

PRIMARY AND BACTERIAL PRODUCTION PROCESSES IN THE LOWER ITAJAÍ-AÇÚ ESTUARY, SANTA CATARINA, BRAZIL

PEREIRA FILHO, J.^{1,*}; RÖRIG, L. R.¹; HESSE, K.²; POREMBA, K.²; SCHETTINI, C. A. F.^{1,4}; PROENÇA, L. A.¹ & SANTOS, J. E.³

¹ Universidade do Vale do Itajaí, CTTMar, R. Uruguai, 458 – Itajaí, Santa Catarina, Brazil, 88302-202.
*Contact Author: jurandir@univali.br

² Forschungs- und Technologiezentrum Westküste der Christian-Albrechts-Universität zu Kiel, Hafentörn, 25761 Büsum, Germany

³ PPG ERN, Universidade Federal de São Carlos, Rod. Washinton Luiz, km 235, São Carlos, São Paulo, 13565-905, Brazil

⁴ Present address: Instituto de Ciências do Mar - LABOMAR, Universidade Federal do Ceará - UFC, Av. da Abolição, 3207, Fortaleza - Ceará, 60165-081

ABSTRACT

Pereira Filho, J.; Rörig, L. R.; Hesse, K.; Poremba, K.; Schettini, C. A. F.; Proença, L. A. & Santos, J. E. 2009. Primary and Bacterial Production processes in the lower Itajaí-Açu estuary, Santa Catarina, Brazil. *Braz. J. Aquat. Sci. Technol.* 13(1): 1-10. ISSN 1808-7035. Primary and bacterial productivity (PP and BP, respectively) were measured in the lower Itajaí-Açu estuary and in the adjacent shelf, under low river discharge conditions. The experiment was carried out in April, 2000, when physical, chemical and biological variables were recorded in five stations: three in the estuary and two in the inner shelf. Salinity, temperature, turbidity and light intensity were determined in vertical profiles; dissolved oxygen, nutrients, chlorophyll-a, primary (PP) and bacterial production (BP) were sampled at surface and near the bottom. The BP ranged from 0.5 to 11.3 mg C.m⁻³.h⁻¹, and the highest values were recorded at the inner stations of the estuary, associated with lower salinity and light intensity and higher dissolved nutrients concentration. On the other hand, PP was higher in the inner shelf, with PP increasing from 2.0 to 30 mg C.m⁻³.h⁻¹. The phytoplankton biomass showed the same trend, increasing from 0.2 to 8.4 µg/L at the surface. The PP was limited by light in the inner estuary and by the PO₄ concentration in the inner shelf. The higher productivity zone was formed in front of the estuarine mouth, as expected, since water transparency increases leading the consumption of the rich-nutrient waters from the estuary by autotrophic organisms. The data indicated that the ecosystem metabolism shift from heterotrophic to autotrophic in a very small length scale (few kilometers) during the sampled conditions.

Keywords: estuarine chemistry, nutrients, ecosystem metabolism, primary and bacterial productivity, estuarine processes

INTRODUCTION

Organic matter dynamics in estuaries is very complex, since it is influenced by factors such as river discharge, mixing processes due to tides and the several different effects from human activities. These factors can alter the balance between production and mineralization processes of organic matter, which can also be modified along the estuarine gradient due to changes in environment varying from fluvial to marine conditions. These changes influence the amount of particulate and dissolved organic matter and their elemental composition (carbon, nitrogen and phosphorus; C, N, P), as well as dissolved inorganic nutrients concentrations. The balance between autotrophy and heterotrophy in aquatic ecosystems is important for the assessment of the flux of organic carbon along the trophic chain. High BP/PP (Bacterial Production/ Primary Production ratio) have been shown to increase as a direct function of terrestrial

carbon input and of the fraction of PP processed by bacteria (Ram *et al.* 2007).

Primary and bacterial production are usually correlated in aquatic systems. This behavior suggests that phytoplankton is the most important source of organic matter supporting bacterial growth in these ecosystems. On the other hand, in coastal and estuarine systems, substrates for bacterial growth can derive from sources other than phytoplankton, such as river borne material, terrestrial runoff, anthropogenic loads and water-sediment fluxes (Almeida *et al.* 2005). Alterations induced by anthropogenic activities have modified the structure and function of coastal aquatic systems around the world (Bowen and Valiela, 2001). The metabolism of estuarine systems is greatly influenced by the entrance of nutrients and organic matter. These inputs have augmented in the last decades due to changes in land use and occupation (Revilla *et al.* 2002), particularly due to frequently untreated domestic and industrial

effluents. In addition, the contribution of organic matter and nutrients has increased hypoxia and anoxia in estuaries and coastal environments (Diaz, 2001; Rowe, 2001), as a result of the elevated consumption of O_2 .

The bacterial activity in estuaries has not been extensively studied in Brazil. Cesar & Abreu (2001), demonstrated that a large part of the understanding of the functioning of estuaries in Brazil comes from studies of the Lagoa dos Patos Estuary, which has been the focus of various investigations on related bacterial communities (Abreu *et al.*, 1995; Abreu *et al.* 1992; Abreu, 1997).

The estuary of the Itajaí-Açú river, on Santa Catarina coast, has been subjected to several studies since 1995 (Schettini *et al.* 1996, 1998, Schettini, 2002; Pereira Filho *et al.* 2003, Rörig *et al.* 2003, Proença, 2004, Pereira Filho *et al.* 2006). Its watershed has high human population density and strong economic activity, receiving a number of impacts and discharges. As a consequence, chemical characteristics of the river and estuarine waters have been changed (Pereira Filho *et al.* 2003). Next to the mouth of estuary, phytoplankton blooms have been recorded with the occurrence of water discoloration and high biomass (Proença, 2004).

The Itajaí-Açu estuary presents a highly stratified circulation pattern and its transport processes is very dependent of river flow and tides. During high river discharge the river waters are directly delivered to the shelf. On the other hand, during low river discharge the salt intrusion can reach up to 30 km in the inner estuary and tides plays a major role in mixing and transport (Schettini *et al.* 1996, 1998, 2006; Schettini, 2002), with direct implications on the nutrient dynamics (Pereira Filho *et al.* 2003, 2006) and local and nearshore biological processes (Rörig *et al.* 2003; Proença, 2004). The transport and transformation processes in the Itajaí-Açu/inner shelf region are reasonable understood, and its metabolism can be hypothesized following the basic rules where the autotrophy increases as river water nutrients rich becomes less turbidity areas, as it is mixed with coastal waters.

The objective of this study was to investigate and quantify primary and bacterial production along the intense physical and chemical gradients in the lower Itajaí-Açu and the adjacent shelf. It is important to emphasize that the results presented here comes from a short term experiment, although its representativeness is high since the hydrological conditions which it was performed comprises most of the time.

MATERIAL AND METHODS

Study Area

The Itajaí-Açu Estuary is located in the state of Santa Catarina, Southern Brazil (Lat. 26.9°S and Lon. 48.66°). The regional climate is humid subtropical without water deficit, with rains well distributed throughout the year, a typical Cfa, according to the classification system of Köpenn. Mean temperature is about 18°C, with mean annual precipitation and evapotranspiration rates of approximately 1400 mm and 1080 mm, respectively (Gaplan, 1986).

The Itajaí-Açu river basin is the most important in the Santa Catarina State, presenting high human population density and strong economic activity, receiving a number of impacts and discharges. It presents watersheds area of 15,500 km², where the cities of Blumenau, Brusque and Rio do Sul are located. In the lower river state the Itajaí and Navegantes harbors, and an active fishery industry. As a consequence of all these human activities, chemical characteristics of the river and estuarine waters have been changed (Pereira Filho *et al.* 2003).

The Itajaí-Açu river accounts with 90 % of the fresh water input to the estuary, while the remaining 10% is mainly from two smaller tributaries named Luis Alves river and Itajaí Mirim river. The averaged annual discharge of Itajaí river is 228 m³.s⁻¹, with historical minimum and maximum of 17 m³.s⁻¹ and 5390 m³.s⁻¹, respectively (Schettini, 2002). The regional tidal regime is microtidal semi-diurnal, ranging from 0.4 to 1.2 m during neap and spring tide periods, respectively (Schettini, 2002). The physical setting of (i) small tidal range, (ii) highly variable river discharge regime and (iii) the deep and uniform channel morphology results in a highly stratified estuarine structure (Schettini *et al.* 1996). A two water layers structure separated by an intense halocline is observed most of the time, being stronger during neap tide periods. The salt intrusion during low discharge periods extends up to 30 km from the mouth, meanwhile all salt water is flushed out when the river discharge exceeds about 1000 m³.s⁻¹. The former situation usually lasts for weeks until a couple months; meanwhile the latter usually lasts for hours to few days.

Sampling and Sample Processing

The field surveying and incubation experiments were performed on April 17, 18 and 19 of 2000 at five stations located along a transect comprising the lower stretch of Rio Itajaí-açu estuary and the adjacent shelf area (Fig. 1), and under low river discharge condition. The estuary stations #1, #2 and #3 were sampled on April 17; the adjacent shelf stations #4 and #5 were sampled on the follow days, on April 18 and 19, respectively.

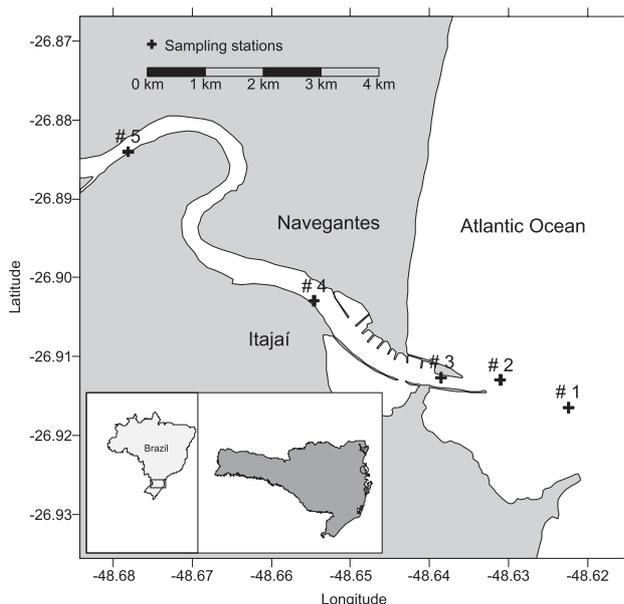


Figure 1 - Lower Itajaí-Açu River Estuary and the 5 sampling stations (1-5), in the Southern Brazil (Santa Catarina).

Vertical profiles of salinity, temperature, turbidity and irradiance were taken in all stations in the beginning of the experiments, for every 0.5 m of water column. Salinity, temperature and turbidity were recorded with a CTD probe model SD-202 by Saiv™ A/S, where the turbidity was an optical backscatter probe by SeaPoint™. The turbidity was converted to mass concentration of suspended sediments (mg.L^{-1}) by a calibration curve. The light irradiance was recorded with a direct reading probe by Licor™.

Water samples were taken at near surface and near bottom for the determination of pH, alkalinity, dissolved inorganic nutrients, chlorophyll-a, and qualitative and quantitative analysis of phytoplankton. Further water samples were taken for the incubation experiments of primary and bacterial productivity. The pH was measured with an Orion™ pHmeter. Alkalinity was analyzed by titration with HCl. The incubations for primary and bacterial production were limited by the number of racks. The incubations experiments were carried out at near surface and near bottom at the estuarine stations #3, #4 and #5, and only at near surface level at station #1, the in the shelf area.

The aliquots for nutrients determinations were kept on ice until processing in the laboratory (up to 3 h). In the laboratory, the samples were filtered (Whatman® GF/F) and frozen for later determination of NH_4^+ , NO_2^- , NO_3^- , PO_4^{3-} and Si(OH)_4 using standard colorimetric methods (Strickland & Parsons, 1972). The filters were also frozen and later utilized for the determination of Chl *a* after extraction with 90% acetone v/v. The pigment quantification was carried out by reverse-phase high efficiency liquid chromatography

(HPLC) according to Mantoura *et al.* (1997). Aliquots of the samples were preserved in Lugol's solution for later identification and quantification of phytoplankton organisms with an inverted microscope according to Utermöhl (1958). Total CO_2 was calculated from pH and alkalinity data, using a model of ionic interaction (Carmouze, 1994). Alkalinity was measured by HCl titration.

River discharge data for the Itajaí-Açu river was obtained with the Brazilian Water Agency for the Indaial linmetric gauge station. This station is located nearly 90 km upstream from the estuarine mouth, although is the closest which does not influenced by tides, and represents nearly 70% of the total drainage basin. The discharge data are available at daily basis since 1929. To characterize the hydrological conditions of discharge and assess the representativeness of the present experiment, it was used the period from 1991 until 2000.

Primary and bacterial productivity

Water samples of 50 ml were transferred to polycarbonate bottles (Zenoko) containing 4.5 mCi $\text{NaHC}^{14}\text{O}_3$ and incubated at different intensities of natural light (*in situ* incubation). After the incubation period, the samples inoculated with C-14 were filtered, transferred to vials that received scintillation cocktail, after elimination of $\text{NaHC}^{14}\text{O}_3$ from filters with HCl. Sample radioactivity was later read in a Packard® scintillation counter. The results obtained were converted to $\text{mg C.m}^{-3}.\text{h}^{-1}$, based on the radioactivity measured (dpm) using the formula described in IOC/UNESCO (1994), for incubation times of 3 to 3.5 h. The results were plotted as Photosynthesis vs. Irradiance curves (Pxl curves) and adjusted to generate mathematical models by using Sigma-plot® software routines. The best model was chosen based on the best equation fitting the Pxl curves, using calculated adjustment coefficients.

During the incubation period, irradiance at the surface was recorded with a Licor® Radiometer. Integrated surface irradiance (I_0) for the period was calculated, considering the total irradiance determined during incubation, which was expressed as $\text{mE.m}^{-2}.\text{s}^{-1}$. The light profile, integrated by the incubation period, was obtained by combining the integrated irradiance at the surface (I_0) with the light profile in the water column at each station. The productivity profile in the water column was calculated by combining the light profiles in the water column and the Pxl curves obtained at each station. From the primary productivity profile, the potential primary productivity was determined for each sample, integrated by depth, expressed in $\text{mg C.m}^{-2}.\text{h}^{-1}$.

For bacterial production, subsamples of 10 ml were supplemented with 7.5 nmol (the pre-checked saturation level) (^3H) methyl-thymidine (TdR purchased from NEN Dupont, specific activity $80 \text{ mCi.}\mu\text{mol}^{-1}$) and

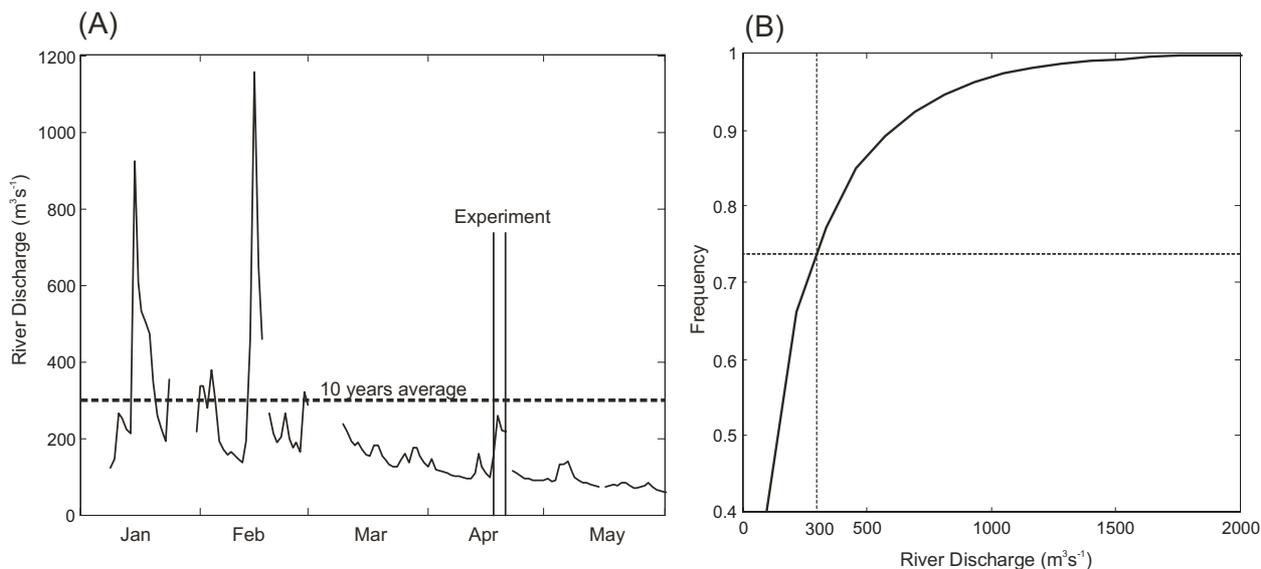


Figure 2 - (A) Hydrogram of daily Itajaí-Açu river discharge for the Jan-May period of 2000, with indication of the period of the experiment. (B) Accumulative frequency distribution of river discharge for the period 1991-2000, with indication of the mean discharge.

incubated in a water bath under *in situ* temperatures. Each determination consisted of 3 replicates and 1 formalin-fixed control. After 45 min, incubation was stopped by adding 200 μ l of 35 % formaldehyde. In the laboratory, samples were filtered through 0.2 μ m polycarbonate membranes. The filters were rinsed 1 time with cooled, pre-filtered (0.2 μ m) seawater and 5 times with 2 ml of a cooled solution of 5 % trichloroacetic acid (TCA) before being transferred to 6 ml vials. Scintillation counting was done in a Packard LSC after a 2 days storage in the scintillation cocktail (Lumagel, Packard). Calibration with a known amount of labelled thymidine allowed the calculation of incorporated thymidine. Bacterial carbon biomass production was estimated by using a conversion factor of 1.5×10^{18} cells mol^{-1} thymidine (Admiraal *et al.* 1985) and 20 fg C cell⁻¹ (Lee and Fuhrmann, 1987).

RESULTS AND DISCUSSION

Physical and chemical variable

The experiment was conducted during low river discharge (average 211 m^3s^{-1}), and after a prolonged period without significant discharge peaks (Fig. 2a). The 10-year averaged discharge (1991-2000) was 300 ± 302 m^3s^{-1} , and discharge values below the average occurs nearly 75% of the time (Fig. 2a). As pointed out by other studies in the Itajaí-Açu estuary, the system presents high hydrological variability (Schettini, 2002; Schettini *et al.*, 2006). This variability rises from two main factors: the meso-thermic climate with rains uniformly distributed along the year (Gapan, 1996), and the reduced size of the drainage basin, what results in short concentration time, i.e. the time elapsed from the beginning of a rain to the peak of discharge, in the order of hours.

Table 1: Calculated equations used to obtain the light profiles and the primary production profile on each sampling site. I_z: Light intensity ($\mu\text{E}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) on the depth z (m), I₀: integrated light intensity in the surface ($\mu\text{E}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). Calculated P_{xl} equations (n=7) showing the relationship between Primary Productivity (PP) and Light Intensity (I) on each sample; the determination coefficients (r²).

Samples	Light Profile Equations	r ²	n	I ₀	P _{xl} Curve Equations	r ²
1S	$I_z = I_0 * e^{-2.22*z}$	0,96	12	80,6	$PP = (0,0687*I)/(1 - 0,0101*I)$	0,99
2S	$I_z = I_0 * e^{-1.37*z}$	0,95	11	80,6		
3S	$I_z = I_0 * e^{-1.23*z}$	0,98	8	80,6	$PP = (0,04616*I)/(1 + 0,0175*I)$	0,83
4S	$I_z = I_0 * e^{-2.92*z}$	0,96	8	429,5	$PP = [(319,1007*I)/(3845,1473+I)] + (-0,0713*I)$	0,74
4B					$PP = (2,7207*I)/(185,6819+I)$	0,88
5S	$I_z = I_0 * e^{-2.86*z}$	1,00	8	1896,5	Bad correlationship	
5B					$PP = 4,4932 - [26,8171/(1 + 0,0042*I)^{5,6593}]$	0,73

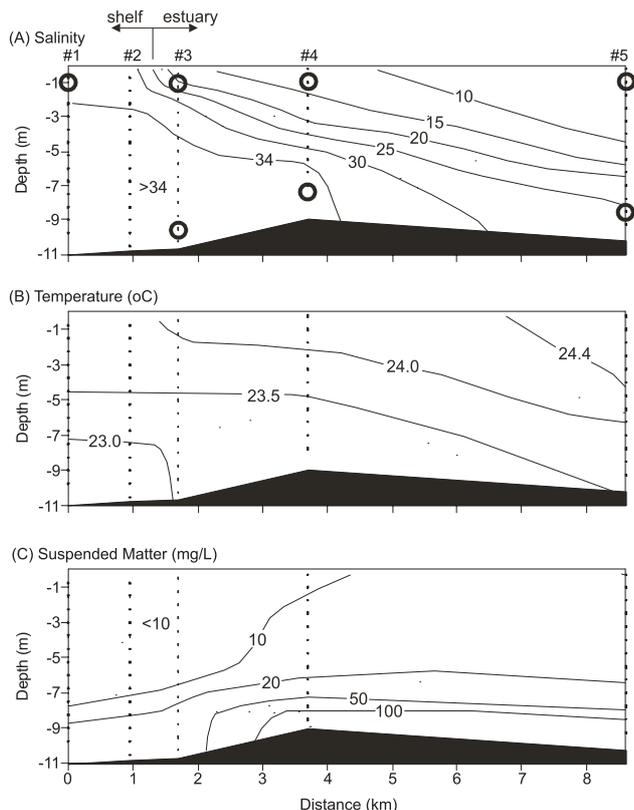


Figure 3 - Spatial distributions of (A) salinity, (B) temperature and (C) particulate suspended matter during the experiment. The hollow circles in the upper panel indicate the location of the incubation experiments.

Additionally, the regional climatology can be inter-annually affected by large-scale phenomena such as El Niño (Grimm *et al.*, 2000). Therefore, river discharge is usually below the averaged value, intercalated with randomly occurrences of high discharge peaks. The periods of low discharge can last for several weeks, or even for several months. Thus, in spite of the present experiment is time limited in terms of observation, it presents reasonable representativeness taking into account the hydrologic conditions.

Salinity ranged from 4 (#5 at surface) to 35 (# 1 at bottom), presenting strong longitudinal and vertical gradient (Fig. 3a), typically observed under the low river discharge condition (Schettini, 2002; Schettini and Toldo, 2006). The temperature did not present significant horizontal or vertical gradient (Fig. 2b). The salinity distribution in the estuary presented a highly stratified/salt wedge pattern, where the salinity increases tens of unities from surface to bottom. The vertical salinity gradient was not so strong at the shelf stations, although with a vertical variation of several unities, indicating the influence of estuarine water in forming a estuarine plume (Schettini *et al.*, 1998; Trochimczuk & Schettini, 2003).

The suspended particulate matter (SPM) concentration ranged from ~10 to higher than 150 mg.L⁻¹, with the highest values being observed near the bottom

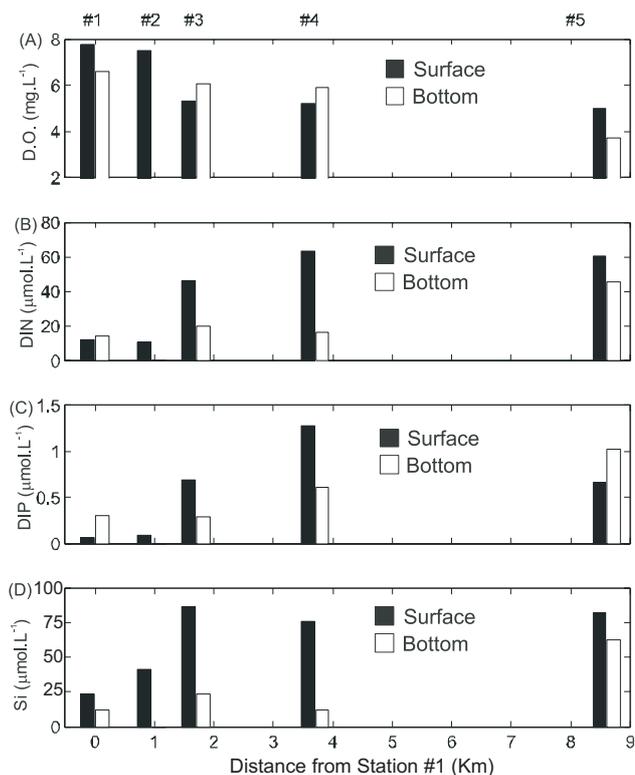


Figure 4 - (A) Dissolved oxygen, (B) dissolved inorganic nitrogen, (C) dissolved inorganic phosphorus and (D) reactive silicate in the Itajaí-Açu River Estuary.

and in the estuary (Fig. 3c). Benthic material resuspension by tidal currents and/or mechanical perturbation caused by ship traffic or dredging are the main factors controlling the SPM distribution in the lower estuary (Schettini and Toldo, 2006). This scenario is strongly modified during river discharge peaks, when the river borne SPM can increase up to 1000 mg.L⁻¹. This invert the SPM vertical structure as the higher concentrations are associated with lighter fresh water, which flows over the heavier coastal saline waters. Nevertheless, such events last shortly from several hours until few days.

The light profiles for each station showed that only the first meters of the water column presented sufficient light for phytoplankton primary production. The attenuation of light was particularly high at the estuarine inner most stations (#4 and #5), meanwhile the influence of coastal waters resulted in deeper euphotic layers in the shelf stations and in the near estuarine mouth station (#1 to #3). The equations that best described the light profiles at each sampling station are shown in Table 1.

The concentrations of dissolved oxygen varied between 3.7 and 7.8 mg.L⁻¹ O₂. The highest values were associated with the surface and with the outermost portion of the estuary, and the lowest were recorded at the inner stations, at the bottom (Fig. 4a). The dissolved

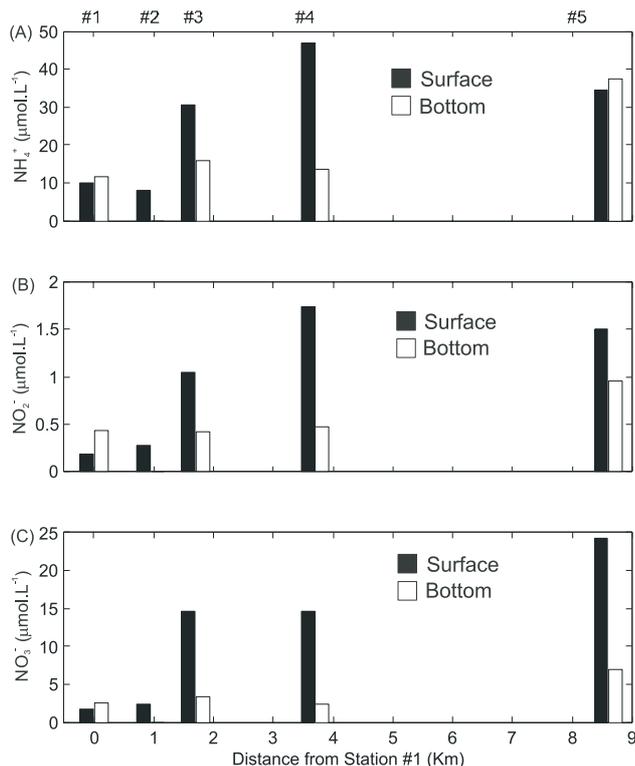


Figure 5 - Dissolved inorganic nitrogen as: (A) N-ammonium, (B) N-nitrite and (C) N-nitrate in surface and bottom samples.

inorganic nutrients presented inverse relationship with salinity. The highest values occurred at the surface and at the inner most stations (#4 and #5), meanwhile the inorganic nitrogen ($\text{DIN} = \text{NH}_4^+ + \text{NO}_2^- + \text{NO}_3^-$), phosphorus ($\text{DIP} = \text{PO}_4^{3-}$) and Silica ($\text{Si} = \text{Si}(\text{OH})_4$) decreased seawards (Fig. 4b, c and d). The concentrations of DIN varied between 12.0 and 63.3 mmol.L^{-1} . NH_4^+ was the main form of DIN (76%) at all the stations, followed by NO_3^- and NO_2^- (Figs. 5a, b and c). The predominance of ammonium over the other nitrogenous nutrients has already been observed in previous studies for this environment (Pereira Filho *et al.* 2003).

The concentrations of DIP varied between 0.1 and 0.8 $\mu\text{mol.L}^{-1}$, and the concentrations of Si varied between 12 and 87 $\mu\text{mol.L}^{-1}$. DIP, Si and NH_4^+ presented non-conservative increases at a salinity range of 10 to 30 (Figs. 6a, b, c, d and e) and suggest decomposition of organic matter along the estuarine gradient. The organic matter would be related to anthropogenic sources, as indicated by the high levels of ammonium. The high turbidity in the estuary favors the predominance of mineralization processes over those associated with phytoplankton primary production, resulting in an increase in nutrients at the inner most stations. The concentrations of Si and DIP were particularly low in the shelf stations, what increases the N:P ratio. At the station #1 the N:P ratio was higher than 200.

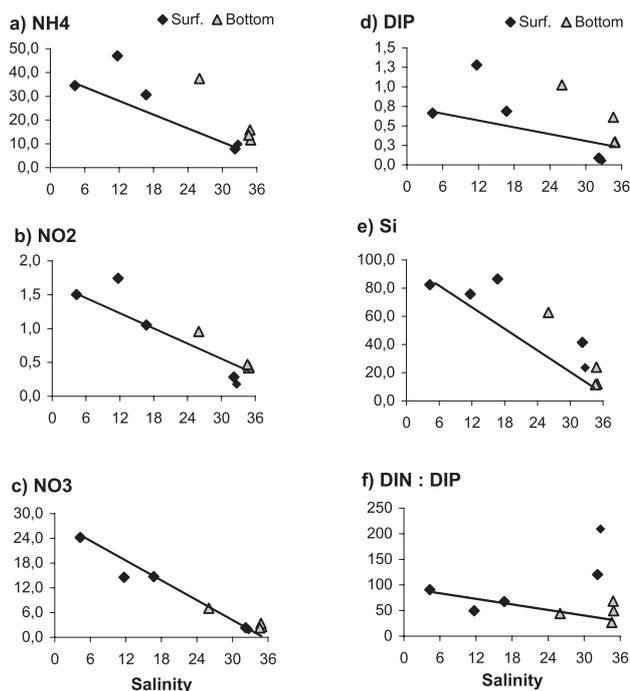


Figure 6 - Property-salinity plots of nutrients ($\mu\text{mol.L}^{-1}$) in the Itajaí-Açu River Estuary. (a) NH_4^+ : N-A ammonium, (b) NO_2^- : N-nitrite, (c) NO_3^- : N-nitrate, (d) DIP: dissolved inorganic phosphorus (P-phosphate), (e) Si: Si-silicate and (f) DIN:DIP ratio.

Chl a and Phytoplankton

The Chl a concentration decreased towards the estuary (Fig. 7a). The highest value was 8.0 $\mu\text{g.L}^{-1}$, at the surface of station #2, similarly to the phytoplankton abundance, which also revealed higher values of cells density at the surface, with a maximum at station #2 (Fig. 7b). Autotrophic organisms were dominant in the stations #1 (surface and bottom), #2 (surface) and #3 (surface), represented by chain forming diatoms (Bacillariophyceae, > 20 μm) (Figs. 8a and b). There was a predominance of the nanoplankton fraction (Fig. 8b) and higher influence of heterotrophic organisms in samples #3 (bottom) and #4 (surface and bottom).

The qualitative and quantitative analysis of the phytoplankton showed various characteristic patterns along the estuarine gradient. The higher cells densities were found at stations with lower turbidity, with the maximum occurring in the outer station (#1). A similar finding had already been recorded in the region under high river discharge condition; however, in that case the maximum values occurred farther from the mouth (Rörig *et al.* 2003). The lowest abundances were found in bottom samples, supporting the notion that light is a critical factor for phytoplankton in the inner estuary, since relatively high levels of nutrients occurred in all water column of most stations. The higher abundance of heterotrophic and nanoplanktonic organisms in bottom samples is a further indication of this process. The

predominance of diatoms in almost all the samples indicates a favorable condition for opportunistic organisms, which benefit from relatively high concentrations of nutrients. However, in the shelf (station #1) the phytoplankton biomass decreased (Figs. 7a and b). This was probably related to dilution effect and decrease in the nutrient concentrations, mainly DIP (Fig. 4d), what increases the N:P ratio, suggesting a limitation of phosphorus to phytoplankton growth in the coastal water.

Primary Productivity

The primary production profiles for each station, are shown in Fig. 9. There was sufficient light for primary production only in the first meters of the water column, mainly in the inner most stations of the estuary (#4 and #5), what can be attributed to the higher turbidity levels. The bottom samples, when exposed to light, showed values of productivity comparable to those obtained at the surface, suggesting that light is a limiting factor for productivity at the bottom for inner most stations and that populations at the bottom are physiologically capable of producing when eventually exposed to high levels of irradiance.

The highest level of primary productivity was recorded at station #1, of the order of $30 \text{ mg C.m}^{-3}.\text{h}^{-1}$, decreasing to less than $2 \text{ mg C.m}^{-3}.\text{h}^{-1}$ at the inner most stations (Fig. 9). This result was expected on the basis of physical, chemical and biological gradients previously

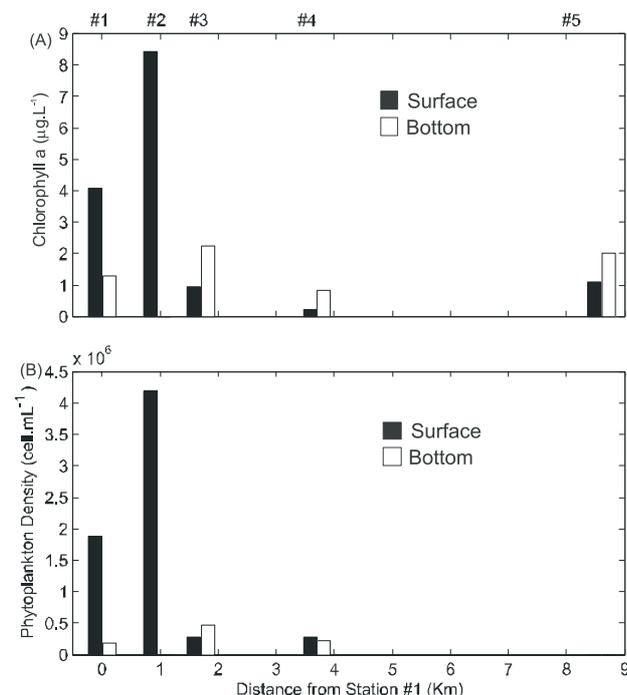


Figure 7 - (A) Chl a concentrations (mg/l) and (B) phytoplankton density (cell/ml) in the Itajaí Açú River Estuary in surface and bottom samples.

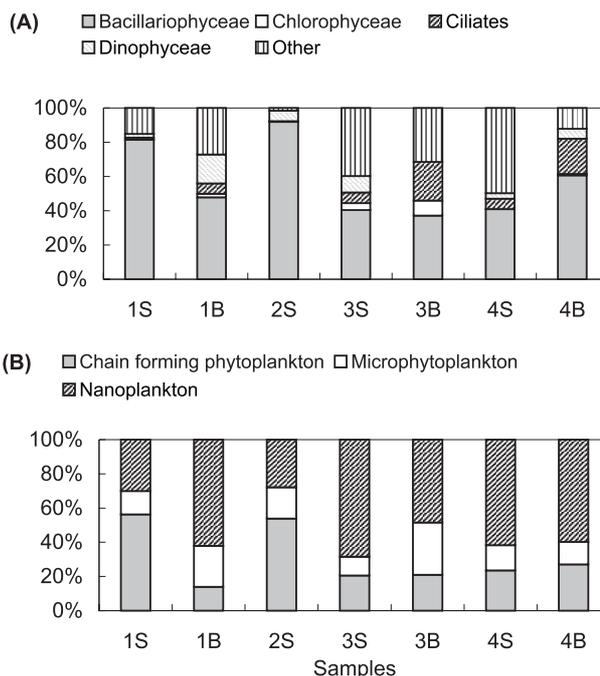


Figure 8 - (A) Phytoplankton group (% from density) and (B) phytoplankton in size class (% in the Itajaí-Açú River Estuary in surface (S) and bottom (B) samples).

described, and resulted from mixing of estuarine water, rich in nutrients although more turbid, with coastal water of low turbidity, resulting in an increase in productivity. A increasing phytoplankton productivity along the estuarine/shelf salinity gradient has been reported in other estuarine systems (e.g., Filardo and Dunstan, 1985; Fisher *et al.* 1988; Robertson *et al.* 1998; Pereira Filho *et al.* 2001). In the present case the localization of the maximum productivity was between stations nearby station #2, where the salinity was 32. The localization of the region of highest productivity differs among different estuaries and within the same estuary under different flow conditions (Dagg *et al.* 2004). In this case, the region of biggest phytoplankton biomass and abundance was situated in the shelf just in front the estuarine mouth. In an study carried out along the Itajaí-Açu estuary and shelf during a period of high river discharge, the gradients were located several kilometers offshore (Schettini *et al.*, 1998; Rörig *et al.* 2003).

The integrated productivity in the water column presented maximum value ($5.9 \text{ mg C.m}^{-2}.\text{h}^{-1}$) at station #1, and decreased towards the estuary where it was of $1.1 \text{ mg C.m}^{-2}.\text{h}^{-1}$ (Fig. 10a). The same tendency was observed for Chl a (Fig. 7a), however, the peak of Chl a was recorded at station #2, where primary productivity was not determined. The distribution of phytoplankton abundance has the same pattern as the productivity, i.e., showing an increase in phytoplankton biomass in the transition of coastal and estuarine waters, with

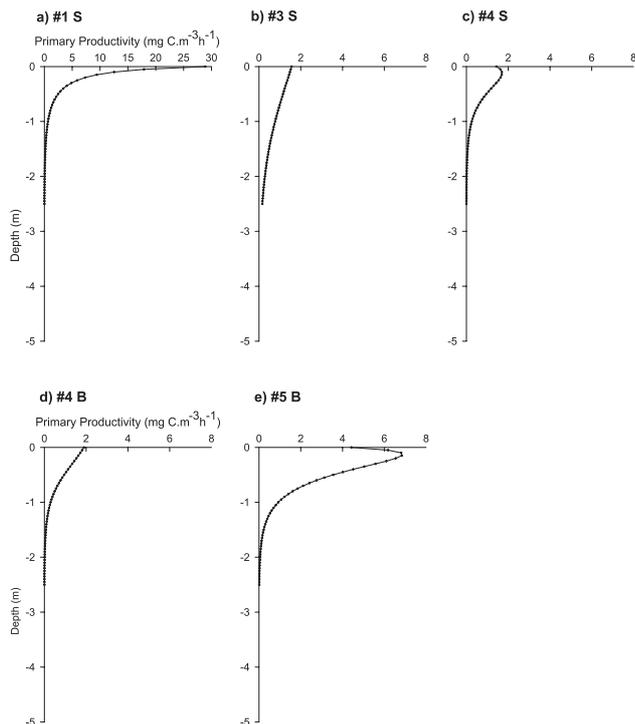


Figure 9 - Profiles of primary productivity estimated for each sampling point. The profiles were calculated using Pxl curves obtained from each sample and from the light profile at each station. S: Surface, B: Bottom.

greater concentration of organisms in the front of estuarine and coastal water masses.

Bacterial Production

The bacterial activity in estuaries has not been extensively studied in Brazil. César and Abreu (2001) demonstrated, based on a compilation of data, that a large part of the understanding of estuaries in Brazil comes from studies of the Lagoa dos Patos Estuary, which has been the focus of various investigations on bacterial communities (Abreu *et al.*, 1995; Abreu *et al.* 1992; Abreu, 1997). In the present study, the bacterial activity increased upstream at stations of intermediate salinity (Fig. 10b). The lowest values were recorded at the bottom, with a minimum of $0.5 \text{ mg C.m}^{-3}.\text{h}^{-1}$, at a salinity of 34.5, while the highest values occurred in samples of the surface with a maximum level of bacterial production of $11.3 \text{ mg C.m}^{-3}.\text{h}^{-1}$ at a salinity of 11. Dagg *et al.* (2004) showed that bacterial production in river plumes, corresponding to a salinity between 8 and 32, is typically higher than that of fresh/brackish (salinity < 2) and coastal (salinity > 33) waters. Meanwhile, the low river flow during this study resulted in the penetration of coastal saline waters into the estuary, differing from the previous situations reported by Schettini *et al.* (1998) and Rörig *et al.* (2003), where equivalent salinities were found at the river plume in the adjacent coastal zone.

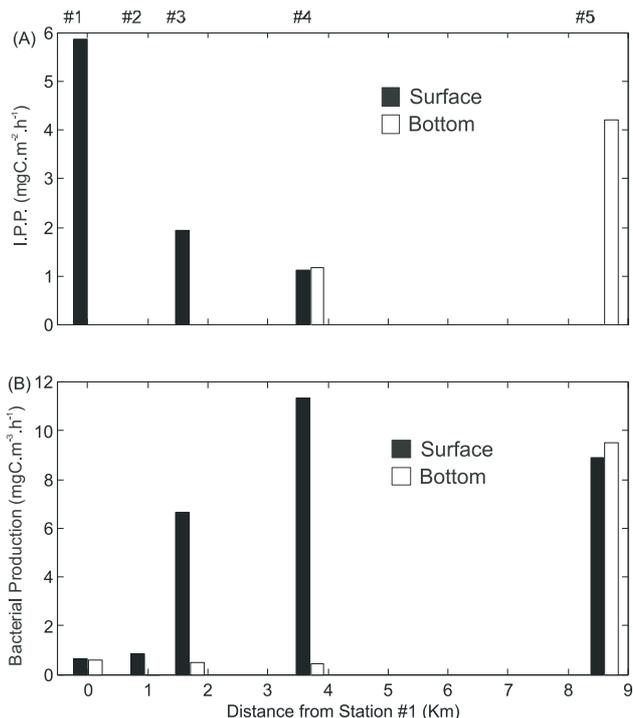


Figure 10 - (A) Potential area of productivity and (B) bacterial production for each sampling site in the Itajaí-Açu River Estuary.

The values obtained were higher than those found for the plume of Lagoa dos Patos, which varied between 0.1 and $6.5 \text{ mg C.m}^{-3}.\text{h}^{-1}$ (Abreu *et al.* 1995), but within the typical range observed for several river plumes (Dagg *et al.* 2004). This pattern can be explained by the influence of salinity, exerting an inhibitory effect on bacterial activity, and by the drop of organic substrates once the estuarine waters mixes with coastal waters. Moreover, the diminution of inorganic nutrients also means a decrease in substrates for bacterial activity. This tendency was also found by Abreu *et al.* (1995) in the region of the estuarine plume of Lagoa dos Patos, in the extreme south of Brazil. They suggested that the decrease in bacterial activity in the region of the estuarine plume was associated with stress caused by the rapid change in salinity in this type of system.

The pattern of variation of bacterial production was inverse to that of Chl *a* (Figs. 7a and 10b), suggesting that phytoplankton biomass does not support bacterial activity, as occurs in oceanic environments (Cole *et al.* 1988). On the other hand, being an estuarine region, the bacterial production was probably sustained by material of allochthonous origin, such as domestic and industrial effluents, and detritus from the drainage of the basin. The increase in bacterial activity coincided with increases in nutrients in the estuary, mainly NH_4^+ , and with a decrease in dissolved O_2 , which also was

related to the decomposition of organic matter throughout the salinity gradient in the estuary.

CONCLUDING REMARKS

The bacterial and primary production rates showed a shift in the lower Itajaí-Açu estuary and the adjacent shelf present from a heterotrophic metabolism (estuary) to an autotrophic metabolism (adjacent shelf) under low discharge condition. The formation of a region of higher productivity occurred in the shelf just in front the estuary mouth, where there was an increase in the levels of primary productivity and phytoplankton biomass. This increase in phytoplankton primary production was the result of an increase in light intensity in the water column, associated with the availability of nutrients from the estuarine water. This pattern was observed in many estuarine ecosystems and their location has been attributed to differences in salinity, and where suspended particulate matter concentration decreased to less than 10 mg.l⁻¹ (Dagg et al, 2004).

The phytoplankton photosynthesis showed a pattern strongly dependent on the irradiance in the estuary, being relevant wherever irradiance was significant. Where the high turbidity prevented light penetration, phototrophic phytoplankton was rare, indicating increased importance of heterotrophic processes. The considerable variability of nutrients and organic matter in almost all transect probably generated the transition between autotrophic to heterotrophic condition. However, phytoplankton was limited by light at the bottom and at the inner most stations and bacterial activity was limited by dilution and osmotic stress produced by the salt influence. On the other hand, in the outer estuary, the low levels of phosphorus and high N:P ratio suggested that the phytoplankton growth was nutrient limited in the coastal waters.

ACKNOWLEDGEMENTS

The authors would like to thank Luciana Spillere who helped in the laboratory analysis and Dr. Albert Leyva who assisted in the preparation of manuscript with English language editing. This research was funded by the International Bureau - GLR (Germany) and is part of the Brazil Germany Cooperation Agreement in Marine Sciences (MCT-Mar41). CNPq grant N.o 306217/2007-4.

REFERENCES

- Abreu, P.C.; Granéli, H.W. & Odebrecht, C.. 1995. Produção fitoplanctônica e bacteriana na região da pluma estuarina da Lagoa dos Patos – RS, Brasil. *Atlântica* 17: 35-52.
- Abreu, P.C.; Biddanda, B.B. & Odebrecht, C. 1992. Bacterial dynamics of the Patos Lagoon Estuary, southern Brazil (32°S, 53°W): relationship with phytoplankton production and suspended material. *Estuarine, Coastal and Shelf Science* 35: 621-635.
- Abreu, P.C. 1997. Coastal and marine environments and their biota - bacterioplankton. p.104-105. In U. Seeliger, C. Odebrecht & J.P. Castello [eds], *Subtropical convergence environments: the coast sea in the southwestern Atlantic*. Springer-Verlag.
- Admiraal, W.; Beukema, J.J. & van Es F.B. 1985. Seasonal fluctuations in the biomass and metabolic activity of bacterioplankton and phytoplankton in a well mixed estuary: the Ems-Dollard (Wadden Sea). *Journal of Plankton Research* 7: 877-890.
- Almeida, M.A.; Cunha, M.A. & Alcântara, F. 2005. Relationship of Bacterioplankton Production with Primary Production and Respiration in a Shallow Estuarine System (Ria de Aveiro, NW Portugal). *Microbiological Research*, 160: 315-328.
- Bowen, J.L. & Valiela, I. 2001. The ecological effects of urbanization of coastal watersheds: historical increases of nitrogen loads and eutrophication of Waquoit Bay estuaries. *Canadian Journal of Fisheries and Aquatic Science* 58 (8): 1489-1500.
- Cesar, D.E. & Abreu, P.C. 2001. Ecology of aquatic microorganisms in southern Brazil: state of art. P. 153-172. In B.M. Faria, V.F. Farjalla & F.C. Esteves, [eds]. *Aquatic microbial ecology in Brazil*. Série Oecologia Brasiliensis, IX. PPGE-UFRJ. Rio de Janeiro.
- Cole, J.J.; Findlay, S. & Pace, M.L. 1988. Bacterial production in fresh and salt ecosystems: a cross system overview. *Marine Ecology Progress Series* 43: 1-10.
- Dagg, M.; Benner, R., Lohrenz, S. & Lawrence, D. 2004. Transformation of dissolved and particulate materials on continental shelves influenced by large rivers: plume processes. *Continental Shelf Research* 24: 833-858.
- Diaz, R.J. 2001. Overview of hypoxia around the world. *Journal of Environmental Quality* 30: 275-281.
- Filardo, M.J. & Dunstan, W.N. 1985. Hydrodynamic control of phytoplankton in low salinity waters of James River estuary, Virginia, USA. *Estuarine, Coastal and Shelf Science* 21: 653-667.
- Fisher, T.R.; Harding Jr., L.W.; Stanley, D.W. & Ward, L.G. 1988. Phytoplankton, nutrients and turbidity in

- the Chesapeake, Delaware and Hudson estuaries. *Estuarine, Coastal and Shelf Science* 27: 61-93.
- IOC/Unesco. 1994. Protocols for the Joint Global Ocean Flux Study (JGOFS) core measurements. IOC Manual and guides: 29. p.170.
- Gaplan - Gabinete de Planejamento de Santa Catarina, 1986. Atlas de Santa Catarina. Rio de Janeiro, Aerofoto Cruzeiro, 173pp.
- Grimm, A.M.; Barros, V.R.; Doyle, M.E. 2000. Climate variability in southern South America associated with El Niño and La Niña events. *Journal of Climate*, 13(1):35-58.
- Lee, S.H. & Fuhrmann, J.A., 1987. Relationships between biovolume and biomass of naturally derived marine bacterioplankton. *Applied Environmental Microbiology* 53: 1298-1303.
- Mantoura, R.F.C.; Barlow, R.G. & Head, E.J.H. 1997. Simple isocratic HPLC methods for chlorophylls and their degradation products. p.207-226. In S.W. Jeffrey, R.F.C. Mantoura and S.W. Wright [eds.], *Phytoplankton pigments in oceanography*. Unesco.
- Pereira Filho, J.; Spillere, L. C. & Schettini, C.A.F. 2006. Itajaí-açu river estuary (Santa Catarina, Brazil): preliminary budget for dissolved inorganic nutrients. *Journal of Coastal Research*, SI (39): 702-706.
- Pereira Filho, J.; Schettini, C.A.F.; Rörig, L. & Siegle, E.. 2001. Intratidal variation and net transport of dissolved inorganic nutrients, POC and Chl a in the Camboriú River Estuary, Brazil. *Estuarine, Coastal and Shelf Science* 53: 249-257.
- Pereira Filho, J.; Spillere, L.C.; Schettini, C.A.F. & Silva, L.F. 2002. Estuário do Rio Camboriú-SC: variação intramareal e transporte residual de nutrientes, COP e clorofila-a em condições de quadratura e sizígia. *Notas Técnicas da Facimar* 6: 137-151.
- Pereira Filho, J.; Spillere, L. C. & Schettini, C.A.F. 2003. Dinâmica de nutrientes na região portuária do Rio Itajaí-Açu. *Atlântica* 25 (1): 11-20.
- Proença, L.A.O. 2004. A red water caused by *Mesodinium rubrum* on the coast of Santa Catarina, Southern Brazil. *Brazilian Journal of Oceanography* 52 (2): 163-171.
- Ram, A.S. P.; Nair, S. & Chandramohan, D. 2007. Bacterial Growth Efficiency in a Tropical Estuary: Seasonal Variability Subsidized by Allochthonous Carbon. *Microbial Ecology*, 53: 591-599.
- Revilla, M.; Ansoategui, A.; Iriarte, A.; Madariaga, I.; Orive, E.; Sarobe, A. & Trigueros, J.M. 2002. Microplankton metabolism along a trophic gradient in a shallow-temperate estuary. *Estuaries* 25 (1): 6-18.
- Robertson, A.I.; Dixon, P. & Alongi, D.M. 1998. The influence of fluvial discharge on pelagic production in the Gulf of Papua, northern Coral Sea. *Estuarine, Coastal and Shelf Science* 46: 319-331.
- Rörig, L.R., Resgalla Jr., C. & C.A.F. Schettini. 2003. Estrutura da assembléia planctônica através do estuário e da pluma do Rio Itajaí-açu. *Revista de Estudos Ambientais* 5 (1): 76-94.
- Rowe, G.T. 2001. Seasonal hypoxia in the bottom water of the Mississippi River Delta. *Journal of Environmental Quality* 30: 281-290.
- Schettini, C. A. F. 2002. Caracterização física do estuário do Rio Itajaí-açu. *Revista Brasileira de Recursos Hídricos* 7 (1): 123-142.
- Schettini, C.A.F., Carvalho, J.L.B. & Jabor, P. 1996. Comparative Hydrology and Suspended Matter Distribution of Four Estuaries in Santa Catarina State – Southern Brazil. *Proceedings of Workshop on Comparative Studies of Temperate Coast Estuaries*, 29-32.
- Schettini, C. A. F., Kuroshima, K.N., Pereira Filho, J., Rörig, L.R. & Resgalla Jr., C. 1998. Oceanographic and ecological processes aspects of Itajaí-açu River plume during a high discharge period. *Anais da Academia Brasileira de Ciências* 70: 325-374.
- Schettini, C.A.F., Ricklefs, K., Trucolo, E.C. & Golbig, V. 2006. Synoptic hydrography of an highly stratified estuary. *Ocean Dynamics* 56(3-4): 308-319.
- Schettini, C.A.F. & Toldo Jr., E.E. 2006. Fine sediment transport modes in the Itajaí-Açu estuary, Southern Brazil. *Journal of Coastal Research* 39(SI):515-519.
- Strickland, J.D. & Parsons, T.R.. 1972. A practical handbook of seawater analysis. 2nd ed. Fisheries Research. Board of Canada Bulletin.
- Trochimczuk, A. & Schettini, C.A.F. 2003. Avaliação da dispersão espacial da pluma do estuário do rio Itajaí-Açu em diferentes períodos de descarga. *Notas Técnicas da Facimar*, 7:83-96.
- Utermöhl, H. 1958. Zur Vervollkommnung der quantitativen Phytoplankton Methodik. *Mitteilung Internationale Vereinigung für theoretische angewandte Limnologie* 9: 1-38.

Submetido: Novembro/2007

Revisado: Janeiro/2009

Aceito: Abril/2009