



Influence of upwelling induced near shore hypoxia on the Alappuzha mud banks, South West Coast of India



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ABSTRACT

The results of the first time-series measurements spanning 18-weeks (22 April to 20 September 2014) from a coastal environment (Alappuzha, southwest India), where two process of upwelling and mud banks are concurrent during summer monsoon are presented. The upwelling signals were evident from the 2nd week of May onwards and the intensity varied widely from 1st week of June to 3rd week of September. The formation of mud banks was observed during the peak upwelling period (14th June) and once formed, they were persistent till the end of monsoon season (September 2014). The time-series evolution of dissolved oxygen levels showed the incursion of hypoxic waters well in to the mud banks during peak upwelling period. The considerable reduction in the dissolved methane levels (300 to < 50 nM) during hypoxia is an anomaly, which may be due to some microbial processes. The incursion of hypoxic waters in to the Alappuzha mud banks is the first observation and is significant because, it can now explain why mud banks are not always good fishing grounds. The present study shows that the fish availability is mainly dependent on the incursion and prevalence of hypoxic waters in the mud banks.

1. Introduction

The littoral waters along the southwest coast of India (Kerala) develop a unique phenomenon known as mud banks during the peak southwest monsoon season (June to September), which are characterised by extremely calm environment with exceptional biological production (CMFRI Bulletin, 1984). Mud banks are believed to form due to the sudden deposition and prevalence of dense mud suspensions in the coastal regions during monsoon and appear in semi-circular patches extending up to about 5 km from the shore at a water depth of 5–10 m and 4 km alongshore (Balachandran, 2004). The mud banks of Kerala have great socio-economic importance owing to the abundant fish availability, as fishermen use these calm areas as platforms to launch their country crafts when the sea is very rough elsewhere (Gopinath and Qasim, 1974; Rao et al., 1984). However, despite numerous studies on these specialised environments, the formation, sustenance and functions of mud banks are poorly understood (Nair, 1976).

Mud banks are generally reported in the coastal regions adjacent to large river embayment's following the deposition of mud brought by rivers (Wells and Coleman, 1981; Aller, 1998). This kind of river-

induced mud banks have been reported along the Amazon coast (Anthony et al., 2008), the Louisiana coast (Mcbride et al., 2007), the Gulf of Papua (Walsh and Nittrouer, 2004), the northeast coast of China (Liu et al., 2006; Wei et al., 2007) and there are at least 20 places (Kochi, Ponnani, Kozhikode, Quilandi, Ullal etc.) along the south west coast of India also (Kurup, 1977a, 1977b). However, a few mud banks along the southwest coast of India (Fig. 1a) are located far away from any river entrance (eg: Alappuzha), but have been recurrent for centuries. The most striking character of all these mud banks are their extreme calmness when the coastal water in all other places are highly wave-beaten. Several reasons have been suggested as mechanisms for the development of Alappuzha mud banks including the wind-induced upwelling (Ramasastri and Myrland, 1959; Philip et al., 2013; Hareeshkumar and Anand, 2016), rip currents (Varma and Kurup, 1969; Kurup, 1972), waves (MacPherson and Kurup, 1981; Mathew et al. 1984), infra-gravity waves (Tatavarti et al., 1996, 1999; Tatavarti and Narayana, 2006), subterranean mud flow (Silas, 1984), subterranean fresh water flow (Balachandran, 2004; Tatavarti and Narayana, 2006) and hydrocarbon explosion (Nair, 1976; Narayana et al., 2008), though none of these hypothesis have been established.

Another concurrent process experienced by the southwest coast of

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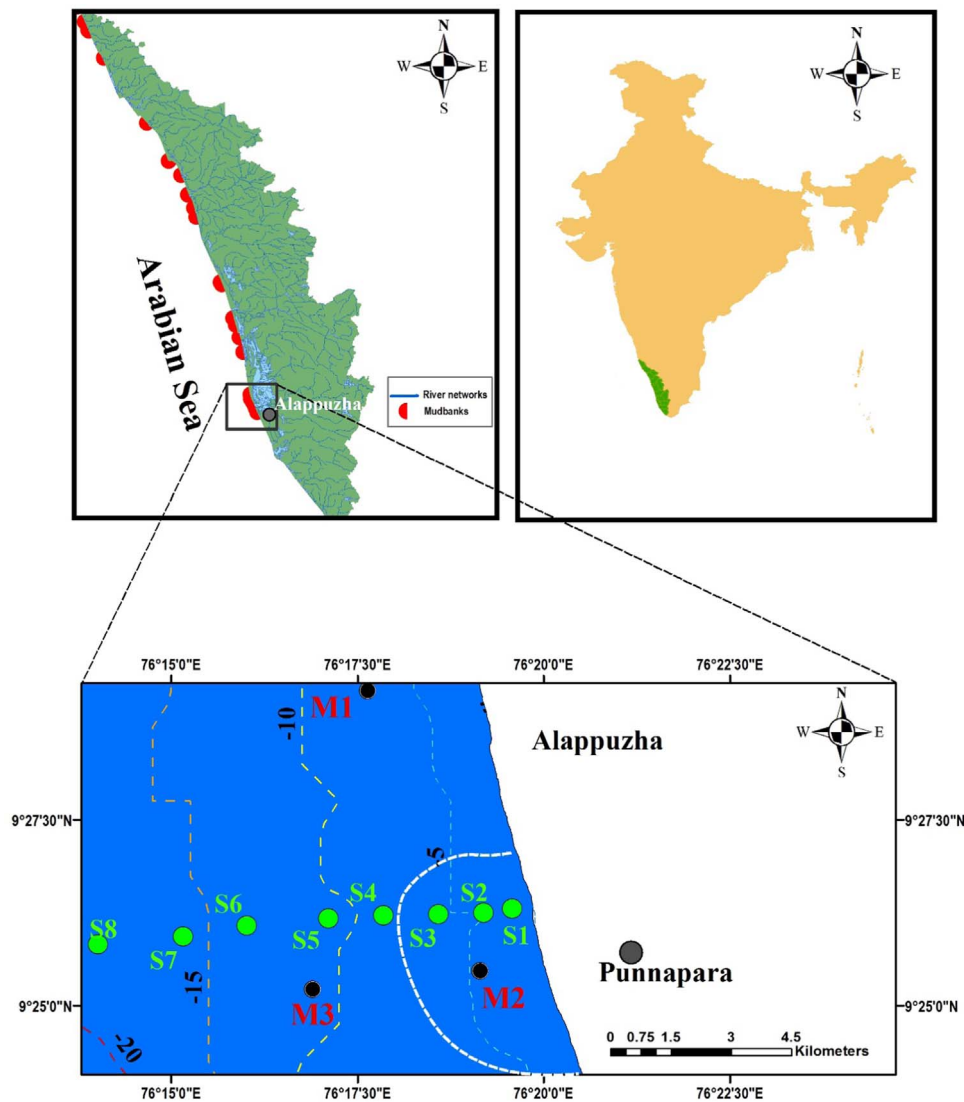


Fig. 1. (a) Map of Kerala coast showing locations of mud banks (b) Time Series locations off Alappuzha (mud bank region), south west coast of India. White discourteous line indicates mud bank area. M1, M2 & M3 (dots in black colour) denotes the time series locations and stations S1 to S8 (dots in green) denotes the sampling stations across the mud bank region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

India is intense upwelling during monsoon, when cold, nutrient-rich and hypoxic waters of the Arabian Sea mid-depth are brought to the surface to enhance the biological production (Naqvi et al., 2000; Guptha et al., 2016). The western continental shelf of India is the only region where the upwelling occurs in conjunction with high fresh water influx that results in strong stratification and increased respiration leading to the development of coastal hypoxia (Naqvi et al., 2000). Hence, the coastal upwelling is co-existent with the formation of Alappuzha mud banks. It should be noted that while coastal upwelling is a basin-wide process over the western continental shelf of India, the Alappuzha mud banks are only a coastal process over a small stretches of 10–15 km and spread in a small area (20–30 km²). Therefore, the present study is the first attempt to show how the hydrochemistry of a mud bank region changes due to intense coastal upwelling.

2. Materials and methods

2.1. Time series sampling

In order to study the hydro-chemical changes associated with two co-existing processes of upwelling and mud banks, a comprehensive time series measurement is essential. Therefore, a continuous 18-week

observation was carried out from three locations (M1, M2 and M3) in and around the Alappuzha mud banks from 22nd April to 20th September 2014 (Fig. 1b). Station M1 (7 m) is a non-mud bank region (reference), while M2 (7 m) represents the Alappuzha mud bank region ~7 km south of M1. Station M3 is an offshore reference point located to west of M2 and at a depth of 13 m. In order to understand the lateral extension of upwelling towards the coast, one transect across the mud bank bisecting both M2 and M3 was also sampled at 8 stations (S1–S8) on four occasions during peak monsoon period (8th, 18th, 31st July and 16th August). The stations S1–S3 were inside the mud bank, while S4–S8 were outside the mud bank, with S8 extending to a depth of 15 m (Fig. 1b). During all the sampling surveys, a conductivity, temperature and depth (CTD) profiler was used to record the temperature (accuracy ± 0.001) and salinity (accuracy ± 0.0001) from each station. For the 3 time-series stations (M1, M2, M3), water samples were collected at every 2 m interval, while during the special transect survey, the sampling frequency was from the surface and near-bottom up to 5 m, from 3 depths up to 10 m and from 4 depth at 15 m. The water samples were collected using a 5 L Niskin bottle and sub-sampled for dissolved oxygen (DO), methane (CH₄), and nutrients. DO samples were immediately fixed by adding Winkler's solutions. Samples for CH₄ were poisoned by adding 300 μ L of saturated HgCl₂ solution. Nutrient

samples were kept in ice and transported to the shore laboratory for analysis.

2.2. Analytical methodology

DO was analysed using Winkler's titrimetric method (Grasshoff et al., 1983) using an automated titration system. The water samples for nutrients were filtered through glass fibre filter paper (0.45 μm pore size) and analysed for NH_4^+ , NO_2^- , NO_3^- , PO_4^{3-} , $\text{Si}(\text{OH})_4$ using a UV–vis Spectrophotometer (Shimadzu UV 1800) following standard procedure (Grasshoff et al., 1983). The CH_4 samples were analysed using a Gas Chromatograph within a week of collection following the procedure adopted by McAullife (1971). Briefly, 25 ml of the sample was equilibrated three times successively with an equal volume of ultra-high-pure helium in a gas-tight syringe for 5 min and the moisture-free headspace was extracted and analysed on a GC (Shimadzu 2010) equipped with a flame ionisation detector. The separation was achieved on a stainless steel column (1.5 m length and 2.2 mm diameter) packed with molecular sieve (5A 80/100 mesh). The detector was calibrated at regular intervals using a standard gas mixture of CH_4 (MED gas) against 4.3 ppm CH_4 Standard Reference Material. To check the linearity of the detector, one laboratory standard was analysed at regular intervals. The ambient level of CH_4 was measured by collecting the atmospheric air in 60 ml gas tight syringe and directly injecting to the GC in the same manner as that of sample headspace.

3. Results and discussion

In general, the hydro-chemical characteristics of the three locations (M1, M2 and M3) did not exhibit significant variations indicating that the changes were almost uniform in the entire study region. Therefore, instead of comparing the mud bank region with reference stations, we have tried to explain the response of upwelling in the Alappuzha mud banks.

3.1. Temperature and salinity

The water column in the entire study region remained warm (30–32 °C) and vertically mixed at all the 3 locations (Fig. 2a) from April to mid-May 2014. From the second week of May onwards, the water temperature started cooling (28–29 °C) for the next two weeks, especially at depths (M3). The commencing of cooling is synchronized with strong north westerly winds indicating the onset of upwelling along the southwest coast of India (Hareeshkumar and Anand, 2016).

The upwelling along the southwest coast of India is known to be wind-driven though some remote forcing is also being attributed (Shetye et al., 1990, Hareeshkumar and Anand, 2016). It can be seen from Fig. 2a that the intensity of upwelling in the study region varied widely from June to September, depending upon the intensity of this north westerly winds (Muraleedharan et al., communicated). Thus, the water temperature progressively decreased from 29 °C to 25 °C from the 2nd week of May to the 2nd week of June. Assuming the temperature of upwelled water to be 26 °C for the south eastern Arabian Sea (Gupta et al., 2016), the period from 2nd week of June to the 2nd week of August can be considered as the peak upwelling period in the Alappuzha mud banks. The first phase of upwelling in the mud bank (M2) region from 1st June to 4th July was characterised by strong north-westerly winds. This was followed by a break monsoon (4th to 26th July), when the upwelling was weak and water column was warm (27 °C). The upwelling intensified (26–24 °C) soon after when the winds became much stronger and persisted up to mid-August, after which, the water column changed to warm (> 26 °C) condition from 3rd week of August to 20th September. Thus, the thermal structure could reveal the following processes cascading down in the mud bank region (i) initiation of upwelling in the deep during the 3rd week of May and its progression up to September (ii) intense, but oscillating upwelling signals from 2nd week of June to 2nd week of July (iii) a break monsoon from 4th to 26th July, when the upwelling became weak and water column was warm and vertically mixed and (iv) a persistent upwelling in the bottom from end of July to mid-August.

In contrast to the wide variations in the water temperature, the salinity (Fig. 2b) did not show significant variations except during the retrieval phase of upwelling. The entire study region remained high saline (34) from April onwards though there were some minor variations in shallow regions. There was a conspicuous lowering of surface salinity by 4 in surface water for about 10 days between August and September, possibly due to the heavy rains over the area during the first two weeks in August. But, the low values of salinity in the bottom of M1 and M2 are erroneous signals due to the *blinding effect* of conductivity sensor of CTD when lowered in to the fluid mud layer (Philip et al., 2014), which were also observed in other environments (Kineke et al., 1995, 1996; Traykovski et al., 2000).

3.2. Upwelling induced near shore hypoxia

The coastal waters were generally well-oxygenated up to the 2nd week of May (Fig. 3a). From the initial appearance of cool and low oxygenated (< 125 μM) waters in the bottom on 17th May, the

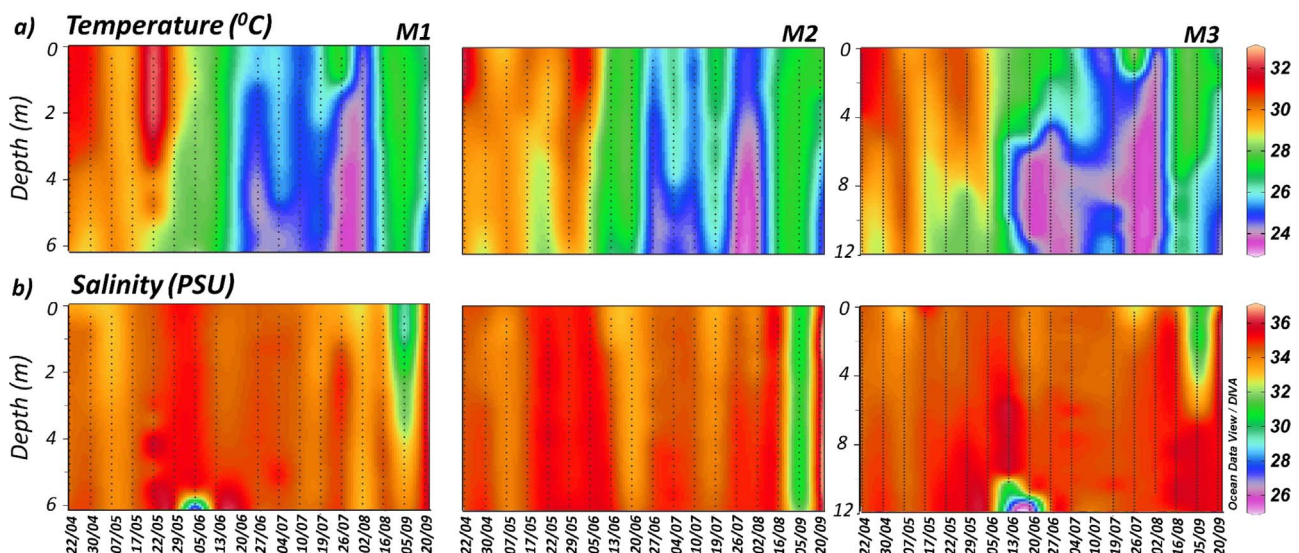


Fig. 2. : Distribution of temperature (a) and salinity (b) in the Alappuzha mud bank region.

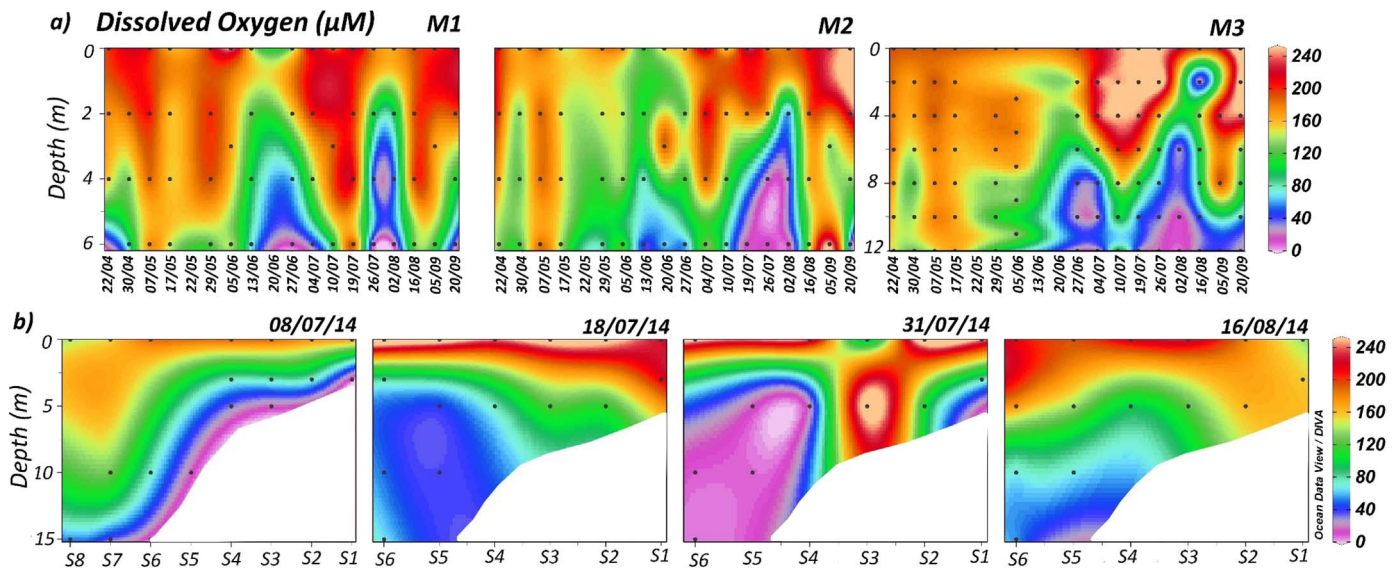


Fig. 3. : Distribution of dissolved oxygen in time series stations M1, M2 and M3 (a) and along the transect stations (b) in the Alappuzha mud bank region.

upwelling progressed faster for the next two weeks to intensify the oxygen deficiency to shallow depths (3 m). A close look at the oxygen profiles show that the subsurface waters remained hypoxic between 13th June and 16th August (except from 10 to 19th July). The thermohaline properties generally explain the water column conditions normally develop during the upwelling period in the south eastern Arabian Sea (Shetye et al., 1990).

The Chl *a* concentrations were at moderate levels ($1\text{--}2\text{ mg m}^{-3}$) in April, which further increased to $3\text{--}4\text{ mg m}^{-3}$ in June and even peaked to $7\text{--}8\text{ mg m}^{-3}$ in July to sustain at high levels until the 1st week of August (Madhu et al., 2015). This enhanced phytoplankton production may increase the oxygen demand of the already oxygen deficient upwelled waters leading to the development of near shore hypoxia including the mud bank regions. The presence of hypoxia (up to $5\text{ }\mu\text{M}$) in the shallow coastal regions (M1 and M2) form the first observation, as no previous observations along the west coast of India could so far sample from such shallow depths due to the rough sea conditions during monsoon. A recent time-series study off Kochi coastal waters have found the hypoxic waters ($10\text{ }\mu\text{M}$) at 10 m water depth (Gupta et al., 2016). Influence of upwelling in the development of suboxia/anoxia along the western coastal environment is already established (Naqvi et al., 2000, 2006), though its shoreward extension is not known. The fact that coastal hypoxic zones are reported off Benguela, Peru and California (Grantham et al., 2004; Diaz and Rosenberg, 2008) signifies the importance of the hypoxic water invasion up to the shorelines.

3.3. Near shore hypoxia and its implications on fisheries

The dissolved oxygen profiles obtained from the special transect on four occasions (8th 18th and 31st July and 16th August) are the first observational evidence on the lateral advection of upwelled waters along the southwest coast of India and in particular, in the Alappuzha mud banks (Fig. 3b). It is evident that upwelling transported the hypoxic waters into the mud bank region on a varying scale depending on the local winds. The automatic weather station (AWS) installed at Alappuzha indicated that the speed of north westerly winds to be 8.5, 5.5, 7.5 and 5.2 m/s respectively on 8th, 18th, and 31st July and on 16th August (Muraleedharan et al., communicated). The incursion of upwelled waters in to the mud bank region was maximum on 8th (wind 8.5 m/s) and 18th (wind 7.5 m/s) July, when the hypoxic waters ($\text{DO} < 20\text{ }\mu\text{M}$) reached as shallow as $< 3\text{ m}$ depth on 8th July and 6 m depth on 18th July. The wind speed was relatively weak on 18th July and

16th August observations, when the oxygen levels were relatively high in the mud banks. This is in support to the earlier observation that local winds have a major influence in the lateral expansion of upwelling towards the coast (Hareeshkumar and Anand, 2016).

The observation that hypoxic waters are intruding to the shallow coastal areas including Alappuzha mud banks has great implications in explaining the uncertainties in the potentials of mud banks as a good fishing ground (CMFRI Bulletin, 1984). Mud banks are generally believed to be rich in fishery, though in actual observation, they are found to yield good fish catch very rarely (Rao et al., 1980). The present observation can be used to explain this anomaly. The mud banks do not generally favour fish aggregation, but when there is a stress such as hypoxia, the fish tends to avoid hypoxic waters by migrating to the surface layers (see Fig. 3b on 8th and 31st July). Although we didn't have any fishery data during our study, we noticed intense fishing activity inside the Alappuzha mud banks on 8th and 31st July, indicating that the fish availability is mainly dependent on the incursion and prevalence of hypoxic waters in the mud banks. In fact, on 8th July, it was a spectacular site to witness lot of people casting nets from the mud banks at knee depth and even handpicking of prawns jumped out of the waters to the beaches (probably due to suffocation).

3.4. Nutrient enrichment in near shore waters

The nutrient concentrations were generally variable with respect to the upwelling intensity in the study region. The NO_2^- concentration was $< 0.5\text{ }\mu\text{M}$ during most of the time, but increased to $1.5\text{ }\mu\text{M}$ only during the peak upwelling period (Fig. 4a), when the oxygen levels were below $25\text{ }\mu\text{M}$. The NO_3^- and PO_4^{3-} showed a progressive increase in response to the upwelling (Figs. 4b and 5a). The NO_3^- concentration was $\sim 2\text{ }\mu\text{M}$ at all the stations up to 5th June (just before the onset of monsoon), which increased sharply to $7.5\text{ }\mu\text{M}$ at M2 and $4\text{ }\mu\text{M}$ at M1 between 5th to 13th June. Further increase was substantial at M3 ($15\text{ }\mu\text{M}$ on 27th June) along with an increase in NO_2^- ($1.75\text{ }\mu\text{M}$) and PO_4^{3-} ($1.75\text{ }\mu\text{M}$) levels. The surface enrichment of nutrients ($6\text{--}8\text{ }\mu\text{M NO}_3^-$; $1.0\text{--}1.5\text{ }\mu\text{M PO}_4^{3-}$) is in sharp contrast to previous observations in the central and north western Indian shelf, where the upwelled water was always capped by a 5–10 m thick low saline waters (Naqvi et al., 2006). It is likely that the wider western Indian shelf retains the upwelled waters for a longer time for better uptake of nutrients by phytoplankton as compared to the narrow southern shelf.

During the peak upwelling period, the NH_4^+ concentration (Fig. 4c)

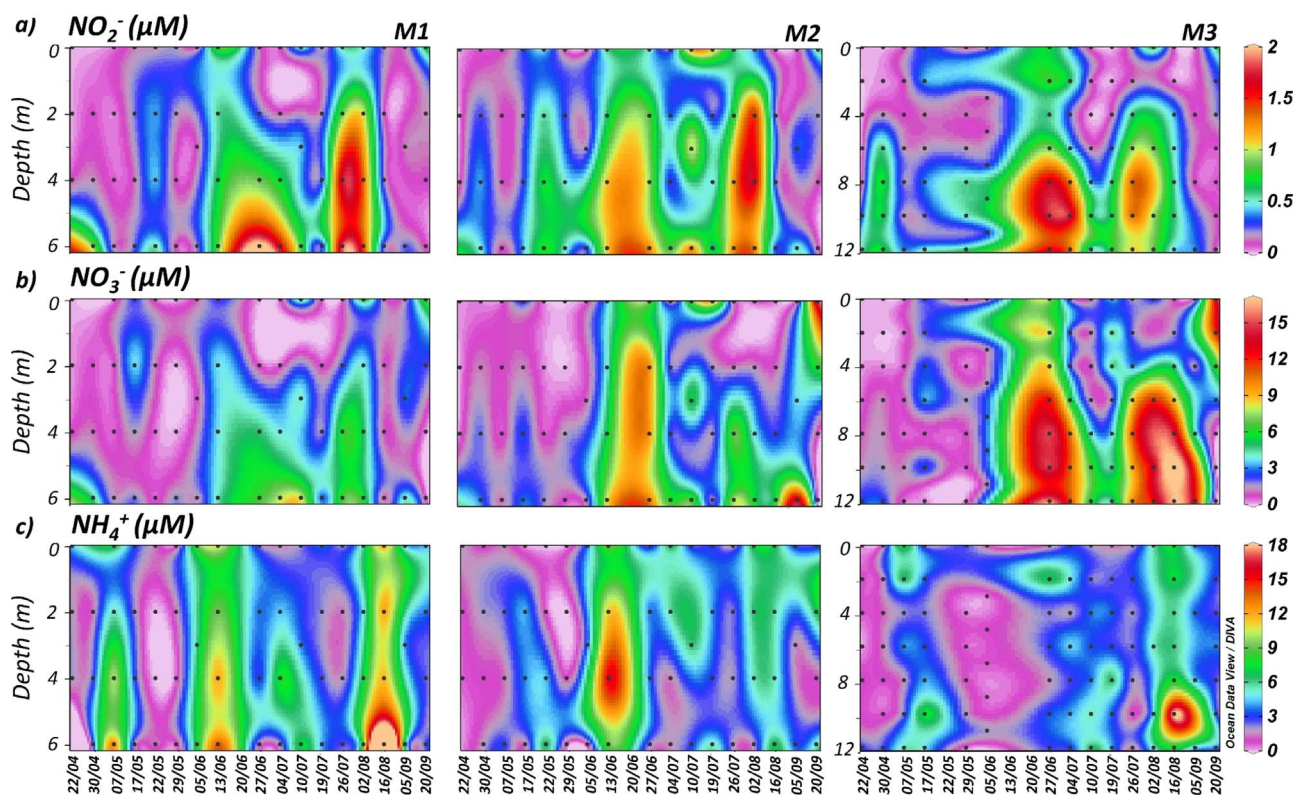


Fig. 4. Distribution of nitrite (a), nitrate (b) and ammonium (c) and silicate (d) in the Alappuzha mud banks.

increased rapidly at M1 and M2 on two occasions ($> 6 \mu\text{M}$ on 5th June and $> 3 \mu\text{M}$ between 20 and 30 June). The first peak may be due to decay of an intense diatom (*Flagilaria Oceanica*) bloom (Jyothibabu, pers. comm). The PO_4^{3-} concentration was generally low ($< 0.75 \mu\text{M}$) up to the 2nd week of May, but increased at mid-depth and bottom (up to $2.0 \mu\text{M}$) between 20 and 30 June. The Si(OH)_4 levels were high ($> 10 \mu\text{M}$) up to 20th June, which however, decreased to $5 \mu\text{M}$ on 26th July, in response to the upwelling intensity (Fig. 5b). Previous studies from this region have shown very high concentrations of $\text{PO}_4^{3-} > 10 \mu\text{M}$, $\text{Si(OH)}_4 > 40 \mu\text{M}$ and $\text{NO}_3^- > 4 \mu\text{M}$ (Rao et al., 1984).

Most of the coastal upwelling zones experiencing hypoxia are reported as denitrifying zones (Diaz and Rosenberg, 2008). The western continental shelf of India is also known to develop coastal

hypoxia as well as denitrification during the summer monsoon (Naqvi et al., 2000, 2006). In the Alappuzha mud bank also, a substantial loss of nitrogen was observed during the present study. The nitrogen deficit (N^*) indicates whether the system was denitrifying ($-\text{N}^*$) or nitrifying ($+\text{N}^*$) (Gruber and Sarmiento, 1997). NO_2^- and NO_3^- are normally considered in N^* calculations, when NH_4^+ concentrations are low in oceanic waters. Since we observed moderate concentrations of NH_4^+ in the mud banks, this was also included in the N^* calculation. The computed N^* deficits for the Alappuzha mud banks (up to $-15 \mu\text{M}$) were comparable with the values reported for the Arabian Sea oxygen minimum zone ($-11 \mu\text{M}$, Gruber and Sarmiento, 1997) indicating an intense water column denitrification (Fig. 6), probably through respiratory denitrification (Naqvi et al., 2006).

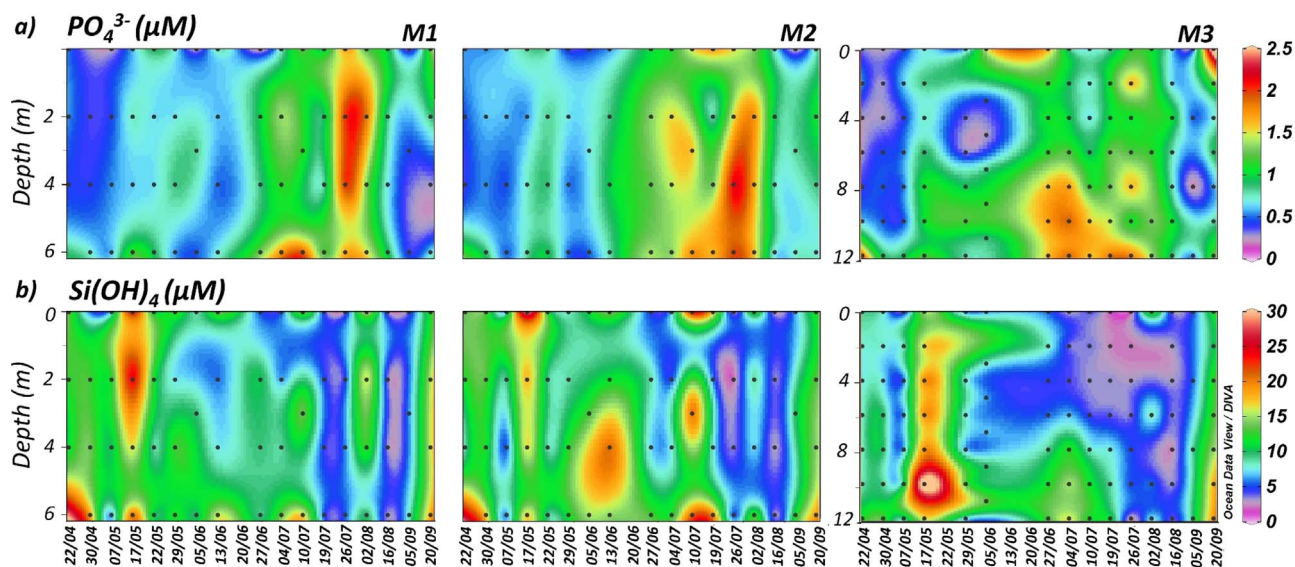


Fig. 5. Distribution of phosphate (a) and silicate (b) in the Alappuzha mud banks.

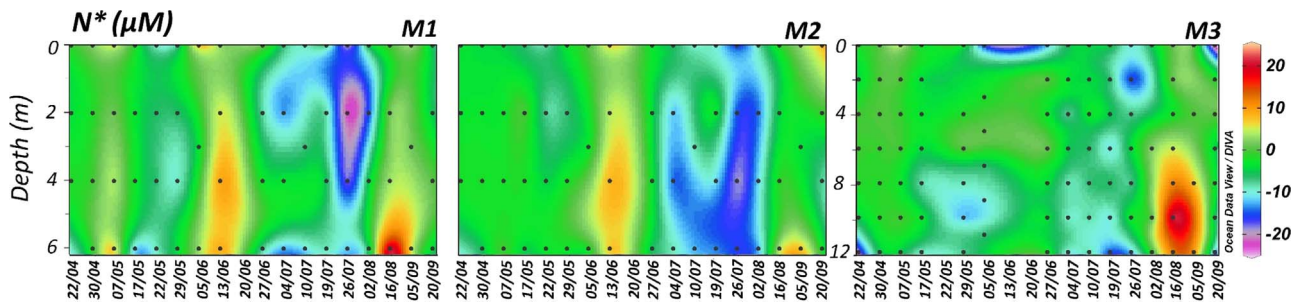


Fig. 6. Nitrogen deficit (N^*) in the Alappuzha mud bank calculated following the method of Gruber and Sarmiento (1997) with minor modifications.

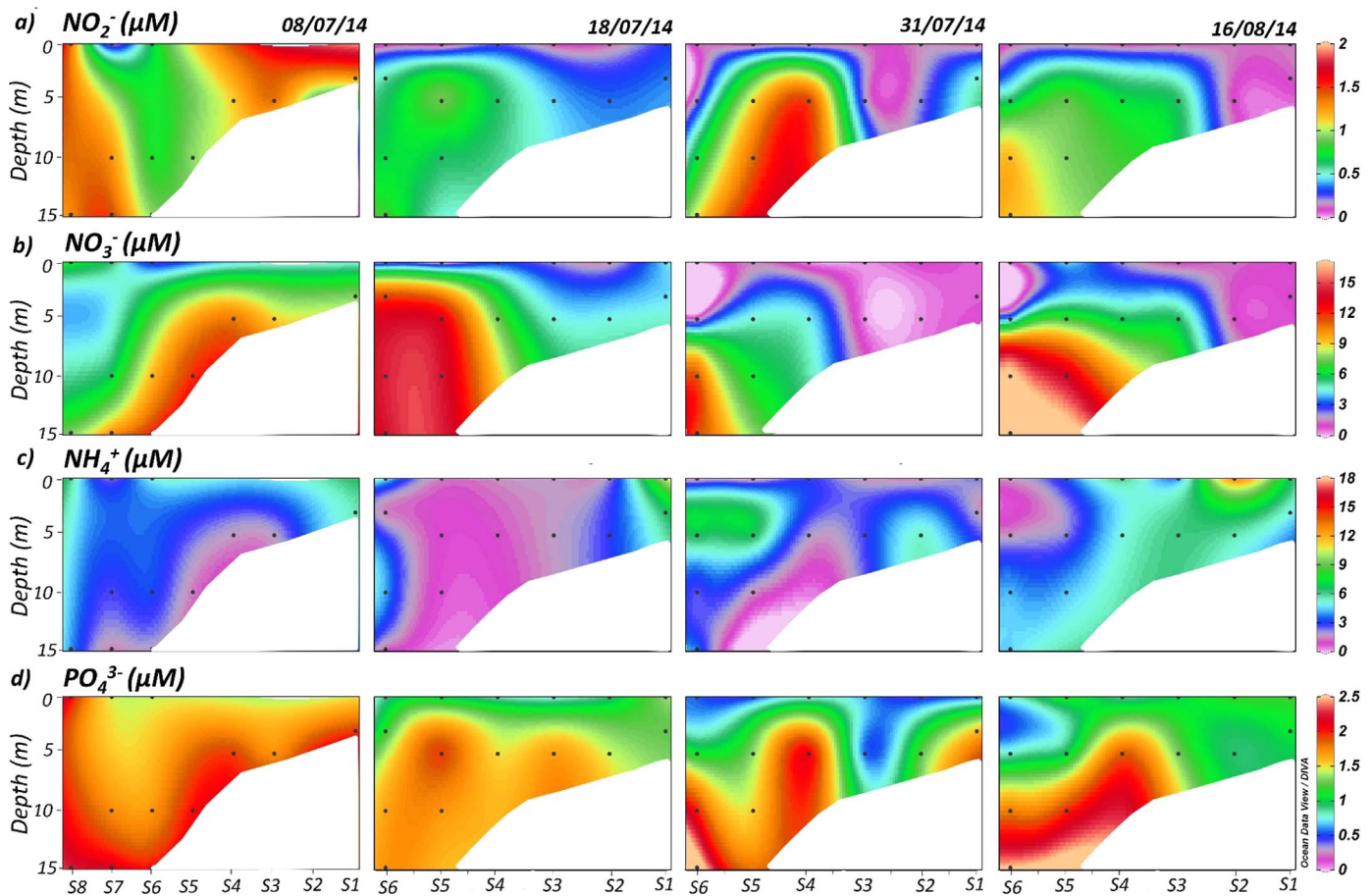


Fig. 7. : Distribution of nitrite (a), nitrate (b), ammonia (c) and phosphate (d) in the mud bank transect stations.

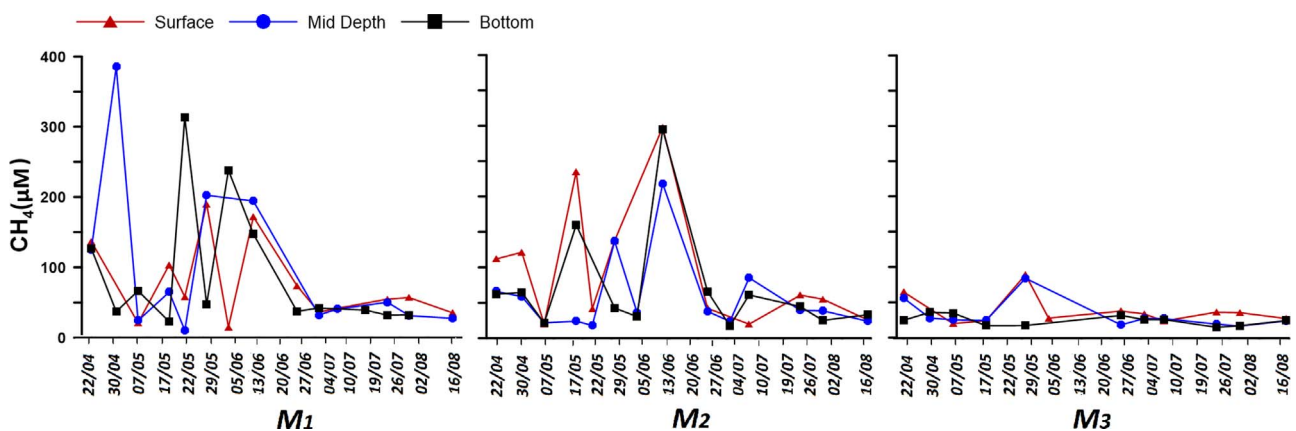


Fig. 8. : Distribution of methane in the Alappuzha mud bank, south west coast of India (mid Depth refers to 3 m depth at station M1 & M2 and 6 m at M3; Bottom depth refers to 6 m depth at M1 & M2 and 12 m at M3).

In order to study the lateral advection of upwelled waters towards the mud banks, an additional transect was sampled on four occasions from 8th July onwards. The varying intensity of upwelling is found to influence the nutrient levels considerably during the four surveys (Fig. 7a-d). There was a rapid enrichment in NO_2^- , NO_3^- and PO_4^{3-} levels in the subsurface during the entire period (Fig. 7a-c). The enriched NO_2^- ($> 1.4 \mu\text{M}$) levels in the hypoxic ($\text{DO} < 10 \mu\text{M}$) waters (on 8th and 31st July) is an indication of intense reducing conditions in the bottom (Fig. 7a). On 31st July observation, the NH_4^+ and PO_4^{3-} concentrations were also very high (Fig. 7c and d) in the surface, probably due to the decay of the bloom *Noctiluca miliaris*, which was abundant in this region during the previous week (Jyothibabu, per.comm). This kind of blooms are quite frequent along the southwest coast of India, especially during the onset and withdrawal phases of monsoon (Venugopal et al., 1979; Rao et al., 1984). The subsequent decay of these bloom can release high amount of NH_4 and PO_4^{3-} in to the water column (Pithakpol et al., 2000; Tada et al., 2004).

3.5. Distribution of methane

The methane concentrations were generally high in the shallow regions (M1 and M2) till the onset of monsoon (April and May), with an exceptionally high value (400 nM) at mid depth on 30th April (Fig. 8). With the onset of monsoon, there was a sudden spurt in the methane values at M1 (50–250 nM) and M2 (50–300 nM) during the last week of May to second week of June, which decreased to < 100 nM in third week of June and remained low (< 50 nM) throughout the study period. A similar trend was visible in M3 also, but with lower values. The concentrations at M2 were slightly irregular (150–250 nM from April to 13th June). Here, the distribution of methane and dissolved oxygen in the mud bank region gives a peculiar pattern that have not been reported elsewhere. The water column in mud bank region contained elevated methane levels during oxic conditions (prior to the upwelling). However, with the onset of monsoon, as the upwelling brought hypoxic waters in to the mud banks, there was an abrupt reduction in the methane concentrations. This is an anomaly as marine hypoxic regions are generally considered as a source of methane (Naqvi et al., 2010). In a seasonal upwelling environment, the Namibia shelf was also found to exhibit an exponential increase in the methane concentration (> 3500 nM) under hypoxic conditions (Monteiro et al., 2006).

The source of dissolved methane in marine environment is generally through sedimentary methanogenesis, which may increase to several folds during hypoxic condition (Naqvi et al., 2010). This was the condition prevailing at M1 and M2 from April to the onset of monsoon. However, the drastic reduction in the methane levels subsequent to the development of hypoxia was unexpected, which could be attributed to microbial processes involving anaerobic oxidation of methane (AOM) coupled with denitrification or oxidative dissolution of Fe and Mn oxides or sulphate reduction (Boetius et al., 2000; Beal et al., 2000; Haroon et al., 2013). Since there are no corresponding measurement on the anaerobic bacterial population, further studies are essential to understand the role of mud banks on methane dynamics.

4. Conclusion

The present study brings out the first time-series record showing the response of Alappuzha mud banks towards the seasonal upwelling and nearshore hypoxia. It was found that the intensity of upwelling and hypoxia along the southwest coast of India was well propagated to very shallow depths (< 3 m) in the mud banks leading to water column denitrification. The substantial reduction in the methane concentrations (300–50 nM) with the activation of mud banks. However, the reduction in methane caused during the hypoxic events was an anomaly, which could be due to anaerobic oxidation of methane coupled with other biogeochemical processes. The undulating hy-

poxic/oxic conditions in the mud bank region has wider implications on the fishing activities around the region.

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