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3 **intrinsic nitrification feeding denitrification.**
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27 **Running title:** *Coastal anoxia - Intrinsic nitrification feeds denitrification*
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81**Abstract:**

Studies on the Arabian Sea coastal anoxia have been of immense interest, but despite its ecological significance there is sparse understanding of the microbes involved. Hence, observations were carried out off Goa (15°30'N, 72°40'E to 15°30'N, 72°59'E) to understand the processes that mediate the changes in various inorganic nitrogen species in the water column during anoxia. Water column chemistry showed a clear distinct oxic environment in the month of April and anoxic condition in October. Our study based on microbial signatures indicated that oxygen deficit appeared as a well-defined nucleus almost 40 km away from the coast during the oxic period (April) and spreads there after to the entire water column synchronizing with the water chemistry. Striking results of net changes in inorganic nitrogen species in nitrification blocked and unblocked experimental systems show that denitrification is the predominant process in the water column consuming available nitrate (~ 0.5 μM) to near zero levels within ~72 hours of incubation. These observations have been supported by concomitant increase in nitrite concentration (~4 μM). Similar studies on denitrification-blocked incubations, demonstrate the potential of nitrification to feed denitrification. Nitrification could contribute almost 4.5 μM to the total nitrate pool. It was found that the relation between ammonium and total dissolved inorganic nitrogen (DIN) pool ($r = 0.98$, $p < 0.001$, $n = 122$) was significant compared to the latter with nitrite and nitrate. The occurrence of high ammonium under low phosphate conditions corroborates our observations that ammonium does not appear to be locked under low oxygen regimes. It is suggested that ammonium actively produced by detrital breakdown (ammonification) is efficiently consumed through nitrification process. The three processes in concert viz. ammonification, nitrification and denitrification appear to operate in more temporal and spatial proximity than hitherto appreciated in these systems and this gives additional cues on the absence of measurable nitrate at surface waters, which was earlier attributed only to efficient algal uptake. Hence we hypothesize that the alarming nitrous oxide input into the atmosphere could be due to high productivity driven tighter nitrification-denitrification coupling, rather than denitrification driven by extraneous nitrate.

Key words: Denitrifiers, Nitrifiers, Coastal anoxia, Arabian Sea

82 INTRODUCTION

83 Progressive and cyclic developing of oxygen deficient waters over the continental shelf of the
84 western India has received much attention (Naqvi et al. 2000). West India Coastal Current (WICC)
85 flows equatorward along the west coast of India during June-September in response to alongshore
86 wind stress and consequent upwelling can be seen along the coast (Shetye et al. 1990). The
87 biological activity over the continental shelf is enhanced during the summer due to intense coastal
88 upwelling and Ekman pumping (Brock et al. 1991). The upwelled water over the shelf covers an area
89 of 180,000 km² (Naqvi et al. 2000) and is extremely oxygen depleted (Banse 1968). Naqvi et al.
90 (2000) reported that this coastal water body could be one of the largest low-oxygen zones, which
91 begins its annual development in June, reaching peak intensity by September-October and
92 dissipating by December. Further, they measured the highest accumulations of hydrogen sulphide
93 (H₂S) and nitrous oxide (N₂O) in open coastal waters and attributed to the addition of anthropogenic
94 nitrate and its subsequent denitrification, which is favored by hypoxic conditions. It is now well
95 understood that coastal anoxia is more widespread geographically with periodic cyclicality. Hence, the
96 cues that trigger such processes could be linked to large scale oceanic processes than hitherto
97 understood. A 5-10 m thick cap of warm, relatively less saline waters over the upwelled water
98 clearly indicate the magnitude of terrestrial runoff accompanied by precipitation (Banse 1959).
99 However, despite its origin from land runoff with sufficient nutrient load, low nitrate values
100 observed in this warm-water cap is attributed to efficient algal uptake (Naqvi et. al 2000). If this
101 were to happen, then the denitrification process would be constrained by the availability of nitrate.
102 The observed high N₂O accumulation (Naqvi et al. 2000) is indicative of availability of nitrate
103 despite algal uptake. Consequently, there could be a more significant pathway dynamically linked to
104 denitrification contributing significantly to NO₃⁻ and N₂O flux. The low O₂ conditions are also known
105 to enhance the yield of N₂O during nitrification, and so the possibility of contribution coming
106 through this pathway cannot be excluded (Goreau et al. 1980). Shailaja (2001) has shown that both
107 denitrification and nitrification occur in several closely spaced layers in the Arabian Sea and the

108 contribution of nitrification to nitrite enrichment in the perennial oxygen minimum zone is
109 significant. Despite the growing interest in mechanisms involved in the development and regression
110 of coastal anoxia and emission of potential green house gases into the atmosphere, the role of
111 microbial processes in driving this ecosystem has received little attention.

112
113 Ammonia-oxidizing nitrifiers and sulphide-oxidizing denitrifiers (Example: *Thiobacillus*
114 *denitrificans* like organisms; TDLO) are physiologically diverse bacterial groups, which respond in
115 tandem to environmental chemistry. Recording the spatial and temporal distribution of these groups
116 and their synchronization with the water column chemistry gives us a better understanding of the
117 dominant microbial processes and their potential contribution to gaseous inputs to the atmosphere.
118 Hence we hypothesize, that ammonification fed nitrification under hypoxic conditions could be more
119 important than previously thought of in these systems. The alarming nitrous oxide input into the
120 atmosphere could be due to a tighter nitrification-denitrification coupling, rather than denitrification
121 driven by extraneous nitrate alone.

122

123 MATERIALS AND METHODS

124 Study area and sampling:

125 A cross shelf transect off Goa (15°30'N, 72°40'E to 15°30'N, 72°59'E) was selected to study the
126 spatial and temporal variation of nitrifiers and denitrifiers with respect to the water chemistry for two
127 contrasting periods viz. April (oxic) and October (anoxic) during the cruises SaSu-40 (April, 2003),
128 49 (October, 2003) and 103A (October, 2005) onboard C.R.V. Sagar-Sukti. Though the cruises
129 conducted in April and October 2003 are the best representative of the contrasting conditions,
130 analysis of additional data from other cruises almost corresponding to the period were undertaken
131 [SaSu-26 (September 2002), 29 (December, 2002)]. A similar transect off Mangalore (13°00'N,
132 74°38'E to 13°00'N, 74°03'E) during cruises SaSu 26, 30 (December, 2002), and 49 have also been

133 included in this analysis. Such extended analyses were undertaken to get a better perspective of the
134 accumulation/oxidation of dissolved ammonium and inorganic phosphate in the water column.

135
136 Portable CTD (conductivity, temperature, depth) was used to obtain temperature and salinity profiles
137 at sampling locations. Seawater was collected using Niskin water samplers attached to the winch
138 wire and triggered with a messenger. Seawater sub-samples for microbiological analyses were
139 collected into sterile containers immediately after retrieval of the bottle. Sub-samples for nitrate and
140 phosphate measurements were frozen for onshore analysis, whereas ammonium and nitrite were
141 measured onboard.

142
143 **Water column chemistry:**
144 Dissolved oxygen (DO) and nutrients (ammonium, nitrite, nitrate and phosphate) in the seawater
145 samples were measured by colorimetric and titrimetric methods respectively (Grasshoff 1983).

146
147 **Abundance of nitrifiers and sulphide oxidizing denitrifiers:**
148 Nitrifiers and Sulphide-oxidizing denitrifiers (*Thiobacillus denitrificans* like organisms, TDLO)
149 were enumerated as Colony Forming Units (CFU) on different selective media. Nitrifiers were
150 enumerated by spread plating onto solidified Winogradsky's medium (Rodina 1972). After
151 inoculation, the plates were incubated for 30-45 days at $15\pm 2^{\circ}\text{C}$. The TDLO were enumerated by an
152 agar shake method on modified Leiske's medium (Loka Bharathi 1989; Loka Bharathi et al. 1988).
153 The culture tubes were incubated for ~30 days at $28\pm 2^{\circ}\text{C}$.

154
155 **Nitrification and denitrification studies:**
156 Seawater for incubation experiments were collected at definite intervals (surface, 8, 13 and 18 m)
157 from a 25m deep station off Goa on R.V. Sagar Sukti #103A in the month of October (2005). Sub-

158 samples in triplicates were then transferred into sterile, plugged, 250 ml, glass conical flasks, which
159 were incubated in the dark onboard under ambient temperature. The temperature in the incubation
160 flasks varied between 26-29°C. Three sets of incubation experiments were carried out viz., – (1)
161 Nitrification was inhibited by adding Allyl thio urea to a final concentration of 86 µM (Ginestet et
162 al. 1998), (2) Denitrification was inhibited by adding Chloramphenicol to a final concentration of
163 300 mg L⁻¹ (Brooks et al. 1992), and (3) Sub-samples of third set were monitored without adding
164 any inhibitors (controls). Aliquots were analyzed at 24 hrs intervals up to 144 hrs (6 days) for nitrate,
165 nitrite and ammonium.

166

167 **Contours, plots and statistical analysis:**

168 Bacterial abundance contour map was generated using Surfer 8.0 (Golden Software, Golden, CO).
169 Gridding used a kriging algorithm with a linear variogram and no anisotropy, as employed in
170 standard topographic applications. Scatter plots and line graphs were constructed using Grapher 4.0
171 (Golden Software, Golden, CO, USA). Statistical analyses were done using Analysis Tool Pack in
172 Microsoft Excel.

173

174 **RESULTS**

175 Surface temperatures roughly followed the solar heating pattern with primary and secondary heating
176 during the March-April and September-October. The salinity profile for October showed the
177 influence of riverine input as evidenced by the development of a less saline, warm water cap.
178 Variations in temperature and salinity during October (Figs.1a and 1b respectively) showed an
179 upwelling signature, possibly during the waning phase of the WICC. The WICC flows northward
180 during January-April, which results in downwelling along the coast. The temperature/salinity
181 profiles for April (Figs.-2a and 2b respectively) also showed downwelling signatures, though weak.
182 The SST was cooler during October than in April, possibly due to the upwelling and the imminent
183 winter. However, the signatures were weak during the transition periods i.e. April and October.

184

185 Changes in water column chemistry (Figs.1 c-e and 2 c-e):

186 During October, the shelf was characterized by low-oxygenated bottom waters ($<0.5 \text{ mL}^{-1}$) of ~40m
187 overlying the shelf. Nitrate values increased gradually to reach $>4 \mu\text{M}$ at around 90m depth. It was
188 observed that the thickness of nitrate-poor surface waters had decreased considerably. It was also
189 interesting to note that nitrite and nitrate values in the month of oxygen deficit (October) showed a
190 similar distribution pattern as that of the oxic month (April) but with enhanced concentrations.
191 Patchiness in nitrite distribution seen during April was lost but replaced by a core of elevated nitrite
192 at around 50 km from the coast (Fig.1e). In April, the concentration of nitrate and nitrite was very
193 low in the top 20 m of the oxic water and it gradually increased to $>1.4\mu\text{M}$ at around 90m water
194 depth. The distribution of nitrite was patchy and elevated concentrations were noticed at around 40
195 km from the coast (Fig.2e).

196

197 Bacterial abundance (Table 1):

198 During April, the abundance of nitrifiers were in the order of $10^{7-8} \text{ CFU L}^{-1}$ and patchy. The TDLO
199 numbers showed that there is a core of elevated abundance almost 40 km away from the coast. By
200 October nitrifier counts fell sharply to even reach non-detectable levels. In October, the distribution
201 of TDLO was uniform and generally increased away from the coast. There was not much difference
202 in the abundance of TDLO ($10^{4-5} \text{ CFU L}^{-1}$) in both the contrasting periods.

203

204 Nitrification and denitrification:

205 In October (2005), the temperature and salinity (Fig.3a) ranged from 26.3-28.6°C and 35-35.5 psu
206 respectively throughout the water column. The levels of nitrite, nitrate and ammonium which served
207 to define the initial conditions during the experimental incubations is illustrated in Fig.3b. The
208 concentration of nitrite increased with depth while nitrate remained almost constant. Ammonium

209 values showed two peaks viz subsurface and bottom indicating that there is considerable amount of
210 spatial heterogeneity in ammonium levels. The results of the incubation experiments are presented in
211 Figs. 4-6.

212
213 ***Denitrification blocked system (Fig 4 a-e):***

214 At the surface (Fig.4a) the levels of nitrite did not vary much over an incubation period of 144 hours
215 when denitrification was inhibited by chloramphenicol, but nitrate increased to almost 2 μM in 96
216 hours and plateaued at the end of incubation (144 hours). The ammonium levels increased at a slow
217 rate over the incubation period to reach final values of around 5.5 μM . At 3m (Fig.4b), the values of
218 ammonium fluctuated with a decrease followed by an increase with very little variation in nitrite but
219 with constant increase in nitrate, which reached 2.6 μM in 144 hours. At 8m (Fig.4c), the variation in
220 nitrite values fairly resembled the surface and 3m incubations except for a sharp decrease in the first
221 24 hours. At 13m (Fig.4d), nitrite and nitrate values evolved as in the 8m water depth though
222 absolute values differed. The irregularities observed in the rise and fall of ammonium values were
223 more pronounced at this depth. At bottom i.e., 18 m (Fig. 4e), it could be observed that both nitrite
224 and ammonium values vary in phase at higher frequency, while nitrate values continuously increase
225 over time, which was to all the sampled depths.

226
227 ***Nitrification blocked system (Fig. 5a-e):***

228 At the entire sample depths nitrate fell below the levels of detection within 48-72 h. At the surface
229 (Fig.5a), when nitrification was inhibited by the addition of allyl thiourea, the levels of nitrite
230 initially increased and followed an elliptical curve to reach values below the limits of detection. The
231 nitrate values decreased to non-detectable levels within 48 hours of incubation due to nitrate
232 reduction/denitrification, while change in concentrations of ammonium was sigmoidal though less
233 pronounced. The trend in the variation of all the three nitrogen species at 3m (Fig.3b) water depth

234 were similar to that observed at the surface waters. The concentrations in nitrite and ammonium
235 varied inversely. Nitrite level increased at the beginning of incubation and then fell to below
236 detection. The peak of nitrite is broader at 8m depth (Fig.5c) and decreased with increasing depth.
237 Changes in ammonium at 8m resembled that of the surface; while at 13 (Fig.5d) and 18m (Fig.5e) it
238 increased rapidly after an initial stationary phase and then flattened out. At 13m the peak of nitrite
239 accumulation was observed at 48 hours while at 18m it was observed at 24 hours. It could also be
240 observed that the fall in level of nitrite at 13m is more pronounced between 96-120 hours where as
241 the depletion of nitrite was more gentle at 18m.

242

243 ***Monitoring the changes in 'N' species in the controls (Fig. 6a-e):***

244 At the surface (Fig.6a) and 3m (Fig.6b), when neither of the inhibitors were added, the levels of
245 nitrite initially increased and then followed an elliptical curve to reach values below the limits of
246 detection, while ammonium levels increased at a very slow rate. At all the depths nitrate values fell
247 to non-detectable levels within 72 – 120 hrs. The pattern of changes in ammonium and nitrite at 8m
248 (Fig.6c), 13m (Fig.6d) and 18m (Fig.6e) were very similar to that of the experiment where
249 nitrification was inhibited by allyl thiourea (Figs 5c-e).

250

251 **DISCUSSION**

252 The presence of a 5-10 m thick cap of warm, less saline water over the upwelled water clearly
253 indicates the magnitude of terrestrial runoff accompanied by precipitation (Banse 1959). Low nitrate
254 values observed in this warm water cap were solely attributed to efficient algal uptake (Naqvi et al.
255 2000). A more significant pathway dynamically linked to denitrification could contribute
256 significantly to NO_3^- and N_2O flux and mediate N_2O production. It was observed that the relationship
257 between ammonium and total dissolved inorganic nitrogen (DIN) pool ($r = 0.98$, $p < 0.001$, $n = 122$;
258 data obtained from various cruises as described in legend to Fig.7) was stronger than the relationship
259 between DIN to nitrite and nitrate. It is therefore inferred that ammonification is a predominant

260 process contributing to DIN. The oxygen-poor waters are conducive for reduction of iron and the
261 subsequent phosphate release from ferric phosphate (Caraco et al. 1989; 1991). Enhanced dissolved
262 inorganic phosphate in the water column is used as an indicator for the degree of anoxia in the
263 region. The reduced compounds such as NH_3 , H_2S , and CH_4 tend to accumulate under anaerobic
264 conditions. Hence low oxygen regimes result in the accumulation of phosphate and ammonia.
265 However, our study showed that under low oxygen regimes with high phosphate concentrations,
266 though ammonium is a significant fraction of DIN, accumulation of ammonium was low. This
267 strengthens our observation that ammonium does not appear to be locked always under low oxygen
268 regimes. Besides, the higher diffusion coefficient of ammonium as compared to other reduced
269 compounds like sulphide (Li & Sandra, 1974) facilitates its mobility to oxic shallower layers. This
270 could probably improve the spatial coupling between the substrate (ammonium) and the utilizer
271 (nitrifier), which could get decoupled due to the development of acute anoxia. Unlimited substrate
272 availability by degradation of organic matter could also eliminate the dependence of culturable
273 bacterial abundance on the distribution of ammonia.

274 Studies generally reveal that 99% or more of the bacterial diversity remains uncultured and
275 unexplored. However, estimates on data compiled for culturability indicate that in seawater and
276 unpolluted estuarine water, percentage culturability can reach up to 0.1 and 3% of direct microscopic
277 counts respectively (Fuhrman & Campbell, 1998). Table 1 presents contrasting distribution of TDLO
278 and nitrifiers. While nitrifiers are mostly detectable only during the oxic period (April), TDLO could
279 be retrieved during both the seasons (April and October) as TDLO is more metabolically versatile to
280 respire either oxygen or nitrate. During April (2003), the culturable fraction of nitrifier population
281 (10^7 CFU/ L^{-1}) decreased towards the open sea. It was also observed that the nitrifier counts vary
282 with water depth at around 40 km from the coast. A zone of high nitrite, high TDLO and low
283 nitrifiers was observed in the same area. Increase of nitrate concentration below 20m depth indicates
284 that nitrification is more pronounced in the deeper depths than in the surface. These observations
285 provide a glimpse of the distribution pattern of bacteria well before the onset of chemical signatures

286 of anoxia. In the post monsoon season (October, 2003) the nitrifier population declined to non
287 detectable levels from $\sim 10^8$ CFU L⁻¹. During this period, very low nitrifier counts in conjunction
288 with a more heterogeneous and regular abundance pattern of TDLO showed that the water column is
289 at the peak of anaerobic conditions. The depth of nitrate-poor surface layers has decreased
290 considerably but showed inputs of nitrate by nitrification from subsurface levels. Though the nitrifier
291 counts have dropped by almost two orders, the elevated nitrate observed could be attributed to higher
292 specific activity of nitrifying bacteria or suboxic nitrification, perhaps at the expense of iron and
293 manganese. The nitrite and nitrate values in the anoxic period showed a similar distribution pattern
294 as that of the oxic period, but the enhanced magnitude due to net nitrate production being more than
295 nitrate reduction suggests that the nucleus of microbial activity spreads during the period of anoxia
296 to cover the entire water column, changing the chemistry. Hence it is proposed that the microbial
297 indicators of oxygen deficit appear as a well-defined nucleus almost 40 km from the coast even
298 during the oxic period (April).

299 Net changes of inorganic nitrogen species in nitrification blocked and unblocked
300 experimental systems during the period of anoxia (October) show that denitrification is the
301 predominant process in the water column consuming available nitrate ($\sim 0.5 \mu\text{M}$) to near zero levels
302 within 48 – 96 hours of incubation. Similar experiments conducted by Naqvi et al. (2000) showed
303 that majority of the available nitrate ($21.8 \mu\text{M}$) is converted to nitrite in the first 48 hours of
304 incubation. Initial levels of nitrite varied with depth and could range between $0.44\text{--}3.87 \mu\text{M}$. The
305 levels of nitrite encountered in the incubation experiments were comparatively higher ($\sim 7\text{--}65$ times)
306 than that reported by Naqvi et al. (2000). When denitrification was blocked, the absence of a well-
307 defined nitrite peak coupled to a steady increase in nitrate clearly indicates the efficiency with which
308 ammonium is oxidized to nitrate. It was found that nitrification could contribute almost $4.5 \mu\text{M}$ to
309 the total nitrate pool, suggesting that ammonium is actively produced by detrital breakdown, but
310 efficiently consumed through the nitrification process. Moreover, the highest rate of ammonia

311 oxidation (0-144 hours) was found to be at the surface (2.34 ng at $\text{NH}_4^+\text{-N l}^{-1} \text{ h}^{-1}$) and the lowest
312 rate of 0.72 ng at $\text{NH}_4^+\text{-N l}^{-1} \text{ h}^{-1}$ was observed at 13 m depth. But contrary to the observed oxidation
313 maxima, nitrite and nitrate production maxima of 5.85 and 2.34 ng at $\text{NO}_3^-\text{-N l}^{-1} \text{ h}^{-1}$ were observed at
314 18m depth. Since the incubation systems were isolated and denitrification was blocked it could be
315 assumed that a major fraction of nitrate was produced by the oxidation of ammonium with an
316 intermediate production of nitrite. The production of nitrate occurred at a much higher rate than
317 ammonium oxidation. This highlights the predominance of ammonification and its contribution to
318 denitrification via nitrification. In addition, the highest rate of nitrate reduction in nitrification
319 blocked systems (0-144 hours) was found to be at 13 m depth (0.05 ng at $\text{NO}_3^-\text{-N l}^{-1} \text{ h}^{-1}$) and the
320 lowest rate of 0.03 ng at $\text{NO}_3^-\text{-N l}^{-1} \text{ h}^{-1}$ at the surface. High ammonium oxidation and low nitrate
321 reduction in surface waters suggest that the physiologically forced synthetic pathway as electron sink
322 is much more dominant in these systems than hitherto accepted. Oxidation of NH_4^+ to NO_2^- in the
323 euphotic zone has been observed in many regions (McCarthy et al. 1984; Ward et al. 1989; Dore &
324 Karl, 1996). Studies by Sambrotto (2001) have also shown that ammonium regeneration rates and
325 concentrations are higher along the coastal waters of Oman during the southwest monsoon season.
326 The unaccounted (~20%) portion of total ammonium sink in the study was attributed to nitrification.
327 Moreover, Mantoura et al. (1993) have attributed elevated N_2O production to nitrification from the
328 Omani coastal region. Hence, the sequential processes viz. ammonification, nitrification and
329 denitrification operate in more spatial and temporal proximity than hitherto believed suggesting their
330 significant role in the dynamics of nitrogen species. Further, the study suggests the potential role of
331 anaerobic/suboxic nitrification that could intrinsically feed the denitrification process.

332

333 CONCLUSION

334 The microbial indicators of ensuing oxygen deficit appear as a well-defined nucleus almost 40 km
335 from the coast even during the oxygenated period and spreads during the period of anoxia to cover
336 the entire zone governing the water column chemistry. Nitrification operates at the base of this

337 suboxic system, very efficiently feeding denitrification. The alarming nitrous oxide input into the
338 atmosphere could be relatively more due to a tighter intrinsic coupling of nitrification-denitrification,
339 rather than denitrification driven by extraneous nitrate alone.

340
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440 **Figure legends:**

441 Fig.1. Hydrography along the transect Off Goa transect in October a- temperature ($^{\circ}\text{C}$); b - salinity
442 (psu); c - oxygen (mL^{-1}); d -nitrate (μM); e- nitrite (μM). Station # 1 was sampled at 1, 5 and
443 17m (bottom depth, 19m); Station # 2 was sampled at 1,5,15 and 25m (bottom depth, 35m),
444 Station # 3 was sampled at 1,15,30 and 60m (bottom depth 79m); Station # 4 was sampled at
445 1,15,30,60 and 90m (bottom depth, 100m).

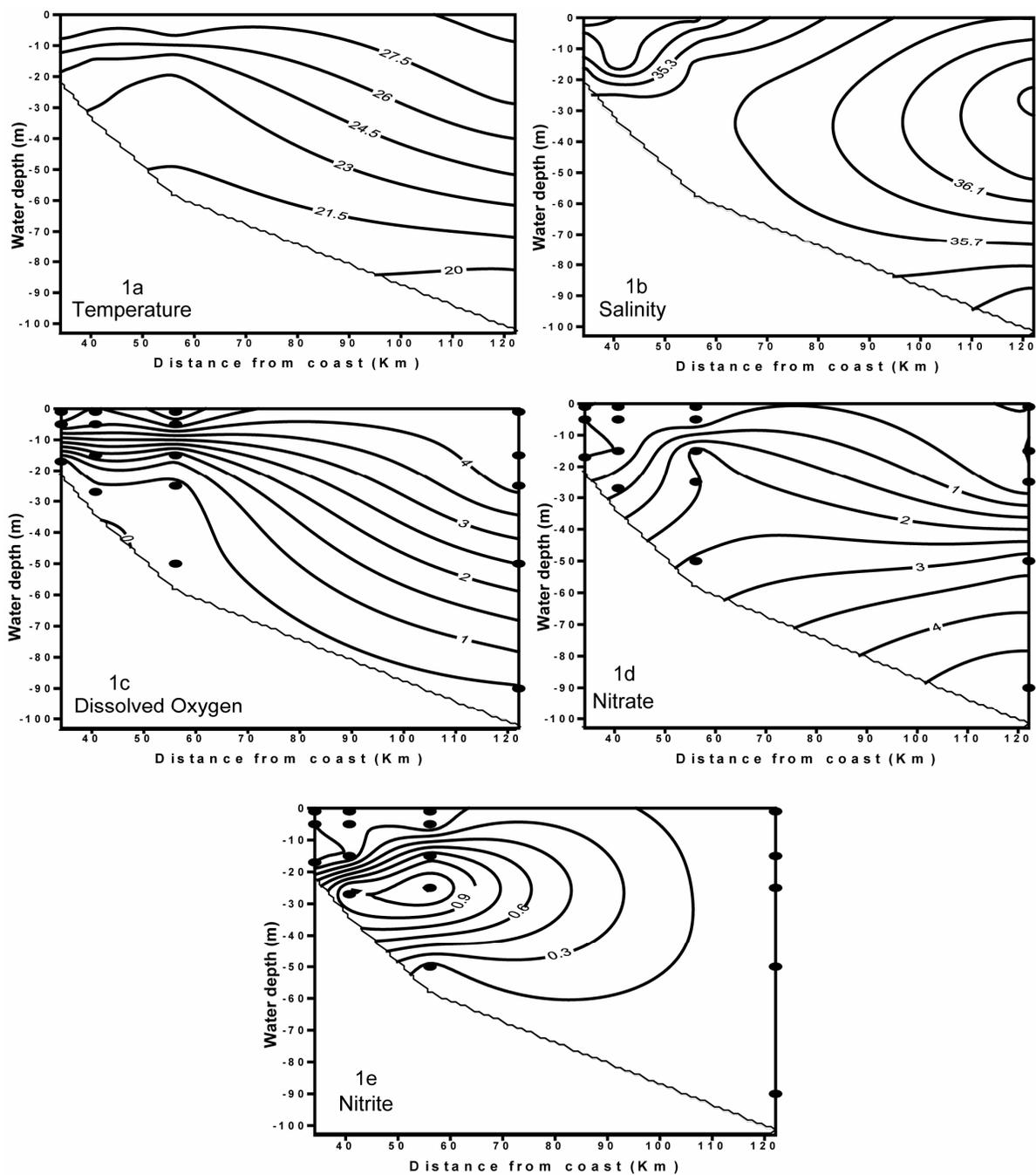
446 Fig.2. Hydrography along the transect Off Goa transect in April. temperature ($^{\circ}\text{C}$); b - salinity (psu);
447 c - oxygen (mL^{-1}); d -nitrate (μM); e- nitrite (μM). Details of sampling depths same as Fig 1.

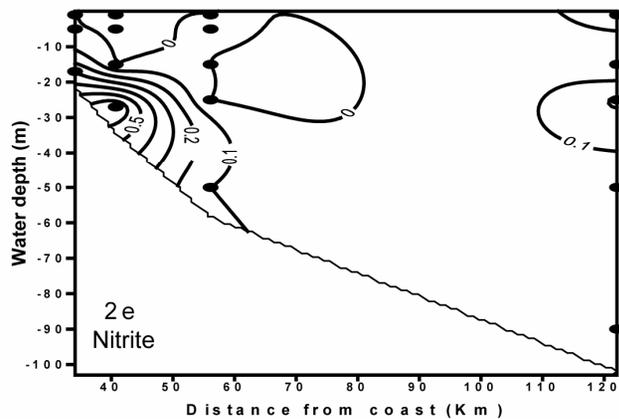
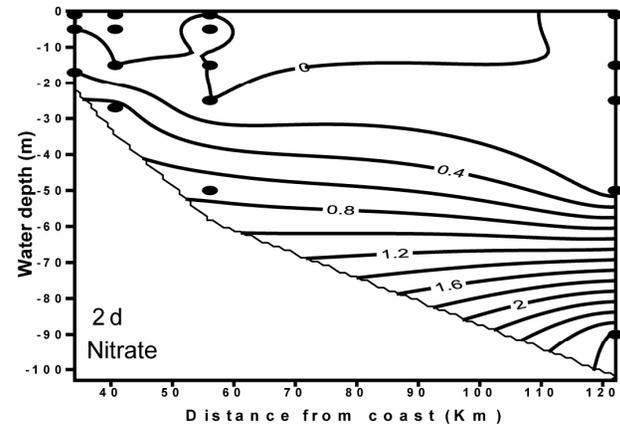
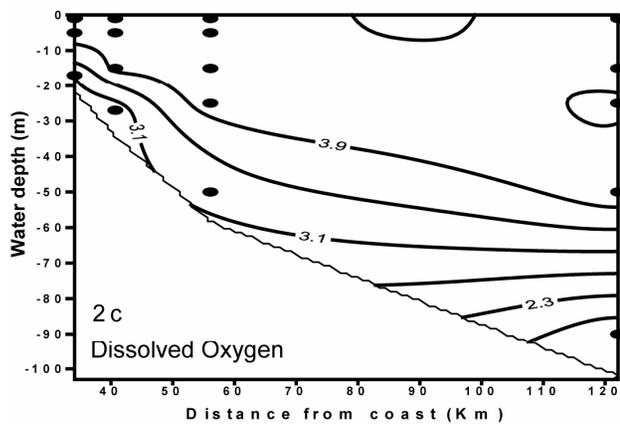
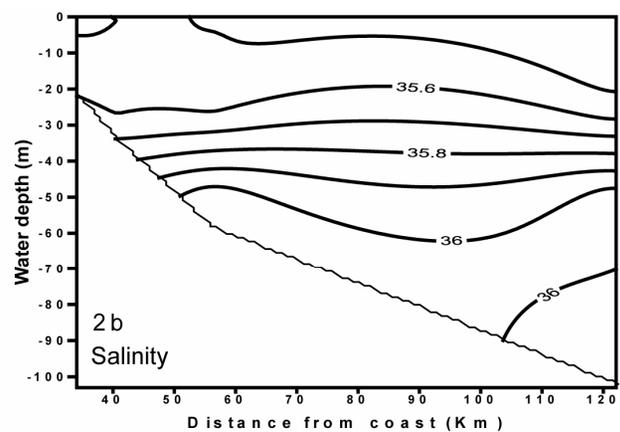
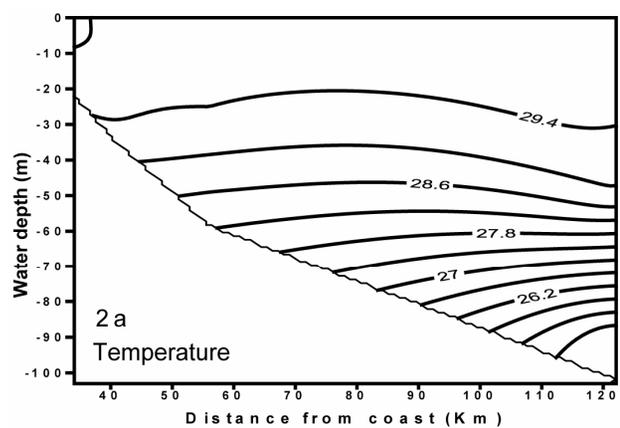
448 Fig.3a-b. 3a represents T-S profiles for station #2 during the cruise SaSu 103A (October, 2005). 3b
449 represents the zero hour levels of nitrite, nitrate and ammonium at station #2 at the start of the
450 experiment.

451 Figs 4a-e represents net changes in 'N' species from denitrification blocked water sample retrieved
452 from - surface, 3,8,13 and 18m respectively. Figs 5a-e and 6a-e show, nitrification blocked and
453 control sample respectively from similar depths. 'x'-axis represent the hours of incubation.
454 (\square Nitrite \bullet Ammonium+ Nitrate).

455 Fig.7. Plot of dissolved inorganic phosphate (DIP) versus ammonium under different oxygen levels
456 for the southwest monsoon cycle. Data from cruises covering the off Goa transect - SaSu-26
457 (September 2002), 29 (December, 2002), 49 (October 2003), 103A (December 2005) and a
458 similar transect off Mangalore - SaSu 26, 30 (December, 2002), and 49 during oxic and anoxic
459 seasons have also been included in this analysis.

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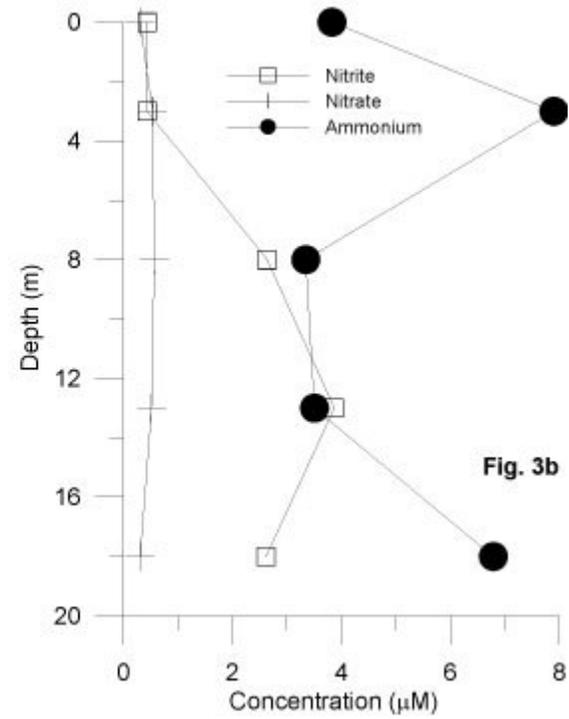
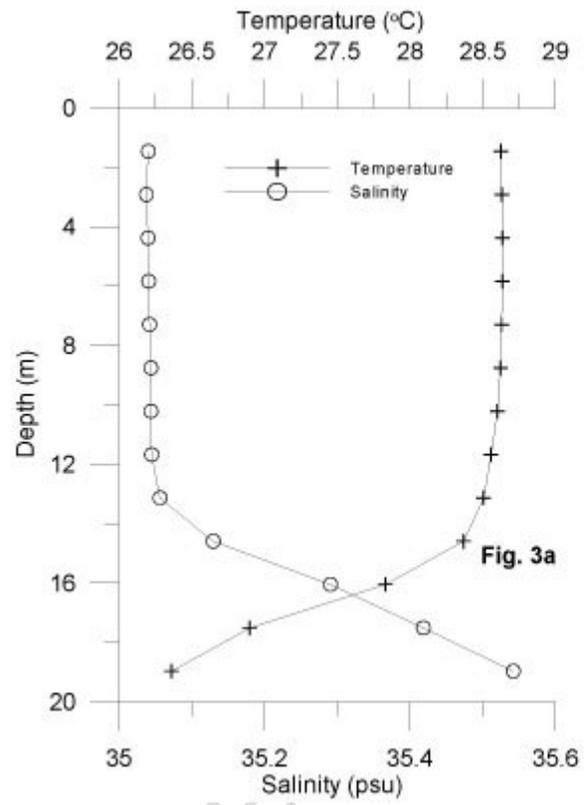


Fig.3 a and b

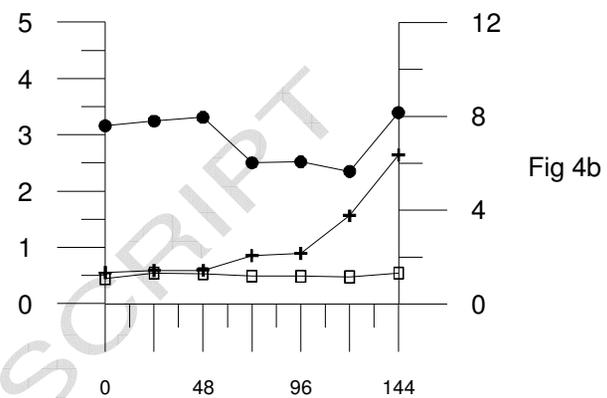
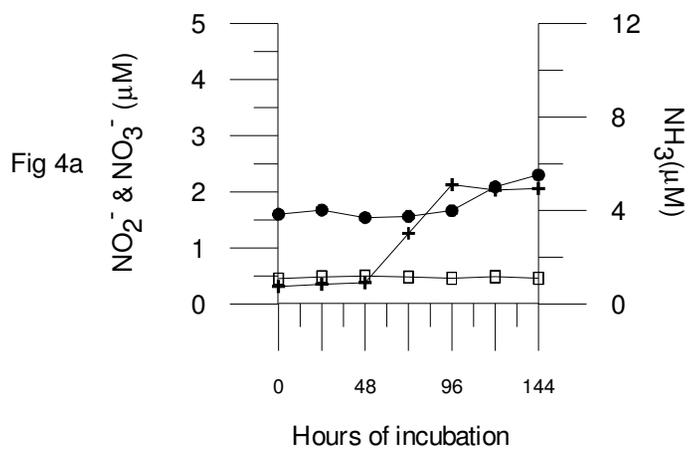


Fig 4c

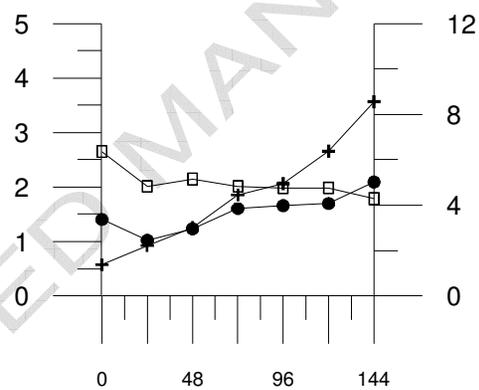
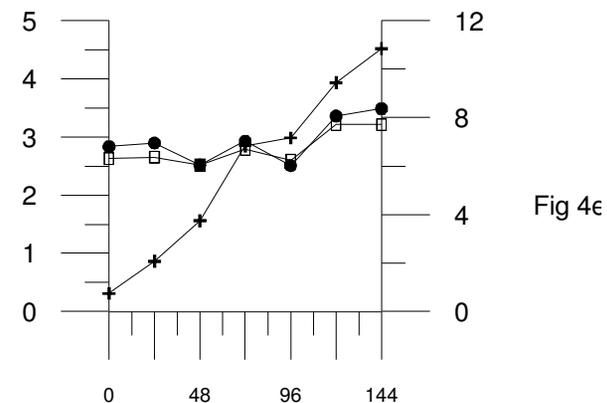
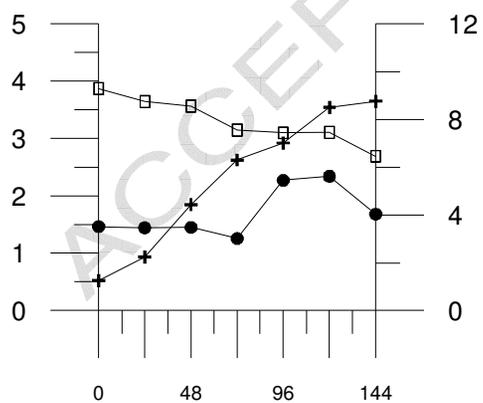
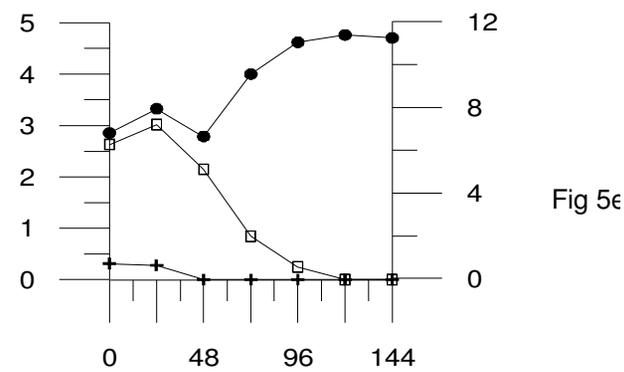
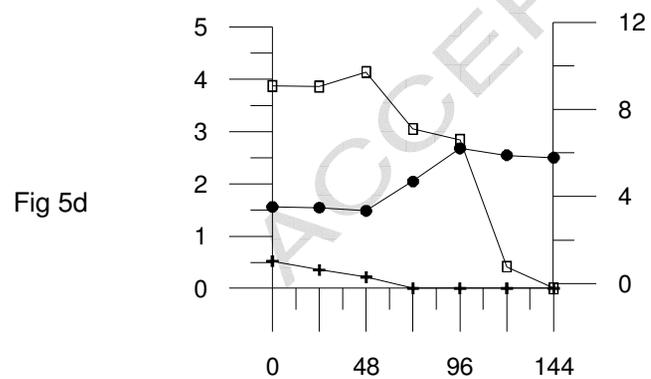
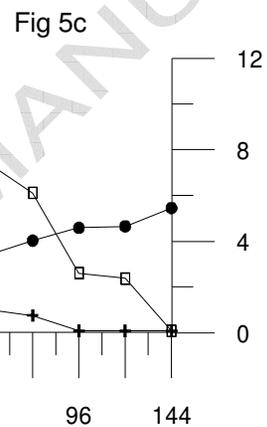
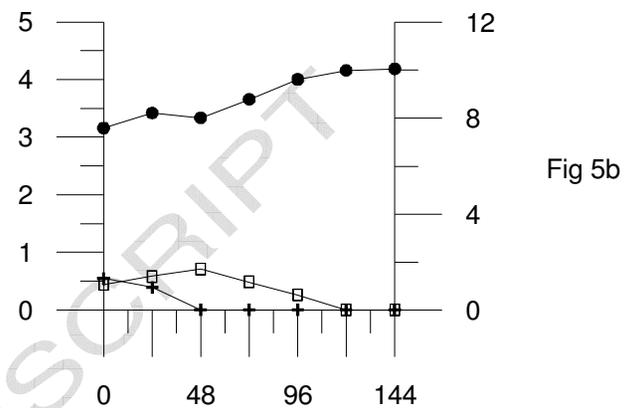
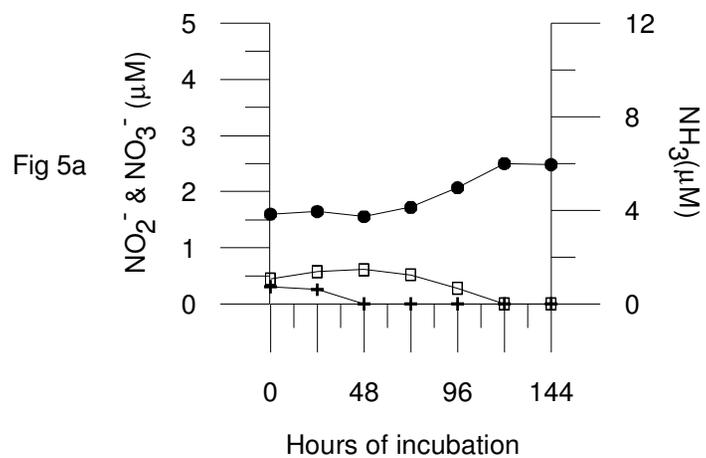
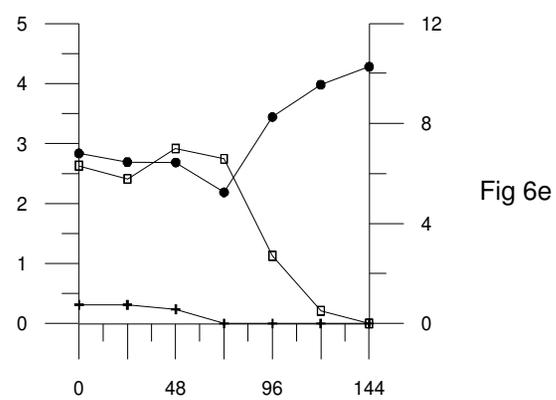
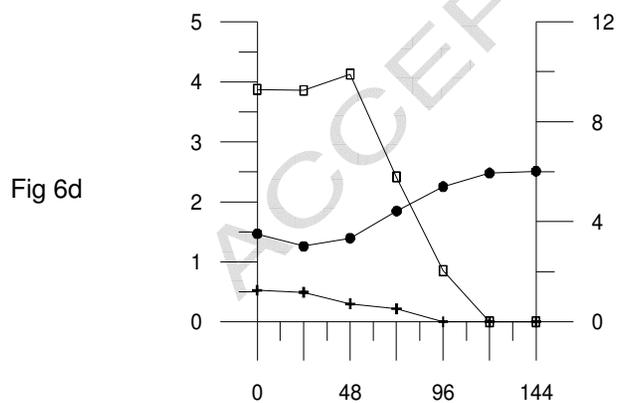
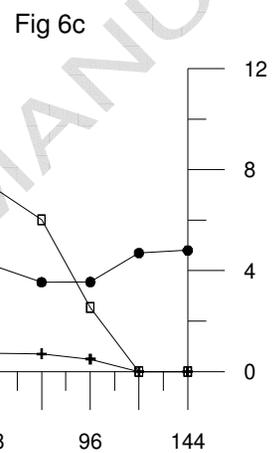
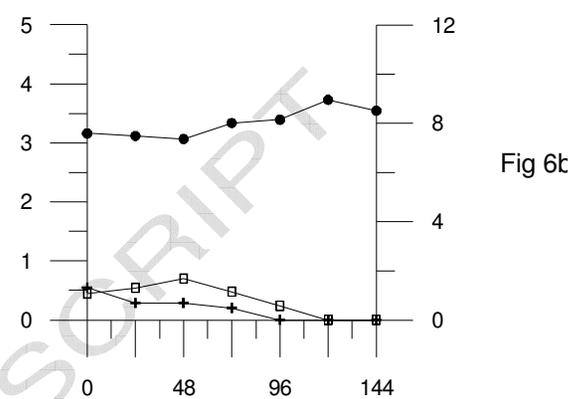
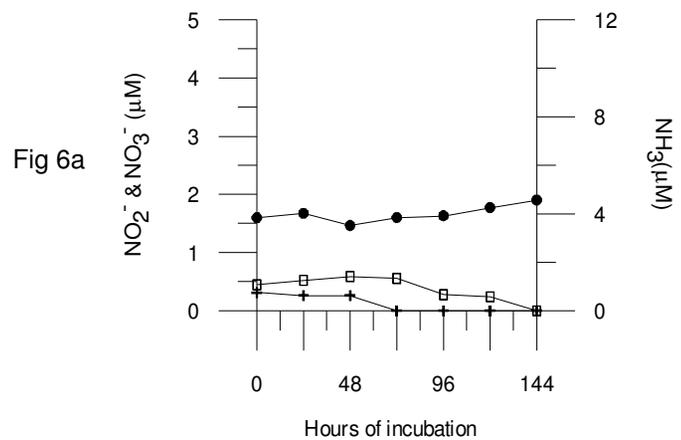


Fig 4d







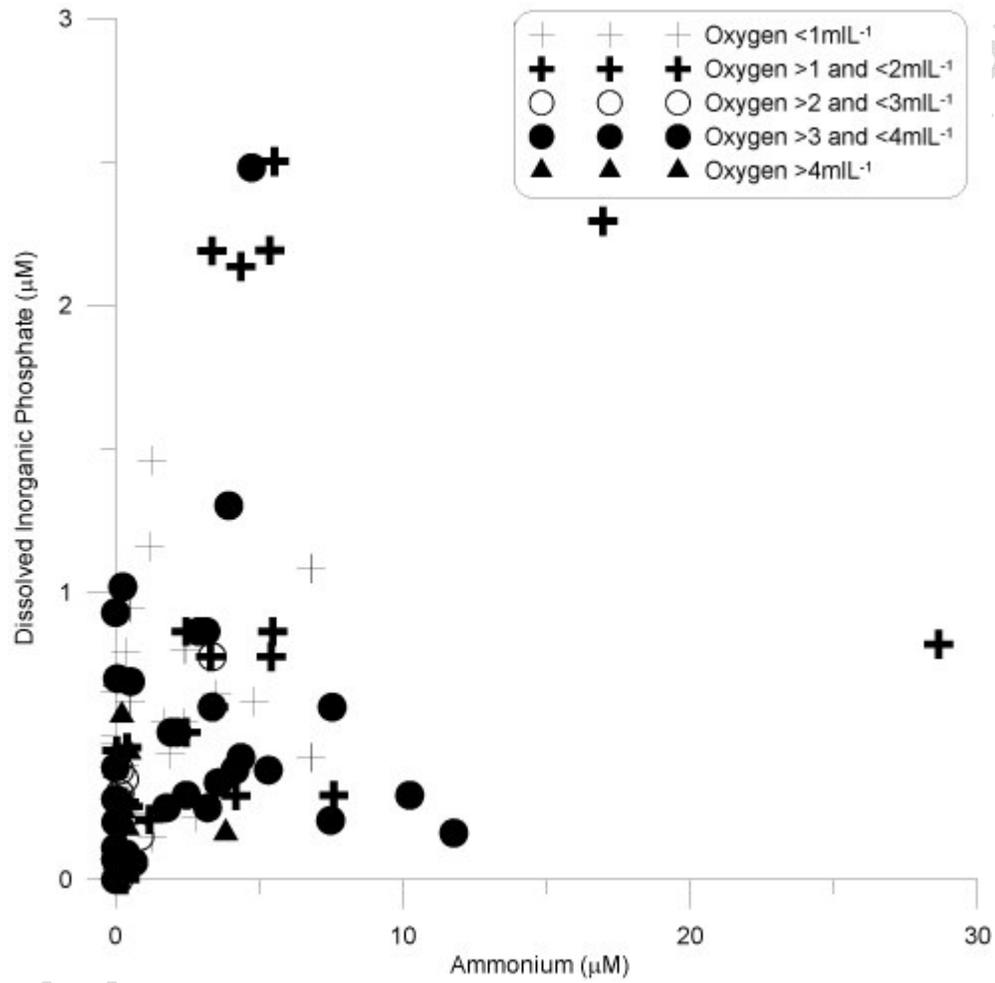


Fig.7.

Table 1. Bacterial groups along the transect Off Goa in April and October 2003

Depth (m)	April								October							
	Nitrifiers ($\times 10^8$ CFU L ⁻¹)				TDLO ($\times 10^5$ CFU L ⁻¹)				Nitrifiers ($\times 10^7$ CFU L ⁻¹)				TDLO ($\times 10^5$ CFU L ⁻¹)			
	#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4	#1	#2	#3	#4
1	2.3	1.2	2.6	0.7	0.1	0.1	0.3	0.3	ND	ND	ND	2.2	0.8	0.5	0.6	1.4
5	4.1	2.3	3.1	0.8	0.2	0.2	0.6	0.3	ND	ND	ND	ND	0.5	0.7	0.6	1.2
15	3.1	1.0	1.2	1.3	2.2	2.2	0.1	0.08	ND	ND	ND	ND	0.07	0.5	0.3	2.4
25	-	1.0	3.7	1.6	-	0.3	0.6	0.3	ND	ND	ND	ND	-	0.5	0.3	1.5
50	-	-	1.5	0.7	-	-	0.2	-	ND	ND	ND	ND	-	-	0.6	1.0

- station number, CFU – Colony Forming Units and ND – not detected