BACTERIAL AND PHYTOPLANKTON PRODUCTION IN TWO COASTAL SYSTEMS INFLUENCED BY DISTINCT EUTROPHICATION PROCESSES

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ABSTRACT

Evaluating the relationships between bacterial (BP) and phytoplankton production (PP) is a first step to understand carbon fluxes through pelagic food webs. In the present study, BP and PP were compared at two tropical coastal systems influenced by distinct eutrophication processes in order to assess the main regulating factors of particulate organic carbon (POC) production rates. The waters of Cabo Frio region (23°00'S; 42°00'W) present high nitrate (N-NO_3) levels and low temperatures resulting from the upwelling of deep water masses – thus, a natural eutrophication process – while the waters in Guanabara Bay (22°54'S; 43°09'W) present high temperatures and levels of dissolved organic carbon (DOC), nitrogen (DON) and nutrients (other than nitrate), resulting from anthropogenic eutrophication, mainly because of sewage wastes. Dissolved organic matter (DOM) elemental composition indicates lower autochthonous contribution in Cabo Frio (C:N ~ 42), probably due to lower phytoplankton production. The elevated temperatures in Guanabara Bay yielded higher PP rates, increasing the phytoplankton contribution to the DOM pool which improved BP. No coupling between BP and PP was observed, and POC production was mainly due to phytoplankton in both systems.
Keywords: Guanabara Bay, Cabo Frio, upwelling, carbon cycling.

RESUMO

PRODUÇÃO BACTERIANA E FITOPLANCTÔNICA EM DOIS SISTEMAS COSTEIROS INFLUENCIADOS POR PROCESSOS DISTINTOS DE EUTROFIZAÇÃO. A avaliação das relações entre produção bacteriana (PB) e fitoplanctônica (PF) consiste em um primeiro passo para o entendimento dos fluxos de carbono através das teias tróficas pelágicas. No presente estudo, PB e PF foram comparadas em dois sistemas costeiros tropicais influenciados por processos distintos de eutrofização a fim de se estimar os principais fatores reguladores das taxas de produção de carbono orgânico particulado (COP). A região de Cabo Frio (23°00'S; 42°00'W) apresenta altos teores de nitrato (N-NO_3) e baixas temperaturas devido à ressurgência de massas de água profundas – um processo de eutrofização natural, enquanto que a Baía de Guanabara (22°54'S; 43°09'W) apresenta altas temperaturas e altos teores de nutrientes (com exceção do nitrato), carbono e nitrogênio orgânicos dissolvidos (COD e NOD) resultantes de um avançado processo de eutrofização antrópica, principalmente através do lançamento de esgotos. A composição elementar da matéria orgânica dissolvida (MOD) indica menor contribuição de fontes autóctones em Cabo Frio (C:N ~ 42), provavelmente devido à menor produção fitoplanctônica. As altas temperaturas na Baía de Guanabara proporcionaram maiores taxas de PF, aumentando a contribuição do fitoplâncton para a MOD como um todo, o que resultou em um incremento da PB. Não foi observado acoplamento entre PB e PF e a produção de COP dos dois sistemas deveu-se principalmente ao fitoplâncton.
Palavras-chave: Baía de Guanabara, Cabo Frio, ressurgência, ciclagem de carbono

INTRODUCTION

Carbon cycling in pelagic systems is directly influenced by local trophic structure. In herbivorous food webs, which are based mainly on larger phytoplankton production, most of the organic carbon produced is exported by sinking or grazing (Legendre & Rassoulzadegan 1996). Conversely, in microbial food webs, which are based on smaller phytoplankton and heterotrophic bacterial productions, most of the organic carbon produced is recycled through heterotrophic respiration (Legendre & Le Fevre 1995).

Phytoplankton production (PP) is controlled by an optimal combination of light, temperature, and nutrient (mainly nitrogenous) availability (Harris 1986), while bacterial production (BP) is chiefly regulated by dissolved organic matter (DOM) lability besides temperature and nutrients availability (Kirchman 2000). The relative contribution of phytoplankton and bacterioplankton to particulate organic carbon (POC) production varies according to the organic carbon supply. In systems where there are no allochthonous inputs of dissolved organic carbon (DOC), BP is primarily supported by phytoplankton exudates and a tight coupling between BP and PP is observed (e.g. Moran *et al.* 2002). On the other hand, when DOC sources are mostly allochthonous, there is no coupling between those plankton compartments and BP may exceed PP (e.g. Findlay *et al.* 1991).

Evaluating relationships between bacteria and phytoplankton is thus primary to understand the trophic interactions and the carbon fluxes of a given system. In the present study we compared BP and PP rates of two tropical coastal systems of southeastern Brazil influenced by distinct eutrophication processes: the Cabo Frio upwelling region and Guanabara Bay (see Guenther *et al.* 2008a,b). The Cabo Frio euphotic zone receives periodical nutrient inputs as a result of a wind-driven upwelling of South Atlantic Central Water (SACW), and it can thus be considered a natural eutrophication process. This nutrient enrichment, however, is accompanied by a steep decrease in surface water temperature. Guanabara Bay is an eutrophic coastal bay that constantly receives great amounts of organic material and nutrients from continental and sewage wastes. Our hypothesis is that these distinct nutrient and organic material sources will influence the quality of DOM and consequently the relationships between bacterioplankton and phytoplankton production in those two coastal systems.

MATERIAL AND METHODS

In Cabo Frio, the study was conducted from a fixed station (23^{o}00'S; 42^{o}00'W) located at the southern end of Cabo Frio Island, known to be the core of the SACW upwelling (Figure 1). Samples were collected within 6-h intervals during 6 days (between February 19 and 24 2002), including both downwelling and upwelling periods. In Guanabara Bay, the study was conducted from a fixed station (22^{o}54'S; 43^{o}09'W) at the main channel, near to the bay entrance. Samples were collected within 3-h intervals during 3 days (between February 09 and 12 2004) spanning from late spring tide to early neap tide (see Guenther *et al.* 2008a,b).

In both systems, surface water samples were collected using Niskin bottles (10L). Individual samples were taken for assessing dissolved oxygen (DO), nutrients, dissolved organic carbon and nitrogen (DOC and DON), BP and PP. Temperature and salinity were locally measured during the samplings using a Seabird Seacat 19 CTD system. DO concentrations were estimated through Winkler titration (Aminot & Chaussepied 1983). Nutrient concentrations were determined following methods in Grasshoff *et al.* (1983) for $N\text{-}NO_2$, $N\text{-}NO_3$, $P\text{-}PO_4$ and $Si\text{-}SiO_4$, and in Parsons *et al.* (1984) for $N\text{-}NH_4$. DOC contents were analyzed with a TOC-5000 Shimadzu Total Carbon Analyzer after filtration with pre-combusted GF/F filters (450^{o}C for 3h). DON contents were calculated by subtracting total amounts of nitrogen inorganic forms ($N\text{-}NO_3$, $N\text{-}NO_2$ and $N\text{-}NH_4$) from total dissolved nitrogen (TDN), which was determined after digesting the samples with potassium persulphate. Samples for BP evaluation were incubated with 10nM L-[4,5-^{3}H] leucine for 1h according to Smith & Azam (1992), and those for PP were incubated *in situ* with 10μCi $NaH^{14}CO_3$ for 3h according to Steemann-Nielsen (1952). See Guenther *et al.* (2008a,b) for further methods details.

Differences between the two areas for each measured variable were verified using t-tests. The correlations between PP and BP were analyzed using Single Linear Regressions. The correlations between POC production (PP and BP) and several predictor variables selected from a preliminary analysis (temperature and nutrients for PP and temperature, DON, DOC, DOM C:N, $N\text{-}NH_4$, $N\text{-}NO_3$ and $N\text{-}NO_2$ for BP) were analyzed using standard forward stepwise multiple regressions (including intercept). The model was executed with tolerance > 0.10 and residual statistics were computed in order to identify any extreme outlier. When one or several cases fell outside ± 3 times the residual standard deviation, these were excluded and the analysis repeated. A

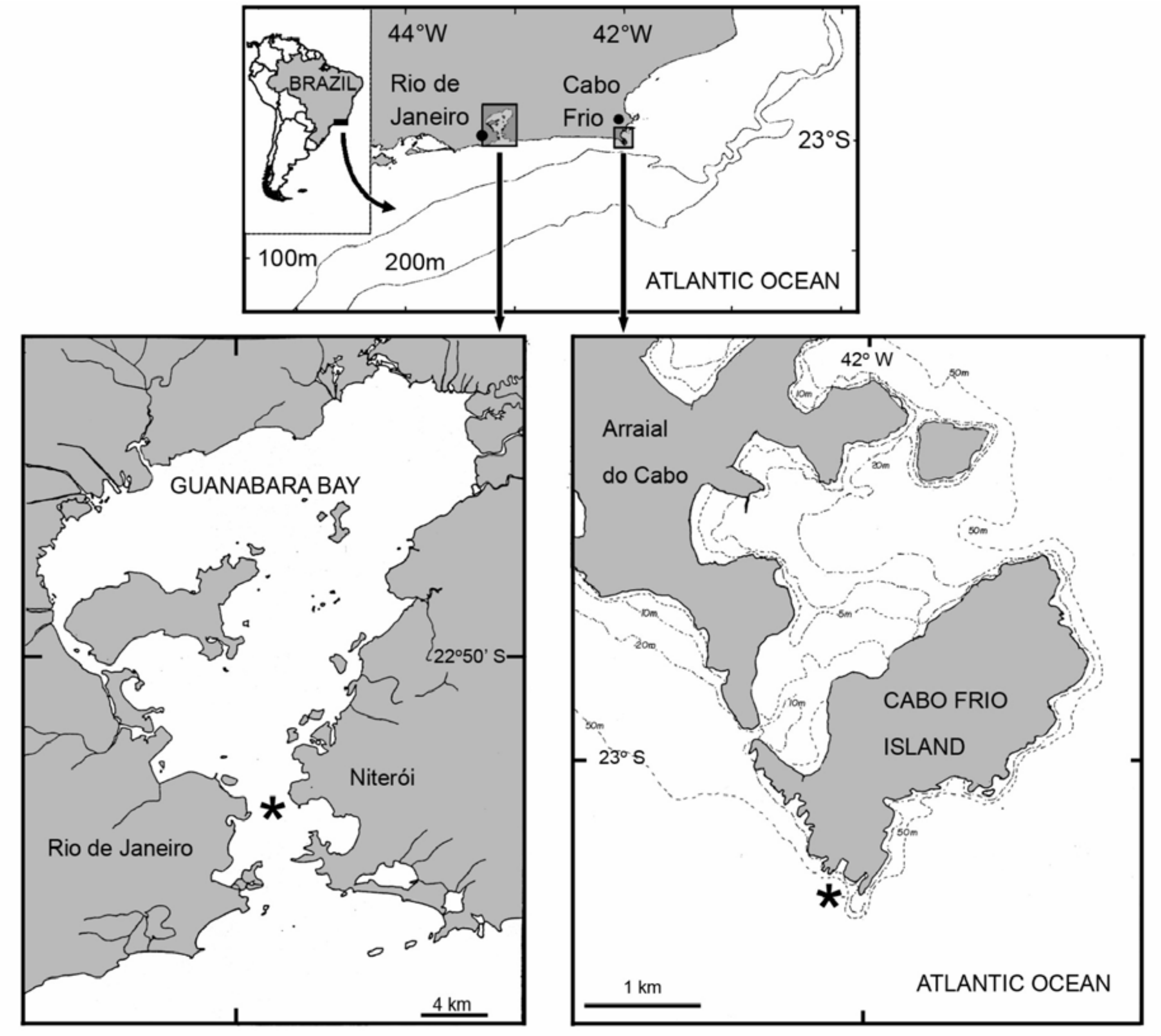

Figure 1. Study area and sampling stations (*).

principal Component Analyses (PCA) was applied to the correlation matrix between all variables to identify the main factors responsible for total variance. Data normality was tested using a Kolmogorov-Smirnov test and a log(x) transformation was applied when data did not fit normality. All tests were performed with Statistica v. 7.0.

RESULTS

Surface water layers in Cabo Frio presented higher salinity (~35) and $N\text{-}NO_3$ levels (~2.5µM), while the surface water layer of Guanabara Bay presented higher temperatures (~24°C) and amounts of DOC (~220µM), DON (~14µM) and the other nutrients: $N\text{-}NH_4$ (~4.0µM), $N\text{-}NO_2$ (~0.5µM), $P\text{-}PO_4$ (~0.6µM) and $Si\text{-}SiO_4$ (~23.4µM). DOM C:N was higher in Cabo Frio (~42) than in Guanabara Bay (~17) (Table I).

Table I. Mean ± SD of measured variables in both areas and p values of the respective t-tests.

System	Cabo Frio	Guanabara Bay	p
Temp. (°C)	20.9 ± 2.50	23.8 ± 0.60	< 0.001
Salinity	35.3 ± 0.45	30.5 ± 1.74	< 0.001
DO (mL L^{-1})	5.48 ± 0.79	4.69 ± 0.96	0.005
$N\text{-}NH_4$ (µM)	1.27 ± 0.41	4.01 ± 2.17	< 0.001
$N\text{-}NO_2$ (µM)	0.17 ± 0.12	0.49 ± 0.13	< 0.001
$N\text{-}NO_3$ (µM)	2.45 ± 1.97	0.44 ± 0.35	< 0.001
$P\text{-}PO_4$ (µM)	0.40 ± 0.16	0.58 ± 0.14	< 0.001
$Si\text{-}SiO_4$(µM)	3.65 ± 1.57	23.4 ± 7.20	< 0.001
DOC (µM)	141 ± 53.3	220 ± 38.4	< 0.001
DON (µM)	3.37 ± 0.68	14.2 ± 5.24	< 0.001
DOM C:N	41.9 ± 13.5	17.1 ± 5.30	< 0.001
BP (µMC h^{-1})	0.05 ± 0.03	2.39 ± 0.89	< 0.001
PP (µMC h^{-1})	5.85 ± 2.58	169 ± 152	0.003
BP:PP	0.01 ± 0.01	0.04 ± 0.05	0.118

Bacterial and phytoplankton production rates were significantly higher in Guanabara Bay (BP=0.9-

4.4μMC h^{-1}; PP=23-582μMC h^{-1}) than in Cabo Frio (BP=0.01-0.13μMC h^{-1}; PP=3-11μMC h^{-1}) (Table I and Figure 2). No correlation between BP and PP was observed in neither areas (Cabo Frio: r=0.22, p=0.54; Guanabara Bay: r=-0.15, p=0.64). BP:PP ratios were equivalent in both areas: 1% in Cabo Frio and 4% in Guanabara Bay.

BP variation in Cabo Frio (R^2=0.68, p<0.001) was inversely dependent on $N\text{-}NO_3$ (β=-0.61, p=0.01) and DOM C:N (β=-0.39, p=0.04). In Guanabara Bay, BP variation (R^2=0.76, p<0.001) was directly dependent on DOC (β=0.86, p=0.007) and inversely dependent on temperature (β=-0.78, p=0.002), DON (β=-2.07, p<0.001) and DOM C:N (β=-1.81, p<0.001). None of the selected variables explained PP variations in neither Cabo Frio nor Guanabara Bay.

The Principal Component Analysis discriminated between the results from the two areas in clear clusters (Figure 3). The 1st component, standing for 56.57% of total variation, grouped Guanabara Bay samples on its positive end, which is characterized by higher values of temperature, $N\text{-}NH_4$, $N\text{-}NO_2$, $P\text{-}PO_4$, $Si\text{-}SiO_4$, DOC, DON, PP and BP, and grouped Cabo Frio samples on its negative end, which is characterized by higher values of $N\text{-}NO_3$, salinity, DOM C:N and DO. The 2nd component, standing for 16.76% of the total variation, grouped Cabo Frio downwelling samples (26–34) on its negative end, with higher values of DO, temperature and DOC, and upwelling samples (38–45) on its positive end, with higher nutrient levels. In Guanabara Bay there was no clear distinction between spring and neap tide phases.

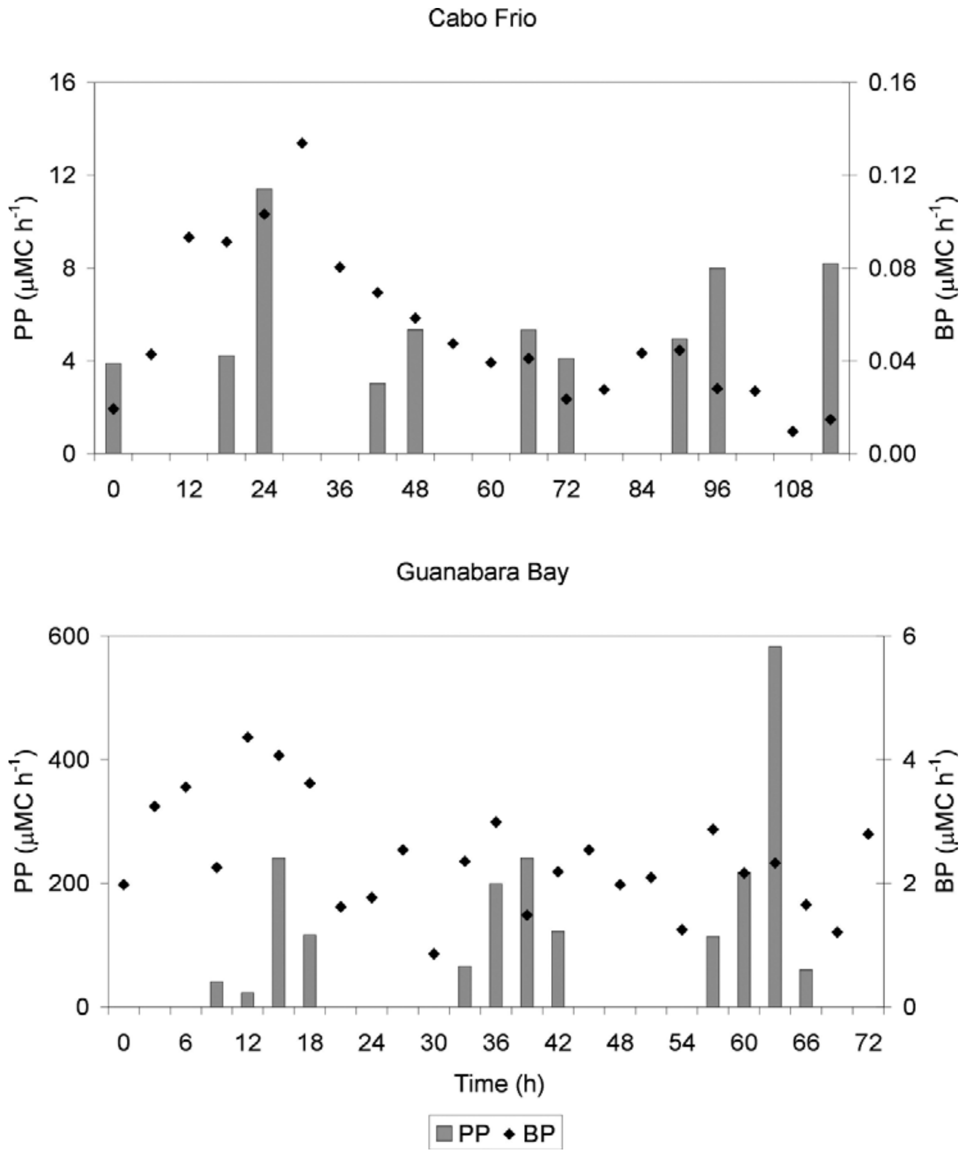

Figure 2. Phytoplankton (columns) and bacterial (dots) production in Cabo Frio (February 19–24 2002) and Guanabara Bay (February 09–12 2004).

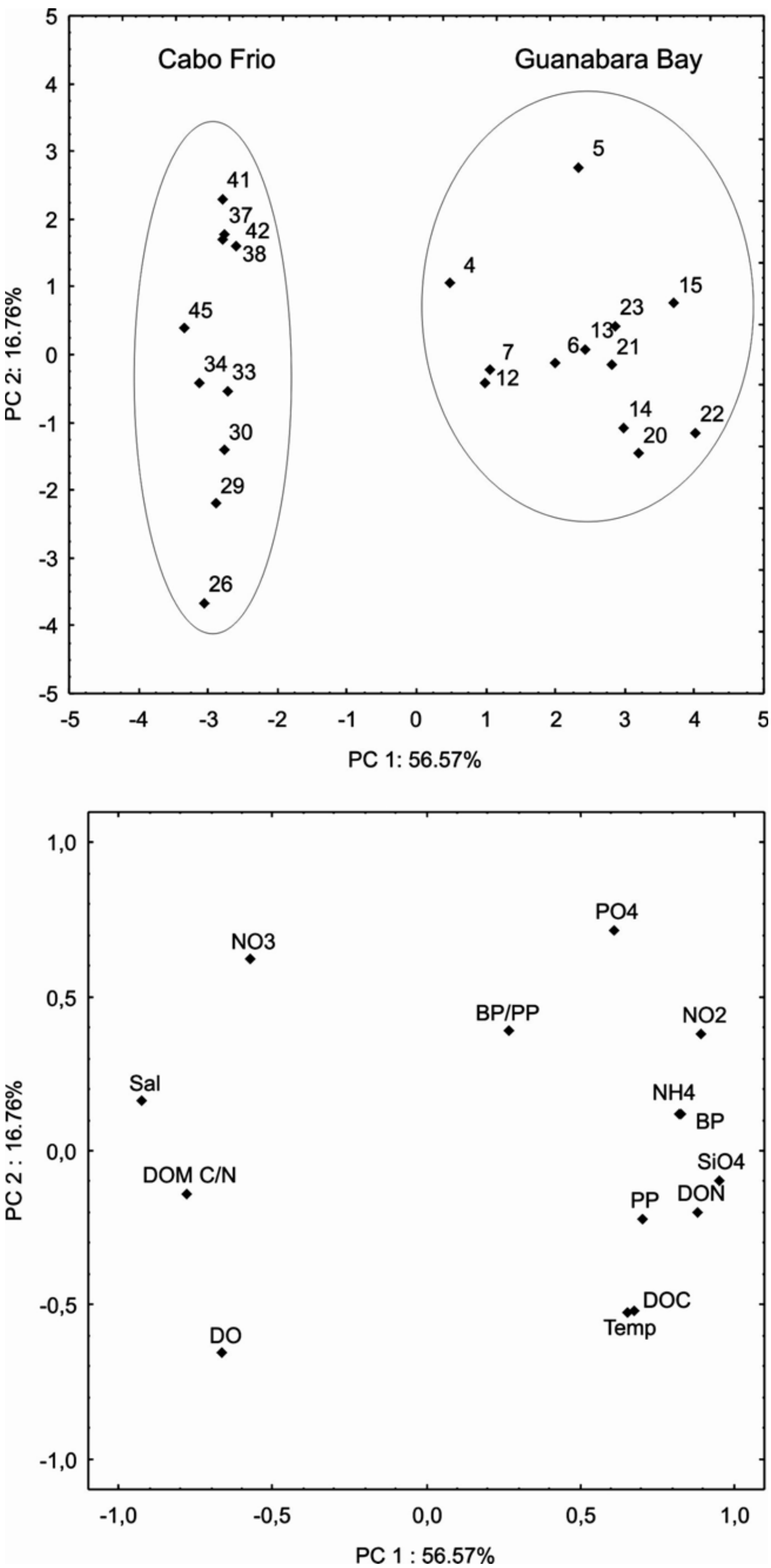

Figure 3. Results of the Principal Component Analysis: distribution of the samples (upper graph) and variables (lower graph) on factorial planes.

DISCUSSION

Guanabara Bay presented higher BP and PP rates than Cabo Frio but the POC production of both areas was chiefly credited to phytoplankton. BP was uncoupled with PP in both areas and was mainly regulated by DOM quality.

The higher nutrient and DOM levels and lower salinity at the entrance of Guanabara Bay result from the continental input referent to the advanced process of anthropogenic eutrophication. In Cabo Frio, the influence from the SACW resulted in the lower temperatures and higher N-NO_3 levels observed. In both areas the high DOM C:N ratios indicate the predominance of allochthonous DOM sources, rich in organic carbon (Findlay *et al.* 1991). In Cabo Frio, despite the apparent lower influence of terrestrial inputs, DOM C:N was unexpectedly higher, which suggests smaller phytoplankton contribution to the DOM pool in comparison to Guanabara Bay, probably due to lower PP rates (Baines & Pace 1991).

The differences between N-NH_4 and N-NO_3 contributions in both areas do not seem to influence the phytoplankton productivity, since even the lower ammonium levels of Cabo Frio did not limit photosynthetic efficiency (Guenther 2006). Therefore, the low PP rates in Cabo Frio must be mostly due to the lower temperatures. Upwelling systems are generally characterized by cycles of nutrient enrichment and productivity: following the surface increase in nutrients and the water column stabilization by solar heating, an increase in photosynthetic activity and nutrient uptake and, consequently, phytoplankton biomass, occurs (MacIsaac *et al.* 1985, Wilkerson & Dugdale 1987). In Cabo Frio, however, the maximum PP rates registered in the present and previous studies (e.g. Gonzalez-Rodriguez *et al.* 1992, Gonzalez-Rodriguez 1994) are under the finds from other upwelling systems (e.g. Gonzalez *et al.* 2004, Montecino *et al.* 2004). This is probably a consequence of reduced surface heating (Valentin 2001) and high grazing pressure over the phytoplankton (Guenther *et al.* 2008a).

The fact that BP and PP in both areas did not couple reflects the prevalence of allochthonous DOC. Bacterial production was inversely correlated with DOM C:N in both Cabo Frio and Guanabara Bay. The optimal DOM C:N for bacterial uptake is around 5.0, which equals their elemental composition (Goldman *et al.* 1987). Therefore, under high DOM C:N conditions, bacterioplankton will adjust the C:N balance by using inorganic N (Kirchman 1994), what compromises their growth efficiency (Guenther *et al.* 2008b). The higher BP rates of Guanabara Bay are thus result of local organic matter quality (i.e., lower DOM C:N) and higher water temperatures.

CONCLUSIONS

Guanabara Bay and Cabo Frio systems differed in the source of nutrients and organic matter as well as in water temperatures, resulting in distinct phytoplankton and bacterial POC production rates. The elevated temperatures of Guanabara Bay provided higher PP rates, increasing the phytoplankton contribution to the DOM pool, which then improved BP. Despite those differences, there was no coupling between BP and PP in neither areas, and phytoplankton seems to be the main POC source for the higher trophic levels.

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