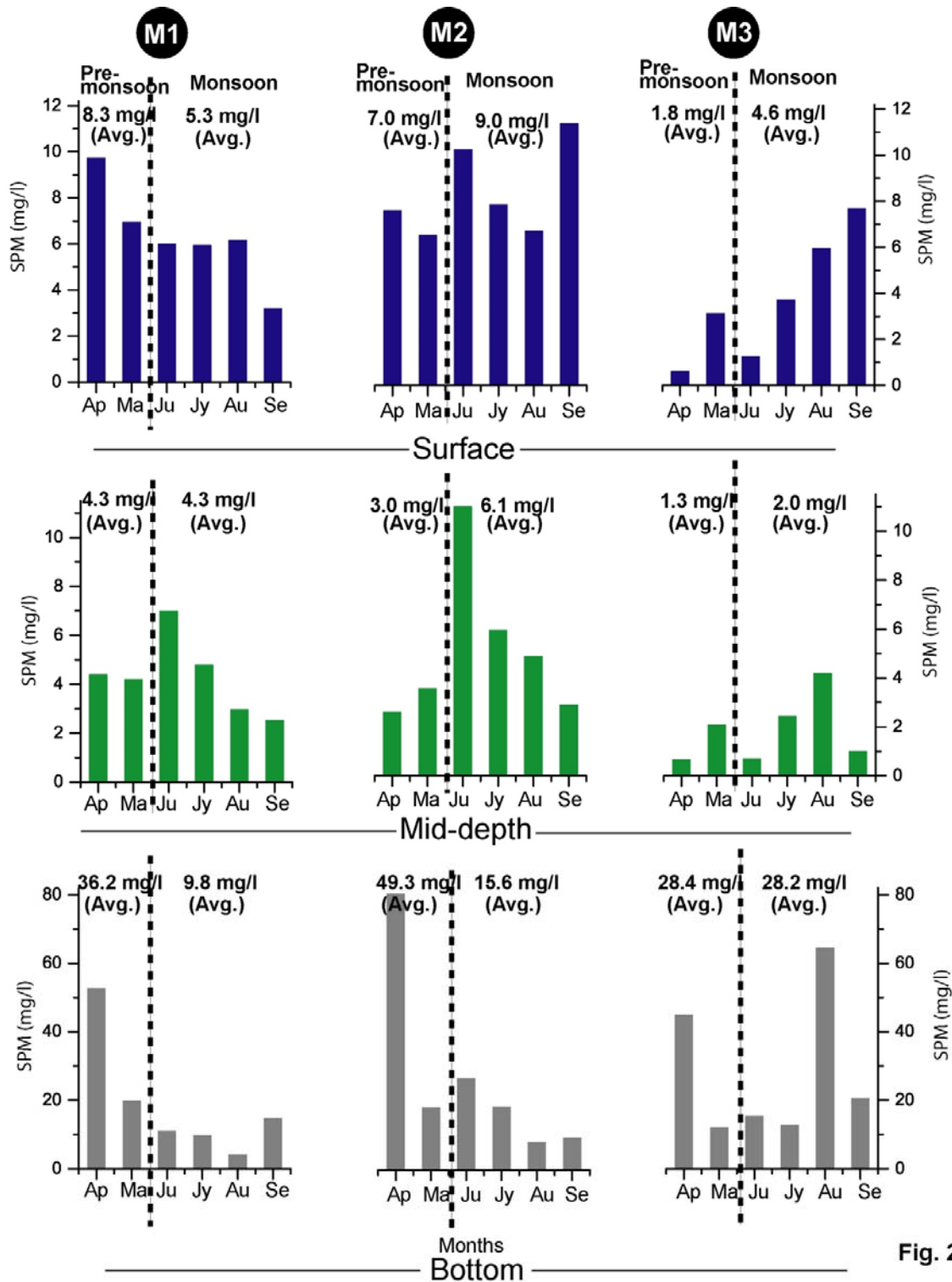
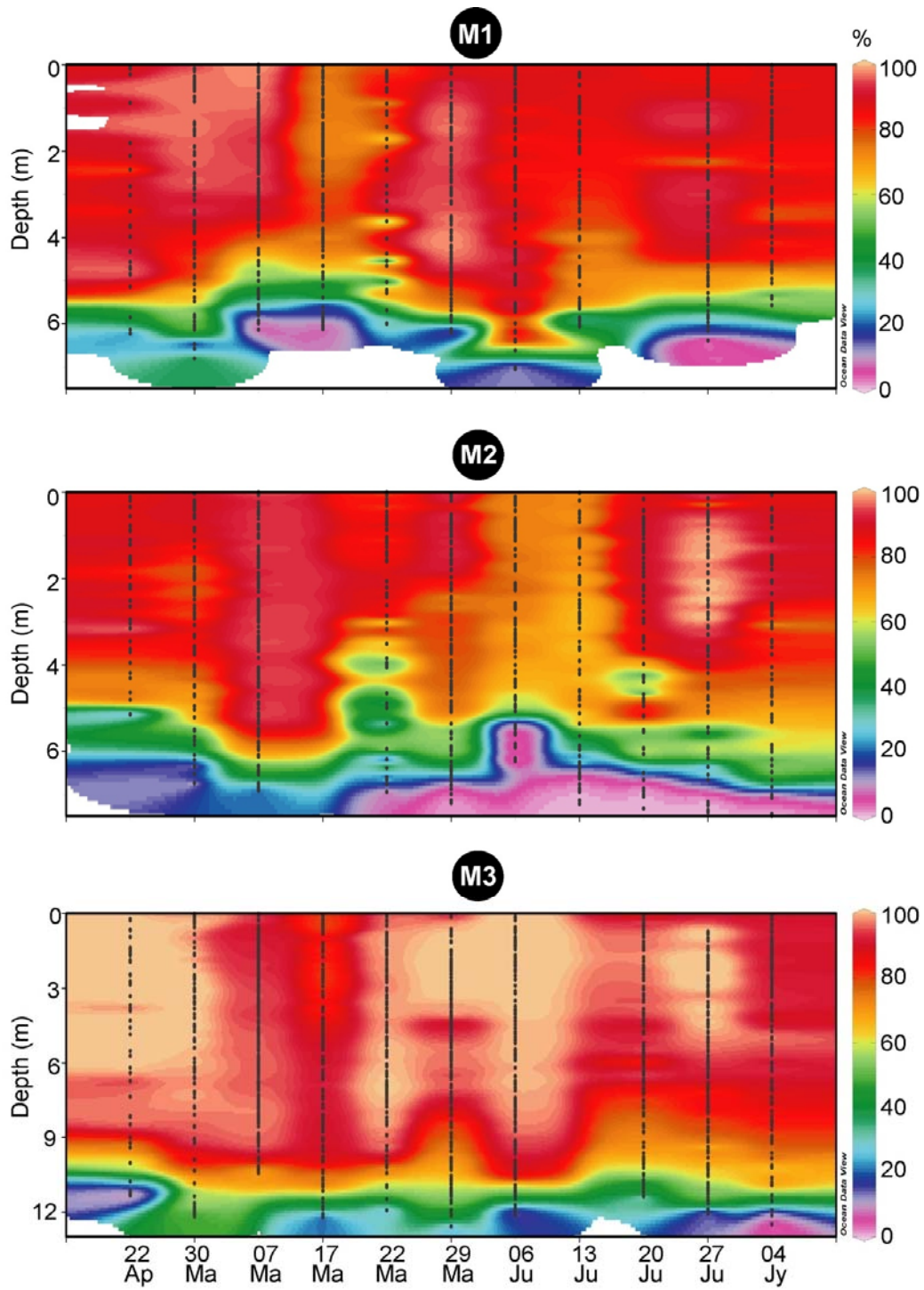


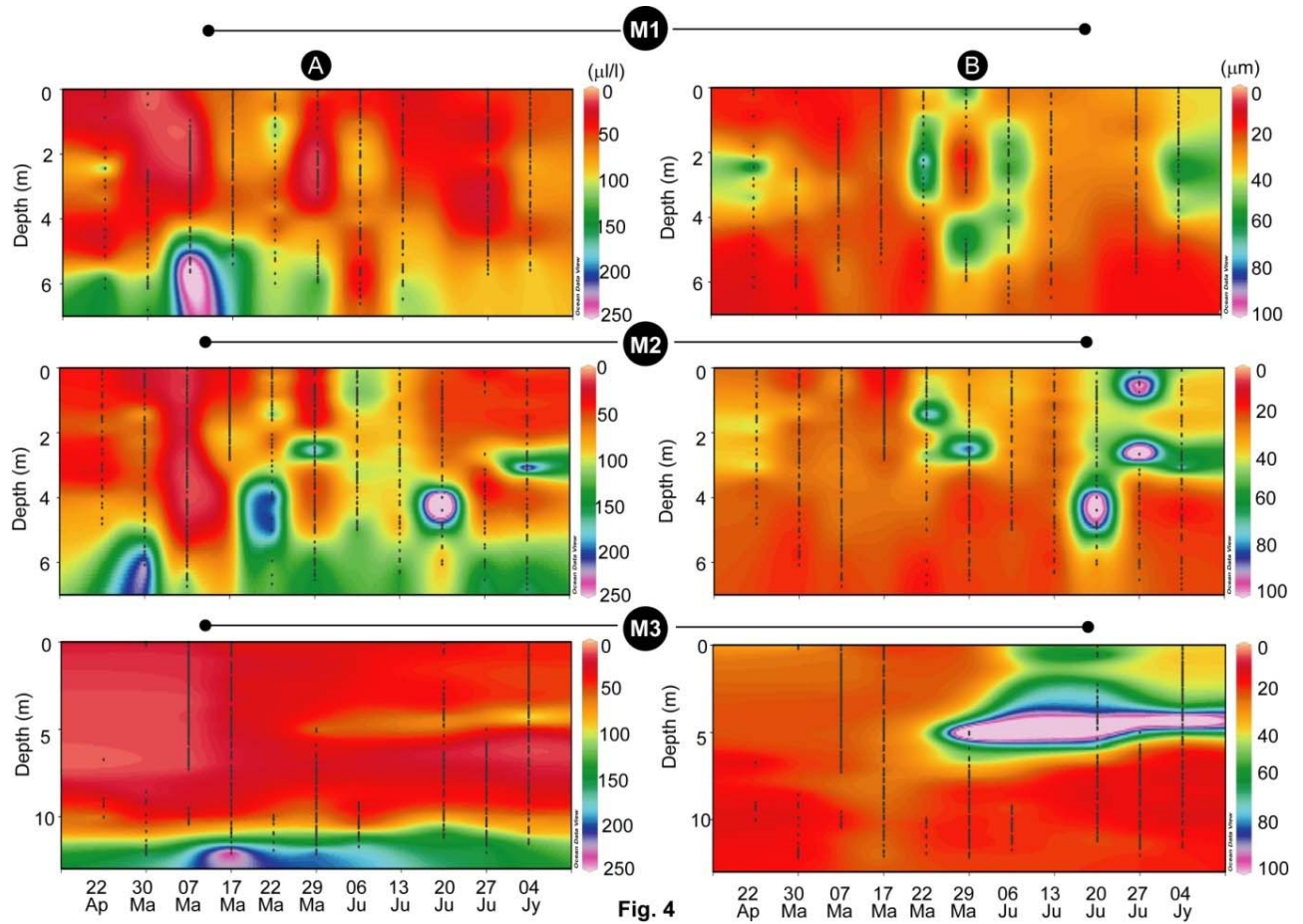
Fig. 2

Fig. 2. SPM concentrations measured at surface, mid-depth and bottom-depth waters at M1, M2 and M3 stations on different dates during the pre-monsoon (April-May) and monsoon (June-September) months.



**Fig. 3**

Fig. 3. Optical Transmission (%) measured at M1, M2 and M3 stations, using LISST-25X. Zero OT% means the SPM concentrations are >1000 mg/l.



**Fig. 4**

Fig. 4. (A) Particle volume concentration (PVC) and (B) Sauter mean diameter (SMD) of particle in the water column measured using LISST-25X at M1, M2 and M3 stations



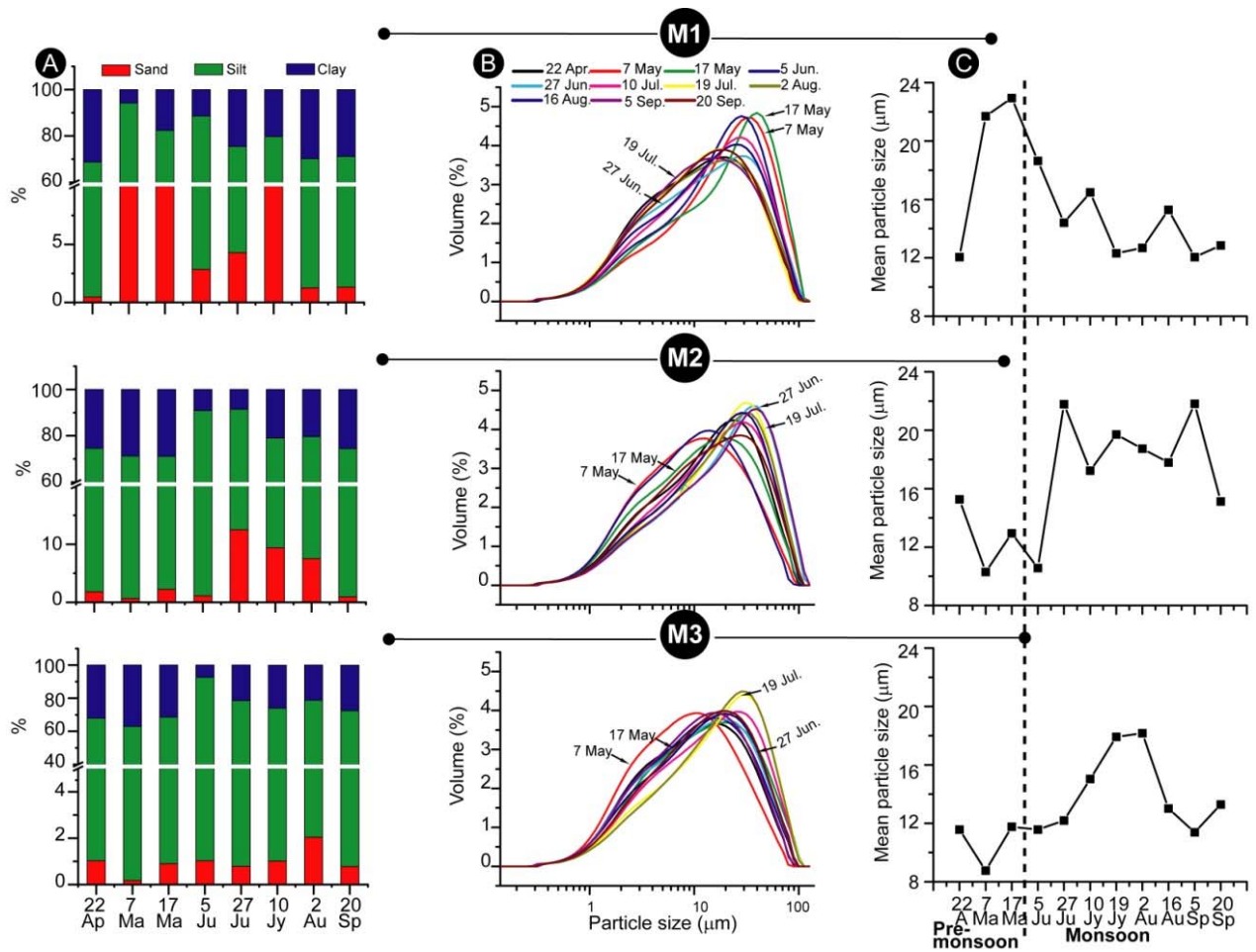


Fig. 5. (A) Sand, silt and clay percentage of the sediments collected on different dates at M1, M2 and M3 stations. (B) A plot between particle size ( $\mu\text{m}$ ) and particle volume (%) of the sediment, using Master sizer 2000. (C) The variations in the mean particle size of the  $<63 \mu\text{m}$  fraction of the sediments collected on different times

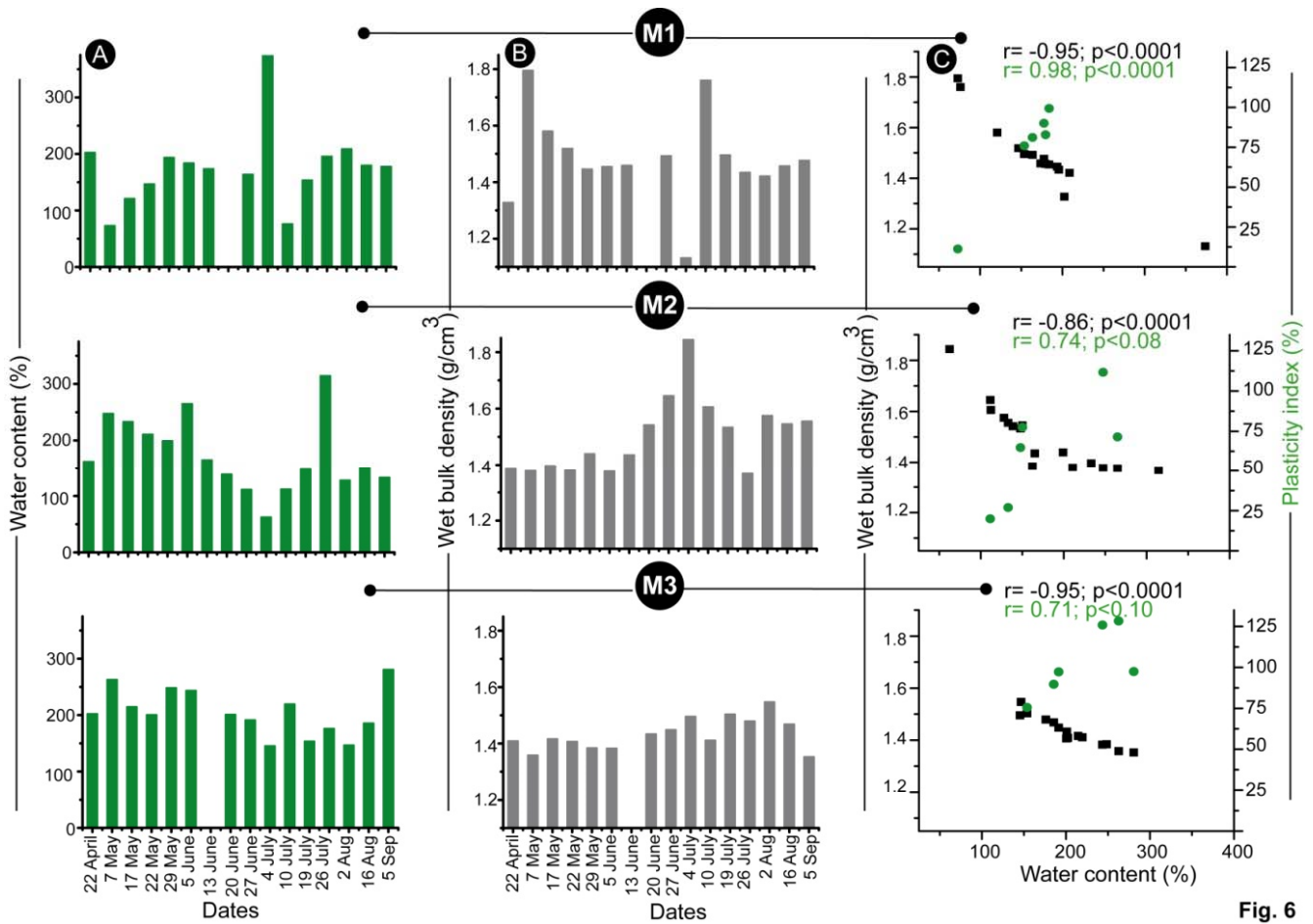


Fig. 6

Fig. 6. Variations in the water content (A) and bulk density (B) of the sediments collected on different dates at M1, M2 and M3 stations. (C) The plot showing correlations between water content and bulk density and, water content and plasticity Index of the sediments at M1, M2 and M3 stations.

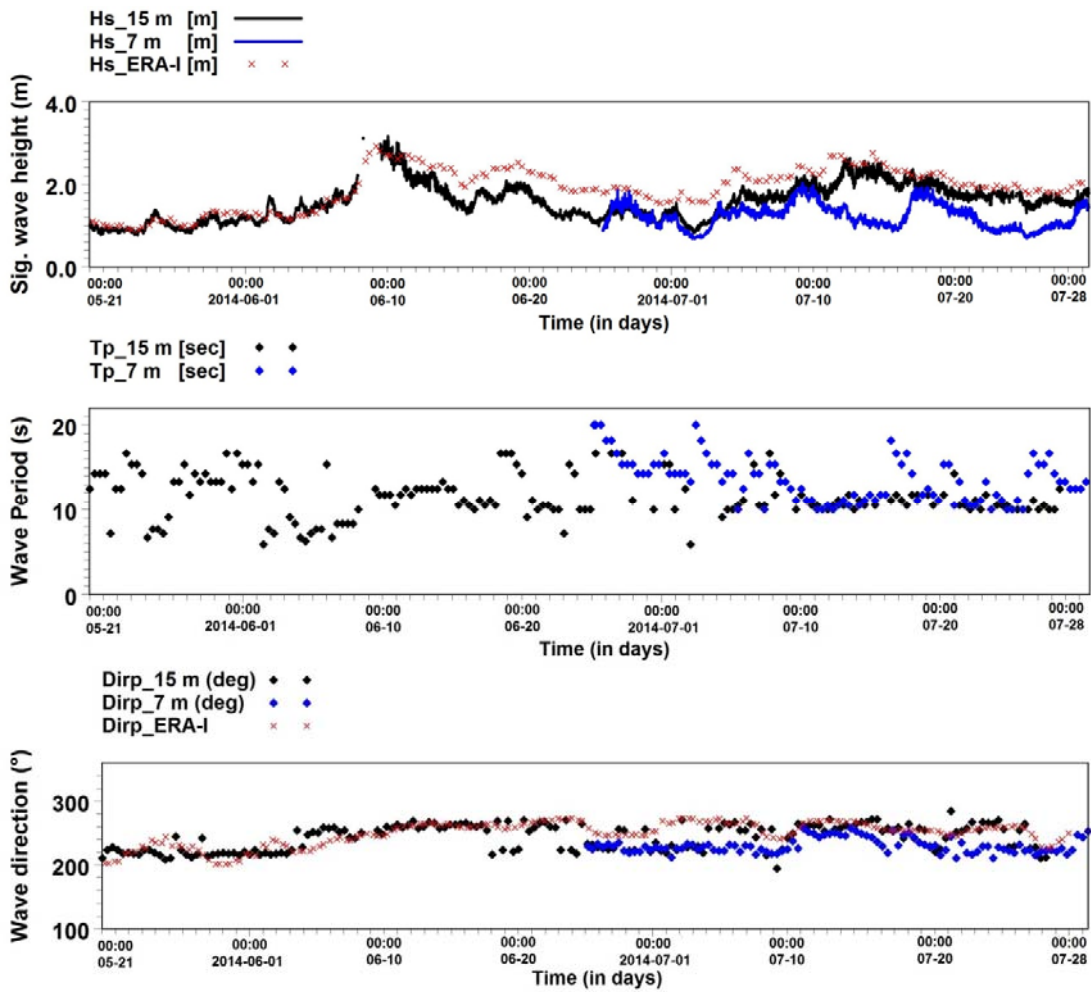


Fig. 7. Wave heights at 15 m and 7 m water depths off Alleppey, Kerala.during 21 May - 30 July 2014

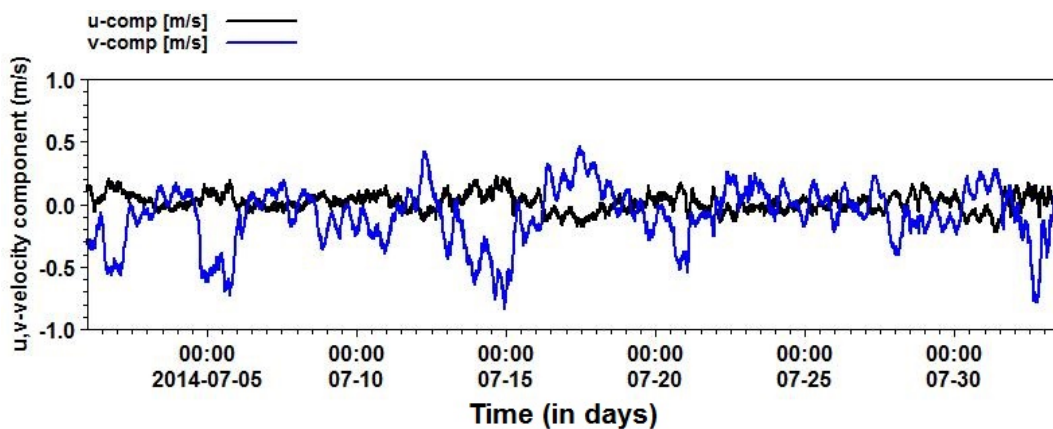


Fig.8. Zonal and meridional velocity components at 7 m water depth off Alleppey, Kerala during 26 June - 2 August 2014



Table. 1 Suspended particulate matter (SPM) concentration in mg/l during the sampling at different stations and depths.

| Stations                | M1          |             |              | M2           |              |              | M3          |             |              | M1          | M2     | M3     |
|-------------------------|-------------|-------------|--------------|--------------|--------------|--------------|-------------|-------------|--------------|-------------|--------|--------|
| Dates                   | Surface     | Mid         | Bottom       | Surface      | Mid          | Bottom       | Surface     | Mid         | Bottom       | Near Bottom |        |        |
| 22-04-2014              | <b>9.74</b> | <b>4.39</b> | <b>52.56</b> | <b>7.60</b>  | <b>2.60</b>  | <b>80.62</b> | <b>0.61</b> | <b>0.66</b> | <b>44.90</b> |             |        |        |
| 07-05-2014              | 0.85        | 1.24        | 34.18        | 1.50         | 0.59         | 6.13         | 1.75        | 0.52        | 21.42        |             |        |        |
| 17-05-2014              | 15.98       | 9.78        | 31.48        | 12.36        | 8.24         | 22.60        | 9.02        | 5.46        | 6.21         |             |        |        |
| 22-05-2014              | 9.12        | 2.70        | 8.46         | 10.73        | 1.13         | 27.34        | 1.06        | 0.49        | 1.00         |             |        |        |
| 29-05-2014              | 1.85        | 3.10        | 5.29         | 1.52         | 4.31         | 16.56        | 0.68        | 1.87        | 19.67        |             |        |        |
| <b>Monthly mean</b>     | <b>6.95</b> | <b>4.20</b> | <b>19.85</b> | <b>6.53</b>  | <b>3.57</b>  | <b>18.16</b> | <b>3.13</b> | <b>2.09</b> | <b>12.07</b> |             |        |        |
| <b>Pre-monsoon Mean</b> | <b>7.51</b> | <b>4.24</b> | <b>26.39</b> | <b>6.74</b>  | <b>3.37</b>  | <b>30.65</b> | <b>2.62</b> | <b>1.80</b> | <b>18.64</b> |             |        |        |
| 05-06-2014              | 8.69        | 7.24        | 7.31         | 15.08        | 11.01        | 18.07        | 0.80        | 0.70        | 3.37         |             |        |        |
| 13-06-2014              | 6.43        | 9.01        | 10.50        | 18.69        | 20.79        | 19.69        | NS          | NS          | NS           |             |        |        |
| 20-06-2014              | NS          | NS          | NS           | 5.19         | NS           | 7.80         | 2.11        | NS          | 21.81        |             |        |        |
| 27-06-2014              | 2.87        | 4.75        | 15.01        | 2.02         | 1.20         | 61.32        | 0.83        | 0.68        | 21.02        |             |        |        |
| <b>Monthly mean</b>     | <b>6.00</b> | <b>7.00</b> | <b>10.94</b> | <b>10.25</b> | <b>11.00</b> | <b>26.72</b> | <b>1.25</b> | <b>0.69</b> | <b>15.40</b> |             |        |        |
| 04-07-2014              | 5.66        | 4.24        | 5.35         | 4.67         | 4.53         | 11.27        | 4.06        | 3.40        | 17.60        |             |        |        |
| 10-07-2014              | 5.68        | 6.10        | 7.94         | 13.24        | 8.70         | 16.97        | 3.22        | 2.06        | 2.21         |             |        |        |
| 19-07-2014              | 4.70        | 4.04        | 9.32         | 3.76         | 3.50         | 30.42        | 2.29        | 2.20        | 18.01        | 42.44       | 9179.8 | 6187.5 |
| 26-07-2014              | 7.72        | NS          | 16.05        | 9.73         | 7.13         | 15.08        | 5.30        | 2.09        | 12.78        |             |        |        |
| <b>Monthly mean</b>     | <b>5.94</b> | <b>4.79</b> | <b>9.66</b>  | <b>7.85</b>  | <b>5.96</b>  | <b>18.43</b> | <b>3.72</b> | <b>2.44</b> | <b>12.65</b> |             |        |        |
| 02-08-2014              | 9.29        | 4.31        | 6.51         | 11.89        | 7.80         | 8.44         | 8.94        | 5.87        | 14.59        |             |        |        |
| 16-08-2014              | 3.06        | 1.62        | 1.80         | 1.56         | 1.95         | 7.79         | 2.95        | 2.51        | 114.54       |             |        |        |
| <b>Monthly mean</b>     | <b>6.17</b> | <b>2.96</b> | <b>4.15</b>  | <b>6.72</b>  | <b>4.88</b>  | <b>8.12</b>  | <b>5.95</b> | <b>4.19</b> | <b>64.56</b> |             |        |        |
| 05-09-2014              | 2.92        | 2.84        | 7.82         | 1.44         | 2.07         | 4.20         | 1.19        | 1.06        | 26.27        |             |        |        |
| 20-09-2014              | 3.48        | 2.20        | 21.50        | 21.29        | 3.73         | 14.48        | 14.18       | 0.93        | 14.82        | 18.70       | 32.9   | 100.9  |
| <b>Monthly mean</b>     | <b>3.20</b> | <b>2.52</b> | <b>14.66</b> | <b>11.37</b> | <b>2.90</b>  | <b>9.34</b>  | <b>7.68</b> | <b>1.00</b> | <b>20.54</b> |             |        |        |
| <b>Monsoon Mean</b>     | <b>5.50</b> | <b>4.63</b> | <b>9.92</b>  | <b>9.05</b>  | <b>6.58</b>  | <b>17.96</b> | <b>4.17</b> | <b>2.15</b> | <b>24.27</b> |             |        |        |