

Fragilariopsis bloom causes yellowish brown waters off Alappuzha (south-central Kerala coast), during the Mud Bank - Upwelling phase

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Abstract

Mud bank (Chakara) of Kerala are calm coastal waters that form in several isolated stretches along the Kerala coast usually during the Southwest Monsoon period (June - September). They are characterized by the damping of incident waves, generating localized calm sea environment conducive for fishing activities while the high monsoon waves create hostile environment in the rest of the region. Here, we report the scientific basis of the yellowish brown discoloration of the water column that occurs off Alappuzha annually during the Peak - and Late - Southwest Monsoon associated with the Coastal upwelling - Mud bank event. The discolored waters that occur off Alappuzha associated with these events is locally known as 'Pola Vellam', which is nothing but diatom blooms. Pola Vellam 2014 was actually caused by the bloom of *Fragilariopsis*(=*Fragilaria*) sp.(hereafter *Fragilariopsis*), which was widespread in the study region, even beyond the Mud bank domain. Therefore, the observed bloom feature is attributable to the nutrient enrichment associated with intense coastal upwelling that was operational in a larger spatial extent in the study domain including the Mud bank. FlowCAM-based plankton data strongly supports the above view, as the abundance, biovolume and biomass of *Fragilariopsis* had similar temporal trend both in the Mud bank and the non-Mud bank regions in the study domain. The general ecology and the importance of *Fragilariopsis* bloom in the study domain, from the point of view of commercial fisheries, is elaborated in this research article.

Key words: *Fragilariopsis*, bloom, upwelling, Mud bank, southeast Arabian Sea

1. Introduction

Mud bank (Chakara) of Kerala is a unique coastal oceanographic feature that occurs in several isolated parts along the Kerala coast, between Alappuzha (south) and Ponnani (north), usually during the Southwest Monsoon (June-September). In the Mud bank, significant damping of the incident waves results in a calm sea environment conducive for fishing while the high monsoon waves create hostile environment in the rest of the region¹⁻⁶. Relatively high concentration of suspended sediments in the water column derived from a few meters thick fluid muddy layer close to the sea bottom is believed to be responsible for the wave damping and calm sea conditions within the Mud bank^{1,5,6}. Several hypotheses are in place to explain Mud bank formation along the Kerala coast⁷; however, a foolproof, scientifically convincing explanation is yet to evolve. Among the several Mud banks that form along the Kerala coast, the one that forms off Alappuzha has enjoyed special scientific and societal attention due to its consistent occurrence every year and also the rich fishery associated with it¹⁻⁴. Indeed, large stocks of planktivorous fishes (sardine, mackerel and anchovies) and shrimps are being landed on the adjacent shore every year associated with the Mud bank off Alappuzha during the Southwest Monsoon²⁻⁴.

Another significant and rather widespread oceanographic process that occurs along the southwest coast of India, having profound biophysical impact in the region, is the Coastal Upwelling operating during the Southwest Monsoon⁸⁻¹³. The physico-chemical signatures of the coastal upwelling include the surfacing of cool, nutrient-rich, low oxygenated (hypoxic to anoxic) waters towards the coast; these eventually induce significantly high plankton biomass and production in the continental shelf region⁸⁻¹³. World over, the coastal upwelling areas possess immense socio-economic significance as they represent the regions of high fishery resource availability^{14,15}. It is very pertinent here to consider the fact that the Mud banks that form in several isolated stretches of the Kerala coast during the Southwest Monsoon actually coexist with the coastal upwelling². Therefore, it was not very clear in the earlier times whether the enhanced plankton production and high fish landings observed every year associated with the Mud bank event was contributed by the Mud bank itself or by the Coastal Upwelling, which has a demonstrated biophysical impact over a large spatial extent². In fact, this enigma was investigated in an extensive fisheries study in the Alappuzha Coastal Upwelling - Mud bank region spanning over several years, which brought to light the fact that the entire region off Alappuzha, predominantly outside the Mud bank region, harbours large quantities of fishes^{3,4}. This study deciphered the enigma and presented a lucid interpretation that the high fish catch landing that is apparently associated with Alappuzha Mud bank is the biological manifestation of the Coastal Upwelling^{3,4}. As proposed originally by Banse^{8,9}, the surfacing of low oxygenated

sub-surface water associated with Coastal Upwelling tends to concentrate the fishes towards the surface waters, and these high fish concentrations in the surface waters are being exploited efficiently by fishermen by operating their fishing vessels through the Mud bank⁷. This implies that the high fishery landing in the adjacent shore of the Mud bank is ‘Coastal upwelling-driven’ and not ‘Mud bank-generated’^{3,4,5}. In short, the Mud bank, being a calm area with smooth sea surface acts as launching/ landing place and safe anchorage for fishing vessels to exploit the coastal upwelling-induced high fish stock available in the surface waters of the Mud bank and its vicinity³⁻⁶. All the above-stated points strongly indicate that the high fish landing associated with Alappuzha Mud bank, which remained enigmatic since long, is no longer a puzzle. Nonetheless, it is a fact that high fish landing occurs on the shore concomitant with the Alappuzha Mud bank event even though its major role is to function as a launching/ landing place and safe anchorage for fisher folks (Figure 1).

In 2014, CSIR-National Institute of Oceanography launched a multi-disciplinary field program off Alappuzha (AMPS- Alappuzha Mud bank Process Studies), mainly to track the causes of Mud bank formation and sustenance during the Southwest Monsoon (Figure 2a). Under AMPS, field sampling in three locations (M1, M2 and M3) was carried out from April (Pre-Monsoon) to September (Late-Southwest Monsoon), which included 15 weekly samplings (April 22nd to 2nd August) and 3 biweekly samplings (16th August to 20th September). Three locations off Alappuzha were sampled in this programme that included one location in the region where Mud bank forms during the Southwest Monsoon (M2). Two other locations (M1 and M3) were considered as reference points of the Mud bank location M2. Locations M1 and M2 were located at 8m depth contour while location M3 was at 13m depth contour. The alongshore distance between M1 and M2 was 8km, whereas the cross-shore distance between M2 and M3 was 3 km. Typically, the Mud bank off Alappuzha forms by the onset of the Southwest Monsoon (June), characterised by relatively high suspended sediments and damping of waves in a roughly semi-circular shape¹. During the present sampling period also, Mud bank formed around location M2 by the Early Southwest Monsoon (June), signified by visually discernible damping of incident waves and the prevalence of calm sea environment in a semi-circular shape, as presented in Figure 1.

During the Peak - and Late - Southwest Monsoon (July and August), when Mud bank had existed at location M2, a peculiar discoloration of the water was noticed in the entire study area. This discoloration was not only found in all three sampling locations but also in the entire sailing route between the three locations (8 km along shore between M1 and M2 and 3 km cross shore between M2 and M3). Importantly, it was noticed that the discoloration was more prominent in the trail of the sampling boat, indicating its high concentrations in the subsurface waters (Figure 2b-c). Several

sightings of such discoloured water during the course of our time-series sampling during the Peak and Late - Southwest Monsoon period motivated us to investigate the history of incidence of such discoloured waters in the study area. Native fisher folks had opined that such discoloration of the water is a characteristic feature off Alappuzha during the Peak and Late Southwest Monsoon period for which the local terminology in use is 'Pola Vellam/Kadal Kara.' Here in this scientific article, we present the scientific basis of 'Pola Vellam' in the near-shore waters off Alappuzha during the Peak and Late-Southwest Monsoon of 2014 and detail the hydrographical setting that favours such an enigmatic feature, with their possible linkages with the high fishery resources in the study domain.

2. Methods

The data collected using the following methods have been utilised to understand the scientific basis of the discoloured water observed off Alappuzha during the Peak - and Late-Southwest Monsoon period of 2014. Temporal variation in the vertical distribution of temperature and salinity in all three locations sampled was measured with a Conductivity Temperature Depth (CTD) profiler sensor (Seabird Electronics, USA). Surface (0.5m) and sub-surface (5m in M1 and M2 and 8m in M3) water samples collected using Niskin samplers were analysed for nitrate and dissolved oxygen concentrations¹⁶. Turbidity of the surface and sub-surface water samples was analysed using a turbidity meter (Eutech TN 100). The temporal change in the surface and sub-surface chlorophyll *a* concentration was estimated using a Trilogy fluorometer (Turner designs, USA)¹⁷ with water samples collected using a Niskin sampler (Hydrobios- Germany). Water samples from the surface and sub-surface were collected from all three locations and quantified the plankton components present in the water column using a FlowCAM (Fluid Imaging Technologies, USA), which is an advanced semi-automated equipment that combines the principles of both microscopy and flow cytometry^{5,18-20}. FlowCAM is an efficient tool to estimate the biovolume of the plankton components present in water samples in addition to the usual qualitative and numerical abundance parameters^{5,18-20}. Unpreserved samples were brought to the laboratory in black polythene bottle in cool condition within ~2 hours of collection and analyzed immediately in FlowCAM. The volume of the samples analyzed was decided on the nature and abundance of the phytoplankton cells present in the samples during different seasons. The FlowCAM analyses was based on 1000ml of water samples during the Pre-Southwest Monsoon/early Southwest monsoon, whereas, only 200 ml of water samples were analyzed during the rest of the Peak and Late-Southwest Monsoon. The quantification of phytoplankton using FlowCAM was based on a combination of 300µm field of view (FOV) flow cell and 4X objective. ABD algorithm of FlowCAM was used in the present estimations as it measures the biomass of complex biological particles with more accuracy than even

a traditional microscope²¹. In Area Based Diameter (ABD) algorithm of FlowCAM, diameter is measured by the number of grey scale pixels of the binary image of particles, which is then automatically converted to a circle with same number of pixels²¹. Subsequently, from the pixel volumes of the image, total biovolume of the individual gets generated, which is more accurate in cases of organisms with extended and protruded body parts²¹. The water samples during each sighting of the discoloured water were collected and analysed with a combination of light (Olympus IX 51), fluorescence (Olympus BX 53) and scanning electron (Neoscope, Nikon) microscopes for obtaining relevant morphological and physical characteristics of the plankton components. Every time during the sighting of the discoloured water, 5-10 Indian oil sardine (*Sardinella longiceps*) specimens were collected from the fish landings on the adjacent shore, which was irrespective of the sampling locations, and the gut contents were inspected qualitatively under an inverted microscope (Olympus IX 51) following standard procedure²². This attempt was to understand whether there is a direct linkage between high landings of oil sardine in the mudbank region with the discoloured water observed there during the Peak- and Late- Southwest Monsoon period.

3. Results and Discussion

The results of the microscopic analyses of the discoloured water are presented in Figure 3. It is clear that the causative organism of the discoloured water in the study area during the Peak- and Late- Southwest Monsoon was *Fragilariopsis*, a long, chain-forming, ribbon-like diatom considered to be significant in sustaining high oil sardine fishery along the Southwest Coast of India²³. The oceanographic process that favoured the blooming of *Fragilariopsis* in the study domain is evident in the temporal evolution of water column temperature in all three study locations (Figure 4). The most significant feature in the vertical distribution of temperature is the significant drop in temperature in the entire water column (cool waters) during the onset of the Southwest Monsoon (June), which indicates the intense coastal upwelling occurring in the study region. This upwelling signature was well-reflected in the concentration of dissolved oxygen and nitrate in all three locations (Table 1). Dissolved oxygen showed a large drop, especially in the sub-surface waters, during the Southwest Monsoon, whereas nitrate concentration noticeably increased in the entire water column during the period. High salinity (>30) prevailed in the study area throughout the study period with a relatively low salinity period during the late Southwest Monsoon period associated with increased rainfall, land runoff and river influx. There was a general increase in the water column turbidity values in all the locations by the onset of the Southwest Monsoon, which was more pronounced in the bottom waters. In the surface waters, relatively more turbidity was found in the M2 location during the Southwest Monsoon due to the prevailing Mud bank in the region. Based on the detailed results of turbidity

levels in the Mud bank region and its influence on the native plankton community has recently been presented, which evidences the fact that the turbidity level in the Mud bank water column is well below the critical level to inhibit the plankton growth and sustenance⁶. Similarly, the detailed results of the size, composition, abundance and diversity aspects of plankton component of AMPS, based on FlowCAM data has been recently published⁵. Importantly, as evident in Table 1, there was a noticeable increase in phytoplankton biomass (chlorophyll *a*) during all the three different phases of the Southwest Monsoon as compared to the Pre- Monsoon. A significant percentage of this high chlorophyll *a* stock during the Southwest Monsoon, especially during the Peak - and Late - Southwest Monsoon, was contributed by the large ribbon-like chains of *Fragilariopsis* dominant during these periods.

The temporal variations in abundance, biovolume and biomass of *Fragilariopsis* based on FlowCam measurements are presented in Table 1. These data reveal some important ecological aspects of *Fragilariopsis* in the study domain during different hydrographical settings, as was the case during the Pre-Monsoon and different phases of the Southwest Monsoon. During the Pre-monsoon, when the water column was warmer and the nutrient concentration was relatively low, the abundance, biovolume, and biomass of *Fragilariopsis* was also low as compared to different phases of the Southwest Monsoon. The most striking ecological feature of *Fragilariopsis* observed in the present study is the increase in their biovolume and biomass during the Peak- and Late-Southwest Monsoon, which was more pronounced than their increase in abundance during these period. As mentioned above, the significantly high biovolume and biomass of *Fragilariopsis* observed during the Peak- and Late- Southwest Monsoon was due to the high abundance of ribbon-like long chains, which was favoured by cool and nutrient-enriched upwelled waters. The FlowCam images representing the overall size of *Fragilariopsis* during the Pre-Monsoon/ Early-Southwest Monsoon and the Peak/Late- Southwest Monsoon are presented in Figure 3e, which depicts the above aspect. During the Pre-Monsoon/ Early Southwest Monsoon, *Fragilariopsis* chains were composed of 2-5 fragments, while during the Peak- / Late - Southwest Monsoon, they appeared composed of tens of fragments. The long chain forming character of diatoms under favourable growth condition in cultured and natural populations has been noticed earlier as well, even though the factor/factors determining the chain length or number of cells per chain in a given species has not been clearly explained²⁴. Also, from the preliminary experimental data we have generated along with AMPS sampling, it seems that the optimum solar radiation requirements of *Fragilariopsis* blooms along the southwest coast of India is quite low (30 - 70 $\mu\text{E m}^{-2}$), and this could be the reason why in the

present study, the blooms were found in less illuminated subsurface waters⁵. Further experimental studies on these line are our future interest so as to make conclusive statements on the above aspects.

A synthesis of the historical records of *Fragilariopsis* bloom along the southwest coast of India is presented below in relation to the present observations. Nair and Subrahmanyam²³ reported extensive blooms of *Fragilariopsis* off Calicut (Kozhikode) and presented the view that the success of the Indian oil sardine fishery is directly linked with such blooms that form every year. Subrahmaniam²⁵ have also discussed the importance of *Fragilariopsis* in connection with the small pelagic fishes along the Southwest coast of India. Later, Devassy²⁶ also recorded blooms of *Fragilariopsis* along the southwest coast of India and related it with successful oil sardine fishery. Even though, the above historical studies described the bloomed diatom as *Fragilaria oceanica*, here we did not consider the species level identity of the bloomed diatom in the present study region. This seems to be essential when considered the standard phytoplankton identification manual of Tomas²⁷, which describes *Fragilariopsis oceanica* as a cold water species. Therefore, we present here the view that more careful and focused investigations are required to become conclusive about the bloom forming diatom *Fragilariopsis*, their species level identity and their linkage with monsoon fishery along the Southwest coast of India. Nonetheless, the present fish gut content data also underlines that *Fragilariopsis* form a major diet content of Indian oil sardine in the study domain (Figure 5). However, due to the limited data, it is currently premature to draw general conclusions regarding the linkage of *Fragilariopsis* stock and oil sardine fishery success along the Southwest coast of India. We suggest that future research on this aspect should consider the fact that *Fragilariopsis* bloom usually occurs very close to the southwest Indian coastline, as was the case in the present study and also in historical times^{23,26}. Therefore, any future research in this line should focus on near-shore waters along the southwest coast of India. A focused multidisciplinary study considering the above aspects could be useful in resolving the current uncertainty associated with the occurrence of *Fragilariopsis* blooms along the southwest coast of India and its proposed linkage with the oil sardine fishery in the region.

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Figure 1- (a) Initial segregation of fishes landed on the shore adjacent to the Alappuzha Mud bank and (b) a typical view of Mud bank as a launching/ landing place and safe anchorage for fishing vessels. A flock of cranes on the shoreline in their usual flight is also visible in the snapshot

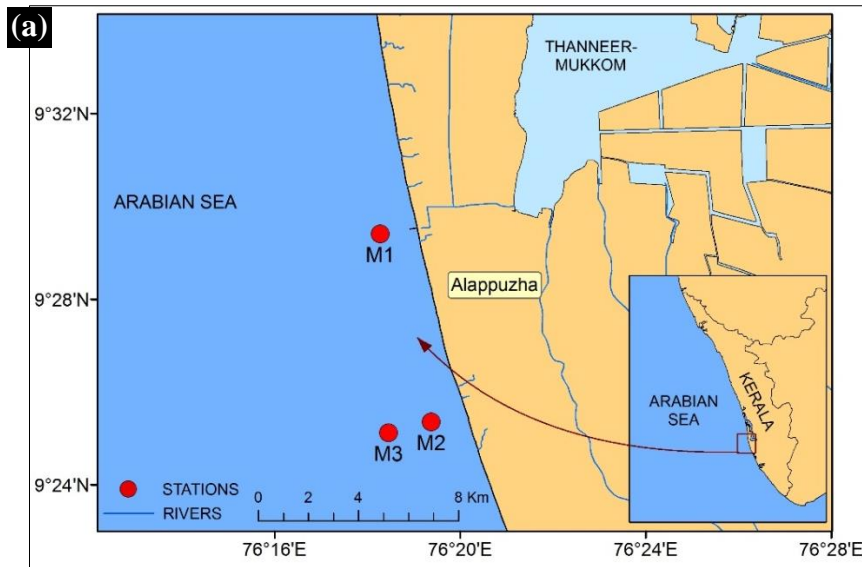


Figure 2- (a) Study area and sampling locations; (b & c) the trails of the boat between locations M1 and M2 that depict the yellowish brown discoloration of the water column due to the proliferation of *Fragilariopsis* sp., more so in the subsurface waters.

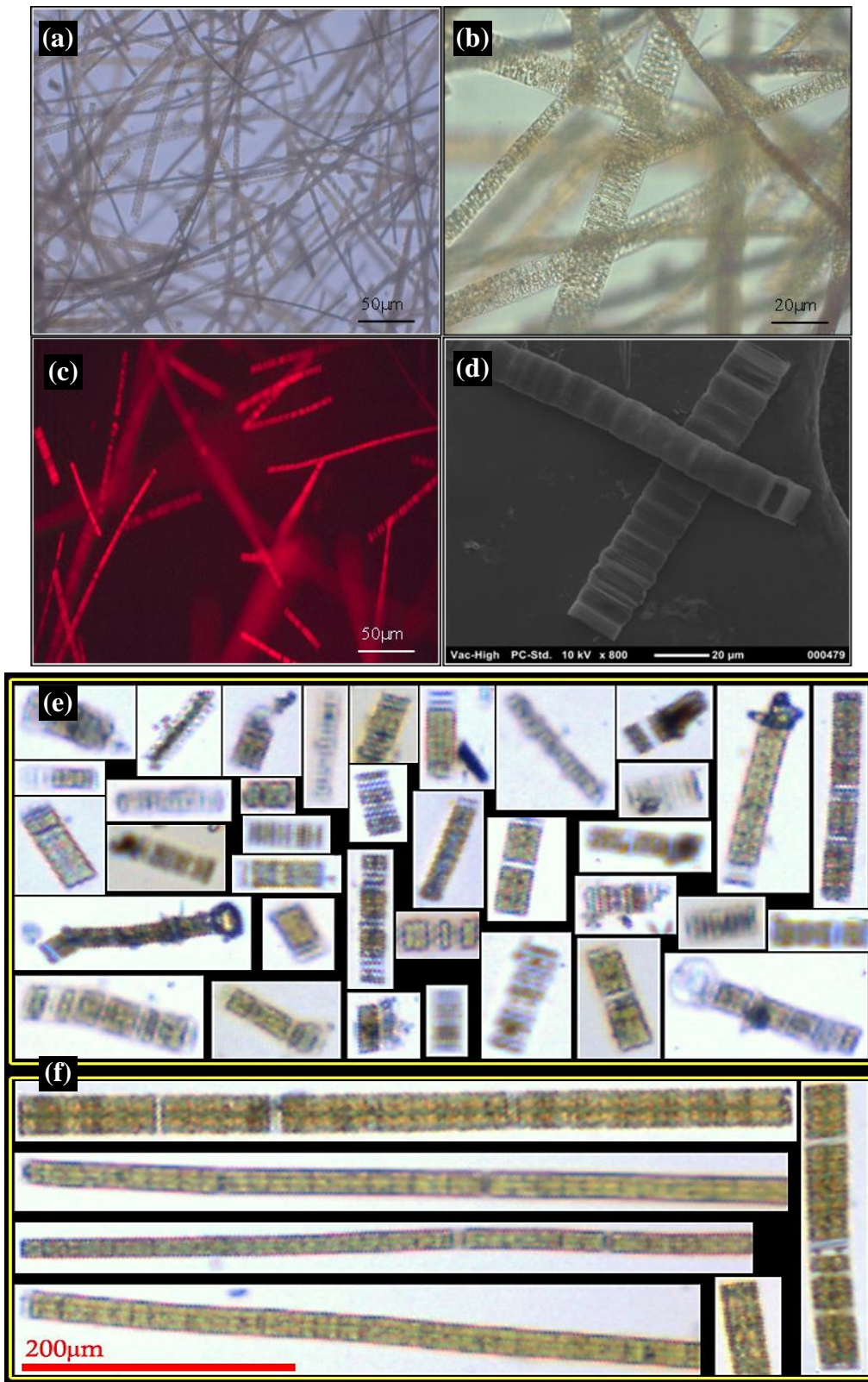


Figure 3 - Photomicrographs of the bloom of *Fragilariopsis* sp.; (a & b) light microscopy, (c) fluorescence microscopy and (d) scanning electron microscopy. FlowCAM images of *Fragilariopsis* sp. during (e) Pre-Monsoon/ Early-Southwest Monsoon and (f) Peak/Late-Southwest Monsoon period. Scale bars of panels (e) and (f) are the same; 300µm FOV flow cell and 4X objective of FlowCAM were used to capture these images.

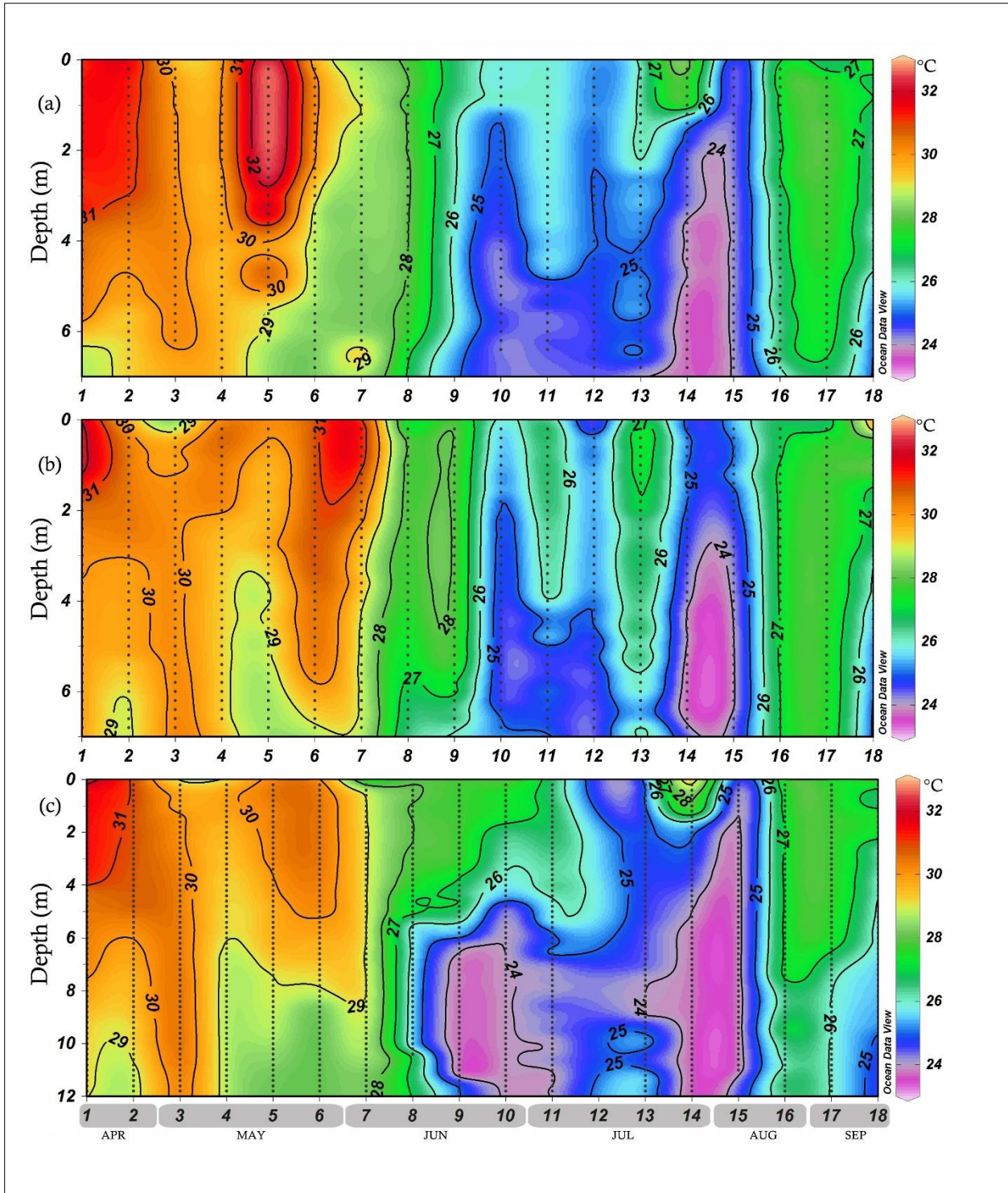


Figure 4 - Temporal variation in the vertical distribution of temperature. Intense coastal upwelling is reflected in all three locations studied, (a) M1, (b) M2 and (c) M3, as a significant drop in water column temperature from June onwards.

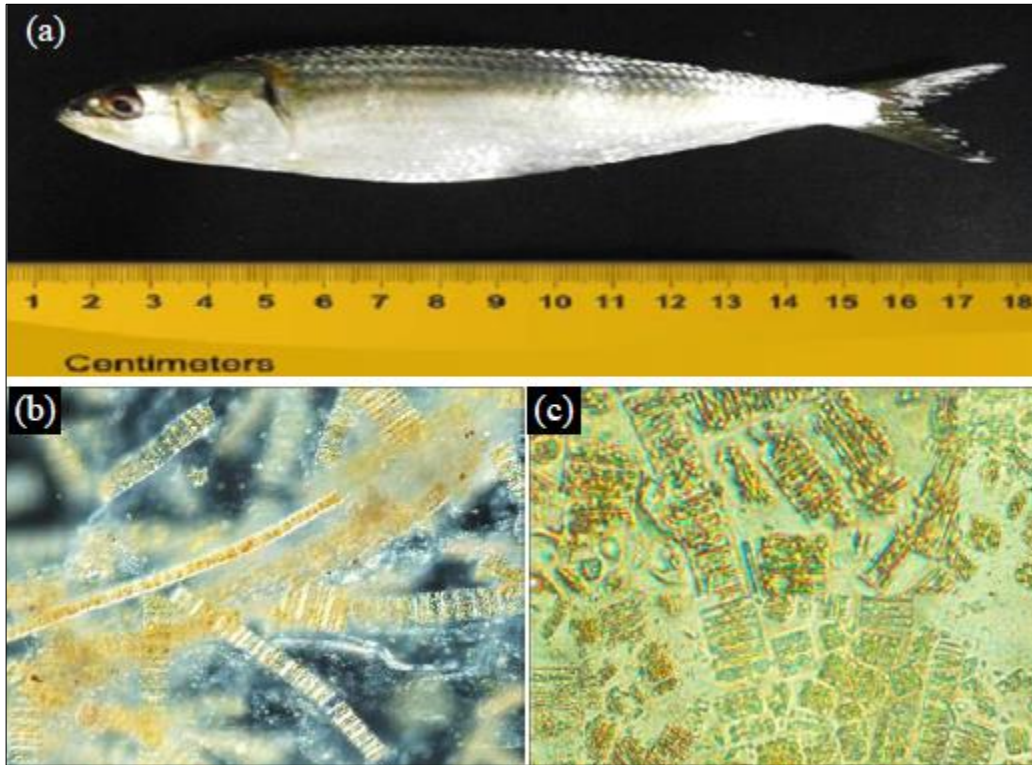


Figure 5- (a) Indian Oil Sardine (*Sardinella longiceps*) specimen from the Mud bank region and (b & c) *Fragilariopsis* sp. in their gut content.

Stn	Parameters	Depth	Pre-Monsoon (April-May)	Early-SWM (June)	Peak-SWM (July)	Late-SWM (August)
M1	Temperature (°C)	S	30.77 ± 1.21	27.45 ± 1.50	26.34 ± 1.30	26.46 ± 1.43
		SS	29.46 ± 0.75	26.82 ± 2.02	24.46 ± 0.65	25.75 ± 1.38
	Salinity	S	34.26 ± 0.64	34.71 ± 0.32	34.15 ± 0.43	32.80 ± 2.45
		SS	34.71 ± 0.42	35.01 ± 0.41	34.48 ± 0.28	34.40 ± 0.84
	Dissolved oxygen (µM)	S	190.48 ± 21.34	172.45 ± 68.90	178.65 ± 37.74	192.18 ± 20.90
		SS	153.64 ± 26.74	66.58 ± 51.53	32.12 ± 25.55	76.19 ± 58.83
	Turbidity (NTU)	S	1.66 ± 0.42	3.67 ± 0.62	5.76 ± 0.72	2.45 ± 1.06
		SS	2.42 ± 0.16	6.65 ± 2.24	11.59 ± 0.71	6.27 ± 0.86
	Nitrate (µM)	S	0.66 ± 0.94	1.18 ± 1.02	3.41 ± 2.13	1.39 ± 0.72
		SS	1.61 ± 1.76	3.65 ± 2.69	6.04 ± 3.27	3.49 ± 2.81
	Chlorophyll <i>a</i> (mg.m ⁻³)	S	1.77 ± 0.85	5.03 ± 2.62	9.3 ± 2.42	3.19 ± 1.84
		SS	1.76 ± 1.59	2.42 ± 1.04	5.20 ± 1.10	3.3 ± 0.49
	<i>Fragilariopsis</i> sp. abundance (ind.L ⁻¹)	S	66 ± 63	126 ± 79	966 ± 650	470 ± 156
	<i>Fragilariopsis</i> sp. biovolume (mm ³ L ⁻¹)	S	0.01 ± 0.01	0.03 ± 0.03	0.27 ± 0.12	0.23 ± 0.05
<i>Fragilariopsis</i> sp. biomass (mgCL ⁻¹)	S	0.01 ± 0.01	0.02 ± 0.02	0.23 ± 0.12	0.20 ± 0.04	
M2	Temperature	S	30.37 ± 1.11	27.58 ± 1.60	25.84 ± 1.43	27.06 ± 1.61
		SS	29.45 ± 0.58	26.88 ± 1.81	24.80 ± 0.95	25.89 ± 1.70
	Salinity	S	34.67 ± 0.23	33.85 ± 0.75	33.93 ± 0.89	32.93 ± 3.52
		SS	34.71 ± 0.53	34.63 ± 0.69	34.57 ± 0.30	34.10 ± 1.91
	Dissolved oxygen (µM)	S	175.06 ± 24.79	147.8 ± 0.52	199.7 ± 51.15	221.55 ± 34.39
		SS	128.34 ± 40.31	69.55 ± 7.54	34.41 ± 30.10	119.72 ± 76.25
	Turbidity (NTU)	S	1.72 ± 0.26	5.41 ± 0.76	6.74 ± 1.91	3.63 ± 1.96
		SS	3.15 ± 0.50	8.20 ± 2.60	12.85 ±	5.96 ± 1.72

					0.60	
Nitrate (μM)	S	0.70 ± 0.69	4.21 ± 3.01	3.25 ± 3.19	1.15 ± 0.97	
	SS	1.94 ± 1.02	5.60 ± 4.30	5.87 ± 4.40	3.91 ± 1.86	
Chlorophyll <i>a</i> (mg.m^{-3})	S	2.66 ± 1.82	4.51 ± 2.92	10.72 ± 7.78	4.98 ± 4.51	
	SS	2.09 ± 2.19	1.66 ± 0.68	5.70 ± 1.27	3.86 ± 1.83	
<i>Fragilariopsis</i> sp. abundance (ind.L^{-1})	S	84 ± 70	323 ± 120	1599 ± 930	280 ± 35	
<i>Fragilariopsis</i> sp. biovolume ($\text{mm}^3 \text{L}^{-1}$)	S	0.02 ± 0.01	0.05 ± 0.02	0.39 ± 0.21	0.92 ± 1.2	
<i>Fragilariopsis</i> sp. biomass (mgC L^{-1})	S	0.01 ± 0.01	0.04 ± 0.02	0.35 ± 0.25	0.77 ± 1.3	
Temperature	S	29.98 ± 1.36	27.52 ± 0.65	26.92 ± 2.08	26.72 ± 1.57	
	SS	28.98 ± 0.76	24.33 ± 0.86	24.32 ± 0.79	25.26 ± 1.17	
Salinity	S	34.34 ± 0.65	34.29 ± 0.35	33.97 ± 0.49	32.91 ± 1.08	
	SS	34.90 ± 0.40	35.02 ± 0.49	34.70 ± 0.11	35.30 ± 0.28	
Dissolved oxygen (μM)	S	181.22 ± 9.65	147 ± 12.30	225.53 ± 60.55	248.07 ± 73.72	
	SS	146.80 ± 30.43	16 ± 11.13	29.94 ± 19.25	41.72 ± 25.23	
Turbidity (NTU)	S	0.61 ± 0.24	1.69 ± 0.72	3.72 ± 1.92	1.37 ± 1.31	
	SS	1.71 ± 0.78	10.18 ± 0.30	9.28 ± 0.71	6.24 ± 0.74	
Nitrate (μM)	S	0.37 ± 0.47	0.54 ± 0.42	1.72 ± 1.53	1.32 ± 1.13	
	SS	2.28 ± 1.41	11.26 ± 5.44	11.11 ± 2.07	11.35 ± 8.51	
Chlorophyll <i>a</i> (mg.m^{-3})	S	0.66 ± 0.20	7.38 ± 6.42	10.05 ± 7.63	3.97 ± 2.95	
	SS	0.63 ± 0.36	2.13 ± 1.49	6.03 ± 3.01	2.82 ± 2.38	
<i>Fragilariopsis</i> sp. abundance (ind.L^{-1})	S	16 ± 20	98 ± 141	1245 ± 534	360 ± 65	
<i>Fragilariopsis</i> sp. biovolume ($\text{mm}^3 \text{L}^{-1}$)	S	0.01 ± 0.01	0.04 ± 0.05	0.31 ± 0.17	0.26 ± 0.01	
<i>Fragilariopsis</i> sp. biomass (mgC L^{-1})	S	0.01 ± 0.01	0.03 ± 0.1	0.27 ± 0.15	0.25 ± 0.02	

Table 1 - Physico-chemical and biological parameters in three locations (M1, M2 and M3) in the study area. Mud bank prevailed in M2 location during the Southwest Monsoon period. Mean \pm Standard deviation are presented. Abbreviations: SWM - Southwest Monsoon, S - Surface (0.5m) and SS - Subsurface (5m in M1 and M2 and 8 m in M3).