

Influence of river discharge on plankton metabolic rates in the tropical monsoon driven Godavari estuary, India

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Abstract

To examine the influence of river discharge on plankton metabolic balance in a monsoon driven tropical estuary, daily variations in physico-chemical and nutrients characteristics were studied over a period of 15 months (September 2007 to November 2008) at a fixed location (Yanam) in the Godavari estuary, India. River discharge was at its peak during July to September with a sharp decrease in the middle of December and complete cessation thereafter. Significant amount of dissolved inorganic nitrogen (DIN, of 22-26 $\mu\text{mol l}^{-1}$) and dissolved inorganic phosphate (DIP, of 3-4 $\mu\text{mol l}^{-1}$) along with suspended materials (0.2-0.5 g l^{-1}) were found at the study region during the peak discharge period. A net heterotrophy with low gross primary production (GPP) occurred during the peak discharge period. The Chlorophyll *a* (Chl *a*) varied between 4 and 18 mg m^{-3} that reached maximum levels when river discharge and suspended loads decreased by >75% compared to that during peak period. High productivity was sustained for about one and half months during October-November when net community production (NCP) turned from net heterotrophy to autotrophy in the photic zone. Rapid decrease in nutrients (DIN and DIP by ~15 and 1.4 $\mu\text{mol l}^{-1}$, respectively) was observed during the peak Chl *a* period of two weeks. Chl *a* in the post monsoon (October-November) was negatively related to river discharge. Another peak in Chl *a* in January-February was associated with higher nutrient concentrations and high DIN:DIP ratios suggest possible external supply of nitrogen into the system. The mean photic zone productivity to respiration ratio (P:R) was 2.38 ± 0.24 for the entire study period (September 2007 to November 2008). Nevertheless, the ratio of GPP to the entire water column respiration was only 0.14 ± 0.02 revealing that primary production was not enough to support water column heterotrophic activity. The excess carbon demand by the heterotrophs could be met from the allochthonous inputs of mainly terrestrial origin. Assuming that the entire phytoplankton produced organic material was utilized, the additional terrestrial organic carbon supporting the total bacterial activity (97-99%) during peak discharge period and 40-75% during dry period. Therefore, large amount of terrestrial organic carbon is getting decomposed in the Godavari estuarine system.

1. Introduction

The coastal ocean is one of the most biogeochemically active zones at the surface of the Earth (Gattuso et al. 1998). Higher rates of biological production, in forms of plants and animals (Odum, 1971), in coastal ecosystems (Kelly and Levin 1986) are attributed to the enhanced nutrient inputs (Nixon et al. 1986). Coastal ecosystems receive a considerable amount of materials including contaminants, from land and exchange with the open ocean. Particularly watersheds (Meybeck 1982; Kemp 1984, Howarth et al. 1996) export significant amounts of organic matter to the system. Besides the externally supplied organic carbon, the active biological pump in coastal regions contributes to significant accumulation of carbon in sediments (Wollast and Mackenzie 1989; Wollast 1998; Smith and Hollibaugh 1993). River-borne organic matter, mainly in dissolved form, is expected to be refractory (Meybeck, 1982) and is mostly unavailable for metabolic breakdown (Ittekkot and Laane 1991). The fate of river supplied organic carbon in coastal ecosystems depends on its characteristics (labile versus refractory) that are not well understood. Estuaries exemplify the complexity of coastal ecosystems with very high variability (Heip et al. 1995) with time and space. Despite the intense biological activity, Borges (2005) showed that estuaries are typically source of carbon dioxide (CO₂) to the atmosphere.

Heterotrophic organisms consume organic carbon to support their metabolic activities. The balance between primary production (P) and total respiration (R) in a particular ecosystem is a measure of its trophic status (Odum 1956). In an autotrophic estuary (when P>R) organic matter can be harvested, buried or exported to adjacent regions (Fisher and Likens 1973). When the estuarine system turns heterotrophic (P<R), its metabolic activities have to be supported by organic matter remaining from that produced *in situ* earlier or that imported from land or coastal ocean.

Our understanding of the metabolic balance in estuarine ecosystems is poor. Some attempts have been made to understand seasonal and spatial variations in plankton metabolic rates in estuaries (Heip et al. 1995; Gazeau et al. 2004; 2005; Caffrey 2004) are largely in temperate regions. In India, attempts to study seasonal metabolic status have been made on Mandovi-Zuari estuarine system (Ram et al., 2003) and Cochin backwaters (Thottathil et al., 2008). Both these systems belong to minor rivers on the west coast of India. The seasonal coverage may not give a clear picture on how plankton metabolic rates change in an estuarine system and how environmental conditions influence them. Hence, we have attempted to study the changes in metabolic activities with a high-resolution daily measurement strategy in Gautami branch of the Godavari estuary on the east coast of India. In this attempt our objectives are to find (1) the influence of river runoff and terrigenous organic

supply on plankton metabolic rates, and (2) the effect of suspended matter on phytoplankton production. Here we present first ever results on daily variations, studied at a fixed location in an estuarine system, in plankton metabolic rates.

2. Material and methods

2.1. Study area

Godavari river ranks 34th and 32nd in terms of catchment area and water discharge respectively, amongst the 60 largest rivers of the world (Ludwig et al., 1996; Gaillardet et al., 1999). Godavari is the third largest river in India, after Ganga and Brahmaputra and covers 3.1×10^5 km² that created an extensive delta on the east coast of India. The river originates at an altitude of about 1600 m near Nasik city in the Western Ghats. It flows eastwards through Godavari graben across the peninsular India, covering a distance of 1480 km, before it is draining into the Bay of Bengal (**Fig. 1**). It traverses through the terrain dominated by Deccan Traps (55%) and granite-gneisses (28%). The basin climate is generally dry with an average rainfall of 1512 mm y⁻¹. Winds change their direction and blows from southwest (SW) during summer, called SW monsoon (June to September) and blows from northeast (NE) during winter, called NE monsoon (November to February) (Shetye et al, 1996). The catchment receives about 82% of annual rainfall during summer monsoon and the remaining in winter monsoon (CPCB, 1995). The discharge in to the Godavari estuary is high during June to September with a peak in August and almost dries up in the upstream between December and May. The Godavari catchment is spread out in an area of 3.1×10^5 km², with an annual discharge of 105 km³ and 25 tributaries join the river in the entire stretch (Rao, 1975). Balakrishna and Probst (2005) suggested that large-scale erosion and deforestation in the catchment led to higher organic carbon in the Godavari compared to other major world rivers. The fluvial system downstream of Rajahmundry is regulated by a century old “Low Dam” at Dawalaiswaram (Fig. 1). Malini and Rao (2004) observed that ~1836 hectares of land was lost during 1976-2001 along the Godavari deltaic coast resulting in the displacement of coastal communities and mangrove destruction. They have also noticed that average sediment loads were also decreased from 1971-79 (145.26 million tons) to 1990-98 (56.76 million tons) due to construction of dams. After Dawalaiswaram dam, the river bifurcates into three distributaries. The eastward flowing major tributary is Gautami-Godavari, while the other flowing southwards is Vasistha-Godavari and Vainateyam. The latter two have relatively minor flow compared to the former tributary, hence, the sampling was conducted in the Gautami-Godavari.

2.2. Sampling and analyses

The time-series observations were made every day at a fixed location and at a fixed time (1100 hrs) at Yanam (Fig. 1) in the Gautami-Godavari estuary where water column depth of 10m. The average tidal range is about 1.5 m and average current speed is 1-2 m s⁻¹ at the sampling location. The present set of high-resolution time-series observations were made from 11 September 2007 to 12 November 2008, covering both wet (summer monsoon; June to September) and dry (December-June) periods. Temperature and salinity was measured using portable Conductivity-Temperature-Depth profiler (CTD; SBE-19 plus, Sea-Bird Electronics, USA). Water samples were collected using 5-l Niskin bottles for dissolved oxygen (DO), chlorophyll-a (Chl-a), nutrients, primary production and suspended particulate matter. Water samples were collected from 1, 5 and 10 m. Here the data collected in the surface, that represents photic layer, are presented. DO was measured using Winkler's titration method of Carritt and Carpenter (1966). The analytical precision, expressed as standard deviation, was $\pm 0.07\%$ for DO. Nutrients analyses were carried on filtered water following standard spectrophotometric procedures (Grasshoff et al. 1983). The precisions of the nitrate+nitrite, phosphate, and silicate were ± 0.02 , 0.01, and 0.02 $\mu\text{mol l}^{-1}$ respectively. About 150 ml of water samples were filtered through preweighed 0.22 μm polycarbonate filters (Millipore), dried at 40° C and reweighed. The difference between two weights was taken as suspended matter content (g l^{-1}). All these analyses were completed within 12 hours of sampling at the shore-based laboratory set up on the bank of the river.

A 150 ml of water sample was filtered through GF/F paper (Whatman). Chl *a* in the filtered sample was first extracted with N,N, Dimethyl formamide, at 4°C in dark for 24 h, and then spectrofluorometrically analysed (Suzuki and Ishimaru, 1990). Size fractionated Chl *a* was separated by filtering 150 mL of water sample through ISOPORE membrane filters (Millipore; polycarbonate; 47 mm diameter) of pore sizes 0.2, 2 and 10 μm and measured after extraction as described above. The analytical precision for Chl *a* analysis was $\pm 4\%$. Primary productivity was measured following the dissolved oxygen method using *in situ* light and dark bottles incubation. Two sets of three BOD (Biological Oxygen Demand) glass bottles each for simulating light and dark conditions were fixed to a nylon rope and incubated, *in situ*, for 24h. The dark bottles were wrapped with black tape and aluminium foil. The dissolved oxygen in both light and dark incubated samples were fixed immediately upon retrieval and analysed in the shore-based laboratory. The changes in DO concentrations in light bottles between initial and after incubation were used as a measure of net community production (NCP). Changes in DO in dark bottles were used to quantify community

respiration (R). Gross primary production (GPP) was estimated as the sum of NCP and R ($GPP = NCP + R$). The metabolic rates measured using changes in DO concentrations were converted to carbon units assuming a photosynthetic quotient (PQ) of 1.2 and respiratory quotient (RQ) of 1 (Laws, 1991). The depth of the photic zone was measured using secchi disc. The GPP, NCP and R were integrated to the photic zone using the secchi disc depth using the measurements made at surface (~0.5 m) and 2m. If the photic depth is <1 m, only surface data was used to integrate to the photic depth. When photic depth is >1 m, the integration was performed using both surface and 2 m data. On the other hand, when photic depth was >2 m, the linear interpolation was performed to the photic depth using surface and 2 m data and integration was performed. The daily mean river discharge data were obtained from the Irrigation department, Dawaleswaram.

3. Results

Depending on the state of runoff, the monsoon fed river discharge, downstream of Dawaleswaram, is largely regulated by Irrigation Department, Dawaleswaram. Therefore, the salinity of Godavari is mainly regulated by controlled discharges from the dam. The discharge is high during monsoon with virtually no discharge during dry periods. Johns et al. (1993) found weakening of coastal upwelling on the east coast of India due to substantial discharge of fresh water during the monsoon season into the Bay of Bengal. During the period of our observations the Godavari river discharge varied between 0 and $11015 \text{ m}^3 \text{ s}^{-1}$ with its maximum occurring at the beginning of August, 2008 (Fig. 2a). River discharge showed inter-annual variability with significant discharge until October in 2007 whereas it was found until September in 2008 due to less rainfall during latter year. The river discharge virtually stopped by November (Fig. 2a). Hence, entire estuary is filled with the fresh water during peak discharge period with no stratification. Salinity reached a maximum of 28 in February-March 2008 (Fig. 2b). Changes in the salinity during dry periods are mainly due to tides and local precipitation. Water temperature was found to vary between 23.6 and 34.4 ° C. Low temperatures were observed during the first half of January due to low air temperature. From the second-half of January, water temperatures rose gradually to >34 ° C by May. Due to a technical snag in our portable CTD system, two breaks in temperature and salinity data occurred during October-November and November-December 2007. Nevertheless, these data gaps do not influence our inferences or conclusions. The suspended particulate matter concentration varied between ~0.02 and 1 g l^{-1} (Fig. 2c) and showed a positive relationship with river discharge ($r=0.80$; $p<0.001$). The photic zone in Godavari estuary increased gradually from <0.1 m during summer monsoon period to about 3 m during dry period (**Fig. 2d**).

Associated with the freshwater discharge, significant amounts of nutrients were drained into the Godavari estuary during monsoon (Fig. 3a,b). Dissolved inorganic nitrogen (DIN = $[\text{NO}_2 + \text{NO}_3 + \text{NH}_4]$) was 22 - 42 $\mu\text{mol l}^{-1}$ during 11 - 29 September that decreased to $\sim 5 \mu\text{mol l}^{-1}$ by 13 November 2007. It again increased gradually to $\sim 10 - 18 \mu\text{mol l}^{-1}$ by mid January 2008 and thereafter decreased (Fig. 3a). When the river discharge almost ceased, the DIN concentrations were varied between 3 and 10 $\mu\text{mol l}^{-1}$. The DIN concentrations reached to 65 $\mu\text{mol l}^{-1}$ on 7th August 2008, coinciding with the peak discharge ($11,015 \text{ m}^3 \text{ s}^{-1}$). Dissolved inorganic phosphate (DIP) concentration was ~ 3 to 4 $\mu\text{mol l}^{-1}$ at the beginning of the experiment (11 September 2007) but rapidly decreased to 1 - 1.5 $\mu\text{mol l}^{-1}$ by the end of September and then gradually to 0.2 - 0.4 $\mu\text{mol l}^{-1}$ by January 2008 (Fig. 3b). DIP concentrations were 0.1 - 0.4 $\mu\text{mol l}^{-1}$ during the dry period. High DIP concentrations were associated with high river discharge and reached to 22 $\mu\text{mol l}^{-1}$ on 10 August 2008 (Fig. 3b). Importantly, maximum levels of DIN and DIP did not occur simultaneously, although these were associated with freshwater discharge. Episodic inputs of high DIN were observed during dry period but DIP did not exhibit any significant change (Fig. 3a,b). The DIN:DIP ratio varied from 1.62 to 86 (mean 20.3 ± 14.3) with very high values in the middle of January, end of March and at the beginning of August 2008 (Fig. 3c). Dissolved oxygen (DO) saturation was $\sim 60\%$ in September 2007, which increased to $\sim 120\%$ by August 2008 but reverted back to $\sim 60\%$ in September 2008 (Fig. 3d). Following the peak discharge, DO saturation fell by a half (i.e., from over saturation to under saturation) suggesting either a shift in biological regime or enhanced community respiration. It should be noted that the enhanced DO saturation during the dry period was not associated with peaks in nutrients (Fig. 3d).

Chl *a* was low ($< 2 \text{ mg m}^{-3}$) up to the middle of October 2007 and increased rapidly to 13.5 mg m^{-3} in two weeks after and then decreased again (Fig. 4a). Chl *a* concentrations $> 6 \text{ mg m}^{-3}$ occurred during 6 - 16 January and 6 - 14 February 2008. Peaks in Chl *a* (by $> 14 \text{ mg m}^{-3}$) was observed in the middle of July and middle of October 2008 as well. The present data, thus, suggest that the peak Chl *a* in Godavari estuary occurs annually in the middle of October. Due to a technical snag in our spectrofluorometer, break in Chl *a* data occurred between May and June 2008 (Fig. 4). Nevertheless, this data gap does not affect our inferences or conclusions. Size fractionated Chl *a* revealed that the blooms in October of 2007 and 2008 were mainly made up of phytoplankton of 2-10 μm size whereas blooms in January and February were dominated by $> 10 \mu\text{m}$ size fraction (Fig. 4 b-d).

The integrated NCP, GPP and R in the photic zone exhibited large variations from -108 to 124 , 3 to 186 , and -0.3 to $-180 \text{ mmol C m}^{-2} \text{ d}^{-1}$, respectively (Fig. 5a-c). Variations in NCP suggest that net

heterotrophic conditions ($GPP < R$) prevailed in the Godavari estuary at Yanam until the middle of October after which the system gradually turned to net autotrophic. The shift from net heterotrophy to autotrophy in the estuary coincided with decrease in river discharge and suspended matter load but increase in salinity and photic depth. The community respiration in the entire water column (CCR) at Yanam varied from -16.2 to $-1503 \text{ mmol C m}^{-2} \text{ d}^{-1}$, which is about 5 to 8 times higher than photic zone GPP. Much lower GPP than CCR indicates that intense heterotrophic activity prevailed in the water column throughout the study period ([Fig. 5d](#)).

4. Discussion

Ecosystem productivity is described by net community production (NCP), which is the balance between gross primary production (GPP) and community respiration (R). The NCP indicates net metabolic status and so whether a specific region is biologically a net source or sink for atmospheric CO_2 (Odum 1956). The photic layer integrated GPP at Yanam ranged from 3 to $186 \text{ mmol C m}^{-2} \text{ d}^{-1}$ with a mean of $41.9 \pm 38 \text{ mmol C m}^{-2} \text{ d}^{-1}$, which is lower than that reported in other Indian estuaries (Ram et al. 2003; Gupta et al., 2008; Thottathil et al. 2008). Community production and respiration vary with season (Kemp et al. 1992; Smith and Hollibaugh 1997), salinity (Swaney et al. 1999) and depth (Caffrey et al. 1998). The averages of photic zone integrated GPP, R and NCP during peak ($>2000 \text{ m}^3 \text{ s}^{-1}$), moderate ($<2000 \text{ m}^3 \text{ s}^{-1}$) and no discharge periods are listed in Table 1. Higher primary production occurs during moderate discharge period favoured by less suspended load compared to peak discharge period. Nevertheless, Table 1 clearly shows that GPP was the highest during dry period but the lowest during peak discharge periods in both 2007 and 2008. More over dominance of net autotrophy was observed during dry period whereas net heterotrophy during peak discharge period. As we initiated time-series measurements at Yanam in September our GPP estimate for peak discharge period of 2007 may not represent true mean. Notably, the plankton metabolic rates in the photic zone increased 3-10 times after the river discharge decreased ($< 2000 \text{ m}^3 \text{ s}^{-1}$) in consistent with the increased Chl-*a* concentrations. Despite the fact that significant quantities of nutrients (for instance DIN of $17 \pm 9 \text{ } \mu\text{mol l}^{-1}$) were available, however, the Chl-*a* was very low ($< 2 \text{ mg m}^{-3}$) during the peak discharge period. River discharge drains huge amounts of allochthonous matter into the estuary. Gupta et al (1997) observed that during dry season particulate organic matter (POM) is relatively fresh and autochthonous, whereas mainly degraded and allochthonous during wet season. The increase in freshwater inflow increases turbidity (Fig. 2d) thereby reducing the depth of light penetration (Fig. 2e). Consequently, primary production during the monsoon is low (Fig. 4a, 5c). Reduced productivity due to high turbidity was reported in several

estuaries (eg.: Soetaert and Herman, 1995; Cortner et al., 2000; Young and Huryn, 1996). Gomes et al (2000) observed increased phytoplankton biomass (92 mg m^{-2}) during monsoon with reference to increased river runoff and wind driven coastal upwelling on the west coast of Bay of Bengal compared to other seasons, however, the primary productivity was low ($0.3 \text{ gC m}^{-2} \text{ d}^{-1}$) suggesting light limitation due to intense cloud cover and high suspended load associated with higher river discharge.

There was an increase in Chl *a* from 16 October 2007, which remained high (a maximal of 14 mg m^{-3}) for about one-and-a-half month period (until 25 November 2007; Fig. 4a). On the other hand, the peak in Chl-*a* was relatively high, but sustained only for about 3 weeks (6-26th October) during 2008. The sudden increase in Chl-*a* was associated with decrease in river discharge by 70% (Fig. 2a) and suspended load by 97% (Fig. 2d) from that of peak period. The DO levels increased by 25-50 $\mu\text{mol l}^{-1}$ during the bloom period, enhancing its saturation by about 10% compared to that of pre-bloom period (Fig. 3d). Similarly the highest oxygen saturation of 123% observed in the mid of October 2008 coincided with enhanced primary production (Fig. 5c). Tripathy et al (2005) observed that Chl *b*/Chl *a* and Chl *c*/Chl *a* ratios are <1 during end of September 2001, suggesting that possibility of healthy phytoplankton populations in lower light intensity. The Godavari estuarine system (in photic zone only) at Yanam turned from net heterotrophy during high discharge period to net autotrophy, with reduction in discharge, and significant increase in GPP (Fig. 5a-c). However, variability in NCP during January-February bloom might be related to fluctuations in turbidity and reduced river influence. Phytoplankton appears to have rapidly consumed nutrients during post monsoon bloom. For instance, DIN and DIP decreased from ~ 20 to $5.6 \mu\text{mol l}^{-1}$ and ~ 2.0 to $0.6 \mu\text{mol l}^{-1}$, respectively, within a 40 day period (Julian days 284 to 324; Fig. 3a,b). The DIN and DIP removal rates during this period were 0.36 and $0.04 \mu\text{mol l}^{-1} \text{ d}^{-1}$ respectively suggesting active biological pump in operation. These rates are consistent with the study of Padmavathi and Satyanarayana (1999) who observed that annual mean net removal of silicon, ammonium, nitrate and phosphate are 26-36%, 19-24%, 14-16% and 4-18% respectively due to net uptake by the phytoplankton and absorption to suspended matter.

The average DIN:DIP ratio during October-November bloom period was 7.87 ± 0.30 (Fig. 3c), which is much lower than that of Redfield ratio of 16 suggesting either faster removal/supply of nitrogen nutrients or supply of phosphate through domestic sewage. Following the 40- day bloom in October-November Chl-*a* concentration decreased to those levels found during the pre-bloom period ($\sim 0.2 \text{ mg m}^{-3}$; Fig. 4a). The other longer duration phytoplankton bloom occurred with an increase in Chl *a*

from $\sim 0.2 \text{ mg m}^{-3}$ to $4\text{-}10 \text{ mg m}^{-3}$ between 4 January to 23 February 2008. However the rate of increase and levels of Chl *a* were less than that observed during October-November bloom. The increase in Chl *a* is associated again with increase in nutrients and DO levels. During the entire study period DO largely showed under-saturation (58-90%). However, near saturation levels, coinciding with short-term blooms in dry periods and in October 2008, indicate dominant photosynthetic activity over respiration. Importantly, though Chl *a* content in October-November bloom was double to that found during the January-February bloom, the oxygen was clearly undersaturated during the former period. This could be potentially due to deepened photic layer in the latter period (Fig. 2e) and increase in column primary production. The mean NCP during no discharge periods of 2007 and 2008 is 24.4 ± 35 and $31.2 \pm 33 \text{ mmol C m}^{-2} \text{ d}^{-1}$, respectively, with net autotrophy dominating the photic zone. Higher DO saturation, Chlorophyll *a* and NCP variations strongly suggest that primary production was boosted by increased transparency in the presence of nutrients availability in the estuary during no discharge period (**Table 1**). No nutrients are transported to the estuary from upstream as the river discharge completely ceased during dry period. The alternative source could be local supply of nutrients, anthropogenic or resuspension of sediments. The high DIN:DIP ratio during the dry period (>40 , Fig. 3c) strongly suggests the possibility of dominant anthropogenic nitrogen supply.

Both Chl *a* and metabolic rates showed significant variability in relation to changes in the river discharge (Table 1; Fig. 4a). The mean discharges for the periods between the middle of September and 31 October of 2007 and 2008 are 1758 ± 1041 and $818 \pm 1094 \text{ m}^3 \text{ s}^{-1}$, respectively. Reduced discharge by a-half in 2008 is a result of less rainfall than in 2007 (Dr. K. Basha, Indian Meteorological Department, Personal communication, 2008) and consequently suspended load was low and photic depth deepened in the former year. Therefore interannual variability in rainfall, and thus discharge, causes significant changes in metabolic rates in the Godavari estuary.

Our observations suggest that salinity and Chl *a* varied from 0 to 30 and from 0.1 to 17.8 mg m^{-3} , respectively, in the estuary when the discharge was minimum (Fig. 6a,b). Suspended matter and DIN showed positive relationships with discharge (**Fig. 6c,d**). No significant relationship was, however, found between discharge and primary production as it depends on the several factors such as light availability, stability of water column, nutrients etc. The photic zone integrated R to GPP showed positive relationship (**Fig. 7**) with many points falling above the 1:1 line. A least square slope suggests that nearly half of the autotrophic production is respired by the heterotrophs in the photic zone and the remaining may support heterotrophic activity in the aphotic zone.

The phytoplankton production is limited to the photic zone that varied between 0.1 and ~3.5 m during the study period whereas respiration occurred in the entire water column. To examine to what extent the photosynthetically produced organic carbon supports the total water column microbial demands we computed GPP to community respiration (P:R) ratios. The mean P:R ratios in the photic zone were 2.38 ± 0.24 (mean \pm SE) during no discharge period whereas close to metabolic balance (0.94 ± 0.2) was found during peak in river discharge period. The ratios in the photic zone were significantly lower (1.38 ± 0.3) during October-November bloom than January-February bloom (2.99 ± 0.3) due to deeper light penetration during the latter. The community response during these two periods is also different as larger plankton ($>10 \mu\text{m}$ size fraction) mainly contributed to the increased in Chl *a* during January-February whereas $<10 \mu\text{m}$ plankton was higher during October-November (Fig. 4).

On the other hand, column (integrated) community respiration (CCR) marginally increased from $-300 \pm 278 \text{ mmolC m}^{-2} \text{ d}^{-1}$ of peak discharge period to $-360 \pm 359 \text{ mmolC m}^{-2} \text{ d}^{-1}$ in the dry period, however it is statistically insignificant. The CCR is several folds higher than photic zone integrated respiration. The ratio of photic zone production (GPP) to total column respiration (CCR) was very low ranging from 0.001 to 1.18 (mean 0.14 ± 0.02) with higher ratios occurring during bloom periods. The water column productivity to respiration ratios of <1 for nearly the entire year suggests that photic zone production is not sufficient to support resident heterotrophs carbon demands. The additional organic carbon required by the heterotrophs appears to be met through the utilization of terrigenous organic matter drained by the rivers. Balakrishna and Probst (2005) observed that major source of organic carbon during wet season is from the soil, whereas the *in situ* phytoplankton production is the major source during dry seasons. They further noticed that 3-91 times higher organic carbon is transported to the ocean during wet season than dry and therefore may support heterotrophic activity.

If the total community respiration in the estuary is supported by fractions (f_P and f_{TOC}) of primary produced carbon (P) and terrestrial organic carbon (TOC), then community respiration CCR can be written as $\text{CCR} = f_1 \text{TOC} + f_2 \text{P}$

Since organic carbon produced by primary production is expected to be mostly labile, heterotrophs preferentially utilize the same. If we assume that entire primary produced carbon is completely

consumed by the heterotrophs, the amount of terrestrial carbon required to support the heterotrophic respiration can be computed as

$$f_1\text{TOC} = \text{CCR} - \text{P}$$

The fraction of TOC supported heterotrophic activity ($f_1\text{TOC}/\text{CCR}$)*100) was found to be >98%, when river runoff was at its peak, but lower when the discharge decreased (**Fig. 8**). Therefore, during highly turbid peak discharge period entire CCR was supported by TOC since the *in situ* primary production was very low. Consequently, a significant fraction of the TOC decomposed during monsoon runoff. It should, however, be noted that the above stated contribution of TOC to support bacterial decomposition processes in Godavari estuary could be an underestimate since the *in situ* produced organic carbon may not be totally consumed. Interestingly, Somayajulu et al. (1993) observed that dissolved organic carbon (DOC) concentrations (200-1000 $\mu\text{g l}^{-1}$) were low in Godavari compared with the other major rivers in the world. Such low concentrations of DOC may be possibly due to consumption through heterotrophic activity.

Our plankton metabolic rates, particularly of community respiration, may be over estimated as some oxygen could have been utilized for nitrification. Recently Miranda et al. (2008) measured high nitrification rates (8-166 $\text{nmolN l}^{-1} \text{h}^{-1}$) in the Cochin Estuary, southwest coast of India, during the onset of monsoon. The nitrification rates in the Godavari estuary are unknown. However, if similar rates of nitrification in the Cochin estuary are expected in the Godavari, it may influence our respiration rates by <10%. Nevertheless, the P:R ratios estimated for Godavari are consistent with those in other estuaries of India. For instance, Thottathil et al. (2008) observed the ratio of primary production to community respiration to range between 0.05 and 8.5 during different seasons in the Cochin Estuary. Ram et al. (2003) found mean P:R ratios of 0.28 to 0.67 in the Mandovi and Zuari estuaries of Goa (west coast of India) during peak discharge period (monsoon) whereas prevalence of net autotrophic conditions in other seasons (1.49 to 2.53).

Bouillon et al. (2003) found pCO_2 levels in Gautami-Godavari estuary to be $433 \pm 77 \mu\text{atm}$, whereas relatively higher values (450-500 μatm) were observed in the upstream river during 27th May and 1st June 2001. During this period, relatively higher gross production (80-100 $\text{mmol m}^{-2} \text{d}^{-1}$) and net autotrophy (20-60 $\text{mmol m}^{-2} \text{d}^{-1}$) were observed. Lower pCO_2 levels during May-June might be related to high primary production. In contrast to this, Sarma et al. (2001) observed pCO_2 levels of >2000 μatm in the Mandovi-Zuari estuarine system in Goa during monsoon that agree well with the Ram et al. (2003) observation of net heterotrophy in that season. Therefore, enhanced pCO_2 levels in

the Mandovi-Zuari estuarine system during monsoon might have been favoured by increased bacterial respiratory activity. Decomposition of allochthonous organic matter derived from terrestrial and riverine inputs occurs in unproductive aquatic systems (del Giorgio et al. 1997). Cole et al. (2000) and Borges (2005) found high $p\text{CO}_2$ levels in several estuaries and rivers where net heterotrophy was observed and the latter was supported by the terrestrial organic carbon. The quantity of the TOC exported to the coastal region should, however, depend on the amount utilized in the estuary. Ram et al. (2003) observed that from the Mandovi-Zuari estuarine system excess carbon is transported to the coastal regions to support coastal net heterotrophy. Similar process was also found in the Cochin Estuary (Thottathil et al. 2008). Unlike in other estuaries in India, perennial occurrence of heterotrophy is found in the Godavari estuary including during bloom periods. TOC decomposition in the Godavari estuary might be resulting in the export of inorganic nutrients to the coastal Bay of Bengal. Quantification of this nutrient flux is important as this might promote primary production in the coastal Bay of Bengal and lower surface $p\text{CO}_2$. Kumar et al. (1996) observed under-saturation of $p\text{CO}_2$ levels along the west coast of Bay of Bengal during pre-summer monsoon and northeast monsoon periods. However, no information is available for monsoon period. The influence of discharges from the Godavari estuary on the coastal Bay of Bengal depends on the amounts of organic carbon and nutrients exported as this determines whether the adjoining coastal region is a net sink or source of CO_2 to the atmosphere. It appears that most Indian estuarine systems turn heterotrophic during monsoon when land derived organic materials mainly sustain bacterial activities. Our time-series study reveals that terrestrial organic carbon associated with freshwater discharges from Godavari River plays a vital role in the metabolic balance of estuarine ecosystem at Yanam and making the estuary an important source of atmospheric CO_2 .

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Legend to figures

1. Location of the time-series station at Yanam in Godavri estuary, India, Dowlaiswaram dam from where river discharge data were obtained is also shown.
2. Daily variations in surface a) salinity, b) river discharge ($\text{m}^3 \text{s}^{-1}$), c) suspended load (g l^{-1}) and d) photic depth (Sacchi disc; m) at Yanam in the Godavari Estuary.
3. Daily variations in surface a) dissolved inorganic nitrogen ($\mu\text{mol l}^{-1}$), b) dissolved inorganic phosphate ($\mu\text{mol l}^{-1}$), c) DIN:DIP ratio, and d) percent saturation of dissolved oxygen at Yanam.
4. Daily variations in surface a) total, b) microplankton ($>10 \mu\text{m}$), c) nanoplankton ($2-10 \mu\text{m}$) and d) picoplankton ($0.2-2 \mu\text{m}$) chlorophyll *a* concentrations at Yanam.
5. Daily changes in a) net community production (NCP), b) community respiration (CR) and c) gross primary production (GPP) are shown for the photic zone (PZ). Total water column community respiration (CCR) is depicted in (d).
6. Relations between (a) salinity, (b) Chlorophyll *a*, (c) suspended matter and (d) dissolved inorganic nitrogen and the Godavari discharge at Yanam.
7. Relation between Gross Primary Production and community respiration in the photic zone at Yanam in the Godavari estuary during $>2000 \text{ m}^3 \text{ s}^{-1}$ (plus), $<2000 \text{ m}^3 \text{ s}^{-1}$ (open diamond) and no discharge (open circle) periods. The longer line indicates the condition $\text{GPP} = \text{CR}$.
8. Variations in the estimated terrestrial organic carbon demand (in percent, to that of total) to support column community respiration at Yanam in the Godavari estuary.

Table 1: Mean variation in Salinity, photic depth, Chl-a, DO_{sat} (oxygen saturation), SSM, DIN, DIP, Silicate (SiO₄), GPP, NCP and CR (community respiration) with reference to river discharge in the Godavari estuary.

Period	Salinity	Photic depth (m)	Chl-a (mg m ⁻³)	DO _{sat} (%)	SSM (g L ⁻¹)	DIN (μM L ⁻¹)	DIP (μM L ⁻¹)	SiO ₄ (μM L ⁻¹)	GPP (mmol C m ⁻² d ⁻¹)	NCP (mmol C m ⁻² d ⁻¹)	CR (mmol C m ⁻² d ⁻¹)
Discharge >2000 m ³ s ⁻¹	0.07 ±0.01	0.13 ±0.10	1.42 ±0.73	85.5 ±20.4	0.44 ±0.22	38.9 ±12.2	4.98 ±5.94	63.5 ±35.5	15.3 ±32.1	-0.97 ±9.48	-8.50 ±18.23
Discharge <2000 m ³ s ⁻¹	9.96 ±8.0	0.90 ±0.36	4.68 ±4.38	86.4 ±16.7	0.07 ±0.05	18.0 ±12.5	1.23 ±1.37	37.8 ±25.7	44.7 ±39.6	15.71 ±30.8	-26.23 ±28.4
No discharge	22.29 ±3.7	2.05 ±0.6	2.98 ±1.88	88.2 ±12.2	0.05 ±0.03	9.0 ±4.0	0.46 ±0.22	18.6 ±24.3	47.6 ±28.0	26.75 ±36.7	-30.70 ±30.3

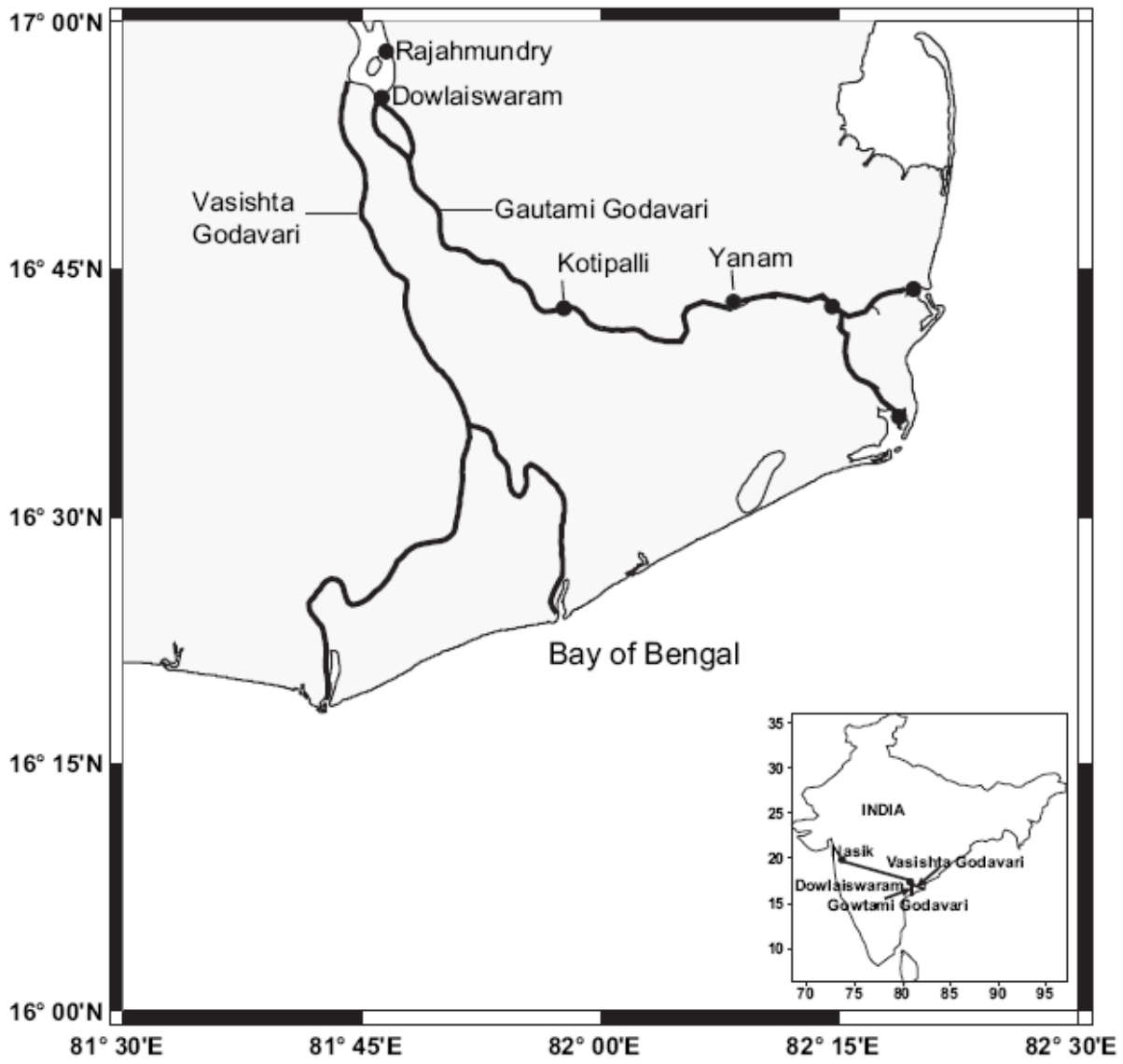


Fig.1

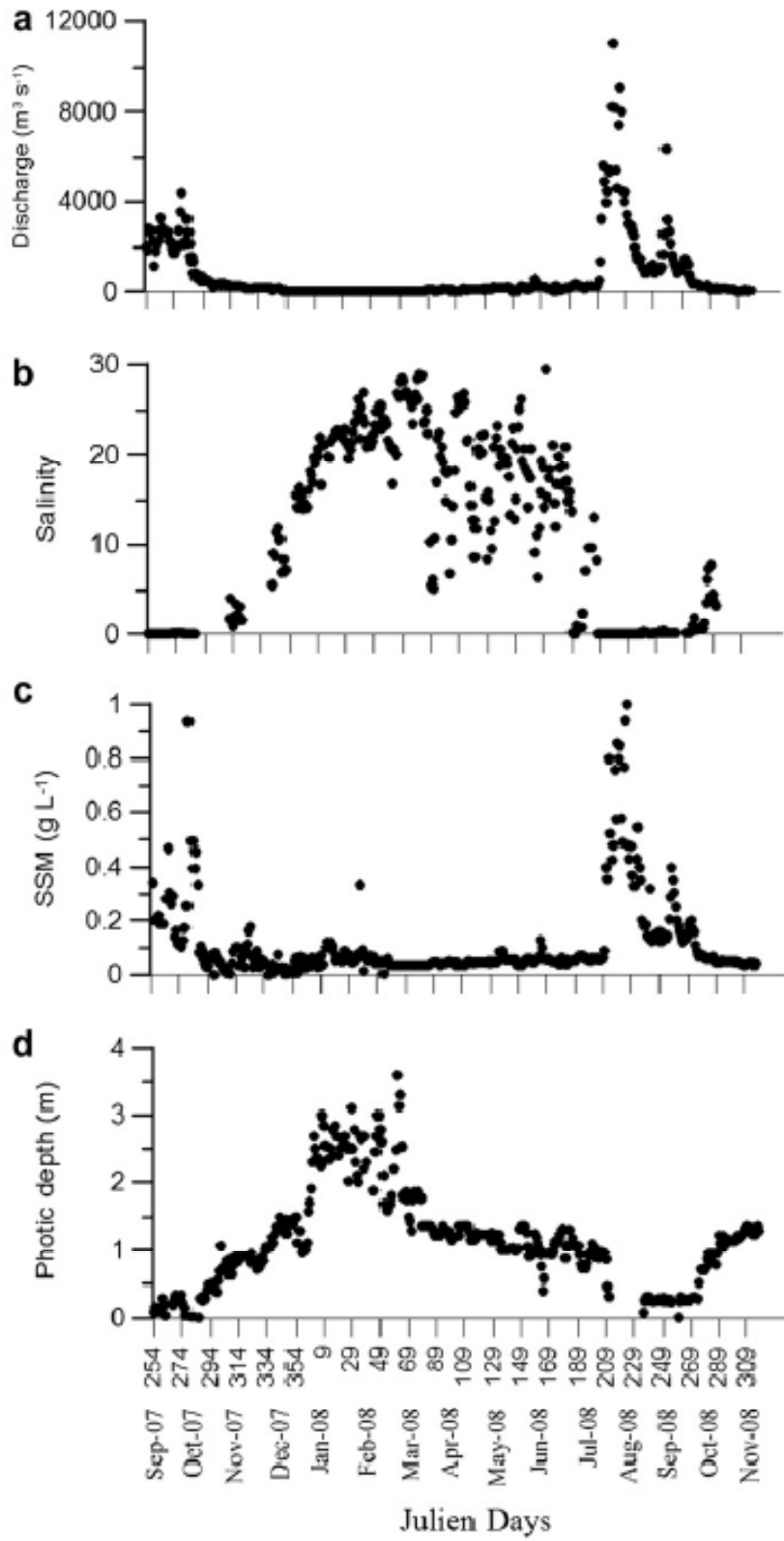


Fig-2

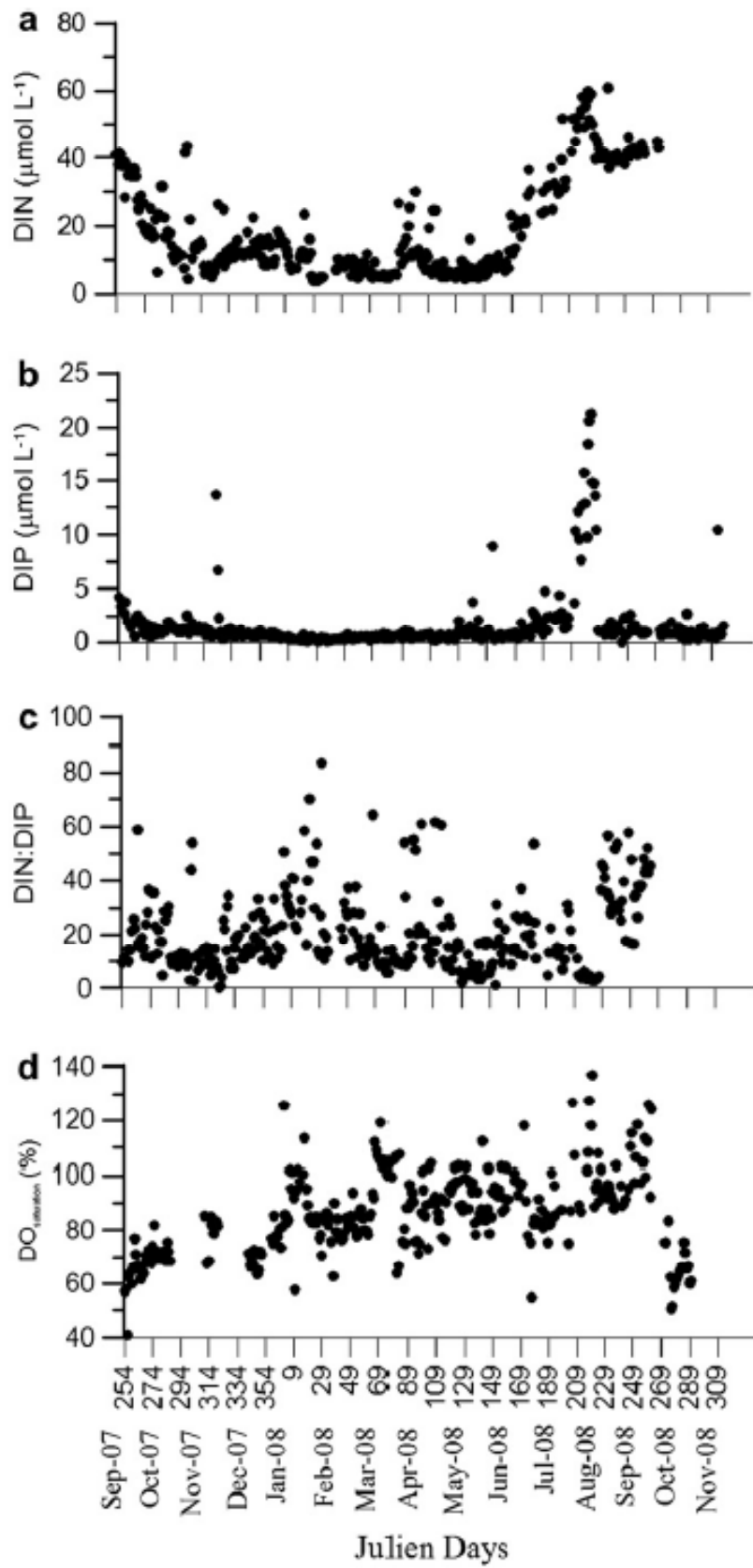


Fig.3

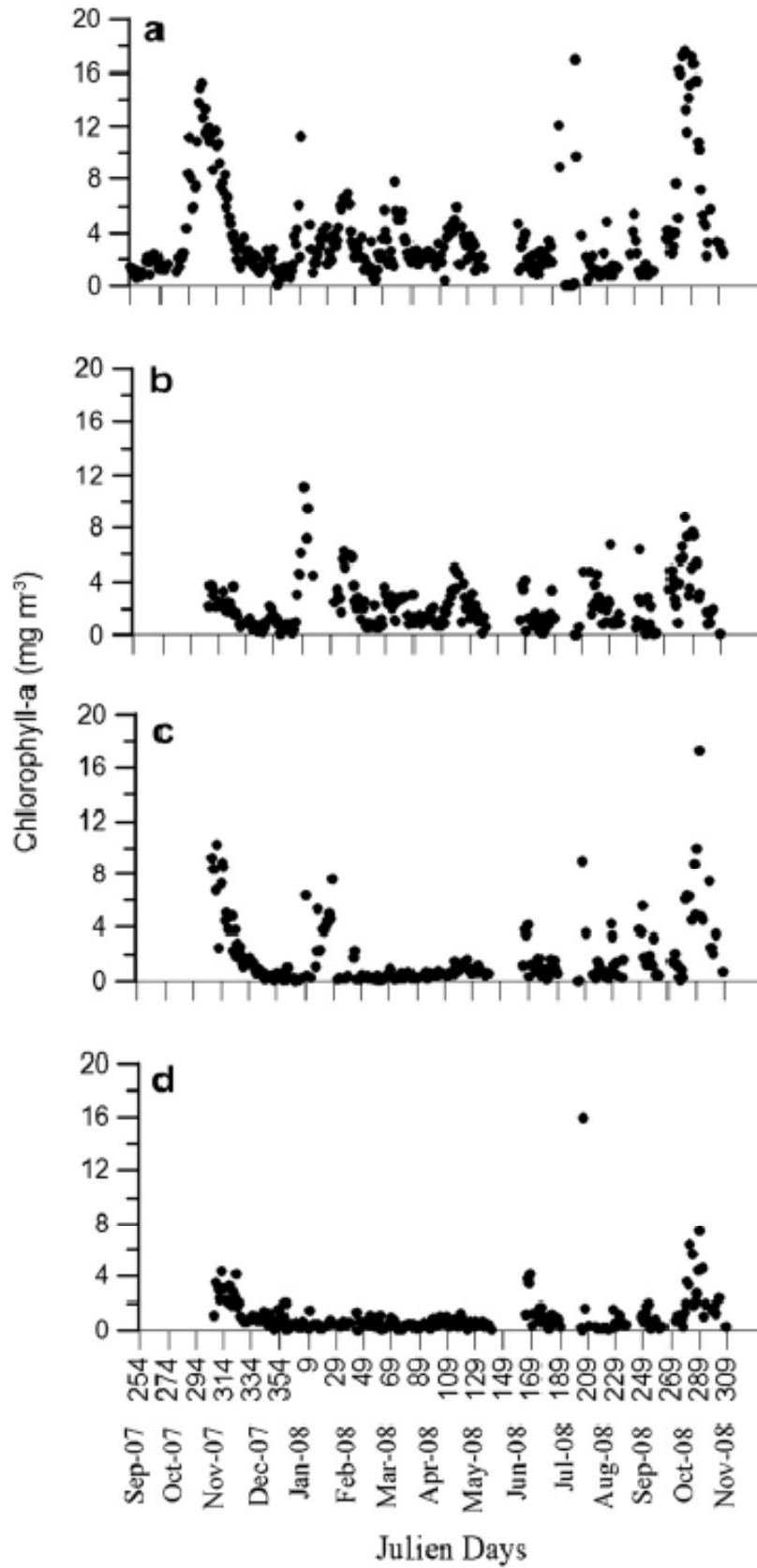


Fig.4

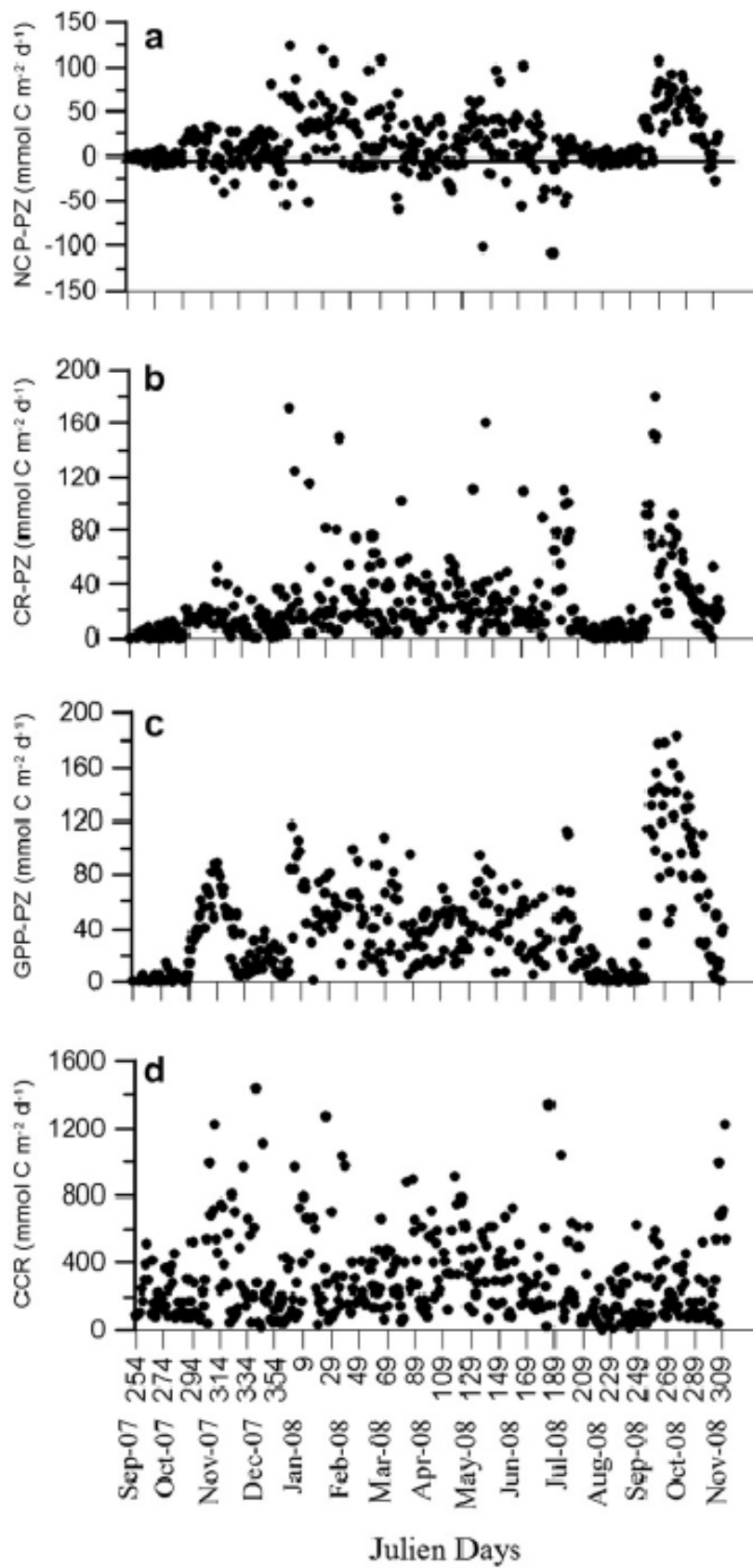


Fig.5

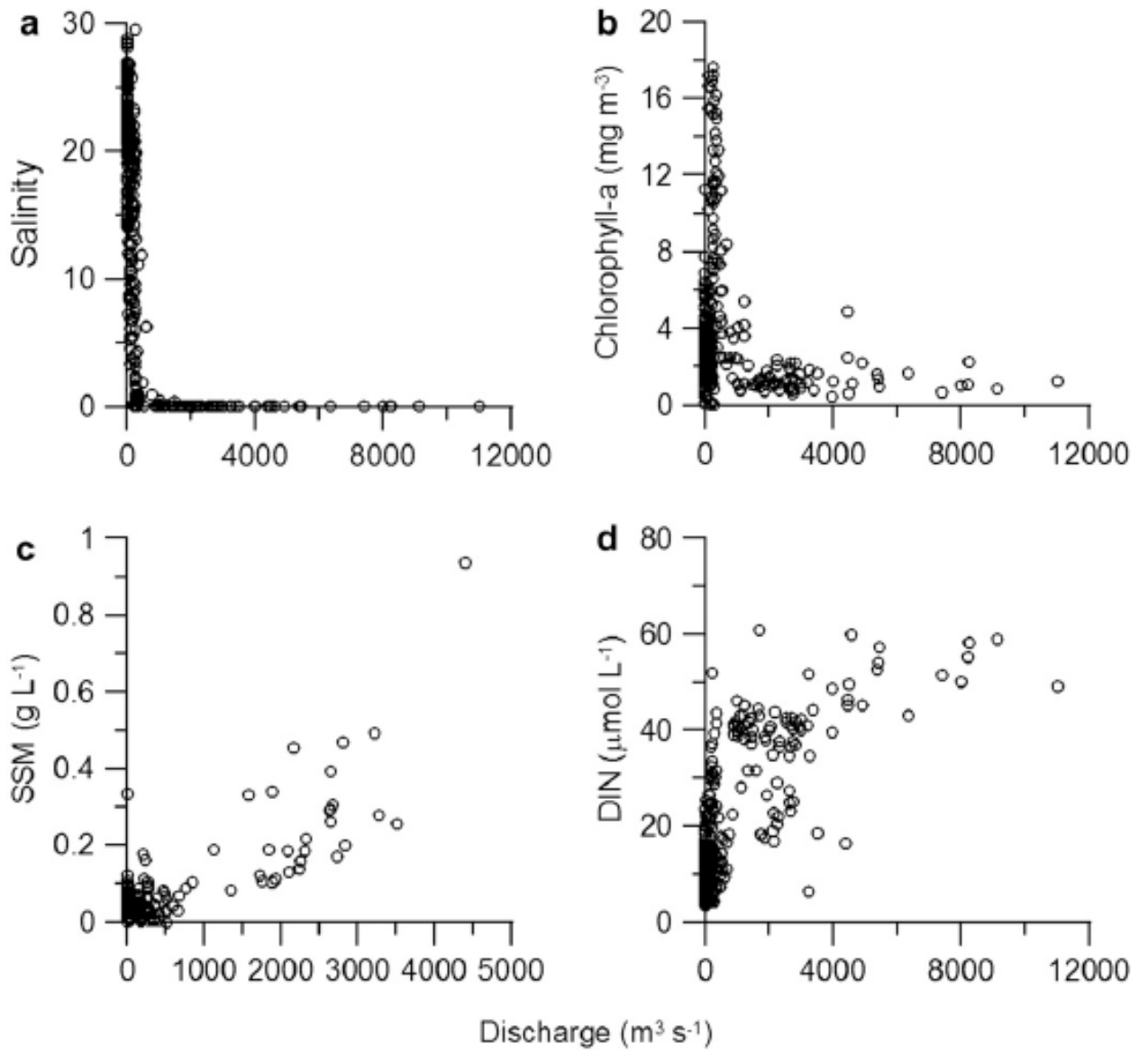


Fig.6

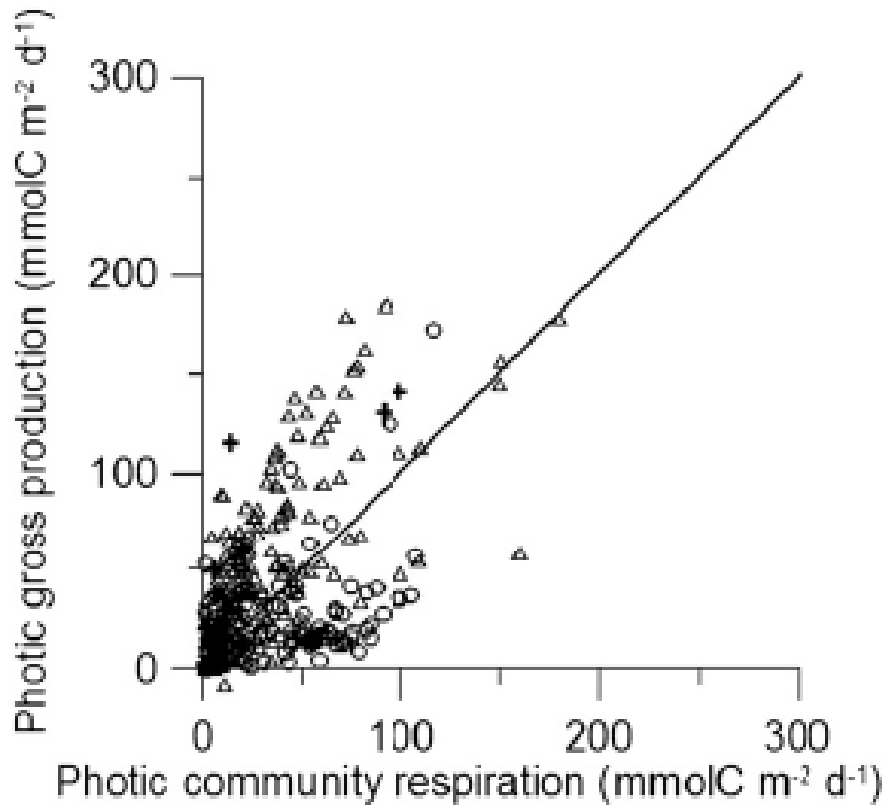


Fig.7

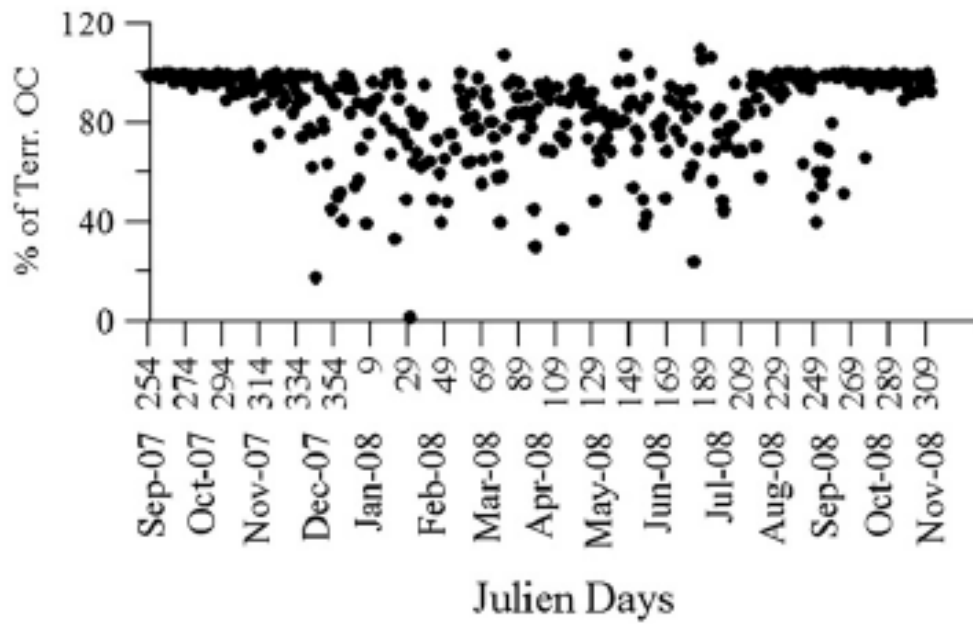


Fig.8