Influence of estuarine dynamics on macrobenthos spatial variability along the southeast continental shelf of Brazil

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Summary: Along the southeast continental shelf of Brazil, the Paraíba do Sul River (PSR) plays a fundamental role in sediment and nutrient transport. This study focuses on the contribution of the PSR and its effect on the benthic macrofauna. Physical and chemical analyses of the sediment were conducted, and the macrofauna were identified and counted. Multivariate analyses were used to compare the distribution patterns of the benthic assemblages related to the depth gradient over two sampling periods. The principal component analysis showed that shallow waters assemblages are mostly influenced by the environmental descriptors temperature, salinity and chlorophyll *a*, whereas pheophytin, degree of sediment sorting, total carbonate and organic carbon were correlated with benthic assemblages at greater depths. The high organic enrichment reflected an increase in surface and sub-surface deposit feeders such as the polychaetes *Spiophanes* sp. and *Prionospio cristata* and the crustacean *Phtisica marina* in the deeper stations, with a corresponding decrease in other trophic groups. This study provides evidence of differences in organic matter sources, from primary production in shallow waters to detritus in deep waters. These sources provide different niches for the corresponding macrofaunal assemblages along the continental shelf adjacent to the PSR, with species richness and abundance of benthic populations related to the river output.

Keywords: sediment; macrofauna; organic carbon; phytopigments; continental shelf; Paraíba do Sul River.

Influencia de la dinámica de estuarios sobre la variabilidad espacial de macrobentos a lo largo de la plataforma continental del sudeste de Brasil

Resumen: A lo largo de la plataforma continental del sudeste de Brasil, el río Paraíba do Sul (RPS) juega un papel fundamental en el transporte de sedimento y nutrientes. Este estudio se enfoca en la contribución del RPS y sus efectos sobre la macrofauna bentónica. Se condujeron análisis físicos y químicos del sedimento, y la macrofauna fue identificada y contada. Se realizaron análisis multivariados para comparar los patrones de distribución de los ensamblajes bentónicos relacionados al gradiente de profundidad en dos periodos de muestreo. El análisis de componentes principales (ACP) mostró que los ensamblajes de aguas poco profundas son influenciados principalmente por los descriptores ambientales de temperatura, salinidad, y clorofila *a*, mientras que la feofitina, grado de clasificación de sedimentos, carbonato total y el carbón orgánico estaban correlacionados a los ensamblajes bentónicos a mayores profundidades. El alto enriquecimiento orgánico se refleja en un incremento de detritívoros superficiales y sub-superficiales como los poliquetos *Spiophanes* sp. y *Prionospio cristata* y el crustáceo *Phtisica marina* en las estaciones más profundas, con el decrecimiento correspondiente en otros grupos tróficos. Este estudio provee evidencia de diferencias entre fuentes de materia orgánica, desde la producción primaria en aguas poco profundas hasta detrito en aguas profundas, que proveen distintos nichos a los ensamblajes macrofaunales correspondientes a lo largo de la plataforma continental adyacente al RPS, con la riqueza de especies y abundancia de las poblaciones bentónicas relativas al flujo del rio.

Palabras clave: sedimento; macrofauna; carbón orgánico; fitopigmentos; plataforma continental; río Paraíba do Sul.

INTRODUCTION

Depositional organic matter (OM) is a significant source of energy and elemental raw materials for most benthic communities, so sedimentary OM dynamics exert strong control over marine benthic biodiversity. Organic enrichment influences community composition by reducing diversity through the exclusion of low-tolerance species and increasing the biomass associated with the dominance of several opportunistic species (Pearson and Rosenberg 1978, Lardicci et al. 1993, Diaz-Castaneda and Harris 2004). An increase in the amount and quality of OM can lead to an increase in the biomass and density of the benthic organisms and also to dystrophic events, such as episodes of hypoxia or anoxia, which can cause massive reductions or elimination of the benthic fauna. Such phenomena are frequent and well documented in the northern Adriatic Sea (e.g., Ambrogi et al. 1990, Crema et al. 1991, Moodley et al. 1998).

Hydrodynamics and depositional environments, with their physical and chemical proprieties, have repeatedly been referred to as the main contributors to the variability of soft-bottom communities (Snelgrove and Butman 1994), which are influenced by characteristics of the bottom currents that favour sedimentation and/or resuspension and sediment transport, particularly in shallow waters (Sternberg 1984 in Leninhan and Micheli 2001, Akoumianaki et al. 2013). Sedimentation rates and the quality and quantity of OM in the sediment can determine the trophic structure, abundance, biomass and colonization pattern in the sediment (Marsh and Tenore 1990, Weston 1990, Dauer and Alden 1995). There is significant evidence that increased terrestrial sediment deposition in coastal zones is detrimental to the biodiversity and ecological value of estuarine and coastal habitats (Thrush et al. 2004). Field studies (Wijsman et al. 1999, Akoumianaki et al. 2013) have provided supporting evidence that sedimentary processes in coastal areas that are influenced by smaller rivers are related to the distance from riverine sources.

Ocean dynamics control the dispersion of particles by riverine plumes and their subsequent mixing and dilution within coastal and oceanic boundary currents, followed by their gradual sedimentation within the shelf area (Albuquerque et al. 2014). All of these sources and processes operate according to their own temporal and spatial constraints, creating a complex scenario for understanding the origins and fates of suspended particles at the ocean margin and their fluxes to the ocean floor (Liu et al. 2010, Schmidt et al. 2010)

The Paraíba do Sul River (PSR) plays an important role in the ecosystem of the southeast continental shelf of Brazil. A recent study showed that the water mixture ratio in the dry season ranges from 23 to 38 $km^2 d^{-1}$, whereas in the rainy period (summer months), it ranges from 65 to 68 $km^2 d^{-1}$ (Souza et al. 2010). According to Carvalho et al. (2002), the PSR shows a large interannual variation of suspended particulate matter discharge (0.8 to 2.0×10^6 t/year), whereas other results indicate a discharge of 0.3×10^6 t/year of dissolved organic carbon (Figueiredo et al. 2011, Ovalle et al. 2013). The water chemistry information associated with spectral mapping of the PSR plume suggest that the continental input provides an important contribution towards the macrobenthic distribution, abundance and diversity in open estuarine areas and continental shelves (Rudorff et al. 2011).

This study examines the species composition and distribution of the macrozoobenthic community according to distances from the PSR outfall and environmental variables in the water column and sediment in a coastal area of Campos Basin, along the southeast continental shelf of Brazil. We tested the hypothesis that, in the shallower coastal area under higher PSR influence, an increase in the abundance of benthic populations is expected because these species take advantage of the high organic nutrient inputs. In the outer shelf region, which is characterized by reduced sedimentation and resuspension levels, the low food inputs should result in lower species abundance.

MATERIALS AND METHODS

Study site

The Campos Basin is located in southeastern Brazil and includes a large portion of the coast of Rio de Janeiro and Espírito Santo States. The study area is located on the continental shelf north of Rio de Janeiro State (southern boundary 22°59'S, 39°93'W; northern boundary 21°11'S, 40°78'W), and it is adjacent to the mouth of the Paraíba do Sul River (Fig. 1A). The Tropical Water, Coastal Water and South Atlantic Central Water masses influence the study area. The latter penetrates the continental shelf during spring and summer and brings nutrient-rich waters (Silveira et al. 2000). The climate is characterized as warm subtropical, and the annual average temperatures range from 18°C to 24°C (Marengo and Alves 2005). The seafloor includes areas with sand of different granulometric fractions and areas with elevated percentages of mud and/or gravel (Lana et al. 1996, Saavedra et al. 1999).

Field sampling

Two oceanographic sampling campaigns were completed: March 2009 (rainy season) and July 2009 (dry season). A valid temporal comparison was not possible because of a lack of replicated wet/dry season sampling, and then both surveys were considered as spatial replicates to reinforce the riverine influence, which must be discerned using spatial differences alone. Therefore, we used two temporal campaigns to define the similarities/differences among the sampling depths. The temporal descriptor was considered as a hierarchical factor in the spatial factor (latitudinal and longitudinal), representing the bathymetry and coastal distance.

The samples were collected in triplicate with a Van Veen grab at 53 stations from 12 to 100 m depth, covering a potential region that is reached by the sediment plume along the continental shelf (Fig. 1B), and then
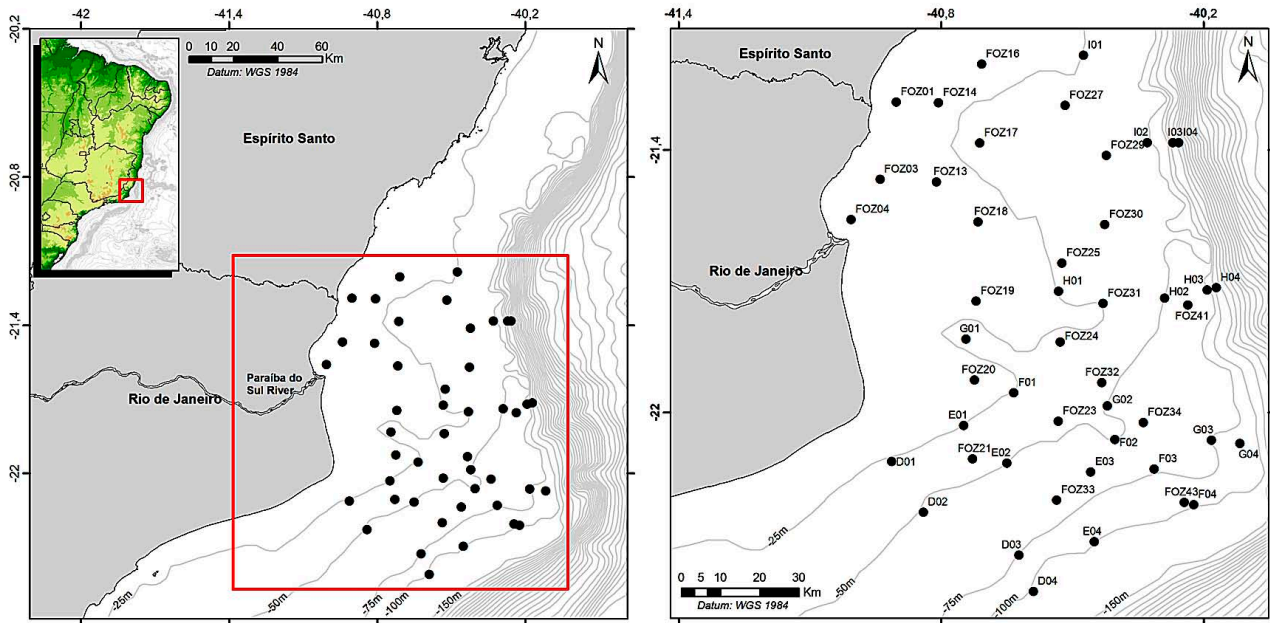
Fig. 1. – A, the study area on the northern coast of the Rio de Janeiro State and southern coast of Espírito Santo State. B, a map showing the locations and depths of the sampling sites.

grouped into four depth strata (<30 m, 30-50 m, 50-75 m and 75-100 m). These stations were configured through a hypsometric curve considering depth versus isobaths (<30 m, internal shelf; 30-50 m, medium shelf; 50-75 m and 75-100 m, external shelf). Four subsamples (10×10×10 cm and 0.004 m³) were collected from the superficial sediment of each sample. The macrofauna subsamples were fixed in buffered 10% formaldehyde. The sediment parameters (grain size distribution, sorting, total carbonate and organic carbon) were sampled independently using 10×10×2 cm corers, and then frozen. The depth, temperature and salinity were measured in situ using a CTD profiler. For the analysis of bacterial abundance and phytopigments, aliquots of the upper layer of the sediment (0-2 cm) were transferred into 2 ml cryogenic tubes with the aid of sterile wooden spatulas (previously autoclaved) and strictly sterile conditions. Immediately after collection, the samples were preserved in liquid nitrogen where they remained until they were analysed in the sample-processing laboratory.

Laboratory analysis

The macrofauna subsamples were sieved through a 500-μm mesh, sorted, identified to the lowest possible taxonomic level and counted. On the sediment subsamples, the grain size distribution was determined by a particle analyser using laser diffraction (Shimadzu Model SALD-3101) in several fractions of the Wentworth scale (Suguio 1973), and classified using the degree of sorting. The total carbonate was determined by acid treatment using 1 g of dry sediment with 20 ml of HCl 1.0M overnight. The organic carbon (OC) was determined by a CHN analyser after removing the carbonate with HCl 1.0M added directly into the silver vials (Hedges and Stern 1984).

For the determination of pigments (chlorophyll and pheophytin), aliquots of approximately 1.0 g were weighed, and the pigments were extracted with 100% acetone for 24 h (in the dark at 4°C) using a fluorimeter (Turner Designs TD-700). The calculations were based on procedures and equations described by Parsons et al. (1984), and the detection method was performed with a focus on metrology (Mattos 2001). The devices were calibrated with pure chlorophyll a (Sigma C-6144), and the detection limit for this assay was 0.02 μg g^{-1}.

Data analysis

Differences in water temperature and salinity were compared using two-sample t-tests of survey-specific estimates (n=159 for March 2009 and n=159 for July 2009). A principal component analysis (PCA) was applied to both campaigns to define the similarities between the 53 sampling sites according to the environmental descriptors (continuous variables), and also to define which descriptors are most influencing the observed pattern.

The pattern of macrofauna distribution was compared among the four depth strata (<30 m, 30-50 m, 50-75 m and 75-100 m) in both periods through a matrix of the transformed abundance data of the representative species (species with a relative abundance >0.5%) and ordinated (non-metric multidimensional scaling [nMDS]) using the Bray-Curtis similarity index (Clarke and Warwick 2001).

A permutational multivariate analysis of variance (Anderson 2001, 2005) was performed for a multivariate comparison of the macrofauna composition among the depth strata on both periods. The Bray-Curtis similarity distance was selected as a base for the PERMANOVA analyses. The species density log-transformed data were permuted 9999 times per analysis at
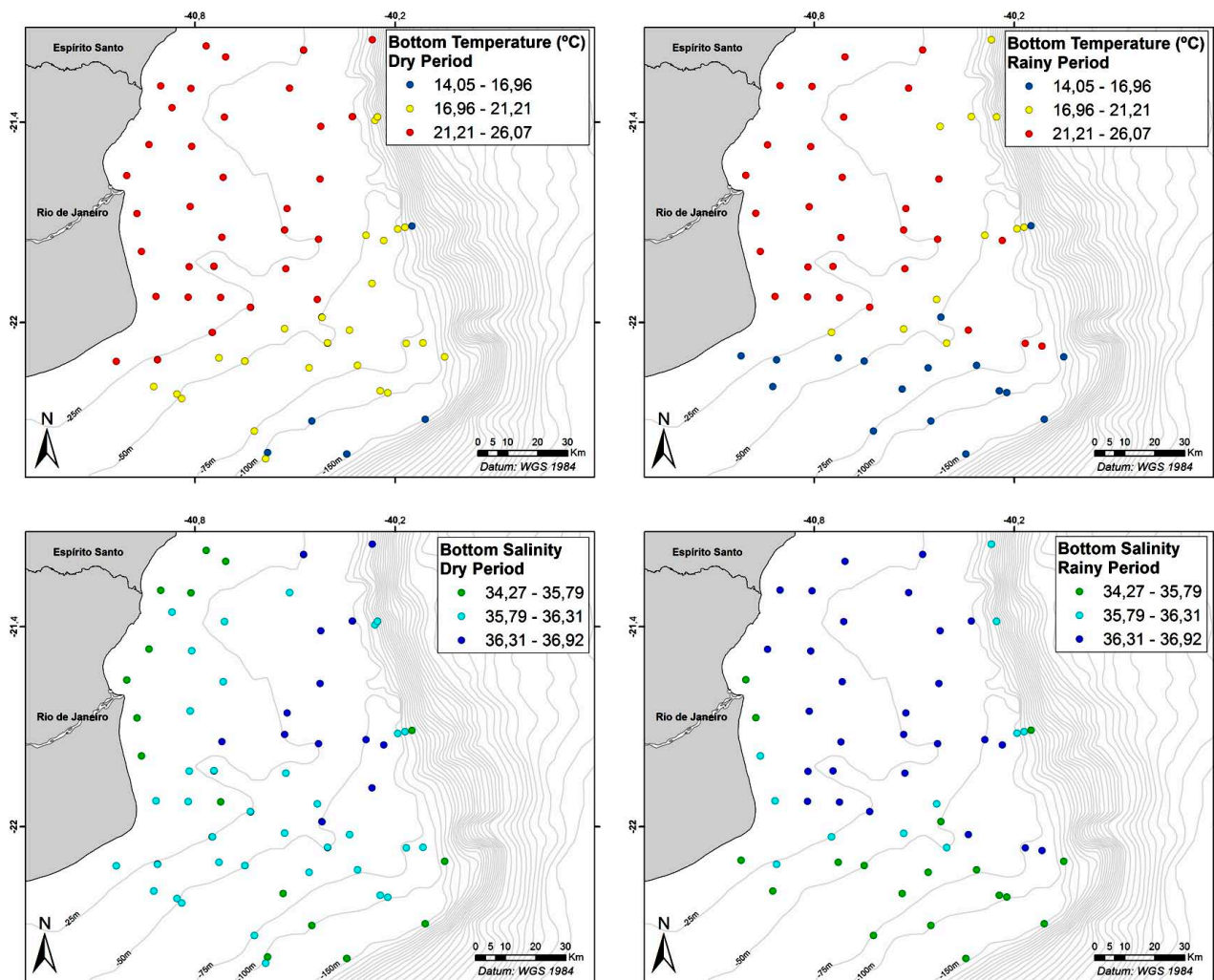
Fig. 2. – The mean temperature and salinity values at the 53 stations located along the southeast continental shelf of Brazil (A, temperature, dry period; B, temperature, rainy period; C, salinity, dry period; D, salinity, rainy period).

a significance level of 0.05. The species' contributions to the similarity were calculated using the identification of the faunal associations (SIMPER). The multivariate analyses were performed using the PRIMER v. 6 statistical software (Clarke and Warwick 2001).

A canonical correspondence analysis (CCA) was used to correlate the macrofauna organisms (species with a relative abundance >0.5%) with the environmental variables temperature, salinity, pheophytin, chlorophyll *a* and the sediment parameters sorting, total carbonate and total OC, which were the only significant variables in the prior permutational test. The significance of the canonical axes and variables was determined using Monte Carlo tests and permutations (Ter Braak 1986) using the software programs CANOCO and MVSP 3.13, respectively.

RESULTS

Abiotic data

During the dry and rainy seasons, the salinity of the bottom water ranged between 34.3 and 36.9 and 35.4 and 36.5, respectively ($t_{est.}$=5.33, D.F.=160.3 and

p<0.0001) and the temperature ranged from 14.4°C to 26.1°C and 14.0°C to 23.1°C, respectively. Therefore, shallow water samples from rainy periods have significantly lower temperature and higher salinity ($t_{est.}$=2.03, D.F.=133.5 and p=0.04) (Fig. 2).

The sediment was predominantly sand (93%), except at stations E1 and 4 during the rainy period, and I4, 7 and 8 during the dry period, which exhibited a predominance of silt; stations H4 and I2 exhibited a predominance of gravel (Fig. 3, Appendix 1). The degree of sediment sorting varied from very poorly or poorly (50%) to moderately selected (50%) (Appendix 1).

The grain size distribution ranged from very coarse sand to medium silt (–0.31 to 6.96 θ) in the rainy period and from very fine gravel to fine silt (–1.43 to 5.25 θ) in the dry period (Figs 3A, B). The total carbonate and OC ranged from <0.01 to 11.6% and 0.08 to 1.53%, respectively, in the dry season and from <0.01% to 11.5% and 0.05% to 0.92%, respectively, in the rainy season. Chlorophyll *a* ranged from 0.02 to 7.36 μg g^{-1} in the dry season and from 0.26 to 7.23 μg g^{-1} in the rainy season. Pheopigments were also low, ranging from 0.02 to 12.90 μg g^{-1} in the dry season and 0.30 to 7.29 μg g^{-1} in the rainy season. Although OC was

lower closer to the outfall PSR stations, the chlorophyll/pheophytin ratio was higher (Figs 3C, D, E, F).

The two principal axes indicated by the PCA explained ~52% of the total variance in both campaigns. Axis 1 (34.5%) revealed that the shallower stations (<50 m), mainly on the left side, were most strongly influenced by temperature, salinity and chlorophyll *a* (Fig. 4) in both the rainy and dry periods. The diagram reveals a direct relationship between pheophytin and the sediment parameters sorting, total carbonate and OM in the deeper ranges (Fig. 4).

Taxonomic composition

The benthic macrofauna included annelids, crustaceans, molluscs, echinoderms, nemerteans and sipunculids. A total of 71415 individuals were collected during the two sampling campaigns, of which 44574 individuals and 1413 species were sampled during the rainy period and 26841 individuals and 1091 species were sampled during the dry period. Considering a relative abundance of over 0.5%, a total of 32 species were recorded in the rainy period, whereas 42 species were obtained during the dry season (Table 1). Among the observed taxonomic groups, Polychaeta and Crustacea showed the highest abundance values, followed by Mollusca, Echinodermata, Nemertea and Sipuncula (Table 1). The most representative taxa differed between periods, with a predominance of the polychaetes *Chone americana* and *Spiophanes* sp. 1 and the crustacean *Phtisica marina* in the rainy season and the polychaete *Goniadides carolinae* and crustaceans *Chevalia anomala* and *Chevalia* sp. 2 in the dry season.

Macrofauna assemblages and spatial comparisons

The pattern of species associations differed significantly between depths considering both sampling periods (pseudo-F=5.623; p=0.001). MDS ordination shows at the bottom of the diagram a close association of macrofauna mainly in the deepest stations (75-100 m) in both periods (Fig. 5), which was confirmed by PERMANOVA, and significant differences (p >0.05) between the other depth strata (Table 2). SIMPER analysis shows in both periods that *Goniadides carolinae*, *Sphaerosyllis* sp. 3 and *Protodorvillea kefersteini* contributed the most (22%) to the shallow and intermediate stations (<30 m and 30-50 m), whereas the polychaetes *Spiophanes* sp. B (20%) and *Prionospio cristata* (12%) and the crustacean *Phtisica marina* (20%),

Table 1. – Total mean number of individuals per station and relative abundance of the most representative taxa (>0.5% abundance) during the rainy and dry periods of 2009 at 53 stations (P, Polychaeta; C, Crustacea; and M, Mollusca).

| Taxa - Rainy period	No inds	%	Taxa - Dry period	No inds	%
Chone americana Day, 1973(P)	1305	8.7	*Goniadides carolinae* Day, 1973 (P)	437	4.6
Phtisica marina Slabber, 1769(C)	731	4.9	*Chevalia anomala* Souza-Filho, 2010 (C)	305	3.2
Spiophanes sp. B(P)	500	3.3	*Chevalia* sp. 2 (C)	274	2.9
Goniadides carolinae Day, 1973(P)	440	2.9	*Exogone* (*Exogone*) sp. 2 (P)	213	2.2
Chevalia sp. 2(C)	421	2.8	*Prionospio cristata* Foster, 1971 (P)	200	2.1
Sphaerosyllis sp. 3(P)	333	2.2	*Sphaerosyllis* sp. 3 (P)	160	1.7
Aricidea (*Acmira*) cf. *taylori* (P)	297	2.0	*Aphelochaeta* spp. (P)	144	1.5
Exogone (*Exogone*) sp. 2(P)	295	1.9	*Protodorvillea kefersteini* (McIntosh, 1869) (P)	141	1.5
Parapseudini sp. (P)	258	1.7	Nemertea	135	1.4
Protodorvillea kefersteini (McIntosh, 1869) (P)	246	1.6	*Spiophanes* sp. A (P)	133	1.4
Chevalia setosa Souza-Filho, Souza & Valério-Berardo, 2010 (C)	236	1.5	Sipuncula	128	1.3
Echinodermata	216	1.4	*Hesionura* sp. (P)	111	1.1
Paraleiopus macrochelis Brum, 1978 (P)	189	1.2	*Paraprionospio tamaii* Delgado-Blas, 2004 (P)	105	1.1
Nemertea	187	1.2	*Mediomastus californiensis* Hartman, 1944 (P)	103	1.0
Hesionura laubieri (Hartmann-Schröeder, 1963)(P)	150	1.0	*Heteropodarke* spp. (P)	98	1.0
Perkinsyllis sp. 1(P)	134	0.9	*Laonice weddellia* Hartman, 1978 (P)	98	1.0
Ampelisca brevisimulata Barnard, 1954(C)	122	0.8	Dorvilleidae sp. 6 (P)	96	1.0
Aricidea (*Aricidea*) *albatrossae* Pettibone, 1957 (P)	121	0.8	*Apoprionospio dayi* Foster, 1969 (P)	95	1.0
Prionospio cristata Foster, 1971 (P)	119	0.8	*Aricidea* (*Acmira*) cf. *taylori* (P)	95	1.0
Mediomastus californiensis Hartman, 1944 (P)	110	0.7	Echinodermata	92	0.9
Cirrophorus sp. 3 (P)	109	0.7	*Cirrophorus* sp. 3 (P)	88	0.9
Chevalia anomala (C)	101	0.6	*Chone americana* Day, 1973 (P)	84	0.9
Heteropodarke sp.1 (P)	101	0.6	*Perkinsyllis* sp. 1 (P)	79	0.8
Kamakidae sp. 2 (P)	98	0.6	*Chevalia caetes* Souza-Filho, 2010 (C)	76	0.8
Laonice weddellia Hartman, 1978 (P)	91	0.6	*Chaetozone* sp. (P)	69	0.7
Prosphaerosyllis sp.(P)	91	0.6	*Parapseudini* sp. (C)	68	0.7
Aphelochaeta sp.(P)	91	0.6	*Ampelisca youngi* Valério-Berardo, 2010 (C)	67	0.7
Sipuncula	89	0.6	*Praxillella praetermissa* (Malmgren, 1865) (P)	67	0.7
Puelche sp. 1 (C)	88	0.5	*Sphaerosyllis* sp. 7 (P)	65	0.6
Parexogone sp. 4(P)	85	0.5	*Parexogone* sp. 6 (P)	65	0.6
Mooreonuphis intermedia (Kingberg, 1865) (P)	85	0.5	*Pteria colymbus* (Röding, 1798) (M)	63	0.6
Heteropodarke sp. 2 (P)	75	0.5	*Paraehlersia* sp. 1 (P)	62	0.6
			Exogone (*Exogone*) sp. 3 (P)	62	0.6
			Prosphaerosyllis isabellae (P)	60	0.6
			Parexogone sp. 3 (P)	60	0.6
			Syllis guidae Nogueira, Yuda-Guarin, 2008 (P)	57	0.6
			Levinsenia sp. 1 (P)	56	0.6
			Aricidea (*Acmira*) cf. *catharinae* (P)	56	0.5
			Loandalia sp. (P)	55	0.5
			Ericthonius sp. 2 (C)	51	0.5
			Mooreonuphis intermedia (Kingberg, 1865) (P)	50	0.5
			Cirratulidae sp. (P)	47	0.5
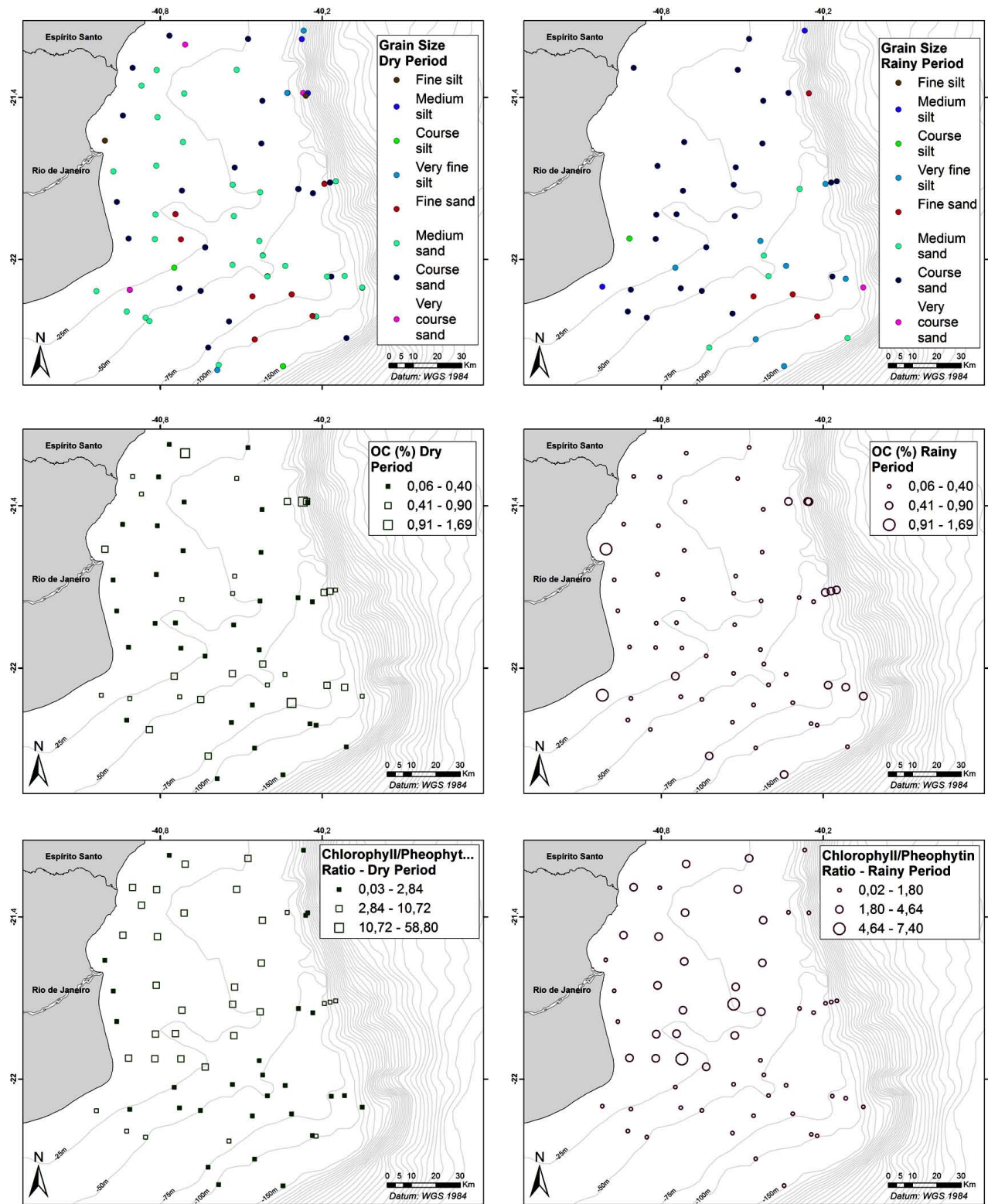
Fig. 3. – The mean grain size distribution, organic carbon (OC) values and chlorophyll/pheophytin ratio at the 53 stations located on the southeast continental shelf of Brazil (A, grain size, dry period; B, grain size, rainy period; C, OC, dry period; D, OC, rainy period; E, chlorophyll/pheophytin ratio, dry period; F, chlorophyll/pheophytin ratio, rainy period).

which are mainly deposit feeders, predominated at the deeper stations (50-75 m and 76-100 m).

The CCA extracted two significant axes that explained 14% of the variation in the abundances of the most representative taxa (see Table 1), of which 60% were attributed to the considered environmental variables (Table 3). Axis 1 was responsible for 11.5% of the variation, with pheophytin, sorting, temperature
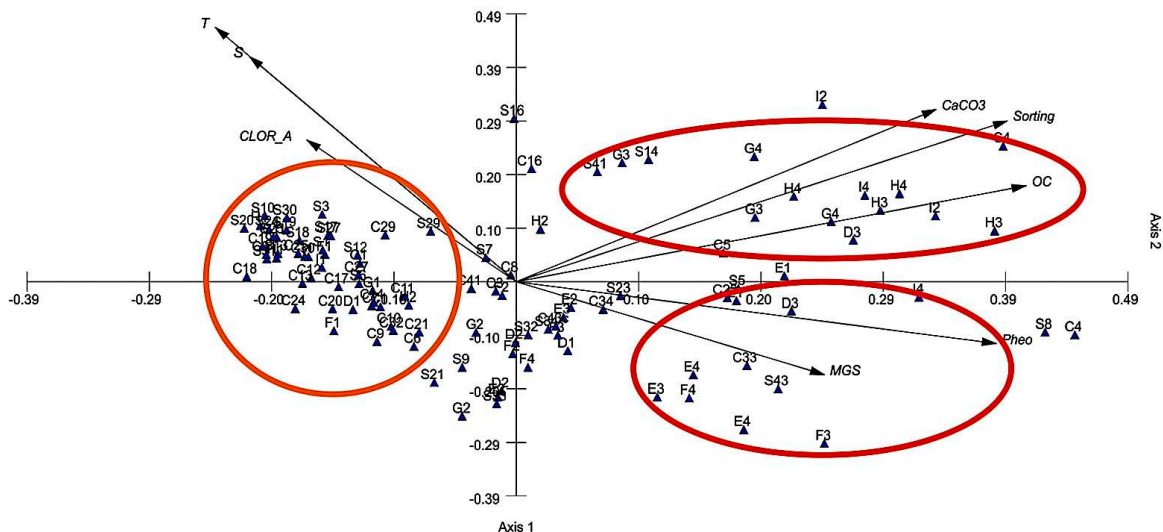
Fig. 4. – The principal component analysis (PCA) for the environmental variables water temperature and salinity, and sediment parameters that included pheophytin (Pheo), chlorophyll *a* (Chl *a*), organic carbon (OC), total carbonate (CaCO₃) and sorting. Orange circle, shallower stations; red circles, deeper stations. Data from the 53 stations sampled during the rainy and dry periods of 2009 are shown on Appendix 1.
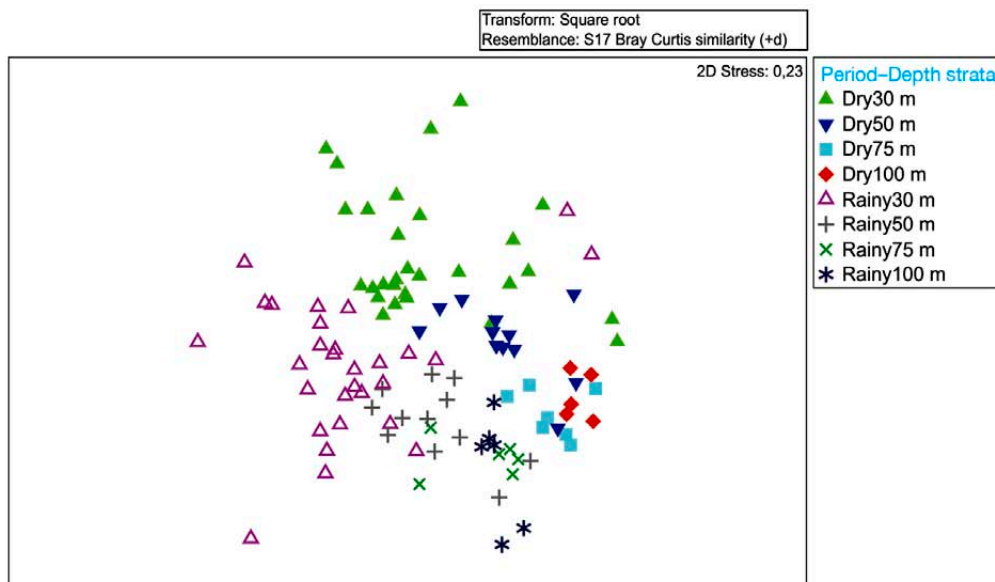

Fig. 5. – MDS relative to the dry and wet period collection and depths of 30, 50, 75 and 100 m in each period.

and OC showing the highest correlations and being responsible for the majority of the variation (56%) (Table 4). This axis indicated an association of species related to shallower depths (<30 m and 31-50 m), such as *Parexogone* sp. 3, *Parexogone* sp. 4, *P. macrochelis* and *Sphaerosyllis* sp. 3, which were positively correlated with temperature and chlorophyll and negatively correlated with sorting and pheophytin (Fig. 6A). The samples distribution along axis 1 indicated a gradient related to bathymetry, with the shallow stations on the positive side of the axis and the deeper stations on the negative side (Fig. 6B); this distribution also highlighted the relationships of OM with depth, which was represented by the highest degree of selection, and the highest concentrations of pheophytin and total carbonate.

DISCUSSION

This study examined the macrozoobenthic composition and distribution according to distances of the PSR outfall in a coastal area of Campos Basin, and provided evidence of differences in OM sources, from primary production in shallow waters to detritus in deep waters. These sources provided different niches for the corresponding macrofaunal assemblages, and higher species richness and abundance of benthic populations on the continental shelf adjacent to the PSR.

A former study at the PSR estuarine system showed the river influence on the structural pattern and composition of the benthic macrofauna exclusively on the inner shelf (<50 m) of the northern coast of Rio de Janeiro (Zalmon et al. 2013). The authors related

Table 2. – Pair-wise tests results from PERMANOVA of the macrofaunal assemblages between the depth strata (30, 50, 75 and 100 m) and periods (dry and rainy). NS: p>0.05

| Groups	t	P (perm)	Unique perms	P (MC)
Dry 30 m, Dry 50 m	2.3098	0.001	999	0.001
Dry 30 m, Dry 75 m	2.9970	0.001	998	0.001
Dry 30 m, Dry 100 m	2.5328	0.001	997	0.001
Dry 30 m, Rainy 30 m	2.9238	0.001	998	0.001
Dry 30 m, Rainy 50 m	2.9822	0.001	997	0.001
Dry 30 m, Rainy 75 m	2.8387	0.001	997	0.001
Dry 30 m, Rainy 100 m	2.7242	0.001	996	0.001
Dry 50 m, Dry 75 m	1.8861	0.001	990	0.011
Dry 50 m, Dry100 m	1.9680	0.002	920	0.006
Dry 50 m, Rainy 30 m	2.9714	0.001	998	0.001
Dry 50 m, Rainy 50 m	2.3537	0.001	997	0.001
Dry 50 m, Rainy 75 m	2.5633	0.001	965	0.001
Dry 50 m, Rainy 100 m	2.6949	0.001	978	0.001
Dry 75 m, Dry 100 m	1.2318	0.137 NS	550	0.183
Dry 75 m, Rainy 30 m	3.0514	0.001	997	0.001
Dry 75 m, Rainy 50 m	2.5958	0.001	992	0.001
Dry 75 m, Rainy 75 m	2.1601	0.002	760	0.005
Dry 75 m, Rainy 100 m	2.4070	0.001	743	0.003
Dry 100 m, Rainy 30 m	2.7597	0.001	996	0.001
Dry 100 m, Rainy 50 m	2.6855	0.001	909	0.001
Dry 100 m, Rainy 75 m	2.4358	0.004	405	0.001
Dry 100 m, Rainy 100 m	2.2502	0.005	402	0.005
Rainy 30 m, Rainy 50 m	2.2184	0.001	998	0.001
Rainy 30 m, Rainy 75 m	2.5204	0.001	998	0.001
Rainy 30 m, Rainy 100 m	2.5815	0.001	999	0.001
Rainy 50 m, Rainy 75 m	1.5697	0.024	969	0.031
Rainy 50 m, Rainy 100 m	2.0245	0.001	975	0.002
Rainy 75 m, Rainy 100 m	1.3581	0.060 NS	410	0.118
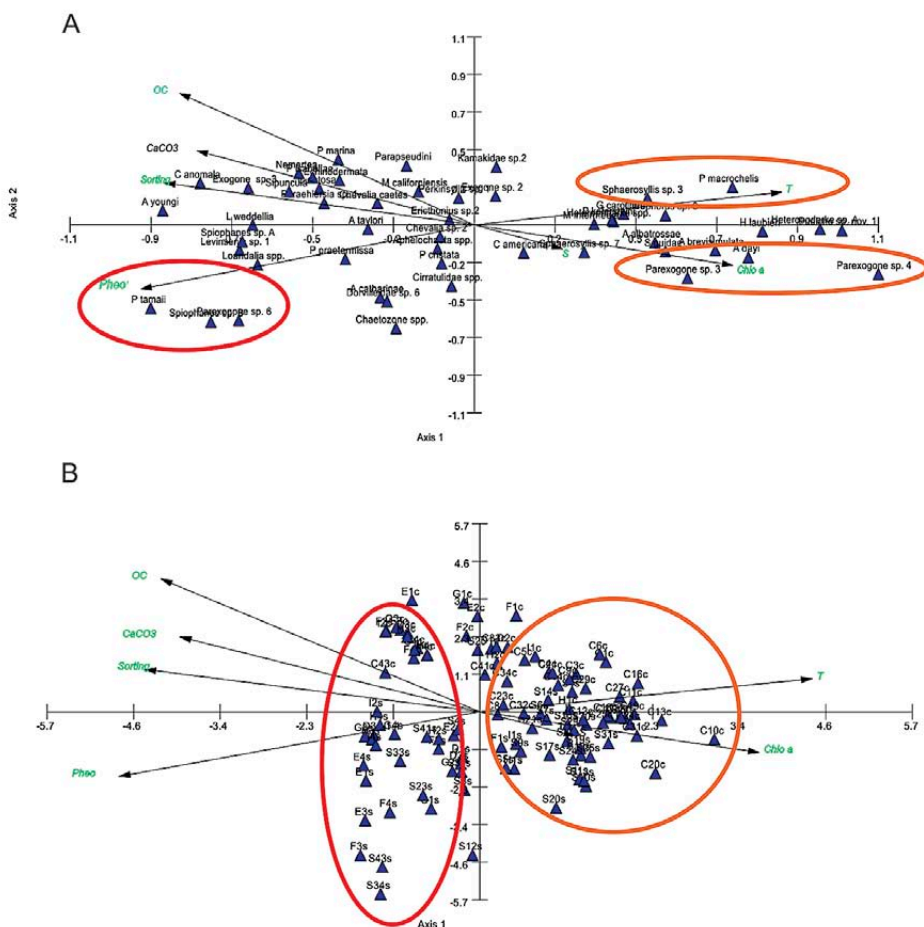
Fig. 6. – Canonical correspondence analysis of (A) the taxa with >0.5% abundance (see Table 1) vs. environmental parameters (T, temperature; S, salinity; OC, organic carbon; CaCO$_3$, total carbonate; Chl *a*, chlorophyll *a*; Pheo, pheophytin; and sorting) and (B) the sampling stations (see Fig. 1) vs. the above environmental parameters. Orange and red circles: species/environmental parameters related to shallower stations and deeper stations, respectively. Data from the 53 stations sampled during the rainy and dry periods of 2009 are shown on Appendix 1.

Table 3. – Results of the canonical correspondence analysis applied to the species and environmental variables. The Monte Carlo test was used for significance of the canonical axes.

Axes	1	2
Eigenvalues	0.254	0.058
Species-environment correlations	0.873	0.572
Cumulative % variance of species data	11.500	14.100
Cumulative % of species-environment relation	56.300	60.000
Summary of Monte Carlo test		
Test of significance of first canonical axis: eigenvalue =0.254		
F-ratio =12.761		
P-value =0.020		
Test of significance of all canonical axes: Trace =0.452		
F-ratio =3.606		
P-value =0.020		

Table 4. – CCA analysis: species-environmental variables correlations on axes 1 and 2, highlighting the significant correlations according to the Monte Carlo permutational test.

	SPEC axis 1	SPEC axis 2
$CaCO_3$	–0.593	0.340
Sorting	**–0.663**	0.193
OC	**–0.631**	**0.604**
Chl a	0.553	–0.186
Pheo	**–0.714**	–0.295
T	**0.658**	0.150
S	0.189	–0.110

the community structure and environmental variations to the PSR discharge, while the present study of the benthic assemblages distinguished between the deepest (75-100 m) and shallowest (<50 m) stations in the rainy and dry periods.

The grain size distribution and moderately sorted sediments in the dry period reflected a lower hydrodynamic regime and more heterogeneous sedimentary environment. The macrobenthic community showed significant variation in composition and abundance influenced by the environmental parameters sorting, total organic carbon, temperature and pheophytin, and might suggest a strong link between OC, which is the chief characteristic of the PSR estuary, and the macrobenthic community. In parallel, the analysis showed that the abiotic variables were controlled by the riverine discharge of compounds such as chlorophyll and OC in the sediment, which had higher values in the rainy/summer season. Samples with higher OC and chlorophyll values were observed in areas under riverine influence, and this finding was interpreted as an indicator of this influence. Although autochthonous inputs could also be considered as sources for OC and chlorophyll, the spatial distribution supports the river as the important source. Oliveira et al (2013), using lipids as biomarkers to distinguish autochthonous from allochthonous sources, showed the predominance of primary (phytoplankton) and secondary (zooplankton) production over terrestrial derived material during winter and summer between 2008 and 2009. However, the nutrient supplies from continental outflow were evident during the summer period, and increased the marine production (primary and secondary) especially in shallow waters (total lipids in winter <30 m, ~1.4 to 3.2 mg g^{-1}; TOC 30-50 m, ~0.8 to1.2 mg g^{-1}; 50-75 m, ~0.9 to 2.4 mg g^{-1}; 75-100 m, ~1.0 to 3.0 mg g^{-1}; summer <30 m, ~1.5 to 6.4 mg g^{-1}; 30-50 m, ~1.6 to 1.8 mg g^{-1}; 50-75 m, ~1.1 to 2.0 mg g^{-1}; 75-100 m, ~0.8 to 1.4 mg g^{-1}).

Most differences between sampling stations emerged when comparing the assemblages at <50 m with those at >75 m. The deeper stations were less affected by the PSR outflows and the sediment mainly characterized by relict sands, with relatively low OC. Thus, they showed a different composition compared with the shallower stations, characterized by several carnivorous, omnivorous and burrowing polychaetes as *Parexogone* spp., *P. macrochelis* and *Sphaerosyllis* sp. The PSR plume only reaches the centre of the basin in summer, when the currents are stronger (>4-5 knots/s: Zalmon et al. 2002, Santos et al. 2010). These additional inorganic supplies fuel primary production in the area which, combined with the export dynamics of dissolved and particulate materials correlated to the rainfall and RPS flow rate (Souza and Knoppers 2003, Figueiredo et al. 2011), contribute to temporary summer deposit formation at the seabed. The high organic enrichment reflected an increase in surface and sub-surface deposit feeder species such as the polychaetes *Spiophanes* sp. and *Prionospio cristata* and the crustacean *Phtisica marina* at the deeper stations, with a corresponding decrease in the other trophic groups, particularly the suspension feeders.

Several models have been proposed to explain the relationship between OM content in the sediment and macrozoobenthic community structure (Pearson and Rosenberg 1978, Weston 1990, Dauwe et al. 1998). Species composition and distribution at the coastal stations considered in this study appeared to be consistent with the most widely accepted model proposed by Pearson and Rosenberg (1978), who suggested that, as the OM content increases, the community ultimately changes to primarily surface deposit feeders. The dominance of suspension feeders suggests less extreme conditions along the northern coast of Rio de Janeiro than in the coastal areas of other eutrophicated seas, such as the Baltic Sea, the Gulf of Mexico and the Black Sea, where predators are the main trophic group (Moodley et al. 1998, Rabalais et al. 2002).

River outflows and periodic dystrophic events are recognized driving forces that determine the structure and composition of the macrozoobenthic community in many estuarine and coastal ecosystems (Seliger et al. 1985, Rabalais et al. 2002). Along the north coast of Rio de Janeiro, the distribution of the macrozoobenthic community suggests an intermittent recovery from periodic and seasonal events that are maintained for long periods of time and also from indefinite, immature, transitory successional stages caused by the increasing frequency of OM in the summer months or rainy season. In addition to this natural process, bottom trawl fishery, which is a common source of income for the local population on the north coast of Rio de Janeiro (Costa and Di Beneditto 2009), could also disturb the sediment and associated communities. The intense fishing activity of the region is concentrated mainly in the isobaths below 30 m and certainly influences the dynamics of the benthic macrofauna.

Despite its importance as a food source, high-particulate OM is often associated with oxygen stress. Several dominant polychaetes widely distributed in the PSR estuary have been considered as organic enrichment and low oxygen-tolerant initial colonizers (McCall 1977, Pearson and Rosenberg 1978, Diaz and Rosenberg 1995). The results suggest that macrobenthic communities in some areas of the continental shelf adjacent to the PSR are typical of slightly eutrophic conditions characteristic of quiescent estuarine environments. The high density of opportunistic species (mainly surface deposit feeders such as *Spiophanes* sp., *Goniadides carolinae*, *Sphaerosyllis* sp., *Aricidea* (*Acmira*) cf. *taylori*, *Exogone* sp., *Prionospio cristata*, *Protodorvillea kefersteini* and *Mediomastus californiensis*) supports the evidence for the eutrophication of some coastal areas along the southeastern Brazilian coast.

Coastal benthic communities are fuelled by a heterogeneous pool of organic detritus derived from various sources, such as phytoplankton blooms, vascular plant debris, winter blooms of seaweeds and in situ microalgal production. However, phytoplankton production along the southeast continental shelf of Brazil does not display strong seasonality compared with temperate waters (Ciotti et al. 2006), a finding that is reinforced by the stronger spatial correlation with most environmental and biological parameters than with temporal parameters. Higher amounts of chlorophyll *a* were found at the shallower stations and of phaeopigments and OC at the deeper stations during this study. Therefore, most of this production will likely be recycled in the water column rather than deposited onto the coastal seabed, mainly at <75 m. In general, chloroplastic pigments are good indicators of the food energy that is readily available to the various benthic organisms (Giere 1993). OC may serve the same purpose, so food availability does not appears to be the limiting factor.

Previous studies have shown that there is an increase in the nutrient concentrations at the river mouth during the rainy season (Costa et al. 2009). However, higher amounts of chlorophyll *a*, phaeopigments and OC in both periods shows that even with less flow, the PSR contributes with nutrients that sustain primary production on the continental shelf. During the rainy season, this finding might be also related to the deeper penetration of the South Atlantic Central Water in the region of Cabo de São Tomé during the upwelling phenomenon in the spring and summer, a process that brings nutrient-rich waters to the study area (Silveira et al. 2000, 2004).

In summary, this paper presents a breakdown of the input of OM in the trophic chain via primary production in shallow waters (<50 m) and organic detritus in deeper waters (75-100 m), with species richness and abundance of benthic populations related to the PSR output. Two main macrofaunal assemblages were detected concurrently: (1) *Spiophanes* sp. and *Phtisica marina*, which are associated with OC and pheophytin at the deepest stations, and (2) *Parexogone* spp., *P. macrochelis* and *Sphaerosyllis* sp., which are associated with chlorophyll *a* and temperature at most of the shallow stations. The contribution of different environmental variables between the macrofaunal associations and the evidence of differences in OM sources suggest that these associations occupy distinct niches along the continental shelf adjacent to the PSR, with species richness and abundance of benthic populations related to the river output.

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Appendix 1. – Environmental data (Sediment: CaCO$_3$, total carbonate; MGS, mean grain size; sorting, OC, organic carbon; Chl *a*, chlorophyll *a*; Pheo, pheophytin. Water: T, temperature; S,salinity) for the 106 sampling sites during the dry (S) and rainy (C) periods of 2009. Stratum 1, <30 m; Stratum 2, 26-50 m; Stratum 3, 51-75 m; Stratum 4, 76-100 m.

Site	Season	Strata (m)	CaCO$_3$ (%)	MGS (θ)	Sorting (θ)	OC (%)	T (°C)	S	Chl *a* (µg g^{-1})	Pheo (µg g^{-1})
D1	Dry	30 m	2.73	0.42	1.31	0.28	16.3	36.2	1.17	4.15
D2	Dry	50 m	0.57	0.68	0.91	0.18	15.7	35.6	1.21	1.74
D3	Dry	75 m	7.44	1.48	2.57	0.59	15.5	35.6	1.97	2.16
E1	Dry	30 m	2.89	3.25	1.62	0.54	17.3	36.2	2.04	4.31
E2	Dry	50 m	1.67	1.03	0.80	0.12	15.3	35.5	1.68	1.33
E3	Dry	75 m	1.55	1.94	1.28	0.20	14.5	35.4	1.27	3.37
E4	Dry	100 m	4.19	3.22	1.31	0.36	14.8	35.4	0.74	3.97
F1	Dry	30 m	0.11	0.57	0.46	0.28	22.9	36.5	1.89	0.48
F2	Dry	50 m	0.67	1.42	0.59	0.28	18.5	36.0	2.17	4.27
F3	Dry	75 m	2.31	2.71	0.88	0.19	14.5	35.4	1.42	10.5
F4	Dry	100 m	2.01	1.81	1.41	0.25	14.4	35.4	0.33	3.16
G1	Dry	30 m	0.36	1.14	1.28	0.21	23.3	36.5	1.95	1.00
G2	Dry	50 m	0.58	1.39	0.54	0.08	15.4	35.6	1.99	1.97
G3	Dry	75 m	6.68	0.98	2.80	0.48	23.0	36.8	2.47	3.04
G4	Dry	100 m	8.88	3.17	3.19	0.53	23.3	36.9	1.25	2.81
H1	Dry	30 m	0.13	0.87	0.87	0.08	24.0	36.7	3.46	0.62
H2	Dry	50 m	9.41	1.29	1.38	0.32	21.1	36.5	2.39	1.39
H3	Dry	75 m	9.23	3.34	3.98	0.54	19.5	36.3	2.74	3.99
H4	Dry	100 m	9.49	−1.14	2.98	0.49	17.6	35.9	0.42	2.20
I1	Dry	30 m	0.50	0.79	0.69	0.10	22.5	36.7	1.46	0.55
I2	Dry	50 m	8.77	−1.43	3.98	0.73	20.8	36.5	1.68	3.79
I4	Dry	100 m	8.67	4.40	2.91	0.45	17.6	35.9	0.94	4.42
1	Dry	30 m	2.69	0.36	0.93	0.17	24.6	36.4	2.10	0.87
3	Dry	30 m	3.13	−0.31	0.57	0.18	23.9	36.6	1.65	0.55
4	Dry	30 m	3.38	1.43	3.40	1.53	25.4	35.5	1.05	4.05
5	Dry	30 m	4.45	2.02	3.86	0.29	26.1	34.3	0.89	1.18
6	Dry	30 m	1.21	1.53	0.58	0.15	24.6	36.2	0.57	0.61
7	Dry	30 m	0.49	4.67	1.89	0.10	24.8	36.3	1.23	0.33
8	Dry	30 m	4.13	5.25	2.15	1.13	16.7	35.7	1.47	6.15
9	Dry	50 m	0.68	0.59	0.55	0.14	16.8	35.8	0.40	1.16
10	Dry	30 m	0.22	0.76	0.67	0.13	25.0	36.6	3.71	1.04
11	Dry	30 m	0.19	0.66	0.78	0.08	24.5	36.6	2.04	0.58
12	Dry	30 m	1.34	1.43	1.93	0.14	24.4	36.5	2.58	1.02
13	Dry	30 m	0.64	1.22	0.84	0.09	23.7	36.6	3.22	0.78
14	Dry	30 m	9.24	1.24	3.50	0.31	23.7	36.5	1.60	1.41
16	Dry	30 m	11.6	−0.53	1.91	0.32	23.5	36.5	4.83	1.52
17	Dry	30 m	1.00	1.73	0.75	0.16	23.3	36.7	3.56	1.28
18	Dry	30 m	0.22	0.73	0.68	0.15	23.9	36.6	1.91	0.53
20	Dry	30 m	0.22	2.26	0.62	0.15	24.8	36.6	6.31	1.15
21	Dry	50 m	0.68	0.30	0.84	0.15	16.7	35.8	0.31	0.50
23	Dry	50 m	2.49	1.69	2.44	0.23	19.0	36.2	2.90	5.05
24	Dry	30 m	0.18	0.61	0.86	0.15	23.7	36.7	3.48	0.75
25	Dry	30 m	0.40	0.55	0.70	0.11	23.1	36.7	2.95	0.70
27	Dry	30 m	1.81	0.87	0.79	0.18	22.2	36.6	3.71	0.99
29	Dry	30 m	6.28	0.78	0.85	0.27	21.2	36.5	3.19	0.91
30	Dry	30 m	0.59	0.70	0.71	0.16	24.8	36.7	2.51	0.75
31	Dry	30 m	0.15	1.07	0.75	0.10	23.3	36.7	2.77	0.65
32	Dry	50 m	1.46	3.70	1.47	0.17	19.8	36.3	0.84	1.59
33	Dry	75 m	1.06	1.02	0.77	0.13	14.9	35.5	1.67	1.40
34	Dry	50 m	1.13	3.67	1.14	0.21	22.2	36.7	0.88	5.87
41	Dry	75 m	8.14	1.56	2.95	0.33	23.1	36.9	0.52	0.71
43	Dry	100 m	2.15	2.57	1.89	0.28	14.5	35.4	0.61	4.54
D1	Rainy	30 m	0.40	−0.36	0.64	0.16	21.6	36.0	0.08	0.28
D2	Rainy	50 m	0.82	1.03	0.83	0.55	19.2	35.9	0.53	0.99
D3	Rainy	75 m	7.04	0.64	2.56	0.91	17.8	35.9	3.41	5.29
E1	Rainy	30 m	3.43	4.44	1.99	0.63	21.5	35.7	1.69	3.10
E2	Rainy	50 m	1.67	0.89	0.65	0.76	19.1	35.9	0.54	0.47
E3	Rainy	50 m	1.76	2.11	1.49	0.25	18.9	36.1	0.80	2.05
E4	Rainy	100 m	4.20	2.38	1.90	0.38	16.9	35.8	1.13	3.98
F1	Rainy	30 m	0.09	0.47	0.51	0.10	21.0	35.9	1.21	0.18
F2	Rainy	50 m	9.78	1.08	0.72	0.09	19.9	36.1	0.74	0.70
F3	Rainy	75 m	2.51	2.59	0.90	0.27	19.5	36.1	0.77	2.71
F4	Rainy	100 m	2.45	1.04	0.90	0.15	17.4	35.8	0.54	2.49
G1	Rainy	30 m	0.28	1.91	0.78	0.21	22.8	36.2	2.16	0.70
G2	Rainy	50 m	0.64	1.28	0.57	0.60	20.3	36.1	0.49	0.58
G3	Rainy	75 m	7.32	0.94	3.23	0.57	19.6	36.2	2.92	3.91
G4	Rainy	100 m	7.98	1.41	3.93	0.64	19.9	36.2	0.90	2.99
H1	Rainy	30 m	0.08	1.12	0.82	0.12	22.6	36.5	4.10	0.63
H2	Rainy	50 m	<0.05	0.98	0.86	0.45	20.9	36.4	1.33	0.83
H3	Rainy	75 m	8.48	2.72	4.33	0.92	18.0	36.0	2.60	4.50
H4	Rainy	100 m	9.03	0.40	2.31	0.75	17.4	35.9	1.91	4.56
I1	Rainy	30 m	0.12	0.45	1.01	0.11	22.0	36.3	2.43	0.37
I2	Rainy	50 m	9.34	3.65	4.12	0.73	21.7	36.1	1.87	4.33
I4	Rainy	100 m	8.64	3.17	3.33	0.56	21.5	36.4	0.68	3.88
1	Rainy	30 m	0.55	0.33	0.99	0.11	22.4	35.5	1.88	0.32

Site	Season	Strata (m)	CaCO$_3$ (%)	MGS (θ)	Sorting (θ)	OC (%)	T (ºC)	S	Chl a (µg g^{-1})	Pheo (µg g^{-1})
3	Rainy	30 m	7.62	0.51	1.35	0.16	22.4	35.3	2.5	0.58
4	Rainy	30 m	3.23	6.96	1.54	1.13	22.4	35.4	4.36	11.8
5	Rainy	30 m	4.84	1.25	3.92	0.34	22.4	35.3	1.13	1.55
6	Rainy	30 m	0.89	0.90	0.79	0.06	22.3	35.2	0.71	0.25
7	Rainy	30 m	0.21	0.44	1.05	0.05	21.2	35.8	1.49	0.24
8	Rainy	30 m	0.29	1.22	1.61	0.32	21.7	35.9	0.03	0.10
9	Rainy	50 m	0.59	1.15	0.70	0.09	20.8	36.0	0.30	0.34
10	Rainy	30 m	0.14	1.17	0.65	0.32	21.3	35.8	2.24	0.39
11	Rainy	30 m	0.26	1.76	0.86	0.31	22.3	36.0	2.19	0.37
12	Rainy	30 m	1.04	1.97	0.86	0.06	22.6	36.3	4.34	0.95
13	Rainy	30 m	0.19	1.38	0.74	0.10	22.4	35.9	5.01	0.54
14	Rainy	30 m	1.08	1.14	0.75	0.18	22.4	35.7	3.16	0.70
16	Rainy	30 m	11.5	–0.31	1.16	0.46	22.4	35.7	6.79	1.46
17	Rainy	30 m	0.71	1.33	0.84	0.17	22.3	36.1	3.76	0.87
18	Rainy	30 m	0.11	1.06	0.78	0.06	22.1	35.8	6.81	0.01
19	Rainy	30 m	0.20	0.95	0.79	0.05	22.6	36.4	4.86	0.66
20	Rainy	30 m	0.11	2.08	0.63	0.09	21.3	35.8	5.06	0.69
21	Rainy	50 m	0.41	0.85	0.72	0.21	20.2	35.9	0.30	0.29
23	Rainy	50 m	3.06	1.18	2.65	0.37	21.1	35.9	2.50	8.13
24	Rainy	30 m	0.13	1.31	0.57	0.06	22.0	36.1	3.25	0.62
25	Rainy	30 m	0.28	0.76	0.77	0.09	22.1	36.4	3.68	0.68
27	Rainy	30 m	1.43	1.07	0.77	0.22	22.0	36.3	2.56	0.52
29	Rainy	30 m	4.95	0.76	0.75	0.15	22.2	36.4	3.03	0.85
30	Rainy	30 m	0.52	0.83	0.72	0.11	21.9	36.4	3.42	0.40
31	Rainy	30 m	0.53	1.19	0.79	0.10	23.1	36.6	3.70	0.50
32	Rainy	50 m	1.09	1.27	0.66	0.13	21.7	36.1	0.79	1.55
33	Rainy	75 m	8.06	0.84	2.08	0.34	14.0	35.3	1.12	2.15
34	Rainy	50 m	2.01	1.81	0.84	0.27	20.0	36.2	1.36	5.92
41	Rainy	75 m	0.33	0.73	1.84	0.38	21.1	36.5	0.96	2.09
43	Rainy	100 m	1.72	2.33	1.21	0.24	18.6	36.1	0.51	1.77