

Observed salinity changes in the Alappuzha mud bank, southwest coast of India and its implication to hypothesis of mudbank formation

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ABSTRACT

Alappuzha mud bank draws special attention among the twenty-mud bank locations reported along the Kerala coast by its remoteness from riverine sources. Among several hypotheses proposed for the formation of mud bank, the subterranean hypothesis was most accepted because of the occurrence of low salinity in the bottom layers. The present study provides evidence to show that occurrence of low salinity waters near the bottom in the mud bank region is an artifact of measuring technique employed for the measurement of salinity. The usual technique of conductivity based salinity determination completely fails in the presence of water laden with high amount of suspended sediment. Laboratory experiments were conducted to determine the response of electrode and conductivity cell sensor types to determine the salinity using a range of suspended sediment in the water column. Actual sediment samples from the mud bank region were utilized for the above studies. Based on field observations and experiments, we conclude that the low salinity was the manifestation of the presence highly turbid fluid mud formation in the mud bank region rather than the influence of fresh water.

KEYWORDS

Mud bank, fluid mud, low salinity, Kerala coast,

1. INTRODUCTION

Mud banks are of region of calm, turbid water with high-suspended sediments that occurs close to the shore during southwest monsoon (June to September) along the Kerala coast (Nair, 1976). Mud banks are seen within a water depth of 15 m, often in a semi-circular shape with a radius ranging from 4 to 8 km. Due to the prevalence of calm waters within the mud bank during south west monsoon, which is a period of very high wind and wave activity, fishermen use this region for launching and landing of small boats for fishing activities. At the same time due to the calmness of this region, the adjacent shore is usually protected from erosion due to high waves. There are nearly 20 locations along the Kerala coast, where mud banks have appeared some time or the other in the past (Fig. 1). Though mud banks are reported at several places along the Kerala coast, the most prominent and persistent one occurs at Alappuzha. Studies by Gopinathan and Qasim (1974) reported the presence of small elevation of 1-2 m in the sea bottom within the Allappuzha mud bank, which consisted of consolidated mud. Subsequent study showed that the sediment density in this region varied from 1080 to 1300 kg/m³ with suspended particle size ranging between 0.5 and 3µm (Faas, 1995).

Various hypotheses have been postulated for explaining the formation of mud banks along the Kerala coast, which can be broadly classified into two – local water-column dynamics in the near shore region, and remotely mediated processes such as subterranean flow of mud and fresh water from hinterlands or adjacent lagoons. Under the former there are four hypothesis, which are (1) formation of fluid mud due to upwelling and Ekman divergence at the bottom (Ramasastry and Myrland, 1959; Phillip et al., 2013), (2) suspended sediment transport under littoral current and rip current system (Varma and Kurup, 1969; Kurup, 1977), (3) wave-induced oscillation and wave dampening (Pherson and Kurup, 1981; Mathew and Baba, 1995), and (4) infra-gravity waves interacting with undertow and reflections from shore leading to mud suspension (Tatavarti et al., 1996, 1999; Tatavarti and Narayana, 2006). Under the remotely-mediated processes, there are five hypothesis, which are (1) passage for soft mud from rivers and backwater during monsoon through subterranean channels as evidenced by the mud cones observed in the beaches of Alappuzha (Crawford, 1860; King, 1881; Menon, 1924), (2) water-bearing subsurface strata churning up mud within the region of mud bank (Rhode, 1886; Bristow, 1938), (3) seepage of methane gas, produced by marsh deposit, due to injection of fresh water from lagoon following heavy monsoonal rain (Narayana et al., 2008) or due to the pressure fluctuations of the short-period storm waves associated with the monsoon (Nair,1976), (4) existence of submerged trending faults from AchanKoil shear zone to Allappuzha (Hedberg, 1974; Mallik et al., 1988), (5) a combination of subterranean fresh water flow from the

adjacent Vembanad Lake through the shallow trending faults over the lime shell bed during summer monsoon (Balachandran, 2004). The central premise of the remotely mediated process hypothesis is that the fresh water from either in the adjacent lagoon or from hinterland through underground facilitates mud suspension in the mud bank region. Therefore several authors have endeavored to seek the evidence for this through changes in the bottom salinity within the mud bank, but with limited success (Mallik et al., 1988; Mathew and Gopinathan, 2000; Balachandran, 2004; Nair, et al., 2013).

The present study focuses on capturing the bottom salinity changes associated with the initiation of mud bank at Alappuzha with the help of targeted measurements using more than one technique. We show that the observed lowering of salinity near the sea bed associated with the initiation of mud bank at Alappuzha was not actually due to the introduction/addition of subterranean fresh water; rather it was the manifestation of the interaction of high quantity of suspended bottom mud in the salinity measurements.

2. MATERIALS AND METHOD

The objective of study being the testing of the hypothesis of subterranean flow of freshwater and mud triggering the mud bank formation, a field measurement programme was initiated to collect water samples and temperature and salinity profiles from a station located at 76° 22' 16.8'' E longitude and 9° 25' 21.4'' N latitude, where the water depth was 6 m (Fig. 1). The station was chosen in such a way that it was located within the reported occurrence of mud bank in the Alappuzha region (Silas, 1984).

2.1 Sampling

The field measurement consisted of weekly profiling of temperature, salinity, turbidity and photosynthetically active radiation (PAR), which was initiated on 24th April 2014 well ahead of the southwest monsoon onset and continued until 20th October 2014,. A Seabird SBE 19plus conductivity-temperature-depth (CTD) profiler with Turbidity and PAR sensor was used for the profiling. The instrument was well calibrated and having measuring range for conductivity 0-9S/m (accuracy of ± 0.0005 S/m), for temperature -5 to 35°C (± 0.005 °C) and 0.1% of full scale for a pressure rating of 100m depth. Bio-spherical PAR sensor was used to measure the quantum of solar radiation ($\mu\text{E}/\text{cm}^2 \cdot \text{s}$) ranging from 400-700 nm with a flatness of $\pm 10\%$. WET Labs ECO-FLNTUrt Turbidity sensor, 0-25 NTU ranges with a sensitivity of 0.01% was used to measure turbidity of water column.

To capture the onset of southwest monsoon an Automatic Weather Station (AWS) developed at CSIR-National Institute of Oceanography (CSIR-NIO, Goa), was mounted at 10 m height on a building located close to the station to measure wind speed (range 0-60 m/s, accuracy 0.2 m/s) & direction (range 0-360°, accuracy 3°), barometric pressure (range 800-1060mbar, accuracy 0.4mbar) and relative humidity (range 0-100%, accuracy 3%), at 10 minute intervals. For rainfall data, we have used daily averaged precipitation data from Tropical Rainfall Measuring Mission (TRMM) (<https://mirador.gsfc.nasa.gov>).

2.2 Experimental Setup for measurement of salinity under varying suspended sediment

The characteristic of the mud bank is the suspension of sediment in the water column, with an increasing concentration towards bottom. As the measurement of salinity is based on the electrical conductivity of the medium, it is expected to be impacted by the presence of suspended sediment in the medium. In order to decipher the impact of suspended sediment in the water column to the electrical conductivity measurements, we conducted 3 sets of experiments namely, concentration, filtration and desorption, the details of which are listed below.

2.2.1 Concentration experiment

To find out the response of electrode and conductive cell to the varying concentrations of suspended sediment while measuring salinity, we conducted a concentration experiment in the laboratory as follows. Ambient seawater sample from close to the bottom and bottom surficial sediment from the mud bank station (Fig. 1) was collected on 12th April 2014 using Niskin sampler and Van Veen grab respectively. The salinity of the collected sample was determined using EuTech electrode meter in the shore laboratory. Subsequently, 10g of sediment was suspended uniformly with 1 liter of ambient seawater, each time, and salinity was determined. This was continued until a concentration of 250 g/l was achieved.

For conductive cell, a Sea-Bird 19 Plus CTD conductivity cell (large volume of water is required) was used to measure salinity of the mud bank sea water samples by varying the concentration of suspended sediment in the shore laboratory. A hundred-liter container (Tub Experiment) was filled up to 80% of its volume with ambient seawater collected from the mud bank station close to the bottom using 5 liter Niskin sampler. About 90 kg of bottom surficial sediment from the mud bank station (Fig. 1) were also collected using Van Veen grab having a grabbing area of 0.04 m². Both samples were collected on 18th July 2014 when the mud bank was active. The salinity was determined by immersing the CTD into the container containing the ambient sea water. Subsequently, the concentration of suspended sediment in the container was increased from ambient

to 1223 g/l in 15 steps (Table 1) and the salinity of the seawater with suspended sediment was determined.

2.2.2 Filtration Experiment

During 27th June 2014, when the mud bank was active, we collected fluid mud from the station (Fig. 2) to conduct filtration experiment. The in-situ observed salinity of the fluid mud at the station was recorded by SBE 19plus CTD. The fluid mud so collected was filtered in the shore laboratory by passing it through a fresh piece of cotton fabric to eliminate any large debris usually present in the field. The salinity of the filtrate, about 50 ml, was determined using EuTech electrode sensor. The filtrate was further passed through 300 μm and 200 μm mesh sieve and the salinity of each was determined. The fluid mud obtained after passing through the 200 μm mesh was centrifuged and the salinity of the supernatant was determined. Initial salinity of the in-situ fluid sample using salinometer was 27.89 psu (practical salinity unit) (in-situ CTD salinity 27.67 psu), after first, second and third filtering the salinity values using salinometer increased to 31.25 psu, 33.76 psu, 35.13 psu and finally by centrifuging salinity was 36.03 psu.

2.2.3 Desorption experiment

In addition to the change in salinity due to the change in bulk conductivity by the suspended sediment in the water column, there could also be an increase in salinity due to desorption of ions from the sediment into the water column. In order to decipher the effect of desorption and dissolution on salinity, from the Tub Experiment 50 ml of sample (suspended sediment + ambient sea water) was collected at each time during 15-step experiment and centrifuged. The residue as well as the supernatant was separated for analyzing the salinity. The residue was dried in a hot oven at 60°C for 3 days and weighed using a precision mass balance to determine the dry weight of the suspended sediment.

3. RESULTS AND DISCUSSION

The Alappuzha mud bank being far away from river mouth or lagoon, input of suspended sediments from river/lagoon as a triggering mechanism for the formation is ruled out. Hence, our field study focused on the remarkable drop in salinity at the bottom layers during the observational period as it has implication to the hypothesis of subterranean fresh water flow for the formation of mud bank.

Our observation started on 22th April 2014 with weekly interval, which was well before the onset of monsoon to identify the presence of subterranean flow to the mud bank region. Southwest monsoon condition being the pre-cursor of the mud bank activity, we examined the surface meteorological parameters to decipher the onset of southwest monsoon. Atmospheric pressure (Fig. 2a) varied from

1002 mb to 1012 mb during the observational period with discrete falls during 4th to 8th May 2014 (~1002.5 mb), 5th to 12th of June 2014 (~1003 mb), 24th to 27th June 2014 (~1005 mb), 3rd to 6th July 2014 (~1005.7 mb), 27th to 8th August 2014 (~1007 mb), 18th to 24th August 2014 (~1004 mb), 27th to 4th September (~1006 mb). The Land-Sea breeze prevailing in this region with an average speed of 1.5 m/s during pre-monsoon period was replaced after the onset of southwest monsoon with westerly to northwesterly winds of 6 m/s (Fig. 2b). A delay of 2-4 days was noticed for intensification of winds to maximum with respect to lowest atmospheric pressure. Strong wind events with high relative humidity (>90 %) were observed during the low to high-pressure transitional period except mid of June to August, while summer monsoon rainfall was more or less similar pattern. Precipitation (Fig. 2c) from 4th to 8th May 2014 was varied from 4 to 90 mm/day, which was associated with passage of depression over the study region. Pre-monsoon showers (<2.5 mm/day) were noticed up to 4th of June 2014, from which continuous and heavy rainfall (ave. 25.7 mm/day) was noticed up to 13th June 2014, Indian Meteorological Department announced 6th June 2014 as onset of summer monsoon over Indian continent. Episodes of rainfall, which during persisted more than 3 days with an intensity >10 mm/day were noticed during 26th June to 2nd July 2014 (15.2 mm/day), 9 July to 15th July 2014 (37.1 mm/day), 31 July to 8th August 2014 (42.3 mm/day), 17th August to 23rd August 2014 (31.2 mm/day), 29th August to 5th September 2014 (11.2 mm/day) and 25th to 30th September 2014 (average value of 25 mm/day).

An examination of the time evolution of the vertical structure of temperature and salinity obtained from CTD showed very warm surface waters having 30°C with strong thermal stratification, which persisted from 22nd of April to 29th May (Fig. 3a). However, 1°C cooling of surface water was noticed on 7th May 2014 that was associated with the atmospheric depression as inferred from the meteorological parameters (Figure 2). Subsequently, with the onset of southwest monsoon on 6th June 2014, a sudden cooling of 3°C was noticed and the entire water column was vertically well mixed. This cool and well-mixed water persisted till the end of the observation on 20th September 2014. The distinct feature during this period was the occurrence of three episodic cold waters, with temperature less than 27°C, during (1) 13th June to 10th July, (2) 26th July to 16th of August, and (3) 29th August to 20th September 2014 respectively. Note that these occurrences of cold water were related to intense wind events. While salinity section (Fig. 3b) depicts homogeneous water column having salinity about 34.4 psu (practical salinity unit) on 22nd April 2014. Freshening of surface water (Fig. 2b) by 1 psu was observed on 7th May 2014 during the passage of depression. Episodic freshening of surface waters to a salinity of 33.5 psu was linked to the 3 episodic atmospheric events described above. Interestingly, a drastic drop of salinity by 7 psu in the bottom layers was also

observed coinciding with the above 3 atmospheric events. Density profile of the water column (Fig. 3c) almost mimicked temperature profile during pre-monsoon, while after the onset of monsoon it mimicked the salinity. Initially, the average water column density was 1021 kg/m^3 , which increased to 1023 kg/m^3 during monsoon period. Low-dense water seen at the bottom layers, having a density of $\sim 1019 \text{ kg/m}^3$, was due to the drastic drop of salinity. Highly turbid water (Fig. 3d) was observed in the bottom layers ($>15 \text{ NTU}$), which further increased beyond the measurement limit of the instrument during 13th June to 27th June 2014, 26th July to 2nd August 2014, and 5th September 2014, co-occurred with the low salinity. The negative values in the figure 3d beyond 25 NTU in the bottom layers indicated the presence of fluid mud of very high concentration. The results imply occurrence of low density (warm and low salinity) water mass at the bottom of high density overlaying. This is inconsistent as such a system cannot exist. This inconsistency prompted us to examine the association of low salinity and high turbidity of the bottom water.

To resolve the above inconsistency, we examined the vertical profiles of water column temperature, salinity, PAR and turbidity obtained from CTD on 27th June 2014. Temperature profile (Fig.4a) showed a decreasing trend from surface (25.6°C) to a depth of 6.2 m (24.3°C) and thereafter increased about 1°C towards bottom. While salinity profile (Fig.4 a) was more or less uniform from surface (34.2 psu) to 6.2 m depth, thereafter it decreased significantly to 27.6 psu at a depth of 8 m. Turbidity (Fig. 4b) showed a gradual increasing trend from surface (3 NTU) to a depth of 6.2 m (6 NTU), and afterwards it was beyond the instrument measuring limit. The PAR sensor recorded surface irradiation intensity of $1000 \mu\text{E}/\text{cm}^2/\text{s}$, which gradually decreased to $330 \mu\text{E}/\text{cm}^2/\text{s}$ at a depth of 1.3 m, thereafter dropped rapidly to 0 at a depth of 6.2 m (Fig. 4b).

The characteristics of the sediment in the bottom layer of Allappuzha mud bank station was initially dominated by clay (80%) followed by silt (15%) and sand (5%) (Shynu Personal communication). Studies by Van Rijin, (2007) showed that the constituents present in clay particles are mainly negatively charged and in close proximity strengthens attractive and repulsive forces. In coastal waters, salinity enhances the attractive forces due to the presence of positive sodium-ions forming a cloud of positive ions around the negatively charged clay particles resulting in the formation of flocculation (flocs). The strong wind ($>6 \text{ m/s}$) events that prevailed after the onset of monsoon (Fig. 2b) exerted large shear stress at bottom layers and helped to breakdown the flocs into smaller particles leading to the creation of highly turbid environment. We hypothesize that fluid mud formed in the bottom layers of the study region significantly impacts the salinity measurements. In order to elucidate this, we conducted a series of experiment for salinity measurement under varying suspended sediment concentration.

Serial mixing of bottom sediment with ambient water of the mud bank station depicts the dropping of the salinity towards increasing suspended concentration (Fig. 5). Results showed that both conductive and electrode type sensors fail to measure salinity accurately in the highly turbid environment. We attribute the observed patch of low salinity waters (27.89 psu) near to the bottom (about 1 m above) in the CTD profiling during 27th June 2014 was due to the presence of fluid mud. When the suspended load was removed from the samples collected from this patch by filtration experiment, the salinity was 36.03 psu. This confirms that the low salinity waters seen in the CTD profile is not due to the presence of freshwater, rather it is the manifestation of high turbidity impacting the salinity measurements. Results from Tub experiment points to this fact. Initial salinity of the in-situ sea water in the container measured by CTD was 34.60 psu, while that by electrode was 34.85 psu. There was a difference of 0.24 unit of salinity between the two measurements. When the suspended sediment in the in-situ sea water was increased from its ambient value to 1223 g/l in 15 steps by adding surficial sediment (Table 1), salinity dropped from 34.85 psu to 29.20 psu. Note that the filtered value of the sample after 15th mixing showed an increase of 0.26 psu that gives quantification of desorption of ions, which attached with the clay minerals released by mixing. Comparing to the increase of salinity by desorption due to mixing of bottom sediment to the water column (0.26 psu) to the drop in salinity due to high suspended load (5.6 psu) gives an indication that low salinity patch is not due to fresh water percolation, but due to presence of fluid mud. The observed drifting of salinity from actual values were almost similar to Held et al., (2014), where an increase of 1.5% salinity up to suspended particular matter (SPM) of 10 g/l and decreased to 30% of actual value at a SPM of 300 g/l. Thus, we attribute the lower salinity observed at bottom layers is the manifestation of fluid mud in the measurements.

4. CONCLUSION

Surficial sediment of Alappuzha mud bank was dominated by clay, so cohesive nature of bed can forms large flocs in saline environment. Strong wind (>6 m/s) events during summer monsoon induce large shear stress at bottom cause mixing of cohesive sediment layer and breakdown of flocs to smaller particles to fluidized mud. Concentration experiment portrays the negative response by various instruments in measuring salinity to elevated sediment concentration. While filtration experiment confirms the absence of freshwater influx (36.03 psu) in the fluid mud present in the mud bank station. Possibility of increase in salinity by desorption ions attached in the clay minerals due to mixing of bottom sediment to the water column was quantified during Tub experiment. We conclude that low salinity patch near the sea bed associated with the initiation of mud bank at Alappuzha was not actually due to the introduction/addition of subterranean fresh water; rather it was the

manifestation of high quantity of suspended mud (fluid mud) in the salinity measurements. Our results implicitly eliminate the possibility subterranean passage, activated trending faults, water bearing stratum and river deposition hypothesis for the formation of Alappuzha mud bank.

ACKNOWLEDGEMENTS

This forms a part of Alappuzha Mud bank Process Studies (AMPS), a joint programme between CSIR-National Institute of Oceanography (CSIR-NIO), Goa and Central Marine Fisheries Research Institute (CMFRI), Kochi. Authors thank Dr. S. W. A. Naqvi, Director, CSIR-NIO for his support in the formulation and execution of this programme. We also thank Dr. A. Gopalakrishna, Director, CMFRI for his active involvement in this programme and providing FV Silver Pompano for data collection. The authors thank all the AMPS participants for their active support in the data collection and discussion. This is NIO contribution number xxxx

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Legends to figures

- Figure 1 Map showing prominent mud bank stations along the Kerala coast (left panel) and location map showing Alappuzha mud bank observation station for the year 2014 (right). The scale is for the elevation/depression in meters.
- Figure 2 a,b and c showing meteorological parameters (Atmospheric pressure & Humidity, Wind speed and Precipitation) prevailed over the study region during the observational period. The vertical dotted lines represent the observed data points.
- Figure 3 Temporal variation of temperature ($^{\circ}\text{C}$) (a), salinity (psu) (b), density (kg/m^3) (c) and turbidity (NTU) (d) of the water column during the observational period 24th April to 20th October 2014.
- Figure 4 Vertical profile of temperature ($^{\circ}\text{C}$) & salinity (psu) (a) and turbidity (NTU) & ($\mu\text{E}/\text{m}^2$) at mud bank station on 27th June 2014 when fluid mud was present.
- Figure 5 Inter-comparison of salinity (psu) measured using electrode and conductive cell under varying suspended sediment used in the Tub Experiment.

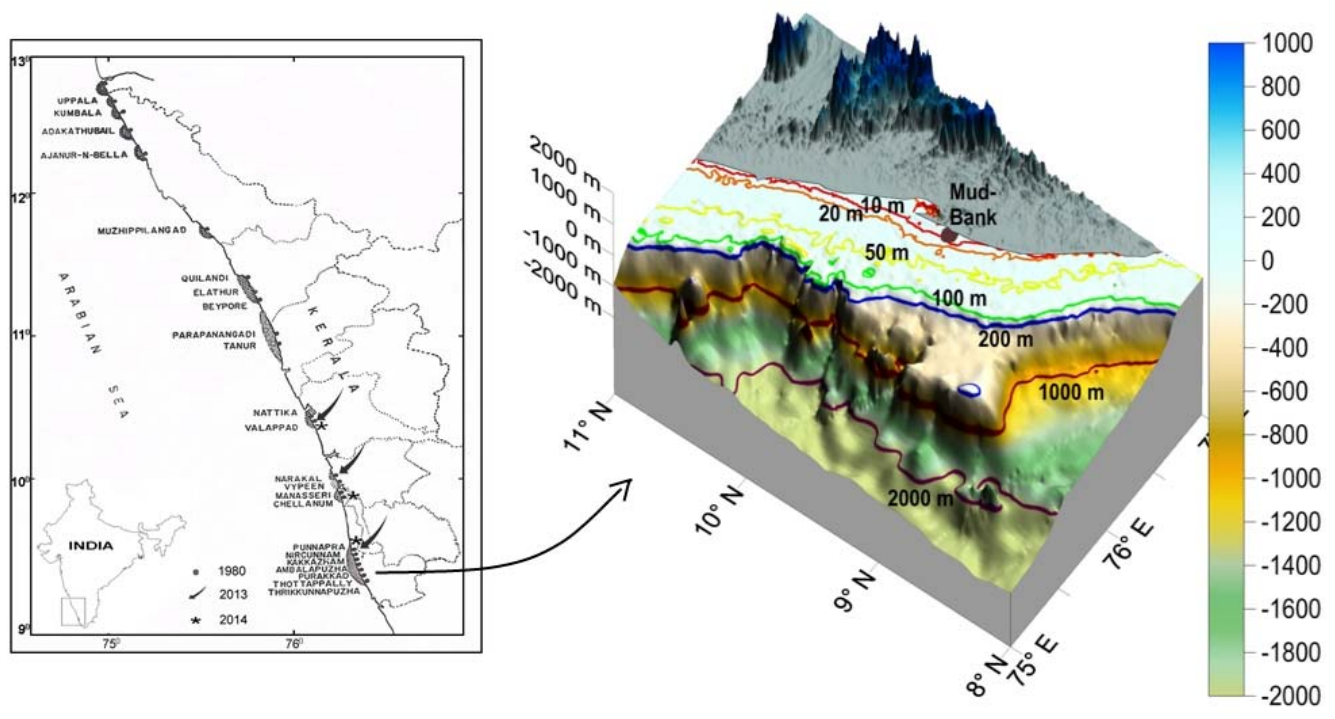


Figure 1.

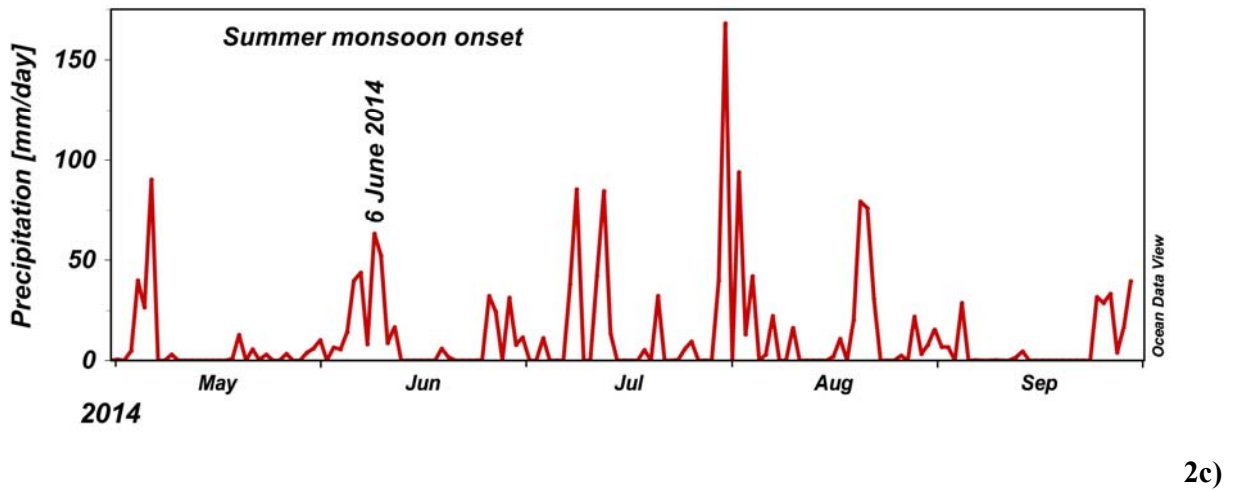
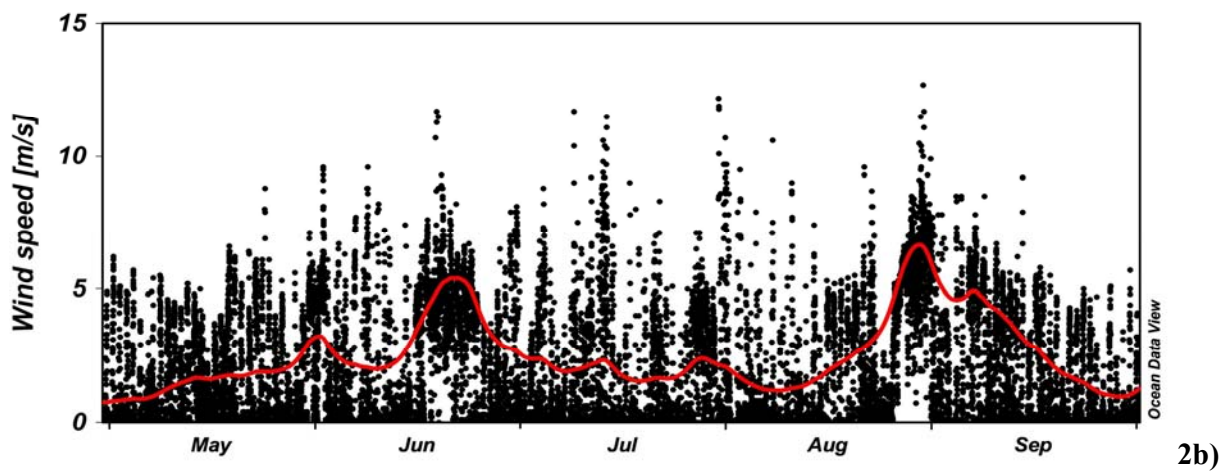
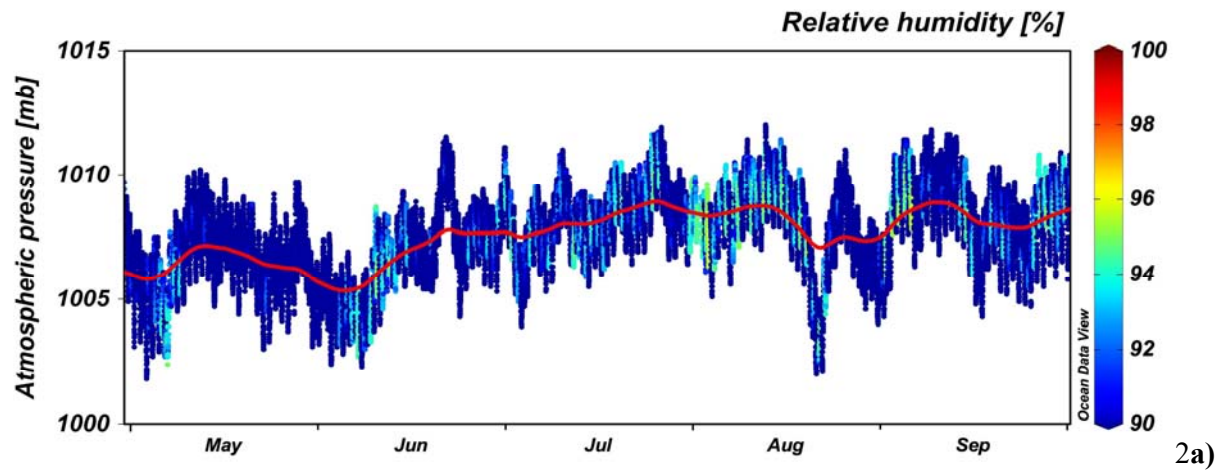
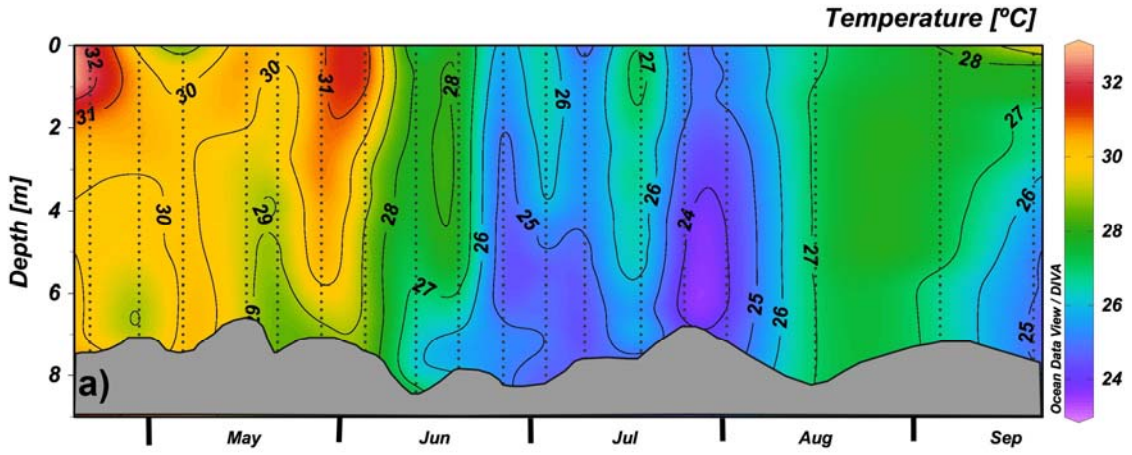
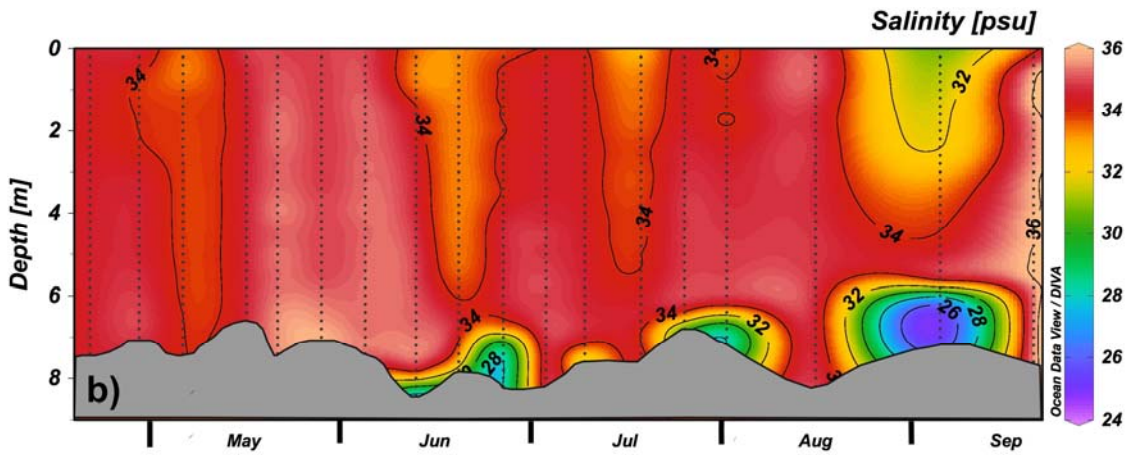


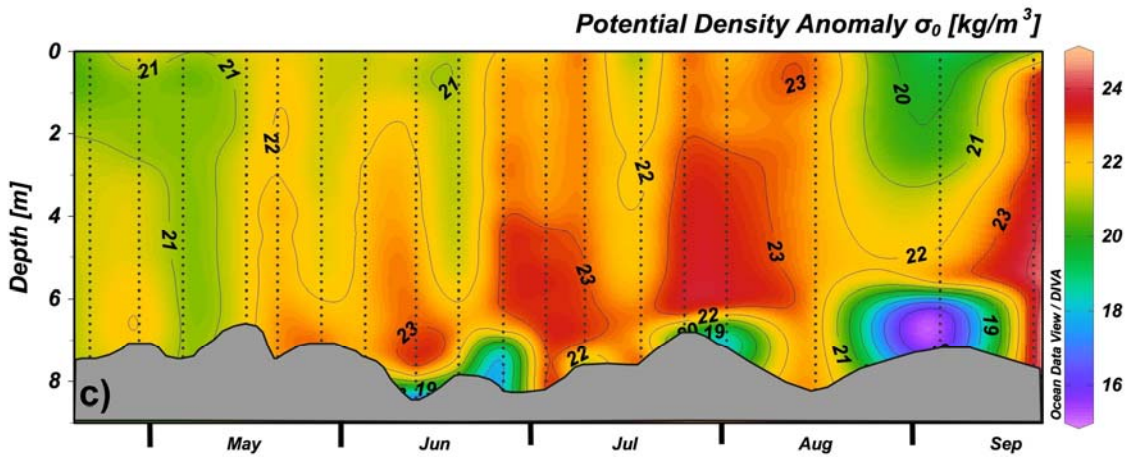
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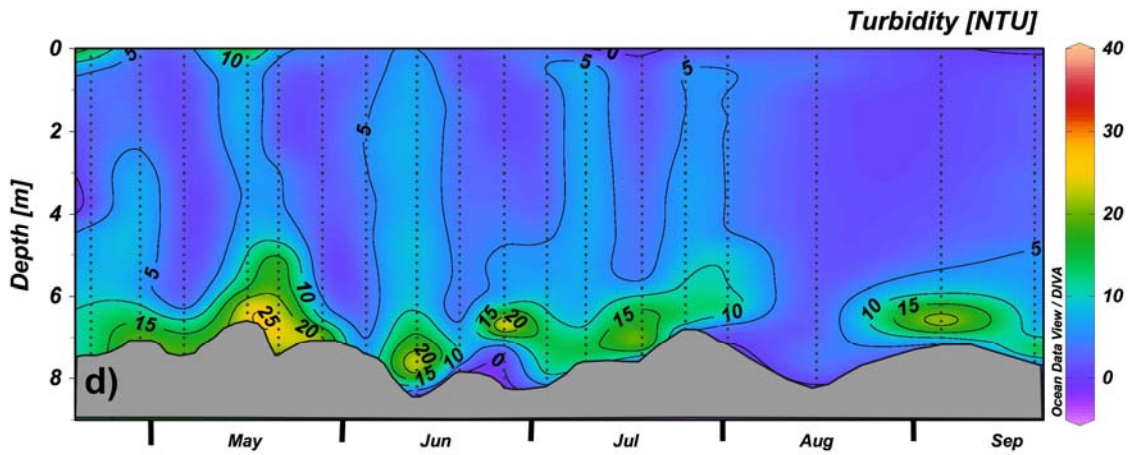
3a



3b



3c



3d

Figure 3.

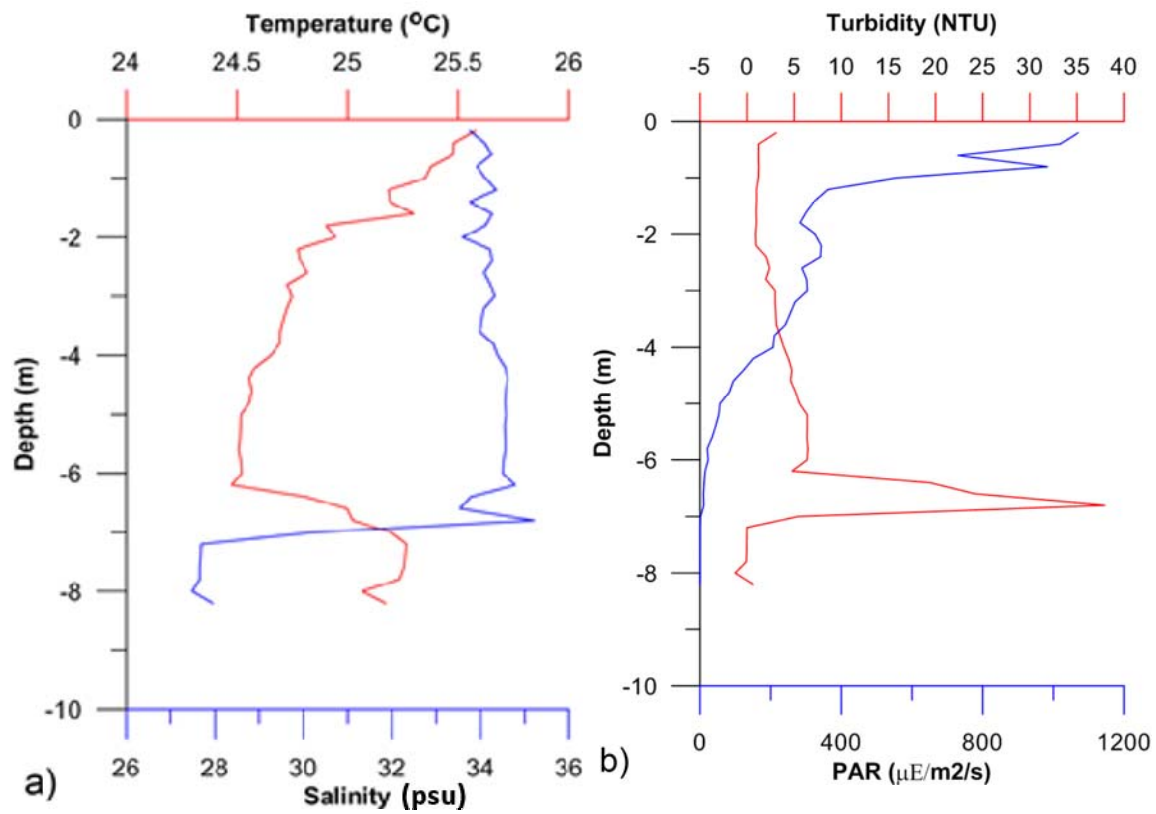


Figure 4.

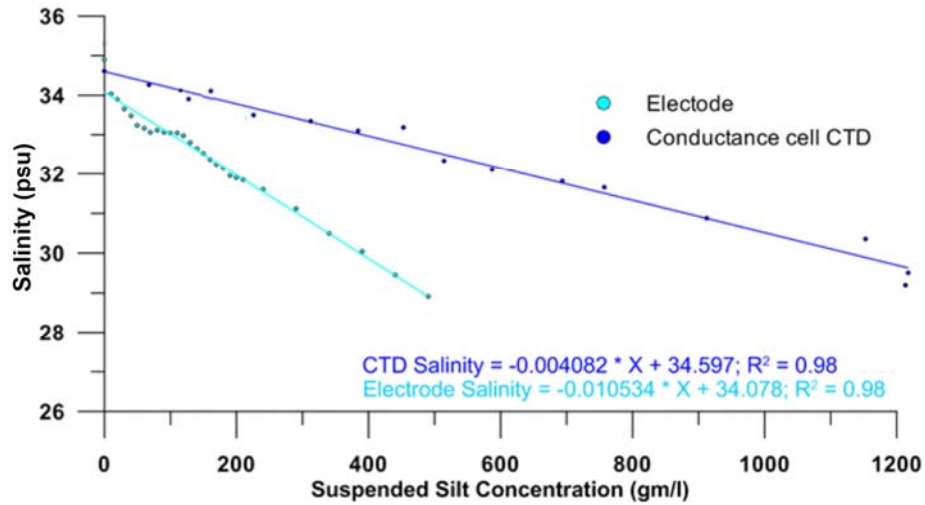


Figure 5.

TABLE. 1 Salinity values (psu) determined by CTD and EuTech salinometer for a range of suspended sediment used in the Tub Experiment

| Serial Number | Suspended Weight in g/l) | Suspended Weight in kg/m ³ | Salinity (psu) using CTD after adding sediment | Salinity (psu) using salinometer after adding sediment | Salinity (psu) of supernatant using salinometer |
|---------------|--------------------------|---------------------------------------|--|--|---|
| 0 | 0 | 0 | 34.60 | 34.83 | 34.84 |
| 1 | 68 | 6.8 | 34.27 | 34.45 | 34.48 |
| 2 | 130 | 13 | 33.97 | 34.19 | 34.41 |
| 3 | 149 | 14.9 | 33.99 | 34.25 | 34.80 |
| 4 | 226 | 22.6 | 33.49 | 33.71 | 34.61 |
| 5 | 312 | 31.2 | 33.34 | 33.52 | 34.71 |
| 6 | 384 | 38.4 | 33.09 | 33.31 | 34.60 |
| 7 | 453 | 45.3 | 33.18 | 33.39 | 34.56 |
| 8 | 514 | 51.4 | 32.33 | 32.57 | 34.55 |
| 9 | 587 | 58.7 | 32.11 | 32.41 | 34.50 |
| 10 | 694 | 69.4 | 31.81 | 31.99 | 34.64 |
| 11 | 757 | 75.7 | 31.66 | 31.78 | 34.88 |
| 12 | 912 | 91.2 | 30.87 | 30.99 | 34.87 |
| 13 | 1153 | 115.3 | 30.35 | 30.48 | 34.87 |
| 14 | 1217 | 121.7 | 29.50 | 29.62 | 35.01 |
| 15 | 1223 | 122.3 | 29.20 | 29.34 | 35.10 |